GPS World *Innovation* Columns

Vol. 1, No. 1 (1990) to Vol. 21, No. 12 (2010)

1.01   GPS: A multipurpose system   Wells, Kleusberg

Wells, D., and A. Kleusberg (1990). GPS: A multipurpose system. *GPS World,*
    January/February, Vol. 1, No. 1, pp. 60-63.
    Innovation: capabilities of GPS; tomorrow's world today (where am I?; where are you?; how
    far am I from you?; how far are you from me?; how far am I from you? Give it your best shot.
    I'm willing to wait; how far am I from you? Give it your best shot. I need to know NOW;
    which way am I pointing?; what time is it?). GPS works by simultaneously measuring the
    distance from a GPS receiver to each of several GPS satellites. GPS is the most accurate time
    transfer method available.

1.02   The limitations of GPS   Kleusberg, Langley

Kleusberg, A., and R.B. Langley (1990). The limitations of GPS. *GPS World,* March/April, Vol.
    1, No. 2, pp. 50-52.
    Innovation: three limitations (GPS signal reception, GPS signal integrity, GPS signal
    accuracy); types of error (satellite errors, signal propagation errors, receiver errors, GPS
    geometry); improving GPS accuracy. The atmosphere claims its toll on the GPS signal twice.
    In general, an increase in position accuracy does not come for free.

1.03   Why is the GPS signal so complex?   Langley

Langley, R. B. (1990). Why is the GPS signal so complex? *GPS World,* May/June, Vol. 1, No. 3,
    pp. 56-59.
    Innovation: the carriers; the codes; the broadcast message; binary biphase modulation.

1.04   Electronic charts and GPS   Casey, Kielland

Casey, M. J., and P. Kielland (1990). Electronic charts and GPS. *GPS World,* July/August, Vol.
    1, No. 4, pp. 56-59.
    Innovation: ECDIS — its capabilities (ECDIS display features, safety of navigation features,
    corrections and updating issues); ECDIS at work (charting problems associated with using
    ECDIS and GPS); GPS accuracy and reliability issues (the integrity issue, differential
    operation, how much positional accuracy and integrity does an ECDIS need? how much
    positional accuracy and integrity can GPS provide? what about selective availability?); future
    GPS performance. When in differential operation, the limiting GPS integrity factor is the
    reliability of the differential data link itself.

1.05   The issue of selective availability   Georgiadou, Doucet

Georgiadou, Y., and K.D. Doucet (1990). The issue of selective availability. *GPS World,*
    September/October, Vol. 1, No. 5, pp. 53-56.
    Innovation: history; implementation; SA effects; can we live with SA?

1.06   Comparing GPS and GLONASS   Kleusberg

Kleusberg, A. (1990). Comparing GPS and GLONASS. *GPS World,* November/December, Vol.
    1, No. 6, pp. 52-54.
    Innovation: comparing systems; combining systems.

2.01   The GPS receiver: An introduction   Langley

Langley, R. B. (1991). The GPS receiver: An introduction. *GPS World,* January, Vol. 2, No. 1,
    pp. 50-53.

Innovation: the antenna; the RF section; the signal trackers; the microprocessor; user interface; data storage and output; the power supply. Most GPS receivers use precision quartz crystal oscillators, enhanced versions of the regulators commonly found in wristwatches.

2.02   Precise, real-time dredge positioning   DeLoach
DeLoach, S. R. (1991). Precise, real-time dredge positioning. *GPS World,* February, Vol. 2, No. 2, pp. 43-45.
> Innovation: reasons for development; history of kinematic GPS; preliminary design; operational constraints; practical considerations. There are many marine platforms, such as a large dredge or a floating buoy used as a tide gauge, that should experience little or no loss of signal.

2.03   The orbits of GPS satellites   Langley
Langley, R. B. (1991). The orbits of GPS satellites. *GPS World,* March, Vol. 2, No. 3, pp. 50-53.
> Innovation: Kepler's Laws; the Keplerian elements; orbit perturbations; launching GPS satellites; orbit data. Newton hypothesized that, given the right initial velocity, a projectile fired from the earth would go into orbit around it. The Master Control Station collects the pseudorange and carrier-phase data obtained by the tracking stations and, with sophisticated software models, predicts the future orbits of the satellites.

2.04   Ionospheric effects on GPS   Klobuchar
Klobuchar, J. A. (1991). Ionospheric effects on GPS. *GPS World,* April, Vol. 2, No. 4, pp. 48-51.
> Innovation: pseudorange error; error correction; range-rate errors; scintillation effects; magnetic storms; solar cycle; conclusion. How the earth's ionosphere perturbs GPS signals and what can be done about it. When severe magnetic storms occur, the auroral effects can move down into the mid-latitudes, and precise positioning with GPS can be affected by the ionosphere over the entire North American landmass for periods lasting up to one or two days.

2.05   GPS vehicle location and navigation   Krakiwsky
Krakiwsky, E. J. (1991). GPS vehicle location and navigation. *GPS World,* May, Vol. 2, No. 5, pp. 50-53.
> Innovation: ancient AVLN systems; modern AVLN systems; terrestrially based AVLN; GPS-based AVLN; outlook. This article looks at a combination GPS and electronic chart system for cars and trucks. The 1990s will be the decade in which AVLN systems will blossom at the high end of the market. Correction: In Table 1, NavTel 2000 should read NAVTRAX (see p. 64, Vol. 2, No. 6, June 1991).

2.06   Continuous monitoring of crustal deformation   Bock
Bock, Y. (1991). Continuous monitoring of crustal deformation. *GPS World,* June, Vol. 2, No. 6, pp. 40-47.
> Innovation: the earthquake process; GPS monitoring; Parkfield alignment array; a Japanese GPS network; Southern California array (network description); handling the data (data storage and dissemination, data processing and software development); prospects for the future. This is an in-depth article on an application of GPS that is of great significance not only to scientists but to society as a whole: the monitoring of earthquake fault motion.

2.07   The mathematics of GPS   Langley

Langley, R. B. (1991). The mathematics of GPS. *GPS World,* July/August, Vol. 2, No. 7, pp. 45-50.

  Innovation: determining positions from pseudoranges (linearization of the pseudorange equations, inconsistent equations); position accuracy measures (user equivalent range error, other accuracy measures); conclusion. This article looks at some of the mathematics involved in determining a position using GPS pseudorange measurements, and examines some of the ways of gauging the accuracy of GPS positions.

2.08   GPS in civil aviation   McDonald

McDonald, K. D. (1991). GPS in civil aviation. *GPS World,* September, Vol. 2, No. 8, pp. 52-59.

  Innovation: background; applications and benefits; GPS civil limitations; aviation community activity; GPS and GLONASS; implementation concerns. This article is on present and future applications of GPS in civil aviation.

2.09   GPS — satellites of opportunity for ionospheric monitoring   Coco

Coco, D. (1991). GPS — Satellites of opportunity for ionospheric monitoring. *GPS World,* October, Vol. 2, No. 9, pp. 47-50.

  Innovation: investigating the ionosphere; GPS ionospheric measurements; the ideal GPS receiver; past efforts and future plans; benefits for other GPS users. The use of GPS satellites to monitor the ionosphere.

2.10   Time, clocks, and GPS   Langley

Langley, R. B. (1991). Time, clocks, and GPS. *GPS World,* November/December, Vol. 2, No. 10, pp. 38-42.

  Innovation: the quartz crystal resonator; atomic resonators; just a second; universal time; GPS time; relativistic effects; selective availability; conclusion. Cesium clocks are well known for their excellent long-term stability. Not even an atomic clock keeps perfect time.

3.01   Using GPS and ROVs to map the ocean   Peyton

Peyton, D. R. (1992). Using GPS and ROVs to map the ocean. *GPS World,* January, Vol. 3, No. 1, pp. 40-44.

  Innovation: motivation; system description; integration of GPS; applications; conclusion. ROVs are used to map the ocean floor. GPS and packet radio antennas are mounted on the ROV's snorkel.

3.02   Basic geodesy for GPS   Langley

Langley, R. B. (1992). Basic geodesy for GPS. *GPS World,* February, Vol. 3, No. 2, pp. 44-49.

  Innovation: historical perspective; the geoid; geodetic coordinates; WGS 84; NAD 83; UTM; conclusion. Geodesists realized that for higher accuracies, the earth's ellipsoidal shape must be taken into account. In effect, WGS 84's coordinate system was realized by adopting coordinates for more than 1500 U.S. Navy Navigation Satellite System (Transit or Doppler) stations worldwide. See Letters, p. 12, Vol. 3, No. 9, October 1992.

3.03   The Federal Radionavigation Plan   Langley

Langley R.B. (1992). The Federal Radionavigation Plan. *GPS World,* March, Vol. 3, No. 3, pp. 50-53.

  Innovation: the systems (Loran-C, Omega, VOR/DME, TACAN, ILS, MLS, Transit, radiobeacons, GPS); conclusions. Both FAA and DoD are studying the feasibility of

replacing VOR/DME with an alternate system such as GPS. Some doubt the need for widely deployed MLS facilities given the improvements recently made to ILS and the potential of global navigation satellite systems. See Letters, p. 12, Vol. 3, No. 8, September 1992.

3.04   Precision long-range DGPS for airborne surveys   Columbo, Peters

Colombo, O. L., and M.F. Peters (1992). Precision long-range DGPS for airborne surveys. *GPS World,* April, Vol. 3, No. 4, pp. 44-50.

Innovation: carrier-phase differential GPS; the crawl of continents; in search of cycle slips; accuracy over long distances; interpreting data with GPS; the Greenland survey; conclusion. The development of a precise differential GPS positioning technique for airborne surveys and its application to a geophysical investigation of Greenland.

3.05   Measuring the earth's rotation and orientation with GPS   Freedman

Freedman, A. P. (1992). Measuring the earth's rotation and orientation with GPS. *GPS World,* May, Vol. 3, No. 5, pp. 42-50.

Innovation: polar motion, universal time; reference frames; solving for earth orientation; recent work; future plans. Just as GPS has become famous for precise and rapid terrestrial positioning, so, too, it should be able to provide precise and frequent estimates of the earth's orientation in space. The collocation of GPS receivers with VLBI sites links the GPS terrestrial reference frame to the VLBI celestial reference frame. Preliminary work suggests that GPS can be used to measure Universal Time changes accurate to better than 100 microseconds over a few hours.

3.06   High-accuracy GPS marine positioning for scientific applications Rocken, Kelecy

Rocken, C., and T.M. Kelecy (1992). High-accuracy GPS marine positioning for scientific applications. *GPS World,* June, Vol. 3, No. 6, pp. 42-47.

Innovation: high-accuracy positioning; marine positioning techniques; kinematic positioning (kinematic positioning, resolution of carrier-phase biases); ocean buoy experiments (Scripps pier experiment, Harvest platform experiment, ERS-1 overflight experiment); conclusion. Another innovative use of GPS — precisely determining the height of the ocean surface. In addition to supporting high-accuracy scientific research, low-cost GPS-equipped buoys can provide an accurate sea surface monitoring network to supplement the global tide gauge network. In the future, housing the GPS antenna and receiver in the buoy would be more practical to avoid the high costs of running a ship during GPS data collection. One of the most encouraging findings is that signal multipath noise in the ocean is considerably lower than on land. See Letters, p. 12, Vol. 3, No. 9, October 1992, including Kelecy and Rocken reply to Liu.

3.07   Precise differential positioning and surveying   Kleusberg

Kleusberg, A. (1992). Precise differential positioning and surveying. *GPS World,* July/August, Vol. 3, No. 7, pp. 50-52.

Innovation: carrier-phase positioning; static differential positioning; pseudokinematic surveying; stop-and-go surveying; rapid static surveying; implications and trends. Methods for precise differential GPS positioning and surveying are looked at and associated observation procedures are described. Also on the horizon is the development of data communication links for GPS surveying receivers and real-time in-field data processing and quality control.

3.08   Measuring velocity using GPS   May

May, M. B. (1992). Measuring velocity using GPS. *GPS World,* September, Vol. 3, No. 8, pp. 58-65.

Innovation: velocity users; basic concepts; GPS receiver measurements; GPS receiver processing; unaided GPS velocity results; GPS/INS integration.

3.09   A new chapter in precise orbit determination   Yunck

Yunck, T. P. (1992). A new chapter in precise orbit determination. *GPS World,* October, Vol. 3, No. 9, pp. 56-61.

Innovation: orbit accuracy; dynamic orbit determination; kinematic tracking with GPS; the whole picture; TOPEX/Poseidon demonstration; future missions; experimental results; final comment; acknowledgements. This article is on the use of GPS receivers on board orbiting spacecraft to determine their orbits with unprecedented accuracy.

3.10   Using GPS-equipped drift buoys for search and rescue operations   Leger

Leger, G. T. (1992). Using GPS equipped drift buoys for search and rescue operations. *GPS World,* November, Vol. 3, No. 10, pp. 36-41.

Innovation: satellite telemetry; GPS positioning; variable geometry; sea trials; sensors. This article is on the development of a drifting buoy that mimics the movement of a four-person life raft or a person wearing a life jacket. It is deployed from an aircraft or a ship in a search area to track the unpredictable movements of floating objects being pushed by winds and currents. The drifter determines its precise location using a GPS receiver. Position and sensor data are relayed to a search and rescue (SAR) coordination centre via a geostationary communications satellite. Tracking the movements of a small number of these drifters will aid coast guards in defining accurate search patterns during SAR operations.

4.01   Effect of the troposphere on GPS measurements   Brunner, Welsch

Brunner, F. K., and W.M. Welsch (1993). Effect of the troposphere on GPS measurements. *GPS World,* January, Vol. 4, No. 1, pp. 42-51.

Innovation: Nature of the delay; measurements; meteorological ground data; estimating zenith delays; effects on geodetic networks; conclusions. As they propagate from a satellite to a receiver on the ground, GPS signals must pass through the earth's atmosphere. In previous columns, the effect that the ionosphere—the ionized part of the atmosphere—had on GPS signals has been examined. Here the effect of the nonionized or neutral part, the bulk of which lies in the troposphere, is discussed.

4.02   Heights and GPS   Schwarz, Sideris

Schwarz, K. -P, and M.G. Sideris (1993). Heights and GPS. *GPS World,* February, Vol. 4, No. 2, pp. 50-56.

Innovation: defining heights; GPS heights; relation to other heights; accuracy; conclusions; the future. A GPS receiver determines its position in three dimensions — latitude, longitude, and height. The height coordinate is different from the horizontal coordinates in both how it is defined and how accurately it can be measured. In this column, the authors delve into the problems associated with determining heights from GPS observations.

4.03   Using GPS to determine the attitude of a spacecraft   Martin-Neira, Lucas

Martín-Neira, M., and R. Lucas (1993). Using GPS to determine the attitude of a spacecraft. *GPS World,* March, Vol. 4, No. 3, pp. 49-54.
    Innovation: GPS attitude determination; noise, cycle slips, multipath; the invariant phase observable; spin-stabilized satellites; LEOs, HEOs, and GEOs; some test results. It is well known, at least to the readers of *GPS World*, that a GPS receiver can accurately determine the position and velocity of a moving platform. Less well known is the fact that with only slightly more sophisticated hardware and software, we can also use GPS to determine the orientation or attitude of the platform. Here is described the development of such a GPS-based system for determining the attitude of orbiting spacecraft.

4.04   The GPS observables   Langley
Langley, R. B. (1993). The GPS observables. *GPS World,* April, Vol. 4, No. 4, pp. 52-59.
    Innovation: The pseudorange; carrier phase; point positions; relative positions (the single differences, the double difference, the triple difference); other linear combinations; conclusions. In previous columns, the structure of the signals transmitted by the GPS satellites and the basic operations performed by a GPS receiver in acquiring and processing the signals have been discussed. Here we take a closer look at the nature of the observations themselves, the biases and errors that afflict them, and how these effects can be removed or mitigated through modeling and data-differencing techniques.

4.05   Communication links for DGPS   Langley
Langley, R. B. (1993). Communication links for DGPS. *GPS World,* May, Vol. 4, No. 5, pp. 47-51.
    Innovation: Differential corrections (LF/MF, HF, VHF/UHF, mobile satellite communications); conclusion. To improve the positioning accuracy of a moving GPS receiver to the level of 10 metres or better, differential techniques must be used. To obtain such accuracy in real time, a datalink must be established between the moving GPS receiver and a fixed reference station. This article examines some of the communication link alternatives currently available or under development.

4.06   Making sense of GPS for marine navigation training   Shaw
Shaw, S. G. (1993). Making sense of GPS for marine navigation training. *GPS World,* June, Vol. 4, No. 6, pp. 40-45.
    Innovation: As GPS approaches full operational capability, it will bring navigators to the brink of a new era. Teachers of navigation in our maritime colleges and other institutions must adequately prepare their students for this era by fully incorporating GPS into the curriculum. Students must learn the principles of the new technology, but they also must be made aware of its limitations and pitfalls. This month's article tells how the California Maritime Academy in Vallejo is innovatively training budding navigators in the use of GPS. The conceptual shift. Trusting the black box (failure to look out the window; waypoint and route errors; failure to appreciate that the system can err; inability to understand or access available information). Learning to learn GPS. A new century and a new era.

4.07   Effects of the equatorial ionosphere on GPS   Wanninger
Wanninger, L. (1993). Effects of the equatorial ionosphere on GPS. *GPS World,* July, Vol. 4, No. 7, pp. 48-54.
    Innovation: When she was good, she was very, very good, but when she was bad, she was

horrid. These lines from the familiar children's nursery rhyme might justifiably be used to describe the ionosphere. Under normal conditions in the mid-latitudes, the ionosphere is for the most part well behaved. GPS receivers can track the satellite signals from near horizon to horizon without difficulty, and the bias contributed by the ionosphere to pseudorange and carrier-phase observations can be readily removed by using dual-frequency observations. However, in the vicinity of the earth's magnetic equator, the ionosphere is at times quite "horrid," making life for the GPS user somewhat difficult. Wanninger describes the behavior of the equatorial ionosphere and how it affects the performance of GPS receivers. Scintillations. Monitoring scintillations. High total electron content. Large horizontal gradients. Conclusions.

4.08   [Showcase issue - no column]

4.09   Inertial navigation and GPS   May
May, M. B. (1993). Inertial navigation and GPS. *GPS World,* September, Vol. 4, No. 9, pp. 56-66.
  Innovation: The Global Positioning System (GPS) and inertial navigation systems (INSs), both of which can be considered discrete systems providing position and velocity information, were once regarded as potentially competing technologies. In this article, we explore the currently more prevalent viewpoint that the complementary or synergistic relationship between GPS and INSs could yield a marriage made in navigation heaven. Inertial navigation operation. History of inertial navigation. Inertial navigation mechanics. INS errors. GPS-INS integration. GPS benefits to INS (Calibration). INS benefits to GPS (Jamming; Velocity; Attitude; Integrity monitoring; Precise positioning). Status. Outlook.

4.10   GPS and the measurement of gravity   Kleusberg
Kleusberg, A. (1993). GPS and the measurement of gravity. *GPS World,* October, Vol. 4, No. 10, pp. 54-56.
  Innovation: This article describes an application of GPS in a supporting role for the measurement of gravity. The article is limited to a brief discussion of the importance of gravity measurements for various fields of science and engineering, the problems encountered when measuring gravity on moving platforms, and how GPS can help to overcome these problems. Gravity and gravity anomalies. The measurement of gravity. Status.

4.11   Relativity and GPS   Ashby
Ashby, N. (1993). Relativity and GPS. *GPS World,* November, Vol. 4, No. 11, pp. 42-47 (incomplete).
  Innovation: Relativistic effects in the Global Positioning System are surprisingly large, and users must carefully account for them, otherwise the system will not work properly. Important relativistic effects arise from relative motions of GPS satellites and users, and from the gravitational field of the earth. Even the earth's rotational motion requires significant relativistic corrections. This article describes these effects, quantifies them, and relates them to Einstein's fundamental principles: the constancy of the speed of light and the principle of equivalence. Constancy of light speed. Time dilation. The principle of equivalence. Sagnac effect. GPS time. Relativity in GPS. Conclusion. See December Showcase, Vol. 4, No. 12, p. 44, 1993 for the complete Conclusions segment of this article.

4.12   [Showcase issue - no column]

5.01   GLONASS receivers: An outline   Gouzhva et al.
Gouzhva, Y., I. Koudryavtsev, V. Korniyenko, and I. Pushkina (1994) GLONASS receivers - an
    outline. *GPS World,* January, Vol. 5, No. 1, pp. 30-36
    Innovation: Although not as close to full operational capability as the U.S. Navstar Global
    Positioning System, the Russian Globalnaya Navigatsionnaya Sputnikovaya Sistema or
    Global Navigation Satellite System (GLONASS) also holds great promise as a "Swiss army
    knife" for all kinds of navigation, positioning, and timing problems. Unfortunately, there has
    been a dearth of readily available detailed information on GLONASS and, in particular, on
    GLONASS user equipment in English. This column will help to remedy this situation with an
    article on the principles of operation of GLONASS receivers. GLONASS basics; GLONASS
    signal structure; GLONASS receiver design (antenna, radio frequency converter, digital
    signal processor, navigation processor, ancillary blocks); Conclusion.

5.02   Detecting nuclear detonations with GPS   Highie, Blocker
Highie, P., and N. K. Blocker (1994). Detecting nuclear detonations with GPS. *GPS World,*
    February, Vol. 5, No. 2, pp. 48-50
    Innovation: Most users of GPS are unaware that the GPS satellites serve a dual role. In
    addition to carrying the navigation and timing payload, the satellites carry a payload that
    enables them to detect nuclear weapons bursts; this system is called the Nuclear Detonation
    (NUDET) Detection System. Starting with the launch of satellite vehicle 8 (PRN 11), the
    GPS satellites have formed an important component in the U.S. arsenal for monitoring
    compliance with the nuclear weapon Non-Proliferation Treaty. This column describes the
    GPS NUDET system.

5.03   Monitoring the earth's atmosphere with GPS   Kursinski
Kursinski, R. (1994). Monitoring the earth's atmosphere with GPS. *GPS World,* March, Vol. 5,
    No. 3, pp. 50-54
    Innovation: The spectrum of GPS uses seems to be limited only by the imagination of its
    users. Over the past four years, this column has examined many innovative ways to use GPS.
    Scientists and engineers have reported on their work dredging harbours, monitoring
    earthquake fault motion, mapping the ocean's surface and floor, studying the earth's rotation,
    finding survivors of marine accidents, determining the attitude of a spacecraft, and
    monitoring nuclear detonations — all with the help of GPS. This month's column features
    yet another innovative use of GPS signals: keeping tabs on the earth's atmosphere. Radio
    occultation. Technique overview. Spatial resolution. Sources of error. Applications.
    Opportunities and conclusion.

5.04   On-the-fly ambiguity resolution   Abidin
Abidin, H. Z. (1994). On-The-Fly ambiguity resolution. *GPS World,* April, Vol. 5, No. 4, pp. 40-
    50
    Innovation: Developments in GPS user equipment technology are happening at a dizzying
    pace. These developments are not just restricted to hardware. Improvements and new
    concepts in software for processing GPS data have been just as noteworthy. One of the most
    recent additions to the GPS toolbox is on-the-fly (OTF) ambiguity resolution — determining
    the correct number of initial integer cycles in carrier-phase measurements, while a receiver is

in motion. Developments in OTF ambiguity resolution have taken place at a number of research labs, and software that incorporates such resolution has recently become available from some receiver manufacturers. However, research is ongoing to provide faster and more reliable resolution. This paper explains some of the concepts involved in OTF ambiguity resolution and describes an algorithmic approach to provide fast and reliable ambiguity resolution. OTF ambiguity resolution; The technique; Computational aspects (use of ellipsoidal search space; use the narrow-land pseudorange position; the search space should be well sized); Geometrical aspects (use a longer wavelength; use more satellites; use fixed-reference satellite differencing; use periods of favorable satellite geometry; use a high data rate; use more than one monitor station); Prospects and limitations.

5.05 RTCM SC-104 DGPS standards   Langley

Langley, R. B. (1994). RTCM SC-104 DGPS standards. *GPS World,* May, Vol. 5, No. 5, pp. 48-53.
   Innovation: In establishing a real-time differential GPS service, service providers are confronted with many choices. In addition to selecting the GPS receiver to be used at the reference station, they must select an appropriate radio communications link and interface it with the GPS receivers at the reference and user stations. The modulation technique and the content and format of the data to be transmitted to the users must also be specified. In an attempt to standardize some aspects of DGPS operation, the Radio Technical Commission for Maritime Services has recommended a standard receiver interface and the content and formation of data messages. In this article, we will take a brief look at these recommendations. Version 2.1. Differential Corrections. Message Format. Message Types (message type 1; message type 2; message type 3; message type 5; message type 5; message type 6; message type 7; message type 9; message type 16; message types 18-21). Datalink. Equipment Interface. With the current level of selective availability, the SC-104 transmission rate is sufficient to keep the one sigma positioning error to less than 3 metres at a 95 percent probability level, even in the case of 11 satellites.

5.06 Wide area differential GPS   Mueller

Mueller, T. (1994). Wide area differential GPS. *GPS World,* June, Vol. 5, No. 6, pp. 36-44.
   Innovation: With real-time differential GPS (DGPS), users can obtain position accuracies better than five metres and, under some circumstances, even better than one metre, utilizing broadcast pseudorange corrections that significantly reduce the effects of satellite position and clock errors (including the contributions of selective availability), and ionospheric and tropospheric propagation delays. However, using DGPS with a single reference station has some drawbacks, including the localization of the highest position accuracies to a relatively small area. To overcome these disadvantages, several research groups are developing the technology of wide area differential GPS (WADGPS). This month's column tells us about WADGPS, its advantages and disadvantages, and the different algorithms that have been developed for its implementation. WADGPS Pros and Cons. Network Architectures. Types of Network Algorithms. Proposed Network Algorithms (measurement domain algorithms; state-space domain algorithms). Performance Estimates.

5.07 RINEX: The receiver-independent exchange format   Gurtner

Gurtner, W. (1994). RINEX: The receiver-independent exchange format. *GPS World,* July, Vol. 5, No. 7, pp. 48-52.

Innovation: The survey in the January 1994 issue of *GPS World* listed some 50 manufacturers of GPS receivers. Most of these manufacturers use their own proprietary formats for recording or outputting the measurements made by their equipment. This Babel of formats could have been a problem for surveyors, geodesists, geophysicists, and others doing postprocessed GPS surveying who wanted to combine data from receivers made by different manufacturers. Luckily, a small group of such users had the foresight several years ago to propose a receiver-independent format for storing GPS data — RINEX. This format has been adopted as the lingua franca of GPS postprocessing software, and most manufacturers now offer a facility for providing data from their receivers in this format. Werner Gurtner, one of the authors of RINEX, outlines the evolution of the format, its inherent philosophy, and the structure of its files. It is important to define precisely the meanings of the observables in RINEX observation files so that they can be properly interpreted by the processing software. Background. The Format (RINEX observation files; RINEX navigation message files; RINEX meteorological data files). Current and Future Status

5.08 [Showcase issue - no column]

5.09 Laser ranging to GPS satellites with centimetre accuracy Degnan, Pavlis
Degnan, J. J., and E.C. Pavlis (1994). Laser ranging to GPS satellites with centimetre accuracy. *GPS World,* September, Vol. 5, No. 9, pp. 62-70.
Innovation: In 1960, Theodore H. Maiman, of the Hughes Aircraft Company, successfully operated the first device to generate an intense beam of highly coherent monochromatic radiation. He called his device a laser — for light amplification by the stimulated emission of radiation. The laser has become ubiquitous, with literally hundreds of uses ranging from optical surgery to precision machining. Lecturers use laser pointers; surveyors use laser distance-measuring devices; police officers use laser radar units to catch speeder. Most of us unwittingly use a laser each time we listen to our CD players — the light reflected from the microscopic pits on the CD is generated by a precisely positioned laser. One application of the laser that is not so well known is satellite laser ranging. This column introduces us to satellite laser ranging and describes the efforts to track two of the Navstar GPS satellites using this technique. SLR Principles. GPS Retroreflector Array. SLR Tracking of GPS. Orbital Analysis and Results.

5.10 GPS simulation May
May, M. B. (1994). GPS simulation. *GPS World,* October, Vol. 5, No. 10, pp. 51-56.
Innovation: Whether one refers to it as virtual reality, augmented reality, or simulation, today's testing facilities enable one to "experience" GPS under dynamic conditions while being in a controlled laboratory environment. The capability to perform repeatable, realistic testing representing varying user, space, and control segment conditions has resulted in significant efficiencies. Test facilities represent the only practical context for the evaluation of responses to many failure modalities. Applications. Mechanization (satellite generator; satellite simulator system; user equipment test facility). Modes of Operation. SA and AS. Current Uses. Outlook.

5.11 GLONASS spacecraft Johnson
Johnson, N. L. (1994). GLONASS spacecraft. *GPS World,* November, Vol. 5, No. 11, pp. 51-58.
Innovation: Despite the significant economic hardships associated with the breakup of the

Soviet Union and the transition to a modern market economy, Russia continues to develop its space programs, albeit at a reduced level compared with that of the Cold War era. In particular, the Russian Global Navigation Satellite System (GLONASS), cousin to the U.S. Navstar Global Positioning system, continues to evolve toward full operational capability with the promise of enhancing the reliability and integrity of positioning using GPS alone. Although Russia is making GLONASS available to the world community, information on certain aspects of its operation is still hard to find. This article gives a detailed description of GLONASS spacecraft, how they are launched, and how the constellation of spacecraft has evolved since the first one was put into orbit in October 1982. Program Background. The Spacecraft (satellite lifetimes). Orbit and Delivery (placing the craft in orbit; deployment phases). Constellation Development. Future Directions.

5.12   [Showcase issue - no column]

6.01   Understanding GPS receiver terminology: A tutorial   Van Dierendonck

Van Dierendonck, A. J. (1995). Understanding GPS receiver terminology: A tutorial. *GPS World,* January, Vol. 6, No. 1, pp. 34-44.

Innovation: Buying a GPS receiver can be a lot more difficult than buying a car. In the Receiver Survey in this issue, no fewer than 275 different receivers are listed, ranging from basic handheld instruments costing a few hundred dollars to geodetic-quality receivers costing, in some cases, quite a bit more than a typical family sedan. In addition to price, these receivers may differ in how they access the GPS signals and how they process them to provide the raw observables or the computed coordinates. A growing lexicon of terms for describing how a GPS receiver works has evolved: codeless, semicodeless, codeless squaring, multibit sampling, all in view, time-to-first-fix — to cite a few. But what do these terms precisely mean and what do they indicate about the capability of a particular receiver? Background. Codeless and Semicodeless (squaring the signals; avoiding squaring's limitations with cross-correlation; codeless vs. semicodeless; performance considerations; interference considerations). Precorrelation Sampling (hard-limiting or 1-bit sampling; multibit sampling; interference considerations). Carrier and Code Tracking (carrier tracking; code-tracking terminology). Satellite-Tracking Strategies. All in View. Time-to-First-Fix. Measurement Accuracy. Receiver Sensitivity.

6.02   New tools for urban GPS surveyors   Santerre, Boulianne

Santerre, R., and M. Boulianne (1995). New tools for urban GPS surveyors. *GPS World,* February, Vol. 6, No. 2, pp. 49-54.

Innovation: GPS is often touted as a go-anywhere, do-anything positioning and navigation system with few, if any, limitations. However, there is one real limitation to GPS: The satellite signals will not pass through most obstacles without being severely attenuated. The strength of the signals received inside buildings, for example, is usually well below the tracking threshold of GPS receivers. Outside, other buildings, trees (especially those with dark, wet foliage), and various structures can effectively block the signals. This presents a problem to GPS users in urban settings, particularly GPS surveyors. This article describes two tools that could greatly benefit the urban GPS surveyor. GPS Mission Planning. Soft-Copy Photogrammetry (testing the method; expanding applications). Up the Telescopic Mast. An Updated Surveyor's Toolbox.

6.03   Ocean tide loading and GPS   Baker et al.

Baker, T. F., D.J. Curtis, and A.H. Dodson (1995). Ocean tide loading and GPS. *GPS World,*
March, Vol. 6, No. 3, pp. 54-59.

Innovation: Everyone is familiar with the tides in the ocean; those of us living near the
seashore or visiting it on holidays have seen the water's ebb and flow. Most of us know a
little about what causes the tides: the combined gravitational pulls of the moon and the sun
on the oceans cause them to deform slightly or bulge; these bulges may be greatly amplified
in narrow, shallow inlets. What may come as a surprise to many is that the solid earth, despite
having an average rigidity about twice that of steel, is actually like an elastic ball, and it too
deforms in response to tidal forces. A person standing on the earth's surface near the equator
moves up and down with respect to the centre of the earth by about half a metre — twice a
day! On top of this so-called body tide, there is an even more subtle displacement of the solid
earth caused by the weight of the tidal waters. This ocean tide loading displacement and its
effect on GPS measurements is the subject of this month's column. Tides in the Earth.
Modelling Ocean Tide Loading. Ocean Tide Loading in the U.K. GPS Measurements. Future
Developments.

6.04   A new way to fix carrier-phase ambiguities   Teunissen et al.

Teunissen, P. J. G., P.J. de Jonge, and C.C.J. M. Tiberius (1995). A new way to fix carrier-phase
ambiguities. *GPS World,* April, Vol. 6, No. 4, pp. 58-61.

Innovation; Of the two basic GPS observables, the pseudorange and the carrier phase, the
carrier phase is by far the more precise. It has, however, an Achilles' heel: the initial
measurements of the carrier phases of the signals received by a GPS receiver as it starts
tracking the signals are undetermined, or ambiguous, by an integer number of carrier
wavelengths. A GPS receiver has no way of distinguishing one carrier cycle from another.
The best it can do is measure the fractional phase and then keep track of phase changes.
Therefore, the initial unknown ambiguities must be estimated from the GPS data, and the
correct estimates must be integers. There lies the rub: what is the best way to determine the
correct integer ambiguities? Much research has been performed to find the most efficient,
dependable, and accurate way to fix the ambiguities at their correct integer values. In this
article we will learn of a new approach for ambiguity fixing: the least-squares ambiguity
decorrelation adjustment method devised by a team of researchers from Delft Geodetic
Computing Centre. Why Fix Ambiguities? Integer Least Squares. An Inefficient Search. The
Ideal Situation. Decorrelated Ambiguities. The N-Dimensional Case. Test Results (Reduction
in elongation; Improvement in precision; Efficiency; A further test).

6.05   Why on-the-fly?   DeLoach et al.

DeLoach, S. R., D.E. Wells, and D. Dodd (1995). Why on-the-fly? *GPS World,* May, Vol. 6, No.
5, pp. 53-58.

Innovation: A lot of research and development effort is going into finding fast and efficient
ways to resolve carrier-phase ambiguities. Such methods can enable GPS users to realize
easily the maximum potential accuracy of GPS phase measurements for almost any
application. With a quick and easy-to-implement technique to resolve ambiguities, GPS users
can process carrier-phase measurements as easily as pseudorange measurements, even in real
time. One such very promising technique is on-the-fly (OTF) ambiguity resolution, which
allows ambiguities to be resolved even when a receiver is in motion. This month, we will
briefly review the hows and whys of OTF ambiguity resolution and look at a number of very

encouraging OTF tests in the marine environment. What is OTF? Why do we Need OTF? What is OTF's Status Today? (Kennebecasis Bay test; The Reversing Falls test; Testing the maximum range of OTF; OTF tide buoy test; OTF reliability test). What is the Impact of OTF?

6.06   DGPS with NASA's ACTS   Austin, Dendy

Austin, A., and R. Dendy (1995). DGPS with NASA's ACTS. *GPS World,* June, Vol. 6, No. 6, pp. 42-50.

Innovation: The use of differential GPS (DGPS) is growing at a rapid rate. Witness the ongoing deployment of DGPS-enhanced low- and medium-frequency (LF and MF) beacon stations by the U.S. Coast Guard and other agencies in the United States and elsewhere, the recent introduction of commercial FM subcarrier-based DGPS correction services, and the increased use of private, site- or project-specific DGPS stations using high, very high, or ultrahigh frequency (HF, VHF, or UHF) communications links. These local DGPS operations can yield pseudorange-derived position accuracies at a few-meter level and, in some cases, even better than 1 m. But there are some limitations to these DGPS systems. The VHF and UHF systems are suitable for only line-of-sight use; the LF, MF, and HF systems must contend with noise and the vagaries of propagation; and most of these terrestrial systems are constrained to relatively narrow radio-frequency bandwidths that limit the rate at which DGPS corrections can be transmitted. These constraints may be circumvented by using satellites to transmit the corrections. The use of satellites to transmit DGPS corrections is not a new idea and already some commercial satellite-delivered DGPS services are available. But given their huge potential, much research remains to be done to push the edges of the technology envelope of such services. These limits are being pushed, in part, through a series of tests using a National Aeronautics and Space Administration (NASA) experimental satellite in geosynchronous orbit above a spot about 800 km west of the Galapagos Islands. This satellite, NASA's Advanced Communications Technology Satellite (ACTS), was launched in 1993 to test new satellite communications technologies and new services these technologies could provide. Among these services is DGPS. ACTS DGPS experiments are described and some of the results are given. ACTS technologies (spot beams; onboard switching; high rates). DGPS tests (static tests; kinematic tests). Communications performance (transmission latency; bit error rate). Conclusions and forecast.

6.07   NMEA 0183: A GPS receiver interface standard   Langley

Langley, R. B. (1995). NMEA 0183: A GPS receiver interface standard. *GPS World,* July, Vol. 6, No. 7, pp. 54-57.

Innovation: The world of GPS receiver interfaces and data formats is a veritable alphabet soup of acronyms: RS-422-A, RTCM SC-104, AX.25, ARINC 429, TTL, PCMCIA; the list goes on and on. One acronym that has generated a lot of recent interest is NMEA 0183. It is the name of the standard developed by the National Marine Electronics Association for interfacing marine electronic devices, and it has become a standard interface for GPS receivers whether they're used at sea, on land, or in the air. In this month's column, we'll take a brief look at this interface standard and overview its electrical characteristics, data types, and data formats. Electrical characteristics. Data formats. Software.

6.08   [Showcase issue - no column]

6.09   Mathematics of attitude determination with GPS   Kleusberg

Kleusberg, A. (1995). Mathematics of attitude determination with GPS. *GPS World,* September, Vol. 6, No. 9, pp. 72-78.

Innovation: Several "Innovation" columns in earlier issues of *GPS World* described applications of GPS for the determination of attitude for aircraft, vessels, and spacecraft. These previous articles focused on the performance of GPS attitude systems in terms of accuracy and described the main error sources in GPS signals. The present "Innovation" article complements these earlier ones with a tutorial on the basic mathematics behind attitude description and determination. The equations and derivations in the article use a number of simplifying assumptions that may not be completely valid in real-life applications. The reader should be aware of these limitations, which are listed at the end of the article. The meaning of attitude. Rotation angles and matrices. The local level system. Body fixed system. Attitude from GPS. Practical considerations.

6.10   A GPS glossary   Langley

Langley, R. B. (1995). A GPS glossary. *GPS World,* October, Vol. 6, No. 10, pp. 61-63.

Innovation: The GPS lexicon can be overwhelming for newcomers to the technology. The different languages of the wide range of technologies that comprise GPS can sometimes be confusing to industry experts as well. In this month's column, we present a glossary of some of the more frequently encountered GPS terms — from almanac to Z-count — to assist the newcomer and expert alike. almanac, ambiguity, antispoofing, binary biphase modulation, coarse acquisition, carrier, carrier phase, carrier-to-noise power density, carrier-tracking loop, chip, circular error probable, code-tracking loop, costas loop, cycle slip, delay-lock loop, differential GPS, dilution of precision, doppler effect, double difference, ephemeris, geodetic datum, geodetic height, geoid, geoidal height, GLONASS, GPS time, GPS week, hand-over word, Kalman filter, Keplerian elements, L-band, local area DGPS, microstrip antenna, multipath, multiplexing, narrow correlator, narrow lane, navigation message, NMEA 0183, on-the-fly, orthometric height, precision code, phase-lock loop, precise positioning service, pseudorandom noise code, pseudorange, quadrifilar helix, real-time kinematic, RINEX, RTCM SC-104, selective availability, single difference, spherical error probable, spread-spectrum, standard positioning service, triple difference, coordinated universal time, user equivalent range error, UT1, wide area augmentation system, wide area DGPS, wide-lane observable, world geodetic system 1984, y-code, z-count.

6.11   GPS and the Internet   Langley

Langley, R. B. (1995). GPS and the Internet. *GPS World,* November, Vol. 6, No. 11, pp. 59-63.

Innovation: The Internet is revolutionizing the way we communicate and exchange information. Everyone from government officials to restaurant managers now seems to be using this "supernetwork" to get or give information. Some of the bits whizzing back and forth on it are messages and files that have something to do with GPS. In this month's column we'll take a look at just how the Internet is being used to disseminate information about GPS, GPS data, and related products. GPS on the net. Discussion groups. Internet terminology.

6.12   [Showcase issue - no column]

7.01   The GPS user's bookshelf   Langley

Langley, R. B. (1996). The GPS user's bookshelf. *GPS World,* January, Vol. 7, No. 1, pp. 56-63.
Innovation: In November's column we took a look at the various sources of GPS information in electronic format available through the Internet. This month, we turn to the printed word and present an overview of the growing library of books and other publications about GPS and its many applications. Introductory (the Trimble booklets; Getting Started with GPS Surveying; A Comprehensive Guide to Land Navigation with GPS; the Federal Radionavigation Plan). Intermediate (the Navstar Global Positioning System; Guide to GPS Positioning; Global Navigation — A GPS User's Guide; Aviator's Guide to GPS). Advanced (the red books; Global Positioning System, Theory and Practice; GPS Satellite Surveying; ICDS-GPS-200; Global Positioning System Standard Positioning Service Signal Specification; The Global Positioning System: A Shared National Asset; The Global Positioning system: Charting the Future). Proceedings and journals. Forthcoming (GPS — Theory and Applications; GPS for Geodesy; The Global Positioning System and GIS; Understanding GPS: Principles and Applications).

7.02 The synergy of VLBI and GPS   Gipson

Gipson, J. (1996). The synergy of VLBI and GPS. *GPS World,* February, Vol. 7, No. 2, pp. 49-55.
Innovation: Although developed in the mid-1960s by rival teams of American and Canadian radio astronomers for studying compact extragalactic radio sources such as quasars, very long baseline interferometry (VLBI) was quickly taken up by geoscientists as a tool for studying the earth. VLBI uses two or more radio telescopes to pick up the extremely faint signals from quasars and their kin. The technique is extremely sensitive to the relative positions of the radio telescope antennas and, with the appropriate signal processing, these positions can be determined to the subcentimetre level, even if the baselines connecting the antennas span a continent or an ocean. Gipson describes the VLBI technique, how it has been used to learn more about how the earth "works," and the similarities and differences between VLBI and GPS and their important synergistic relationship. VLBI and geophysics. How an interferometer works. What is a quasar? The VLBI technique. Comparison of VLBI and GPS. Station positions. The future.

7.03 Double duty: Russia's DGPS/DGLONASS maritime service Chistyakov et al.

Chistyakov, V. V., S.V. Filatchenkov, V.I. Khimulin, and V.V. Kornyenko (1996). Double duty: Russia's DGPS/DGLONASS maritime service. *GPS World,* March, Vol. 7, No. 3, pp. 59-62.
Innovation: The Russian Institute of Radionavigation and Time (RIRT) is developing a differential Global Navigation Satellite System (DGNSS) service that combines GPS and GLONASS differential corrections to provide safe passage to vessels traveling in Russia's coastal waters. RIRT scientists and engineers have developed this single datalink service by taking advantage of the different update rates needed for GPS and GLONASS corrections. This article describes how the service will work, including the different message types that will be transmitted. The authors all work at RIRT in St. Petersburg. System requirements. Message types. By making the structure of DGPS and DGLONASS messages analogous, both manufacturers and users will benefit from DGNSS equipment simplification. Schedule of messages.

7.04 The role of the clock in a GPS receiver   Misra

Misra, P. N. (1996). The role of the clock in a GPS receiver. *GPS World,* April, Vol. 7, No. 4, pp. 60-66.

Innovation: It sounds a little strange but the most precise way of measuring a distance is to use a clock. Time, the quantity most difficult to define, is the one we know how to measure most precisely. In fact, the length of the metre is defined in terms of the length of the second through the adopted value of the speed of light in a vacuum. It is this fundamental relationship (distance = speed x time) that is at the heart of how GPS works. By measuring the time elapsed for a signal to propagate from a satellite to a receiver and multiplying it by the speed of light, a GPS receiver can determine the range to the satellite. But there's a hitch. Any error in the time-keeping capability of the receiver's clock will be reflected in the computed range. In this month's column, Dr. Misra, will review the role of the clock in a GPS receiver and the effect its performance has on GPS position accuracy. How perfect is perfect? Correlations of 4-D estimates. Clock modelling. Clock-aided navigation. Additional benefits (RAIM; carrier-phase processing).

7.05   The promise of a third frequency   Hatch

Hatch, R. R. (1996). The promise of a third frequency. *GPS World,* May, Vol. 7, No. 5, pp. 55-58. See Letter to Editor, McGibney, D.B., "On a different wavelength," Vol. 8, No. 1, January 1997, p. 12.

Innovation: The recently published reports by the National Academy of Public Administration and the National Research Council recommended the implementation of a third GPS navigation frequency. The motivation for a third frequency was to provide an unrestricted means for measuring the induced ionospheric refraction errors on code and carrier-phase measurements. In this month's column, Ron Hatch discusses the implications that the addition of a third frequency would have not only in reducing ionospheric effects but also in assisting in the resolution of carrier-phase ambiguities and hence in permitting centimetre-level, wide-area differential accuracy. Hatch, a principal with the recently formed company Navcom Technology in Wilmington, California, has a long and distinguished involvement with satellite navigation. He has developed a number of unique processing techniques for the U.S. Navy Navigation Satellite System — commonly known as Transit — as well as for GPS. Perhaps his most widely used GPS innovation is the smoothing of code measurements using the carrier phase. The wide lane (code measurement, carrier-phase measurement, calculating the wide lane). The effect of noise. A second wide lane.

7.06   Navigation solution accuracy from a spaceborne GPS receiver   Mitchell et al.

Mitchell, S., B. Jackson, S. Cubbedge, and T. Higbee (1996). Navigation solution accuracy from a spaceborne GPS receiver. *GPS World,* June, Vol. 7, No. 6, pp. 42-50.

Innovation: GPS receivers are being put to work not just on and near the earth's surface but in space as well. More than 20 spacecraft containing GPS receivers have been orbited so far, and another 40-50 spacecraft already in the design or construction stage are slated to carry GPS receivers. Spaceborne GPS receiver applications include position and velocity measurements, precise time referencing, precision orbit determination using differential techniques, and characterization of the earth's atmosphere. GPS data can also be used on board a spacecraft to perform autonomous navigation. In this month's column, we will examine the performance of the GPS receiver on board the DARPASAT spacecraft. DARPASAT was constructed for the Defense Applied Research Projects Agency (DARPA)

by Ball Aerospace and Technology Corporation in Boulder, Colorado. GPS nav solution accuracy (data gathering; data selection; data analysis; comparison to ranging solution).

7.07   Gravity and GPS: The G connection   May

May, M. B. (1996). Gravity and GPS: The G connection. *GPS World,* July, Vol. 7, No. 7, pp. 53-57.
Innovation: The advances in GPS and terrestrial gravity-measurement technology are so intertwined that it is difficult to discern which is the driving force. The two fields are intimately connected through fundamental laws of science and through mundane practical necessities. In this column we will explore how research in one field has facilitated advancements in the other. Basic gravitational quantities (disturbance quantities; gravity field spectral power). Quality relationships. Gravity databases (gravimeter measurements; artificial satellites; refined gravity models). Present status. Additional techniques. Future development.

7.08   [Showcase issue - no column]

7.09   International terrestrial reference frame   Boucher, Altamimi

Boucher, C., and Z. Altamimi (1996). International terrestrial reference frame. *GPS World,* September, Vol. 7, No. 9, pp. 71-74. See letter to the editor, "Arbitrary alterations," by Thomás Soler, Vol. 8, No. 2, February 1997, p. 12; and answer by C. Boucher, Vol. 8, No. 2, February 1997, p. 12.
Innovation: To answer the question "Where am I?" we could describe verbally our position with respect to nearby landmarks, but it is usually far more useful to describe our position with respect to a reference system of mathematical coordinates. Such systems covering regional land masses have been established by national survey organizations over the past 100 years or so. With the advent of space techniques in geodesy and navigation, there was a need for the development of global or international reference systems and their realizations through the establishment of coordinate reference frames. Several such systems and frames have been introduced, including the series of U.S. Department of Defense World Geodetic Systems. The highest-accuracy global frame is the International Terrestrial Reference Frame (ITRF) established by the Paris-based International Earth Rotation Service. This column will look at the development of the ITRF and its relationship to GPS. ITRF computation. ITRF datum definition (orientation; origin; scale; time evolution). Transformation parameters. ITRF and GPS (ITRF coordinates for GPS sites).

7.10   Measuring GPS receiver performance: A new approach   Gourevitch

Gourevitch, S. (1996). Measuring GPS receiver performance: A new approach. *GPS World,* October, Vol. 7, No. 10, pp. 56-62.
Innovation: What is the best way to compare GPS receivers? That depends. Many features could be considered: Size, ease-of-use, power requirements, cost, and so forth. Those receiver characteristics are fairly easy to enumerate. But receiver performance or the precision and accuracy of the observables — the pseudorange and carrier phase — and the positions computed from them is a little harder to quantify. Unfortunately, some quoted measures of performance tell us very little about how a receiver actually measures up. In this month's column, Sergei Gourevitch points out the problems with some performance measures and suggests an innovative way to assess a GPS receiver's performance. General considerations.

Zero-baseline tests. Test range measurements. The whole story. SVAR. What does it all mean? Very long smoothing times. Dual-frequency receivers.

7.11   GPS for military air surveillance   Van Sickle

Van Sickle, G. A. (1996). GPS for military air surveillance. *GPS World*, November, Vol. 7, No. 11, pp. 56-59.

Innovation: One of the most important and unsung developments of the Second World War was the IFF (Identification Friend or Foe) system. A primitive radar identification system, IFF used a ground-based transmitter to broadcast a pair of coded pulses to aircraft within its range. Friendly aircraft were equipped with a transponder that received the pulses and, if the signal required a response, would transmit a uniquely coded and formatted reply that could be used to determine the specific aircraft's identity. This would then be overlain on a radar display. If an aircraft did not reply or replied with the incorrect code or in the incorrect format, it was assumed to be an enemy aircraft. This system was the progenitor of the modern secondary surveillance radar systems that are used for air surveillance by both military and civil authorities. The modern systems have been able to report an aircraft's altitude, in addition to its identity, for some time now. A new capability is currently being added to civilian systems that will use a GPS receiver on board the aircraft to determine its position and self-report it to air traffic control centers and other aircraft in the vicinity. In this column, these new developments in civil air surveillance will be described and their potential use by the military, which seems to be lagging behind the civil community in this area. What is the problem? The commercial approach. The first steps. The road to ADS-B. The power of CDTI.

7.12   [Showcase issue - no column]

8.01   Coordinates and datums and maps! Oh my!   Featherstone, Langley

Featherstone, W., and R.B. Langley (1997). Coordinates and datums and maps! Oh my! *GPS World*, January, Vol. 8, No. 1, pp. 34-41. See letter to editor by Michael Kennedy, "Coordinates, datums, indeed!" Vol. 8, No. 3, March 1997, p. 12.

Innovation: The walk through the enchanted forest of Oz, with its lions and tigers and bears, was a pretty scary proposition for Dorothy Gale and her friends. Some GPS users find themselves in a similar predicament when they try to understand the enchanted forest of geodesy and the relationship among coordinates, datums, and maps. This column sketches the relationships among the coordinate systems used worldwide for GPS and the coordinate systems and map projections used in various countries. They also discuss how these differences can affect the GPS user when employed incorrectly. Putting GPS on the map. Choose wisely. Transforming coordinates (block shift; Similarity transformations; Projective transformations). Map projections. The links. GPS receiver features. And finally.

8.02   Carrier phase wrap-up induced by rotating GPS antennas   Tetwsky, Mullen

Tetewsky, A. K., and F.E. Mullen (1997). Carrier phase wrap-up induced by rotating GPS antennas. *GPS World*, February, Vol. 8, No. 2, pp. p. 51-57.

Innovation: GPS receivers are ubiquitous. They are now used for a myriad of applications and can be found in the hands of navy frogmen, mounted on tractors, carried aloft by weather balloons, and orbiting in spacecraft. And the miniaturization of receivers allows them to be embedded in such diverse devices as cellular telephones and artillery shells. GPS receivers

work more or less the same way regardless of the kind of platform they are attached to. However, some users have recently concluded that, if the platform is spinning, a rotational effect must be accounted for: carrier phase wrap-up. This effect is the change in the GPS carrier phase caused by rotation of a circularly polarized receiving antenna relative to a circularly polarized GPS signal. If the wrap-up effect is not accounted for, a receiver can make significant position fix errors when fewer than four satellites are in view. This column presents an intuitive derivation of the effect and summarizes the results of an innovative procedure to calculate phase wrap-up. Also presented are predictions for a common antenna type — the crossed dipole — and these are compared with GPS measurements collected from a rooftop spinning-antenna experiment. An intuitive view. General model (calculations and analysis; base mounted; circumference mounted). Experimental data. Summary.

8.03 The GPS error budget   Langley

Langley, R. B. (1997). The GPS error budget. *GPS World*, March, Vol. 8, No. 3, pp. 51-56.
  Innovation: No measuring device is perfect, whether it be a yardstick or a precision analytical balance. A GPS receiver is no exception. The receiver attempts to determine the distances, or ranges, between its antenna and the transmitting antennas of the satellites whose signals it has picked up. Based on those ranges and a knowledge of satellite locations, the receiver can compute its position. However, several errors corrupt range measurements and consequently propagate into the receiver-computed positions. Here we will examine the different errors that corrupt range measurements made by a stand-along GPS receiver operating under the Standard Position Service (SPS). Although higher positioning accuracies can be achieved with differential techniques — even to the subcentimeter level — we will restrict our attention to the stand-alone receiver, by far the largest "species group" in the GPS user community. We will look at the causes of the SPS errors and their typical magnitudes and what, if anything, can be done to ameliorate them. A satellite's signal (measuring the pseudorange). Ephemerides. GPS, clocks, and time (keeping satellite time; intentional signal degradation; receiver clocks). Propagation delays (ionosphere; troposphere; mapping functions). Multipath. Receiver noise (code tracking loop). Dilution of precision.

8.04 Conquering multipath: The GPS accuracy battle   Weill

Weill, L. R. (1997). Conquering multipath: The GPS accuracy battle. *GPS World*, April, Vol. 8, No. 4, pp. 59-66.
  Innovation: We will take a closer look at multipath and the techniques for mitigating its effects, including some recent innovative receiver design. The multipath problem. Spatial mitigation techniques (special antennas; multiantenna spatial processing; antenna location strategy; long-term signal observation). Receiver processing methods (standard range measurements; a correlation function's leading edge; narrow-correlator technology (1990-93); correlation-function shapes (1994-95); the strobe correlator; modified correlator reference waveforms). How good can it get? Carrier-phase ranging. Receiver testing.

8.05 Performance overview of two WADGPS algorithms   Abousalem

Abousalem, M. A. (1997). Performance overview of two WADGPS algorithms. *GPS World*, May, Vol. 8, No. 5, pp. 48-58.
  Innovation: In response to the current growing demand for low-cost, country- and continent-wide differential GPS (DGPS) positioning, and with the help of the ever-advancing communication and computer technologies, industry innovators have recently developed a

variety of real-time DGPS techniques, including wide area differential GPS (WADGPS). The catalyst for this evolution in DGPS has been the accuracy, availability, and accessibility limitations of conventional DGPS techniques. The advantages of WADGPS include coverage of large, inaccessible areas using a minimum number of reference stations. Also, compared with single-reference-station methods, the positioning accuracy degrades much more slowly with baseline length. And, if users employ the correct architecture, WADGPS systems are typically more fault tolerant. This month the author discusses the basic concepts of WADGPS and presents two different algorithms that can be used to implement the technique. Wide Area Differential GPS (orbital errors; atmospheric errors). WADGPS algorithms (measurement domain; position domain; state-space domain). System components (real-time active control points; real-time master active control station; virtual active control points; user segment; integrity monitor stations). Two WADGPS algorithms (measurement domain algorithm; state-space domain algorithm). Test procedure and dataset. Results and analyses. Conclusions.

8.06   GPS receiver system noise   Langley

Langley, R. B. (1997). GPS receiver system noise. *GPS World,* June, Vol. 8, No. 6, pp. 40-45.
Innovation: How well a GPS receiver performs — that is, how precisely it can measure the pseudorange and carrier phase — largely depends on how much noise accompanies the signals in the receiver's tracking loops. The more noise, the worse the performance. This noise either comes from the receiver electronics itself or is picked up by the receiver's antenna. In this article we'll take a look at noise, discuss its causes, and assess its effect on the GPS observables. Thermal noise. Antenna noise (Electromagnetic radiation). Antenna temperature (GPS antennas). System noise (Cable loss; Receiver temperature). Carrier-to-noise density ratio. Code-tracking loop. Carrier-tracking loop.

8.07   GLONASS: Review and update   Langley

Langley, R. B. (1997). GLONASS: Review and update. *GPS World,* July, Vol. 8, No. 7, pp. 46-51.
Innovation: The Navstar Global Positioning System is not the only game in town. Russia's GLONASS is also essentially operational and, despite currently having an incomplete constellation, provides civilian stand-alone positioning accuracies typically much better than those of GPS with the current practice of selective availability. In this column we will briefly review the technical characteristics of GLONASS, comparing and contrasting them with GPS. We will also assess the current development and performance of GLONASS and briefly describe GLONASS and combined GPS/GLONASS receivers. GLONASS segments (Control segment; Space segment; User segment). System characteristics (Navigation message; Geodetic datum). GLONASS receivers. GLONASS performance. Combined GPS/GLONASS use. Other developments. Conclusion.

8.08   [Showcase issue - no column]

8.09   The Kalman filter: Navigation's integration workhorse   Levy

Levy, L. J. (1997). The Kalman filter: Navigation's integration workhorse. *GPS World,* September, Vol. 8, No. 9, pp. 65-71. See Letter to Editor "The ancient mariner revised," by J. C. Sentell, Vol. 9, No. 2, February, p. 12.
Innovation: Since its introduction in 1960, the Kalman filter has become an integral

component in thousands of military and civilian navigation systems. This deceptively simple, recursive digital algorithm has been an early-on favorite for conveniently integrating (or fusing) navigation sensor data to achieve optimal overall system performance. To provide current estimates of the system variables — such as position coordinates — the filter uses statistical models to properly weight each new measurement relative to past information. It also determines up-to-date uncertainties of the estimates for real-time quality assessments or for off-line system design studies. Because of its optimum performance, versatility, and ease of implementation, the Kalman filter has been especially popular in GPS/inertial and GPS stand-alone devices. This column introduces us to the Kalman filter and outlines its application in GPS navigation. Equation-free description. A simple example. GPS/INS integration. GPS-only navigation. Practical design. Conclusions

8.10   Comparing GPS ambiguity resolution techniques   Han, Rizos
Han, Shaowei, and C. Rizos (1997). Comparing GPS ambiguity resolution techniques. *GPS World,* October, Vol. 8, No. 10, pp. 54-61.

Innovation: Centimeter-accurate GPS rapid-static and kinematic positioning require ambiguity resolution to convert ambiguous carrier-phase measurements into unambiguous ranges. During the past decade, the GPS research community has developed many ambiguity resolution techniques with different features and suitabilities for specific applications. In this column, the various techniques and their potential for further improvement are outlined, compared, and discussed. Special operational modes (Antenna swap; Stop and go; Reoccupation; Single-receiver relative positioning). Observation domain search. Coordinate domain search. Ambiguity domain search. Ambiguity recovery technique. Integrated techniques. Concluding remarks.

8.11   Interference: Sources and symptoms   Johannessen
Johannessen, R. (1997). Interference: Sources and symptoms. *GPS World,* November, Vol. 8, No. 11, pp. 44-48.

Innovation: As we become more and more reliant on GPS, it becomes increasingly important to understand its limitations. One such limitation is vulnerability to interference. This column contains a discussion of different kinds of interference, how we may recognize when it occurs, and what we can do to protect ourselves. Interference sources (In-band emissions; Nearby-band emissions; Harmonics; Jamming). How vulnerable is GPS? (GPS and GLONASS differences; Recognizing interference). GPS protection (Manufacturer influence). Consumer advice (Search out the source). In conclusion.

8.12   [Showcase issue - no column]

9.01   GPS accuracy: Lies, damn lies, and statistics   van Diggelen
van Diggelen, F. (1998). GPS accuracy: Lies, damn lies, and statistics. *GPS World,* January, Vol. 9, No. 1, pp. 41-45.

Innovation: "There are three kinds of lies: lies, damn lies, and statistics." So reportedly said Benjamin Disraeli, prime minister of Great Britain from 1874 to 1880. And just as the notoriously wily statesman noted, the science of analyzing data, or statistics, sometimes yields results that one can interpret in a variety of ways, depending on politics or interests. Likewise, we in the satellite navigation field interpret results depending on the information we wish to produce: Using various statistical methods, we can create many different GPS and

GLONASS position accuracy measures. It can seem confusing, even misleading, but as we'll see in this month's column, there's some rhyme to our reason. We'll examine some of the most commonly used accuracy measures, reveal their relationships to one another, and correct several common misconceptions about accuracy. Popular accuracy measures (Ascertaining accuracy: An example; Making valid assumptions; Starting a small test; Closing the circle). Common misconceptions. In conclusion. Deriving the equivalent accuracies table.

9.02   The UTM grid system   Langley
Langley, R. B. (1998). The UTM grid system. *GPS World,* February, Vol. 9, No. 2, pp. 46-50.
  Innovation: All GPS receivers can provide position information in terms of latitude, longitude, and height, and usually in a variety of selectable geodetic datums. For many purposes, position information in this format is more than adequate. However, when plotting position information on maps or carrying out supplemental calculations using the position coordinates, it can be advantageous to work instead with the corresponding grid coordinates on a particular map projection. One of the most widely used map projection and grid systems is the Universal Transverse Mercator (UTM) system. Many GPS receivers can directly output position information in UTM coordinates. Here we look at the UTM system, see how UTM grid coordinates are related to geodetic coordinates, and indicate the corrections to be applied to grid distances and bearings to get the actual true quantities on the earth's surface. Coordinates and projections (Down-to-earth coordinates). Mercator's world (Adopting the ellipsoid). A universal projection (The grid; Military grid reference). An example.

9.03   Pseudolites: Enhancing GPS with ground-based transmitters   Cobb, O'Connor
Cobb, S., and M. O'Connor (1998). Pseudolites: Enhancing GPS with ground-based transmitters. *GPS World,* March, Vol. 9, No. 3, pp. 55-60.
  Innovation: The Global Positioning System was originally conceived and designed as a stand-alone positioning and navigation system. As such, it is unmatched in its cost-effectiveness, accuracy, geographical coverage, and reliability. Nevertheless, to further improve its integrity, availability, and accuracy, developers have enhanced GPS in many ways. These augmentations include differential GPS, combined GPS and GLONASS operation, and the proposed Wide Area Augmentation System, to name but a few. One other GPS enhancement that may not be as familiar has actually been around longer than any other: ground-based transmitters that broadcast GPS-like signals to supplement those generated by the satellites. Here we examine how these pseudo-satellites, or pseudolites, work and how they are being used. What is a pseudolite? Primary pseudolite uses (Code-based ranging augmentation; Code-phase differential ranging; Carrier-phase differential ranging; Changing geometry; Ambiguity resolution applied; Reverse positioning; Indoor pseudolites). The near-far "problem" (Signal pulsing; P-code use).

9.04   Cellular telephone positioning using GPS time synchronization   Klukas et al.
Klukas, R., G. Lachapelle, and M. Fattouche (1998). Cellular telephone positioning using GPS time synchronization. *GPS World*, April, Vol. 9, No. 4, pp. 49-54.
  Innovation: In 1996, the number of daily emergency calls from cellular and other wireless telephones in the United States to 911 operators totalled about 60,000. Experts project that this number will exceed 130,000 calls per day by the turn of the millennium. Landline calls to 911 automatically provide a call-back number and the caller's location thanks to the recently

implemented Enhanced 911 (E-911) service adopted by most communities in the United States and Canada. However, wireless calls do not include this information and often those callers do not know or have trouble describing their exact location, making it difficult for public service operators to rapidly dispatch emergency services. Recognizing the need to make wireless telephones compatible with E-911 emergency calling systems, the Federal Communications Commission (FCC) has directed wireless service companies to enact certain improvements to their network operations. One of these is to provide automatic location identification of wireless 911 calls to within 125 metres (distance-root-mean-square). In this column, we will examine a system that has the potential to meet the FCC's requirement by locating an analogue cellular telephone using differences in arrival times of the telephone's signals at multiple network cell sites. The system uses GPS to make the time measurements to the required accuracy. TOE Estimation. System Description (Time tagging with GPS; Full correlation with MUSIC; Position estimation). Simulations. Field tests.

9.05   The effect of weather fronts on GPS measurements   Gregorius, Blewitt.
Gregorius, T., and G. Blewitt (1998). The effect of weather fronts on GPS measurements. *GPS World*, May, Vol. 9, No. 5, pp. 52-60.

Innovation: On the southeast coast of England, not very far from where the Battle of Hastings occurred, lies Herstmonceux Castle — a fifteenth-century manor house that was, for many years, the home of the Royal Greenwich Observatory (RGO). Although the skies above the castle are generally clearer than those above RGO's original home in the London borough of Greenwich, the frequently cloudy and rainy conditions are less than ideal for astronomy. RGO, therefore, built new telescopes on La Palma in the Canary Islands and moved most of its administrative and research facilities to Cambridge in 1990. The same poor conditions dreaded by astronomers, however, are ideal for studying weather fronts in relation to GPS. The grounds of Herstmonceux Castle (now owned by Canada's Queen's University and operated as an international study center) house an International GPS Service (IGS) station. This site has provided the authors with a wealth of data for their studies of the effects of weather fronts on GPS measurements, which they recount in this month's column. Atmospheric Delay. The Positioning Effect. What is a Weather Front? (Out in front; Sample fronts). The Delay Effect (Delay estimation models; Testing the models). Fronts and GPS Precision (Improving repeatability; Vertical velocity; The horizontal factor). Remedies and Possibilities (Supplementing with satellites; Fixing the time series; Other options). Conclusion.

9.06   The NSTB: A stepping stone to WAAS   Hansen
Hansen, A. (1998). The NSTB: A stepping stone to WAAS. *GPS World*, June, Vol. 9, No. 6, pp. 73-77

Innovation: The accuracy, integrity, and availability of the Standard Positioning Service are currently insufficient for the aviation community to use GPS as a primary means of navigation for en route travel or for nonprecision and Category I approaches to airports. To permit such use, the Federal Aviation Administration, in concert with industry and academic partners, is developing the Wide Area Augmentation System (WAAS). A prototype WAAS — the National Satellite Test Bed (NSTB) — is already in operation. The NSTB affords researchers and system developers the opportunity to validate the WAAS architecture, software algorithms, hardware, and terrestrial and satellite communications systems using live GPS signals. In this month's column, the author outlines some of the research and

development work involving the NSTB being carried out at Stanford University. WAAS in Practice (Reference stations; Error models). The Stanford Connection (Displayed data; Custom configurations and displays). WAAS Metrics (Accuracy; Integrity; Availability). Flight Testing.

9.07   A primer on GPS antennas   Langley
Langley, R. B. (1998). A primer on GPS antennas. *GPS World*, July, Vol. 9, No. 7, pp. 73-77.
Innovation: The GPS receiver is a marvel of modern electronic engineering. By processing the signals transmitted by the constellation of orbiting Navstar satellites, its sophisticated circuitry can deliver position, velocity, and time information to a user anywhere on or near the earth's surface, 24 hours a day, every day. But before the receiver can use the signals, they must first be captured. This is the task of the receiver's antenna. GPS signals are relatively weak compared with the signals from broadcasting stations and terrestrial communications services, and a GPS antenna is specially designed to work with these feeble signals — a coat hanger will not do! In this month's column, the author takes a look at the GPS antenna. This will only be an introduction to the complex subject of antenna design and construction, but it should enable you to better understand antenna specifications and how your receiver's antenna works. Fields and Waves. Antenna Characteristics (Impedance; Standing wave ratio; Bandwidth; Gain pattern; Ground planes; Phase-center variation; Other factors). Low Noise Preamp. Transmission Lines. Loose Ends. Conclusion.

9.08   [Showcase issue - no column]

9.09   RTK GPS   Langley
Langley, R. B. (1998). RTK GPS. *GPS World*, September, Vol. 9, No. 9, pp. 70-76
Innovation: Novare, the Latin root of the word innovation, means to make new. And that is exactly what scientists and engineers working with the Global Positioning System have been doing ever since the conception of GPS in the early 1970s. Not only have they discovered many new GPS applications, they have devised new ways to use the GPS signals. One of their most recent innovations is RTK, real-time kinematic, GPS — a technique that provides position accuracy close to that achievable with conventional carrier-phase positioning, but in real time. In this month's column we'll briefly examine RTK GPS, emphasizing one of the system's critical components: the radio link. A Fix on Accuracy (Craft positioning). Carrier-Phase Positioning (Using the carrier phase; Postprocessing; Real time; Correction message formats). RTK System Architecture. The Data Link (Propagation distances; Predicting signal path loss; Analyzing the link's viability). RTK Solutions (Resolving ambiguities on-the-fly; GLONASS advantages). Conclusion.

9.10   GPS MATLAB toolbox review   Tetewsky, Soltz
Tetewsky, A. K., and A. Soltz (1998). GPS MATLAB toolbox review. *GPS World*, October, Vol. 9, No. 10, pp. 50-56.
Innovation: Simulate, as defined by the Concise Oxford Dictionary of Current English, means to "imitate conditions of (situation etc.) with model, for convenience or training." Very often in the fields of science and engineering, we need to simulate a situation — just as the definition indicates — before it occurs to help us design or understand a system or its components. So it is with GPS. We can carry out GPS simulations using either hardware — which we briefly examined in a previous column — or software, which we'll take a look at

this month. Our discussion will take the form of a review of four GPS simulation packages that use the popular and versatile MATLAB programming language. GNSS toolbox. Constellation toolbox. SatNav toolbox. GPS signal simulation toolbox. Our Approach (Table abbreviations). The Review. Simulation Challenges (First things first; Problem two; Challenge three; Pinning down P4; The key to five; Last but not least). Our Experiences (Comments and suggestions; Orion and Constell; GPSoft; Navsys). Overall Suggestions.

9.11   The GPS end-of-week rollover   Langley
Langley, R. B. (1998). The GPS end-of-week rollover. *GPS World*, November, Vol. 9, No. 11, pp. 40-47.
Innovation: At a few seconds after midnight, Universal Time, on August 22, 1999, the GPS week counter will roll over from 1023 to zero. Although perhaps a little less momentous than the so-called Y2K problem, it has the potential to cause difficulties for some GPS users. In this month's column, we'll examine this event, why it will occur, and the anticipated consequences. GPS Time (Time differences; Z count; Time of week). The Rollover. Receiver Effects (Pinning down the problem). Conclusion.

9.12   [Showcase issue — no column]

10.01   GLONASS to GPS: A new coordinate transformation   Bazlov et al.
Bazlov, Y. A., V. F. Galazin, B. L. Kaplan, V. G. Maksimov, and V. P. Rogozin (1999). *GPS World*, January, Vol. 10, No. 1, pp. 54-58.
Innovation: Although GLONASS is currently operating with a fraction of its full complement of satellites, interest in and use of the system continues to grow as evidenced in part by the International GLONASS Experiment (IGEX) currently underway. In addition to fostering cooperation between the international research community and Russian organizations responsible for GLONASS, IGEX has specific set objectives, which include determining the transformation parameters between coordinate frames of the Parametry Zemli 1990 (PZ-90) system used by GLONASS and the World Geodetic System 1984 (WGS 84) used by GPS. The results of a recently completed Russian project to relate the two systems will assist the IGEX efforts. In this month's column, the team of Russian researchers responsible for that project describe the study and its results. Transformation Model. The Experiment. Analysis. Conclusion. Acknowledgments.

10.02   The stochastics of GPS observables   Tiberius et al.
Tiberius, C., N. Jonkman, and F. Kenselaar (1999). The stochastics of GPS observables. *GPS World*, February, Vol. 10, No. 2, pp. 49-54.
Innovation: We live in a noisy world. In fact, the laws of physics actually preclude complete silence unless the ambient temperature is absolute zero — the temperature at which molecules have essentially no motion. Consequently, any electrical measurement is affected by noise. Although minimized by GPS receiver designers, noise from a variety of sources both external (picked up by the antenna) and internal (generated within the receiver) contaminates GPS observations. This noise will impact the results we obtain from processing the observations. In this month's column, we investigate possible ways of minimizing this impact by considering the random nature, or stochastics, of GPS noise. Mathematical Background (Functional model; Stochastic model). Experiments (Elevation angle; Cross

correlation; Time correlation; Probability distribution; Further considerations). Concluding remarks.

10.03   The integrity of GPS   Langley

Langley, R. B. (1999). The integrity of GPS. *GPS World*, March, Vol. 10, No. 3, pp. 60-63.
   Innovation: How truthful is GPS? Can you believe the position that your GPS receiver computers? The GPS Standard Positioning Service is designed to provide a horizontal position accuracy of at least 100 metres, but such accuracy cannot be guaranteed 100 percent of the time. Satellite or ground system failures could cause a receiver to use erroneous data and compute positions that exceed its normal accuracy level. This month's column explores the different approaches to ensuring GPS signal integrity, including satellite self-checks, receiver autonomous integrity monitoring, and augmented systems. Performance Parameters (Accuracy; Availability; Continuity; Integrity). GPS Integrity (Satellite self-checks; Master control station). RAIM. Snapshot Approaches (Range comparison; Least-squares residuals; Parity). RAIM Availability. Exclusion and Isolation. Aviation Requirements. Augmented GPS Systems (DGPS; WAAS; LAAS). Conclusion. Acknowledgments.

10.04   GPS: A new tool for ocean science   Komjathy et al.

Komjathy, A., J. L. Garrison, and V. Zavorotny (1999). GPS: A new tool for ocean science. *GPS World*, April, Vol. 10, No. 4, pp. 50-56.
   Innovation: There is an old adage in science and engineering: One person's signal is another person's noise. Most GPS users consider signals arriving at their receiver's antenna from nearby reflecting surfaces (multipath) to be noise, as their presence reduces positioning accuracy by interfering with the signals received directly from the satellites. Some researchers, however, are using GPS signals reflected off the ocean surface as a valuable new information source in remote-sensing applications. By analyzing the reflections, they can determine such characteristics as wave heights, wind speeds, and wind direction. In this month's column, one group of researchers describes this innovative remote-sensing technique and some of the interesting results it has already obtained. Bistatic Surface Scattering. Signal Modeling (Theoretical model; Wind-speed remote sensing). Delay-Doppler mapping (Bistatic GPS scatterometer; Remote-sensing aircraft). Wind-Speed Retrieval. Concluding remarks.

10.05   Dilution of precision   Langley

Langley, R. B. (1999). Dilution of precision. *GPS World*, May, Vol. 10, No. 5, pp. 52-59.
   Innovation: Dilution of precision, or DOP: we've all seen the term, and most of us know that smaller DOP values are better than larger ones. Many of us also know that DOP comes in various flavors, including geometrical (GDOP), positional (PDOP), horizontal (HDOP), vertical (VDOP), and time (TDOP). But just what are these DOPs? In this month's column, we examine GPS dilution of precision and how it affects the accuracy with which our receivers can determine position and time. Geometry: A Simple Example. Pseudorange Measurements (The covariance matrix; UERE). The DOPS (The tetrahedron; HDOP versus VDOP; Latitude; More satellites). Conclusion. Acknowledgment.

10.06   Aircraft landings: The GPS approach   Dewar

Dewar, G. (1999). Aircraft landings: The GPS approach. *GPS World*, June, Vol. 10, No. 6, pp. 68-74.

Innovation: The Global Positioning System, considered by many to be the greatest advance in aviation since the invention of the jet engine, will revolutionize the operation of aircraft all around the world. Not only will it direct pilots to the vicinity of an airport, it will also be able to guide a plane along a runway approach route and even permit automatic landings. To enable more efficient operations, air navigation service providers are designing new approach procedures for aircraft using GPS. In this month's column, George Dewar examines these new GPS approaches and how they differ from approaches using conventional navigation aids. Approach Basics (Precision and nonprecision approaches). Conventional Procedures (VORs and NDBs). GPS Approaches ("T" configuration). Design Process (Final segment; Missed approach segment; Waypoint position calculation; Intermediate segment; Initial segment). Flyby, Flyover Waypoints. Flight Inspection (System errors). Conclusion. Acknowledgment.

10.07   Tropospheric Delay: Prediction for the WAAS user   Collins, Langley

Collins, P. and R. B. Langley (1999). Tropospheric Delay: Prediction for the WAAS user. *GPS World*, July, Vol. 10, No. 7, pp. 62.

Innovation: The weather—it affects us all. Sometimes disastrously with vicious storms; sometimes pleasantly with sunshine and warm breezes. It also affects GPS. But, whereas bad weather might disrupt our lives, causing us to curtail or postpone an activity, GPS continues to perform—it's an all-weather system. Rain, snow, fog, and clouds all have a negligible effect on GPS. However, unseen weather—temperature, pressure, and humidity variations throughout the atmosphere—does affect GPS observations. These parameters determine the propagation speed of radio waves, an important factor that must be accounted for when processing GPS or other radiometric observations. Because we cannot predict their exact values ahead of time, these invisible weather variables are a source of error in GPS positioning and navigation. In this month's column, we examine the atmosphere's effect on GPS and discuss how we've attempted to model it for users of the forthcoming Wide Area Augmentation System. The Tropospheric Delay. Delay Models. Developing a New Model (UNB3). Methodology. Average Model Performance. Extreme Delay Errors (Extreme locations; Forecasting extremes; Look-up table). Position Determination Impact (Maximum bias). Conclusions. Acknowledgments.

10.08   [Showcase issue — no column]

10.09   New and improved: The broadcast interfrequency biases   Wilson et al.

Wilson, B. D., C. H. Yinger, W. A. Feess, and C. Shank (1999). New and improved: The broadcast interfrequency biases. *GPS World*, September, Vol. 10, No. 9, pp. 56-66.

Innovation: "Better today than yesterday; better tomorrow than today." This often quoted maxim nicely describes the ongoing efforts by scientists and engineers to improve the Global Positioning System's accuracy, ease of use, and range of application. During the relatively short operational lifetime of GPS, we have witnessed many improvements, such as a range of differential GPS techniques, more accurate satellite orbit ephemerides, and smaller, more powerful receivers. Researchers have also improved the models, or descriptions, of several biases that affect GPS observations including carrier-phase windup, satellite yaw attitude, and antenna phase-center offsets. One of the latest GPS enhancements is an improvement of the interfrequency bias values contained in the navigation message broadcast by GPS satellites. Single-frequency receivers use these values to account for differential satellite hardware

delays in the broadcast clock corrections. The new values were determined through a collaborative effort by a team of analysts from the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL) — managed by the California Institute of Technology, The Aerospace Corporation, and several Department of Defense agencies. In this column, some of the team members discuss the importance of the interfrequency bias and how they obtained the new values. Interfrequency Bias Use. Improvement History. The New Values (GIM maps; GIM and T_{GD}; New versus old). Validation (WADGPS; Single-frequency). Additional benefits (Time transfer; Ionospheric research). Future developments. Conclusions. Acknowledgments.

10.10   The view from above: GPS on high-altitude spacecraft   Powell
Powell, D. T. (1999). The view from above: GPS on high-altitude spacecraft. *GPS World*, October, Vol. 10, No. 10, pp. 54-64.
Innovation: Spaceborne GPS applications occur across a wide range of orbit types. To date, the majority of such applications have been for low-earth orbit spacecraft, but GPS offers significant advantages to space vehicles in geostationary and other high-altitude orbits as well. Making GPS work for high-altitude spacecraft, however, presents some unique technical challenges. This article discusses some of those challenges and how they are being met. Orbital Motion. Ground Tracking. Spacecraft GPS Navigation (Satellite views; The GPS broadcast antenna; Side-lobe signals; Backside antennas). GEO Spacecraft (Weak signals; Availability gaps). HEO Spacecraft. Spacecraft GPS Equipment (Hardware options). Falcon Gold Experiment. Conclusions.

10.11   GPS and leap seconds: Time to change?   McCarthy, Klepczynski
McCarthy, D. D., and W. J. Klepczynski (1999). GPS and leap seconds: Time to change? *GPS World*, November, Vol. 10, No. 11, pp. 50-57.
Innovation: Since ancient times, we have used the Earth's rotation to regulate our daily activities. By noticing the approximate position of the sun in the sky, we knew how much time was left for the day's hunting or farming, or when we should stop work to eat or pray. First sundials, water clocks, and then mechanical clocks were invented to tell time more precisely by essentially interpolating from noon to noon. As mechanical clocks became increasingly accurate, we discovered that the Earth does not rotate "like clockwork," but actually has a slightly nonconstant rotation rate. In addition to periodic and irregular variations caused by atmospheric winds and the interaction between the Earth's core and the mantle, the tidal interaction of the Earth and the Moon causes a secular slowing down of the Earth's rotation. So rather than use the variable time scale based on the Earth's rotation, we now use time scales based on extraordinarily precise atomic time, the basis for all the world's civil time systems — Coordinated Universal Time (UTC). However, because of the desire to keep UTC more or less in synchronization with the Earth's rotation as an aid in determining navigation fixes using astronomical observations, leap seconds are added to UTC — currently about every 18 months. In contrast, the time scale used to regulate the Global Positioning System — GPS Time — is a "pure" atomic time scale without leap seconds. In this month's column, the authors suggest that the practice of adding leap seconds to UTC be done away with or at least modified, as more and more navigators adopt Global Navigation Satellite Systems as their primary means of positioning. A Brief History (Increasing accuracy; The move to Cesium). International Atomic Time. Options for UTC (Continue current

procedure; Discontinue leap seconds; Change the tolerance for UT1-UTC; Redefine the second; Periodic insertion of leap seconds). Conclusion.

10.12   [Showcase issue — no column]

11.01   Enhancing GPS: Tropospheric delay prediction at the Master Control Station

                                                                                  Hay, Wong

Hay, C. and J. Wong (2000). Enhancing GPS: Tropospheric delay prediction at the Master Control Station. *GPS World*, July, Vol. 11, No. 1, pp. 56-62.

Innovation: As Mark Twain reportedly quipped, "Everyone talks about the weather, but nobody ever does anything about it." Not so at the GPS Master Control Station. In this month's article, Curtis Hay and Jeffrey Wong tell us the Master Control Station's plans to improve the modeling of the weather-related tropospheric propagation delay when processing the data collected at the GPS ground segment monitoring stations. The troposphere — or more correctly, the whole electrically-neutral part of the atmosphere — imposes an additional delay on GPS signals ranging from a little more than 2 meters for a signal arriving from directly overhead, to more than 20 meters at an elevation angle of 5 degrees. Improved modeling of this delay will reduce the error of the GPS satellite ephemerides and clock corrections transmitted in the navigation message. The proposed changes will benefit all GPS users, military and civilian alike. The Skies Above. From Filter to Signal. Weather Data Inaccuracy. Model Problems. Another Option. Room for Improvement. Improving the MCA. Acknowledgments.

11.02   Time and frequency transfer: High precision using GPS phase measurements

                                                                                  Schildknecht, Dudle

Schildknecht, T. and G. Dudle (2000). Time and frequency transfer: High precision using GPS phase measurements. *GPS World*, February, Vol. 11, No. 2, pp. 48-52.

Innovation: "What time is it?" This question is asked an untold number of times each day. And the replies? They vary both in accuracy and precision, from "it's about one-thirty" to "10 hours, 32 minutes, and 3.682 nanoseconds." In both cases there is an implicit or explicit reference to some standard of time, accepted as a reference. We have long since abandoned the Earth's rotation as a time standard because its rotation rate varies from day to day and year to year. Instead, we rely on an ensemble of atomic clocks maintained by time-keeping laboratories around the world. The clocks are intercompared to establish a global standard. Over the years, a variety of intercomparison techniques have been developed, but the timekeeping community has looked for ever higher accuracies. Intercomparisons are now routinely carried out using a simple GPS technique that has an accuracy limited to about one nanosecond, when the results are averaged over one day. But scientists would like to compare clocks with even higher accuracies over shorter intervals of time. In this column, two scientists from Switzerland — a country famous for its time pieces — describe a new GPS-based clock comparison technique, one that approaches the level of performance of the clocks themselves. Geodetic GPS Processing. IGS Product Potential. Accessing the Receiver Clock. Local Receiver Delays. An International Effort (Frequency transfer; Time transfer experiment). Conclusions. Acknowledgments.

11.03   Slope monitoring using GPS: A multi-antenna approach   **Ding et al.**

Ding, X., Y. Chen, D. Huang, J. Zhu, M. Tsakiri, and M. Stewart (2000). Slope monitoring using GPS: A multi-antenna approach. *GPS World*, March, Vol. 11, No. 3, pp. 52-55.

Innovation: The Earth's surface in continually deforming. Some of these deformations, such as solid-earth tides and post-glacial rebound, are benign. Some, such as land ruptures caused by earthquakes and volcanic eruptions, are devastating. One particularly common deformation is the landslide. Although usually localized, landslides often cost the lives of many and damage millions of dollars worth of property. In this month's column, we examine the current development of an innovative technique to monitor potentially unstable slopes and existing landslides using GPS. Unlike the standard GPS method, where a GPS receiver is required for each point to be monitored, the new method allows multiple points to be monitored with a single receiver. This approach employs a specially designed switching box to link a receiver to a number of GPS antennas, thereby significantly reducing the cost per monitoring point and making GPS a more viable tool for monitoring the stability of slopes and other structures subject to localized deformation. Deformation Monitoring (Manual survey; The array approach). Multi-Antenna System (Receivers and antennas; Data link; Data processing center; Antenna switching; Motion detection and warnings). Test Results. Conclusion. Acknowledgments.

11.04   Smaller and smaller: The evolution of the GPS receiver   Langley

Langley, R. B. (2000). Smaller and smaller: The evolution of the GPS receiver. *GPS World*, April, Vol. 11, No. 4, pp. 54-58.

Innovation: We have reached another GPS milestone. Just a few months ago, *GPS World* celebrated its 10th anniversary. The first issue of the magazine (a bimonthly in its first year of publication) appeared in January/February 1990. The "Innovation" column has appeared in every regular issue of *GPS World*, and this month's column is number 100. Throughout the column's 10-year history, we have examined many innovative developments in the *GPS World*, including improvements in precise positioning, velocity determination, and the transfer of time; in applications such as real-time dredge positioning, monitoring the deformation of the Earth's crust, the Earth's rotation, and the state of the ionosphere; and the use of GPS on various platforms such as submersible vehicles, aircraft, and satellites. Many of these developments were possible because of advances in GPS receiver technology. The technology has resulted in GPS receivers becoming smaller and more convenient to use and recently permitted receivers so small that they can be incorporated into cellular telephones and other devices. On the occasion of the 100th "Innovation" column, what better time to review the progress of GPS receiver technology through the past 20 years and to take a peek into its future. Essential Elements (Antenna; A front end; Correlators; Microprocessor and memory; Power supply). Receiver Rundown (The Macrometer; The TI 4100; Here come the handhelds). The Workings of a Chipset (Processing the digital signal). Wrist-Mount GPS. Anything but Disappearing. Semiconductor Basics.

11.05   Fixing the ambiguities: Are you sure they're right?   Joosten, Tiberius

Joosten, P. and C. Tiberius (2000). Fixing the ambiguities: Are you sure they're right? *GPS World*, May, Vol. 11, No. 5, pp. 46-51.

Innovation: Fast and precise relative satellite positioning demands resolution of the integer cycle ambiguities. Only then will the corresponding carrier-phase measurements act as if they were high-precision range measurements, thereby allowing the receiver coordinates to be estimated with comparable high precision. Researchers have studied the GPS ambiguity

problem for the past 20 years and have proposed a wide variety of methods to resolve ambiguities. So far, most of these methods have concentrated on the *estimation* of the ambiguities. The problem of addressing the *correctness* of the integer numbers obtained, often referred to as "ambiguity validation," has received considerably less attention. The "mission" of this article is to point out that ambiguity resolution is not strictly a matter of computing integer values for the ambiguities. Before really fixing or constraining the ambiguities to the computed integers in a final baseline computation, we should assess their accuracy. In other words, we should ask ourselves "How sure am I that these values are correct?" In this contribution, we will look at how we might answer this question and discuss some new developments in dealing with the stochastic properties of the integer ambiguity estimator. The ambiguity success rate is presented as a tool for determining the probability of correct integer estimation. Integer Ambiguity Estimation. Ambiguities are Stochastic. Ambiguity Success Rate. Conclusion. The LAMBDA Method. How to Compute Ambiguity Success Rate.

11.06   The GPS accuracy improvement initiative   Hay

Hay, C. (2000). The GPS accuracy improvement initiative. *GPS World*, June, Vol. 11, No. 6, pp. 56-61.

Innovation: The Global Positioning System has become an international utility. While originally designed to serve the armed forces of the United States and its allies, it has evolved into a dual-use system with civil users greatly outnumbering their military counterparts. The predicted further growth of GPS is astounding. The global market for GPS goods and services is expected to exceed $8 billion this year and $16 billion by 2003. In addition to its ease of use, and worldwide, all-weather operation, GPS owes its popularity to the dependable high accuracy with which positions and time can be determined. Although GPS was already better than many other navigation systems, the termination of selective availability last month instantly increased at least five fold the accuracy of standalone civil GPS. And things are going to get even better. In a few years, the first satellites with C/A-code on L2 will be launched, and a couple of years later satellites with a third civil frequency. In addition to these spacecraft hardware augmentations, a number of other upgrades to GPS are being implemented, which will further improve GPS accuracy. One of these upgrades goes by the name Accuracy Improvement Initiative, and in this column the authors will introduce the initiative and describe its benefits to military and civil GPS users alike. Key AII Features. Three OCS Changes. NIMA Tracking Data. Redesigned Kalman Filter. More Frequent Uploads (Enabling the increase). Expected Improvement (Other accuracy initiatives; Atomic clock replacement at the remote monitor stations; Monitor station multipath mitigation; Improved tropospheric delay prediction; Increased use of rubidium clocks). At the End of AII. Acknowledgments.

11.07   GPS, the ionosphere, and the solar maximum   Langley

Langley, R. B. (2000). GPS, the ionosphere, and the solar maximum. *GPS World*, July, Vol. 11, No. 7, pp. 44-49.

Innovation:
Oh, it was wild and weird and wan, and ever in camp o'nights
We would watch and watch the silver dance of the mystic Northern Lights.
And soft they danced from the Polar sky and swept in primrose haze;
And swift they pranced with their silver feet, and pierced with a blinding blaze.

So wrote Canadian poet Robert W. Service in the "Ballad of the Northern Lights." The northern lights, also known as Aurora Borealis, are a product of the complex relationship between the Sun and the Earth. More frequent auroras at more southerly latitudes are evidence of the period of maximum solar activity now upon us. The solar maximum, which occurs approximately every 11 years, also brings with it more active ionospheric conditions. The more frequent ejections of high-energy electromagnetic radiation and particles from the Sun around the time of the solar maximum results in greater ionospheric electron densities and more variable densities. And as the signals from the GPS satellites must pass through this more active ionosphere on their way to Earth-bound receivers, there are potential problems for GPS users. In this column, we will look at how solar activity affects the ionosphere, how the ionosphere affects GPS, and how these effects can be ameliorated to reduce their impact. The ionosphere. Solar Activity (Space weather). Refraction Index. TEC Variability. Corrections and Models. Ionospheric Scintillation (Signal fading). Conclusion. Acknowledgments.

11.08   [Showcase issue — no column]

11.09   The new L5 civil GPS signal   Van Dierendonck, Hegarty
Van Dierendonck, A. J. and C. Hegarty (2000). The new L5 civil GPS signal. *GPS World*, September, Vol. 11, No. 9, pp. 64-71.

Innovation: Many newcomers to GPS are surprised to learn that work on system development actually began in the early 1970s. The basic structure of the signals transmitted by the GPS satellites has not changed significantly in the ensuing quarter century — a very long time on the technology development time scale. But modernization of GPS is now underway. Selective Availability, the purposeful degradation of positioning accuracy afforded civil users, was switched off in May resulting in at least a five-fold improvement in accuracy. Further accuracy improvements will stem from enhancements to the GPS control segment recently initiated. But, perhaps the most significant of the GPS modernization efforts are the new signals that will be transmitted by future GPS satellites. The C/A-code will be added to the L2 signal of Block IIR satellites beginning with launches in 2003 along with new military signals on L1 and L2. With the C/A-code on both L1 and L2, civil users will be afforded accurate, real-time ionospheric delay correction, further enhancing the accuracy of positions, velocities, and time. And the Block IIF satellites, starting with launches perhaps as early as 2005, will feature a completely new, dedicated civil signal. The new civil signal, called L5, will be transmitted on a frequency of 1176.45 MHz in a band set aside by the International Telecommunication Union for the aeronautical radionavigation service. Although the L5 signal will be a "safety-of-life" signal for aircraft navigation, it also will serve as a robust third signal for all users. The signal design recently was completed by a special working group assembled by RTCA, the private, not-for-profit corporation that develops consensus-based recommendations for the federal government regarding aviation-related communications, navigation, surveillance, and traffic management system issues. In this column, the authors detail the proposed structure of the new L5 signal. L5 Signal Parameters. SC-159 L5 Signal Requirements. User Requirements. The Signal Structure (Two-components signal; Neuman-Hoffman codes). The Code Structure (Code chipping rate and accuracy; Code period and improved cross-correlation; L5 coder implementation; Code selection and correlation properties). The Data Structure. Conclusion. Acknowledgments.

11.10   Navigation 101: Basic navigation with a GPS receiver   Langley

Langley, R. B. (2000). Navigation 101: Basic navigation with a GPS receiver. GPS World,
    October, Vol. 11, No. 10, pp. 50-54.
    Innovation: The uses of GPS are virtually limitless, from monitoring the bulges of volcanoes
    to synchronizing communications over cellular-telephone networks. With GPS applications
    becoming more and more specialized, some users may have lost sight of the fact that, first
    and foremost, GPS is a navigation system — a system that anyone can use any time, and
    almost anywhere. In this month's column, we present a primer on this most basic use of GPS.
    Where am I? Getting From A to B (Position; Bearing; Distance; Course and track; Desired
    track; Course made good; Speed; Speed made good; Cross-track error; Estimated time on
    route; Estimated time of arrival; Map displays). Augmented Navigation. Conclusion.

11.11   A common time reference: Precise time and frequency for warfighters

Beard, White

Beard, R., and J. White (2000). A common time reference: Precise time and frequency for
    warfighters. GPS World, November, Vol. 11, No. 11, pp. 38-45.
    Innovation: The use of the Global Positioning System as the primary and most accurate
    means of disseminating time and frequency information has created an inherent vulnerability
    within some military systems. As a growing and diverse mix of military positioning,
    communications, sensing and data processing systems are using precise time and frequency
    from GPS, the precise accuracies required for their interoperability are becoming more
    stringent. Consequently, a new system architecture for providing a common time reference to
    the operating forces and their related subsystems is being developed. This architecture will
    provide a robust alternative to the former implementations of GPS as a time and frequency
    subsystem and mitigate the vulnerabilities of those systems to possible GPS countermeasures.
    In this month's column, the authors describe their proposed common time reference approach
    and its relationship to present GPS time and frequency usage. They suggest a robust
    architecture comprising distributed time standards and precise time and frequency standards
    which reduces the sensitivities to GPS anomalies and lack of continuous contact. Utilization
    of existing resources and interconnection of these interoperable systems at the fundamental
    level of time and frequency generation will enable them to function together more effectively.
    Network-Centric Warfare. System Time Utilization (Independent systems; Multiple systems).
    Time Dissemination via GPS. CTR Architecture. Time Dissemination Interfaces. Clock
    Comparison Systems. Composite Time. Local Distribution Media. A System of Systems.
    Acknowledgment. Precise Clocks.

11.12   [Showcase issue — no column]

12.01   GPS and the legal traceability of time   Levine

Levine, J. (2001). GPS and the legal traceability of time. GPS World, January, Vol. 12, No. 1,
    pp. 52-58.
    Innovation: As James Gleick notes in his recent book Faster, "A man with a watch knows
    what time it is. A man with two watches is never sure." From the sundial, to the water clock,
    to the escapement, to the pendulum, to the quartz crystal, to the atomic clock, to the Global
    Positioning System, humanity has been obsessed with knowing what time it is. But just like
    the man with two watches, how do we know whose watch or clock is correct? In other words,
    as the rock band Chicago noted in one of their classic hits, "Does anybody really know what

time it is? Does anybody really care?" The answer to both questions is a resounding "yes." Our modern society depends on knowing the correct time with higher and higher accuracies for everything from time-stamping electronic transactions to synchronizing telecommunications to navigating spacecraft. "Correct" means that the time must be technically, and in some cases legally, traceable to national or international standards. In this month's column, Dr. Judah Levine discusses these standards and the important role GPS plays in keeping the world's timepieces both technically and legally synchronized. The Treaty of the Meter. Time, Frequency, and the BIPM. UTC(NMI) and Circular T. Mutual Recognition Arrangements. Distributing Time and Frequency Signals. Legal Time in the United States. Practical Difficulties at Leap Seconds. Realization of UTC using GPS. Summary.

12.02   Characterizing the behavior of geodetic GPS antennas   Schupler, Clark

Schupler, B. R. and T. A. Clark (2001). Characterizing the behavior of geodetic GPS antennas. *GPS World*, February, Vol. 12, No. 2, pp. 48-55.

Innovation: In high-accuracy applications of GPS such as establishing geodetic control networks, monitoring dam deformation, or measuring the Earth's rotation, effects on GPS measurements as small as a few millimeters can be important. To achieve the required positioning accuracies, such effects must be modeled very carefully or preferably avoided in the first place. Although some potential errors originate with the GPS satellites and some with the ionosphere and troposphere through which the signals must travel, some are due to the receiver's antenna and its immediate environment. High-accuracy applications use special antennas designed to reduce antenna-related errors to a minimum. Just how good are these antennas? It is difficult to check the performance of antennas in the field — where the ground, mounting devices, and nearby structures all may have an effect. To isolate an antenna from its environment as much as possible or to change the environment in a controlled fashion, antennas are tested in anechoic chambers — specially designed enclosures that virtually eliminate reflected signals and in which the position and orientation of the antenna can be precisely controlled. In this month's column, Bruce Schupler and Thomas Clark discuss the procedures they have developed to characterize the behavior of GPS antennas using anechoic chamber measurements and discuss some of the results they have obtained. Geodetic Antenna Requirements. Measurement Procedures. Changes in Antenna Response with Frequency. How Similar are Antennas from Different Manufacturers? Effect of Reflectors and Radomes. The Effect of a Change in Design. Antenna Terminology. What Limits the Frequency Response of the Antennas? Conclusions. Acknowledgments. Manufacturers. Antenna Terminology

12.03   Solving your attitude problem: Basic direction sensing with GPS   Caporali

Caporali, A. (2001). Solving your attitude problem: Basic direction sensing with GPS. *GPS World*, March, Vol. 12, No. 3, pp. 44-50.

Innovation: GPS is well known for its ability to determine a platform's position and velocity with high accuracy. Less well known is the ability of GPS also to provide the orientation of the platform. Using three or more antennas feeding separate receivers, or separate channels in a single receiver, the baseline vectors connecting the antennas can be determined. The directions of these vectors determine the platform's three-dimensional orientation. Using the differences of the carrier phases simultaneously measured by the receiver channels, the baseline orientations can be determined to a fraction of a degree. If only two antennas are

used, then only two angles or directions of the platform can be determined, such as the azimuth or heading of the platform and its elevation angle or pitch. In this month's column, Dr. Alessandro Caporali will introduce us to the basics of direction sensing with GPS and describe a prototype sensor he has built and tested on the canals of Venice. Interferometry. The System. Testing the System. Conclusion. Acknowledgment. Manufacturers.

12.04   Efficient precision positioning: RTK positioning with multiple reference stations
Raquet, Lachapelle

Raquet, J. and G. Lachapelle (2001). Efficient precision positioning: RTK positioning with multiple reference stations. *GPS World*, April, Vol. 12, No. 4, pp. 48-53.

Innovation: Real-Time Kinematic (RTK) positioning is quickly becoming the standard GPS technique for surveying and high-precision navigation. Typically, a single reference station transmits carrier-phase and pseudorange data to a user receiver which uses the data together with its own measurements to determine an accurate position. To achieve the required accuracies, the carrier-phase integer ambiguities must be resolved. This requirement limits the maximum distance between reference and user receivers so that a large network of independently-operating reference receivers would be required to provide RTK service coverage across even a medium-sized city and would be prohibitively expensive. In this month's column, John Raquet and Gérard Lachapelle describe a more efficient and affordable RTK approach using multiple cooperating reference stations. Least squares collocation; Error parameterization in position domain; Explicit error reduction. Least-Squares Collocation (Measuring the DGPS errors; Interpolation; Determining spatial correlation of errors; Least-squares collocation; Application to network RTK problem; Field test example; Predicting network performance). Transmission of Errors to Users (Single virtual reference station; correction grid; correction function). The Future of Network RTK. Acknowledgments. Manufacturers.

12.05   A new approach to an old problem: Carrier-phase cycle slips   Bisnath et al.

Bisnath, S. B., D. Kim, and R. B. Langley (2001). A new approach to an old problem: Carrier-phase cycle slips. *GPS World*, May, Vol. 12, No. 5, pp. 46-51.

Innovation: High-precision GPS positioning and navigation requires that the data preprocessing stage correctly repair cycle slips in the carrier-phase observations. A slip of only a few cycles can bias measurements enough to make centimeter-level positioning or navigation difficult. Over the past decade, researchers have developed numerous methods to detect and repair cycle slips. Yet, invariably, a few cycle slips remain undetected or incorrectly repaired, requiring analyst intervention to fully clean up the data. A perfectly operating, automated GPS data preprocessor remains an elusive goal. However, two of my colleagues at the University of New Brunswick, Sunil Bisnath and Donghyun Kim, have developed a technique that advances preprocessor capability significantly, and they join me in describing their work in this month's column. Detection and Determination (What is a cycle slip?). Automatic Cycle Slip Correction (Detection observables; Geometry-free phase; Widelane phase minus narrowlane pseudorange). Detection Tests. Detection Insensitivity. Determination. Static Data Testing. Kinematic Data Testing. Conclusions and Future Research. Acknowledgments. Manufacturers.

12.06   Determining the attitude of a minisatellite by GPS   Purivigraipong, Unwin

Purivigraipong, S. and M. J. Unwin (2001). Determining the attitude of a minisatellite by GPS. *GPS World*, June, Vol. 12, No. 6, pp. 60-66.

Innovation: In a recent Innovation column, we examined the principles of determining the attitude of a platform with GPS. These principles hold whether the platform is on dry land, the surface of the ocean, or in the air. They even hold in space where they can help to orient and manoeuver satellites. In this month's column, we take a look at how one of the world's leading developers of small satellites is using GPS to determine the orientation of one of their spacecraft. GPS Attitude Sensing Platform. Multiple Antenna Operation and Carrier Phase Tracking. Background on GPS Attitude. Initial Attitude Acquisition. Part I Finding possible pointing of individual baseline. Part II Finding the candidate set. Part III Solving for attitude. Part IV Historical test. Initial Line Bias Acquisition. Fine Acquisition Phase. Flight Data Analysis. Attitude Results. Conclusions. Ongoing Work. Acknowledgments. Manufacturers.

12.07   GPS reference networks' new role: Providing continuity and coverage
<div align="right">Enge et al.</div>

Enge, P., R. Fan, and A. Tiwari (2001). GPS reference networks' new role: Providing continuity and coverage. *GPS World*, July, Vol. 12, No. 7, pp. 38-45.

Innovation: The Global Positioning System, as its name suggests, enables users to determine their position anywhere on Earth. Or does it? The answer is "yes' if the user's receiver (or, more precisely, its antenna) has a clear view of the sky and receives GPS signals unimpeded. Unfortunately, the answer is typically "no' if the user is indoors or in some other environment, such as a dense forest, where the signals are significantly attenuated. While future GPS satellites may transmit somewhat more powerful signals than those currently in orbit, offering improved performance in weak-signal environments, researchers are currently developing techniques to improve continuity and coverage now using the current satellite constellation. One such approach is described in this month's column. Navigation Message Contents. Replacing the Z-Count. Improving Signal Sensitivity (Un-assisted pseudorange estimate: An instructive model; Assisted pseudorange estimation: Several options). Wide Area Reference Networks. Conclusion. Acknowledgments. Manufacturer.

12.08   [Showcase issue — no column]

12.09   Ultra-wideband and GPS: Can they co-exist?   Akos et al.

Akos, D., M. Luo, S. Pullen, and P. Enge (2001). Ultra-wideband and GPS: Can they co-exist? *GPS World*, September, Vol. 12, No. 9, pp. 59-70.

Innovation: Modern society uses radio signals for all kinds of applications. But whether they are used for communications, location-determination, remote sensing, or some other purpose, they are almost all generated by modulating a sinusoidal carrier wave, and the signal energy produced is concentrated in a fairly narrow band permitting a large number of signals to share the frequency real estate. Ultra-wideband (UWB) signals are different. Instead of using a carrier, UWB signals are generated as a sequence of very short pulses which results in the signal energy being spread over a large part of the radio spectrum. Recent advances in UWB technology may lead to devices, which can image objects buried underground or behind walls; permit short-range, high-speed data transmissions for broadband access to the Internet; locate assets with ranging signals; or provide covert, secure communications. Some argue that these low-power devices will be able to operate in the radio spectrum already occupied by existing radio services without causing them interference. But is this true in the case of

GPS? GPS signals are very weak, as anyone who has tried to use a standard GPS receiver indoors can attest. A relatively small amount of interference can disable a receiver. To see if UWB and GPS signals actually can share the same part of the radio spectrum, several government and university research laboratories are conducting compatibility tests. One such set of tests was undertaken by researchers at Stanford University and in this month's column they report their findings. UWB Signal Structure (Coding). Test Procedures (Methodology; Test setup; Test procedure). Test Results (PRF comparisons; Spectral line sensitivity; Effect of modulation; Loss of lock and acquisition test). Other Compatibility Studies. Summary and Conclusions. Acknowledgments. Manufacturers.

12.10   Explorations of the wilderness: Making maps with GPS   Monahan

Monahan, D. (2001). Explorations of the wilderness: Making maps with GPS. *GPS World*, October, Vol. 12, No. 10, pp. 32-38.

Innovation: In this month's column, we look at one of the growing number of interfaces between non-expert users and GPS technology. It illustrates how a layperson can readily create some valuable maps using GPS, a task that would have been impossible just a few years ago. It also illustrates that GPS is following the normal progression traversed by successful technologies as they develop from something that requires experts to operate to something from which the layperson can learn to easily benefit. Just as electric starting for cars meant that a wider range of people could drive, so too have advances in portability and supporting software meant that more people can use GPS. Personal experience; Few landmarks. The Hardware (Receiver). Mapmaking (What to record; Software; Content; Map scale; Georeferencing; Reproducibility; Layers; Download; Export). Conclusion. Manufacturers. Raster and Vector. Elevation Profiles. Map Scale. Georeferencing.

12.11   Monitoring GPS receiver and satellite clocks in real time: A network approach
Lahaye et al.

Lahaye, F., P. Collins, P. Héroux, M. Daniels, and J. Popelar (2001). Monitoring GPS receiver and satellite clocks in real time: A network approach. *GPS World*, November, Vol. 12, No. 11, pp. 44-50.

Innovation: The Global Positioning System is made possible, in large part, by the use of atomic frequency standards onboard the satellites and at the tracking stations here on the ground. These standards, both rubidium vapor cells and cesium beam tubes, control the timing and frequency of the signals emitted by the satellites. They possess the required characteristics of very high stability and high accuracy. Once set to the correct time, clocks driven by these standards maintain the correct time to within tiny fractions of a second for long periods. But no clock, not even an atomic one, is perfect. The performance of individual clocks in the satellites and at tracking stations is compared against GPS System Time which is a synthetic or "paper" time scale derived from the clocks in all of the satellites as well as those at the GPS Control Segment tracking stations. This time scale is kept closely aligned to Coordinated Universal Time (UTC) as maintained at the U.S. Naval Observatory (ignoring UTC leap seconds). In addition to the use of GPS for the monitoring and maintenance of the system clocks, GPS is used by the wider precise time and time interval community for synchronizing clocks and frequency standards around the globe. In this month's article, a team of researchers from the Geodetic Survey Division of Natural Resources Canada describes a technique they have developed for monitoring the performance of both GPS receiver and satellite clocks in real time using a regional network of tracking stations. The

Network. Real-Time Clock Phase Estimates. RTMACS Clock Models (Scheduled maser frequency correction; Unscheduled maser frequency change; Receiver lost the external frequency). Remote Receiver Clock Monitoring. Conclusion. Acknowledgments. Manufacturers.

12.12 [Showcase issue — no column]

13.01 Modeling photon pressure: The key to high-precision GPS satellite orbits
Ziebart et al.

Ziebart, M., P. Cross, and S. Adhya (2002). Modeling photon pressure: The key to high-precision GPS satellite orbits. *GPS World*, January, Vol. 13, No. 1, pp. 43-50.
Innovation: "Photons have mass?! I didn't even know they were Catholic." – Anonymous. Actually photons have no mass, but that does not mean they cannot affect GPS satellite orbits. GPS satellites operate in a harsh, radiation-filled environment 20,000 kilometers above the surface of the Earth. Solar radiation pressure – the force due to the impact of solar photons and the related effects of anisotropic thermal re-radiation and albedo are all tiny forces and yet they have a strong perturbing effect on the GPS satellite orbits. Predicting how GPS satellites will move in space relies upon understanding and modeling these effects, and the accuracy of these predicted orbits underpins the entire system for positioning, velocity determination, and a host of other applications. This month's Innovation column examines the significance of these forces and how they can be modeled. Data and Parameters (Solar irradiance; Spacecraft attitude; Optical properties of spacecraft surface). Spacecraft Description (Thermal properties). Eclipse Seasons. Modeling Methods (Pixel array methods). Discussion. Conclusion.

13.02 Mapping the low-latitude ionosphere with GPS Fedrizzi et al.

Fedrizzi, M., E. R. de Paula, I. J. Kantor, R. B. Langley, M. C. Santos, and A. Komjathy (2002). Mapping the low-latitude ionosphere with GPS. *GPS World*, February, Vol. 13, No. 2, pp. 41-47.
Innovation: Since the late 1980s various research groups have been investigating the behavior of the ionosphere using GPS data. These investigations are based on the total electron content (TEC) measurements derived from dual-frequency GPS observations taking advantage of the dispersive nature of the ionospheric medium. Currently, there is a large number of GPS receivers in continuous operation worldwide. Even through numerous, these stations are unevenly distributed, being situated mostly in the Northern Hemisphere. The relatively smaller number of GPS receivers in the Southern Hemisphere, and consequently the reduced number of available TEC measurements, results in less accurate ionospheric modeling for this region. In this month's column, an international team of researchers describes how they are using GPS data from the Rede Brasileira de Monitoramento Continuo do Sistema GPS (RBMC, the Brazilian Network for Continuous Monitoring of GPS) and other stations to assess the behavior of the ionosphere above South America and neighboring regions. UNB Ionospheric Modeling. Observation and Results. Conclusions and Future Research. Acknowledgments.

13.03 Assisted GPS: A low-infrastructure approach LaMance et al.

LaMance, J., J. DeSalas, and J. Jarvinen (2002). Assisted GPS: A low-infrastructure approach. *GPS World*, March, Vol. 13, No. 3, pp. 46-51.

Innovation: Have you ever tried to use a GPS receiver indoors? Chances are, unless you were on the top floor of a wood-frame house and using a receiver with ample antenna gain, you couldn't get a position fix. GPS is a marvelous positioning tool but it does have some weaknesses, one of which is low signal power. And unlike cellular telephones, conventional GPS receivers do not work well, if at all, unless their antennas have a clear view of the sky. Although future GPS satellites will transmit signals with higher power, it will be a decade or more before the current constellation of satellites is fully replaced. In the meantime, how can GPS be used in skyscraper canyons, inside office buildings, and even in underground parking garages? Assisted GPS comes to the rescue! In this month's column, a team of researchers from the United States and Finland describe their approach for assisted GPS – one which does not require a huge infrastructure investment for service providers. What is AGPS? AGPS Implementation. Initial User Groups. Assistance Data. Why AGPS? (Shorter wait; Greater sensitivity; Customer satisfaction). Infrastructure Requirements. SMS Data Compression. Phone Modifications Required. AGPS Performance. Future Enhancements. Manufacturers.

13.04   Precise platform positioning with a single GPS receiver   Bisnath et al.

Bisnath, S. B., T. Beran, and R. B. Langley (2002). Precise platform positioning with a single GPS receiver. *GPS World*, April, Vol. 13, No. 4, pp. 42-49.

Innovation: With the removal of Selective Availability about two years ago, the twice-distance root-mean-square horizontal accuracy of single-receiver, single-epoch GPS point positioning afforded by the Standard Positioning Service has improved to better than 10 meters in many situations. Differential positioning techniques and the use of carrier-phase data can provide higher accuracies, even to sub-centimeter levels. However, these techniques require raw data or corrections from another receiver. The subject of this month's column is the design of a GPS data processing technique capable of producing positions with accuracies at the few-decimeter level using data from a single receiver, regardless of platform dynamics. This feat is accomplished by combining two processing philosophies: point positioning – making use of precise GPS constellation ephemeris and clock offset information to estimate a single receiver's state; and carrier-phase-filtered, pseudorange processing – supplementing pseudorange-based positioning with carrier-based position-change information. Point Positioning. Pseudorange Processing. Filter Design. Filter Models and Solution. Data Ttesting and Analysis. Static Data Testing. Airborne Data Testing. Spaceborne Data Testing. Conclusions. Acknowledgements. Manufacturers.

13.05   The Block IIA satellite calibrating antenna phase centers   Mader, Czopek

Mader, G. L. and F. M. Czopek (2002). The Block IIA satellite calibrating antenna phase centers. *GPS World*, May, Vol. 13, No. 5, pp. 40-46.

Innovation: A GPS receiver determines the biased distance between the electrical phase center of its antenna and the phase center of a GPS satellite's transmitting antenna as a pseudorange or carrier-phase measurement. This distance measure is biased due to the lack of synchronization between satellite and receiver clocks, atmospheric propagation delays, ambiguities, and other factors. To determine the position of the receiving antenna, the receiver's operating software (or a user's post-processing software) combines a number of simultaneous measurements on different satellites with information on the positions of the satellites, the offsets of the satellite clocks, and other parameter values in an accurate theoretical model of the measurements. The position of a satellite inferred from the

ephemeris data in the broadcast navigation message is actually the position of the phase center of its antenna as determined by the GPS control segment. However, the antenna phase center is not the most natural point of reference for accurately describing the motion of an Earth-orbiting satellite and its response to the various forces that perturb its motion. The satellite's center of mass is more appropriate. Accordingly, the precise GPS ephemerides produced by the International GPS Service (IGS) and others refer to the satellite centre of mass. To both generate and use these ephemerides to process GPS data, the offset between the center of mass and the satellite's antenna phase center must be accurately known. In this month's column, Gerald Mader and Frank Czopek discuss their recent calibration of the phase center of a GPS Block IIA satellite antenna and the implications of the new results. (Absolute calibrations). NGS Calibration Method (Test range; Average phase center; Time delays). Antenna Description (Theoretical offsets). Antenna Calibration Results (Tests; Center of mass; Scale differences). Conclusions. Acknowledgement. Manufacturers.

13.06   Studying the performance of Global Navigation Satellite Systems: A new software tool   Verhagen

Verhagen, S. (2002). Studying the performance of Global Navigation Satellite Systems: A new software tool. *GPS World*, June, Vol. 13, No. 6, pp. 60-65.

Innovation: The performance of a GNSS receiver and the accuracy and reliability of the position information derived from its measurements depend on several factors. How many satellites can it track? To what elevation cutoff angle? Does it provide carrier-phase measurements or just pseudoranges? What are the variances and co-variances of its measurements? Is it a single- or a dual-frequency receiver? Over what time period are the observations being made? Is the data from the receiver being used by itself or combined with data from another receiver? What is the fidelity of the models incorporated into the data processing software? And so on. Depending on the quality of the receiver and how its measurements are made and used, it can yield quite different position accuracies. It would be very useful to be able to predict the level of accuracy that would be obtained for a particular observation scenario — and to be able to answer "What if?" questions, such as: What if I changed the elevation cutoff angle? What if I started the measurements at 2:00 p.m. instead of 4:00 p.m.? What if I used a 3 kilometer baseline instead of a 30 kilometer one? In this month's column, the author describes a software tool she has developed which allows such questions to be asked and answered. Design Computations (Internal reliability; External reliability; Success rates; Dilution of precision). User Interface. Applications. Concluding Remarks.

13.07   GPS signal multipath: A software simulator   Byun et al.

Byun, S. H., G. A. Hajj, and L. W. Young (2002). GPS signal multipath: A software simulator. *GPS World*, July, Vol. 13, No. 7, pp. 40-49.

Innovation: Simulation is a key activity in almost all areas of science and engineering. It enables researchers and developers to characterize a system's performance before it is built or deployed. In fact, simulation studies can help at the system design stage to maximize the future system's performance. In last month's column, we focused on the simulation of different scenarios under which a global navigation satellite system receiver might operate, accounting for such operating parameters as receiver measurement precision and satellite visibility. We now turn to the simulation of the phenomenon of multipath and its effect on GPS observables. A team of researchers at the California Institute of Technology's Jet

Propulsion Laboratory (JPL) has devleoped a multipath simulator which is being used to optimize the choice and location of a GPS antenna to be placed on the International Space Station's Japanese Experiment Module. The antenna will feed a GPS receiver which will help to assess the accuracy of an atomic clock to be flown on the space station. The receiver will be used to determine the position and velocity of the space station with sufficient accuracy to correct the clock's measurements for the effects of special and general relativity. The authors discuss the operation of their simulator and some of the results they have obtained for the space station environment. (Multipath problem; Multipath simulator). GPS Signal Structure. Multipath Effect (Wide sampling interval; Narrow sampling interval). Simulator Description (Multipath modeling; Antenna gain pattern). Application of the Simulator (Spacecraft modeling; Assessing the multipath error; Optimal location of the antenna). Conclusion. Acknowledgements.

13.08   [Showcase issue — no column]

13.09   Ants can successfully design GPS surveying networks   Saleh
Saleh, H. A. (2002). Ants can successfully design GPS surveying networks. *GPS World*, September, Vol. 13, No. 9, pp. 50-61.
Innovation: A common problem in making measurements on a GPS surveying network with a limited number of receivers is deciding the best order in which to visit the sites and carry out the observations. The optimum site occupation schedule would be the one which provides the best results with a minimum cost in time. How does one go about finding the best schedule? It seems that ants know how. In this month's column the author explains how ants efficiently find their food using an indirect communication procedure and how their approach can be mimicked in designing GPS surveying networks. The GPS Network Problem. Metaheuristic Technique. Ants and Aalgorithms. ACS Algorithm (Starting the algorithm; Local search method; The local updating rule; The global updating rule). Implementation of the Algorithm. Computational Results. Comparative Analysis. Conclusion. Acknowledgements.

13.10   A growing concern: Radiofrequency interference and GPS   Butsch
Butsch, F. (2002). A growing concern: Radiofrequency interference and GPS. *GPS World*, October, Vol. 13, No. 10, pp. 40-50.
Innovation: Over the past couple of years, there has been extensive discussion of the potential interference that ultra-wideband (UWB) radio signals might cause to GPS once UWB devices proliferate across the planet. But GPS is also susceptible to interference from more conventional transmissions both accidental and intentional (jamming). For example, a particular directional television receiving antenna widely available in the consumer market contains an amplifier which can emit spurious radiation in the GPS L1 frequency band with sufficient power to interfere with GPS reception at distances of 200 meters or more. Harmonic emissions from high-power television transmitters might also be a threat to GPS. Furthermore, the GPS L2 frequency is susceptible to interference from out-of-band signals from transmitters operating in the lower part of the 1240 to 1300 MHz band which is shared by terrestrial radiolocation services and amateur radio operators. As for intentional interference, the weak GPS signals can be readily jammed either by hostile forces during conflicts or by hackers who could easily construct a GPS jammer from a surplus home-satellite television receiver. So, just how susceptible are GPS signals to interference and how

can such interference be monitored? The author answers these questions. Signal-to-noise Ratio. Estimating S/No; What S/N Says About RFI. Analyzing RFI Impact. Directly Detecting RFI. Locating the Source of RFI. Typical RFI Sources. Conclusion.

13.11 New IGS clock products: A global time transfer assessment   Ray, Senior

Ray, J. and K. Senior (2002). New IGS clock products: A global time transfer assessment. *GPS World*, November, Vol. 13, No. 11, pp. 45-50.

Innovation: The International GPS Service (IGS) has a new suite of clock products available and is continuing to improve their usefulness for practical time and frequency transfer applications. In this month's column, Jim Ray and Ken Senior describe these IGS clock products, use internal repeatability analysis to assess their potential accuracy and stability limits, and compare them with the emerging requirements of the timekeeping community. They conclude that calibration of the internal delays in the GPS receiving equipment will probably continue to set the limit for time transfer accuracy, whereas frequency transfers can already achieve stabilities approaching 10-15 over one-day intervals. (Joint pilot project; Hardware). IGS Clock Products (Required consistency). Improving the IGS Time Scale (New system; Long-term stability). Accuracy Assessments (Clock jumps; Station-dependent performance). Stability Considerations. Prospects for Time Transfer. Acknowledgments. Manufacturers.

13.12 [Showcase issue — no column]

14.01 Jamming GPS susceptibility of some civil GPS receivers   Forssell, Olsen

Forssell, B. and R. B. Olsen (2003). Jamming GPS susceptibility of some civil GPS receivers. *GPS World*, January, Vol. 14, No. 1, pp. 54-58.

Innovation: How susceptible are Standard Positioning Service GPS receivers to different kinds of jamming? The U.S. Department of Defense will use in-theatre jamming of the L1 signal to deny its adversaries the use of GPS. While jamming GPS signals has always been a military option, its use became a necessity following deactivation of Selective Availability. In addition to such military procedures, terrorists might try to jam the GPS signals using easily constructed equipment. GPS signals are also susceptible to unintentional jamming from neighboring users of the radio spectrum. Jamming signals can take different forms, and just how a receiver responds to a jamming signal depends on several factors. In this month's column, two Norwegian authors describe the influence of different types of jamming signals on the ability of L1 C/A-code GPS receivers to acquire and track satellites under various circumstances and they report the results of testing three different receiver types using an advanced GPS simulator system. Our Research Goals. Equipment. Scenarios (Parameters). Simulations. Test Results. Discussion and Conclusions. Acknowledgements

14.02 Standard Positioning Service handheld GPS receiver accuracy   Tiberius

Tiberius, C. (2003). Standard Positioning Service handheld GPS receiver accuracy. *GPS World*, February, Vol. 14, No. 2, pp. 46-51.

Innovation: Officially, the Global Positioning System has two levels of service: the Precise Positioning Service (PPS) which is afforded to the United States military, allied military forces and some other U.S. government agencies, and the Standard Positioning service (SPS), available to all users worldwide. Currently, the SPS is provided by way of the Coarse/Acquisition (C/A) 1.023 megachip per second pseudorandom noise (PRN) code on

the GPS L1 frequency at 1575.42 MHz. The vast majority of GPS receivers now in existence, including virtually all civil-use handheld receivers, are SPS receivers which determine their positions by tracking the L1 C/A-code. SPS policy initially dictated a predictable positioning accuracy of 100 metres, at the 95 percent confidence level, horizontally, and 156 metres (95 percent) vertically. SPS positioning accuracy was purposely degraded to this level through the use of Selective Availability (SA). When SA was removed on May 2, 2000, SPS accuracy improved greatly, approaching that of the PPS. The civil benefits of discontinuing SA. Previously, SA made it difficult to determine which highway a car was on, in areas where several highways run in parallel. Such inaccuracy caused problems for in-car navigation systems which could sometimes give erroneous turn information. Now, it may even be possible to determine which lane of a multi-lane highway a car is traveling. Such distinction not only improves navigation but can also significantly benefit emergency vehicle response to E-911 calls which provide automated position information and roadside assistance vehicles responding to disabled cars. SA removal has also benefited fleet management. Tracking the locations of taxis, buses, tractor trailers, and boxcars has become much more efficient especially in crowded parking lots and railway yards. In the field of aviation, SA removal enhanced the safety of GPS for non-precision runway approaches and generally improved pilot situational awareness. Recreational users of GPS have also benefited from SA removal as their waypoints now more precisely locate favorite fishing holes, boating obstacles, and game left for future retrieval. Fishermen can more accurately locate lobster pots and other fishing gear and with SA removal, the orbits of satellites carrying GPS receivers can be more accurately determined and real-time onboard orbit determination is now possible. Static Analysis (Ground truth; Positioning; Other analyses; Comprehensive testing; Correlations; Signal tracking). Kinematic Analysis (Positioning; Signal tracking). Data Logging. Concluding Remarks.

14.03   Fuzzy logic and GPS benefitting from uncertainty   Wieser

Wieser, A. (2003). Fuzzy logic and GPS benefitting from uncertainty. *GPS World*, March, Vol. 14, No. 3, pp. 38-47.

Innovation: The complexity of GPS requires complex models. However, even the most sophisticated functional and stochastic models used for data processing are not perfect. For example, the models of atmospheric propagation delay, multipath effects, and signal scattering will always be only approximations to the (time-varying) true situations. Consequently, the interpretation of the processing results, especially the estimated confidence regions, is difficult and relies usually on some kind of (human) expert knowledge. This uncertainty is not an inadequacy of the technology but a result of the many unpredictable and unobservable influences on the GPS observables. So rather than trying to model these effects exactly, researchers are investigating modeling decisions based on a relatively new branch of mathematics called fuzzy logic. Fuzzy logic is an extension of the more common two-valued logic whose answers to questions are yes or no, 0 or 1, or true or false. In fuzzy logic, answers may have a degree of truth between 0 and 1. Fuzzy logic has helped overcome similar decision-making difficulties in other disciplines, most notably in systems control (elevators, automatic transmissions, auto-focus cameras, and so on). First investigations indicate that GPS can also benefit from fuzzy logic. One of the first researchers to investigate the potential benefit of fuzzy logic to GPS is Dr. Andreas Wieser and in this month's column he presents a tutorial on the basics of fuzzy systems and introduces a tool

which will help a GPS user to decide whether his or her GPS application might benefit from fuzzy logic. Fuzzy Sets (Membership functions; Truth functions). Elements of Fuzzy Logic. Fuzzy Control (Fuzzification; Inference; Defuzzification). An Example (The goal; Variables; Terms; Rules; Application of the controller). Conclusion.

14.04   Using GPS to enhance data security: Geo-Encryption   Logan, Denning

Logan, S. and D. E. Denning (2003). Using GPS to enhance data security: Geo-Encryption. *GPS World*, April, Vol. 14, No. 4, pp. 40-49.

Innovation: Generals, diplomats, and lovers have used cryptography for thousands of years to encode messages and other documents so that only the intended recipient would be able to read them. Julius Caesar, for example, is reported to have used a substitution encryption scheme or cipher to exchange message with his generals. Each letter in an original message was substituted with another letter obtained by shifting a fixed number of letters further along in the alphabet. So, "a" would be replaced by, say, "c"; "b" would become "d"; and so on. The codes of such simple substitution ciphers are easily broken by noting the frequencies of the letters in the encoded messages. In English words, for example, the letter "e" occurs most often – it is 56 times more common than "q"; the least common letter. And more English words begin with the letter "s" than with any other letter. So over the years, cryptologists have devised ever more sophisticated and complex encryption schemes to provide greater security to encoded information. In this month's column, Logan Scott and Dorothy Denning discuss an innovative encryption scheme that integrates position and time into the encryption and decryption processes. Their geo-encryption approach builds on established cryptographic algorithms and protocols in a way that provides an additional layer of security beyond that provided by conventional cryptography. It allows data to be encrypted for one or more specific locations or areas such as a corporation's campus area. Constraints in time as well as location can also be enforced. Geo-encryption can be used with both fixed and mobile applications and supports a wide range of data sharing and distribution policies such as providing location-based security for digital cinema distribution and forensic analysis in cases of piracy. For the military GPS user, the authors illustrate how individual waypoints can be uniquely encrypted so as to be accessible only when the receiver is physically within the route parameters, both in terms of location and time. Geo-Encryption (Encryption algorithms; The geo-encryption algorithm; PVT-to-geolock mapping function; Antispoof receivers; Relay encryption). Applications (Digital cinema distribution; Waypoint geolocking). Conclusion.

14.05   Monitoring the ionosphere with GPS: space weather   Coster et al.

Coster, A., J. Foster, and P. Erickson (2003). Monitoring the ionosphere with GPS: space weather. *GPS World*, May, Vol. 14, No. 5, pp. 42-49.

Innovation: "Stormy today, clearing up tomorrow." That may sound like a typical forecast given by your local TV meteorologist, but it could just as well be a forecast of space weather. Here on Earth, high winds, heavy rains, deep snow, and other forms of severe weather can disrupt our daily lives. Conditions on the Sun and in the solar wind, magnetosphere, and the ionosphere can also affect our lives through the effects they have on satellites, communications, navigation, and power systems. Scientists are now studying space weather with a wide range of tools to try to learn more about the physical and chemical processes

taking place in the upper atmosphere and beyond. One of these tools is GPS. The signals from the GPS satellites travel through the ionosphere on their way to receivers on or near Earth's surface. The free electrons populating this region of the atmosphere affect the propagation of the signals, changing their speed and direction of travel. By processing the data from a dual-frequency GPS receiver, it's actually possible to estimate just how many electrons were encountered by the signal along its travel path – the total electron content (TEC). TEC is the number of electrons in a column with a cross-sectional area of one square metre centred on the signal path. If a regional network of ground-based GPS receivers is used, then a map of TEC above the region can be constructed. The TEC normally varies smoothly from day to night as Earth's dayside atmosphere is ionized by the Sun's extreme ultraviolet radiation, while the nightside ionosphere electron content is reduced by chemical recombination. But the ionosphere can experience stormy weather just as the lower atmosphere does. Smooth variations in TEC are replaced by rapid fluctuations, and some regions experience significantly higher or lower TEC values than normal. In this month's column, we look at how GPS is being used to study such storms and how it is furthering our understanding of the Earth-Sun environment. Background. TEC Storm Maps. Magnetospheric Connections. Storm-Time Ionospheric Effects. Summary

14.06   How good can it get with the new signals? Multipath mitigation   Weill

Weill, L. R. (2003). How good can it get with the new signals? Multipath mitigation. *GPS World*, June, Vol. 14, No. 6, pp. 106-113.

Innovation: Answer: The winner of the 1971 Nobel Prize for Physics. The question? Who defined the most important signal parameter for controlling GPS multipath? The British/Hungarian physicist Dennis Gabor won the prize for the invention of holography. However, Gabor was also one of a handful of mathematicians and scientists who developed communication theory during the 1940s. Communication theory, also called information theory, is the branch of mathematics that deal with the efficient and accurate transmission of information-bearing signals from one place to another. Key to the theory is the concept of signal bandwidth. Now bandwidth can be defined in a number of different ways, but the particular bandwidth named after Gabor determines, in part, how accurately a GPS receiver can measure pseudorange or carrier phase in the presence of multipath. The Gabor bandwidth is determined by the particular shape of the signal's power spectral density function, and the larger the bandwidth the more resistant is the signal to multipath. The GPS receiver must have a processor that takes advantage of this resistance to provide measurements with minimal multipath contamination. In this month's column, Dr. Lawrence Weill outlines an implementation of a multipath mitigation algorithm based on the statistical theory of maximum likelihood and describes its expected performance with the new GPS signals soon to be available–signals characterized by a higher Gabor bandwidth than those currently transmitted. Receiver-Based Mitigation (MCRW technology). Multipath Signal Model. Bounds on Multipath Error (Error bound with multipath; MMSE estimator; Computational problems). Two-Path ML Estimator. MMT Algorithm (Baseband signal samples; Log-likelihood function; Computation of correlation functions; Secondary path amplitude constraint). Modernized Signal Structures (L1 C/A-coded and L2 civil signals (Class I); P/Y-coded and L5 civil signals (Class II); The M-coded signal (Class III); Spectra of the three signal classes). Simulation Results. Laboratory Tests. Implementation Issues. Concluding Remarks. Maximum Likelihood Estimation.

14.07   An integrated positioning system: GPS + INS + pseudolites   Yi et al.

Yi, Yudan, D. Grejner-Brzezinska, C. Toth, Jinling Wang, and C. Rizos (2003). An integrated positioning system: GPS + INS + pseudolites. *GPS World*, July, Vol. 14, No. 7, pp. 42-49.

Innovation: Kinematic positioning has become a standard GPS technique for precision navigation that supports surveying and mapping systems. One application for which the high accuracy and reliability of kinematic positioning are required is mobile mapping, whose market has significantly expanded in the past 10 years. Inertial navigation systems (INSs) normally augment GPS to provide continuous and accurate trajectory and attitude information from the imaging sensors of mobile mapping systems. GPS contributes high accuracy and long-term stability (with properly resolved integer ambiguities and no losses of lock) and provides a means of error estimation for the INS sensor. A GPS-calibrated INS provides reliable bridging during GPS outages and supports ambiguity resolution after the GPS signals are subject to occasional blockages. But what if GPS signals are lost for extended periods of time or the visible constellation is limited to four or fewer satellites, which can often happen in urban canyons? Pseudosatellites (pseudolites) may be the answer. This month's column discusses an experimental GPS/INS/pseudolite system, with special emphasis on the error spectrum and the navigation performance analysis based on a medium-accuracy and highly reliable INS, limited GPS constellation availability, and a varying number of pseudolites. It also describes simulated and actual pseudolite data in typical noisy environments and analyzes their impact on navigation accuracy. What are Pseudolites? An Integrated System (Data processing). Real and Simulated Data. PL Effects. Ambiguity Resolution. Summary and Conclusions.

14.08   [Showcase issue — no column]

14.09   Getting your bearings: The magnetic compass and GPS   Langley

Langley, R. B. (2003). Getting your bearings: The magnetic compass and GPS. *GPS World*, September, Vol. 14, No. 9, pp. 70-81.

Innovation: The magnetic compass has been guiding travellers for a thousand years or more. It is one of the oldest navigation instruments and is still widely used by ship captains, pilots, Boy and Girl Scouts, and hikers. But thanks to modern microelectronic technology, the compass has been reborn. Electronic versions of the compass are available in standalone units, as a component in multisensor navigation systems, and as embedded modules in GPS receivers. Many cars and trucks now come equipped with electronic compasses. And despite their amazing ability to accurately determine a position, single-antenna GPS receivers cannot determine their heading – the direction in which the receiver, or the platform carrying it, is pointed. The compass comes to the rescue! When GPS signals are blocked by buildings, a GPS-based navigation system might have to resort to dead reckoning. Again, the compass pitches in by providing heading information to improve the procedure. This month's column is a tutorial about these electronic magnetic sensors, how they measure the Earth's magnetic field, and how they complement the capabilities of a GPS receiver. The force. The Geomagnetic Field (Models). The Needle Compass. Electronic Compasses (Fluxgate; Hall-Effect Sensor; Magnetoinductive Sensor; Magnetoresistive Sensor). Calibration. GPS. Conclusion

14.10 A new way to integrate GPS and INS: Wavelet multiresolution analysis
El-Sheimy et al.

El-Sheimy, N., A. Osman, S. Nassar, and A. Noureldin (2003). A new way to integrate GPS and INS: Wavelet multiresolution analysis. *GPS World*, October, Vol. 14, No. 10, pp. 42-49. Innovation: What do fingerprints, Brahms Hungarian Dance Number 1, El Niño, and GPS have in common? They are all being subjected to the relatively new mathematical technique known as wavelet analysis. Wavelet analysis is an extension of Fourier analysis, the classical technique that decomposes a signal into its frequency components. However, Fourier analysis cannot determine the exact time at which a particular frequency occurred in the signal. Wavelet analysis, on the other hand, allows scientists and engineers to study the frequency structure of time-varying signals with unprecedented time resolution. In fact, a signal can be decomposed to obtain a time history of the different frequency bands making up the signal–an approach termed multiresolution analysis. Wavelet analysis can also compress data for more-efficient storage and transmission, replacing the original data values with far fewer wavelet transform coefficients. Although the roots of wavelet analysis can be traced back to the 1930s, the development of the technique for various applications in engineering and the sciences began only about 20 years ago. But in that relatively short time (on the history of mathematics timescale), the technique of wavelet analysis has been adopted for a huge variety of applications, from fingerprint compression to improved processing of GPS data. Making room for fingerprints. A digitized high-resolution fingerprint image requires about half a megabyte of storage, and a complete fingerprint card needs about 10 megabytes. While this might not seem like much, imagine the task of digitizing and storing the approximately 200 million fingerprint cards occupying an acre of filing cabinets at the U.S. Federal Bureau of Investigation in Washington, D.C. Using wavelet analysis, a digitized fingerprint card can be compressed by a factor of 15 or so, greatly easing the storage problem and allowing fingerprint images to be more quickly transmitted from one place to another. Brahms revisited. Wavelet analysis has even been used to restore a heavily damaged recording of Brahms playing one of his own compositions. Part of Hungarian Dance Number 1 was recorded in 1889 on Thomas Edison's original wax-cylinder phonograph. Wavelet analysis of re-recordings of the original, despite being immersed in noise, has allowed researchers to discover that Brahms took liberties with his own published score. For example, he doubled the length of eighth notes in some places, shifted the emphasis on notes in others, and even improvised at times rather than follow the score. Enhancing GPS accuracy. Wavelet analysis is also being used to improve the accuracy of GPS. These uses include the de-noising of GPS pseudorange measurements, cycle-slip detection and elimination in GPS carrier-phase measurements, and separating biases such as multipath from high-frequency receiver noise. Wavelet analysis can also determine anomalies in GPS data used for deformation analysis and to remove seasonal variations and noise from a GPS time series to better estimate crustal motion. In this month's column, University of Calgary researchers discuss the use of wavelet analysis to improve the integration of differential GPS with an inertial navigation system. Multiresolution Analysis (Wavelet transform; Wavelet multiresolution analysis; Implementation of DWT). INS/DGPS Integration (Adaptive error correction). Results and discussion. Conclusion.

14.11 Receiver frequency standards: Optimizing indoor GPS performance
Vittorini, Robinson

Vittorini, L. D. and B. Robinson (2003). Receiver frequency standards: Optimizing indoor GPS performance. *GPS World*, November, Vol. 14, No. 11, pp. 40-48.

Innovation: While orbiting GPS satellites use atomic frequency standards to generate the ranging signals, most GPS receivers can determine position using only a simple frequency standard: a quartz crystal oscillator. Mass-produced quartz crystal oscillators are found in virtually every piece of electronic equipment, from wristwatches to GPS receivers. Oscillators contribute only a fraction of a receiver's manufacturing costs and have helped reduce consumer cost for a basic receiver to less than $100. The common consumer GPS product sold today, however, will generally not function indoors and will have difficulty dealing with signal blockage from buildings and foliage. In recent years, engineers have developed receivers that will perform satisfactorily even with multipath-corrupted and severely attenuated signals such as those found indoors. This month's column examines the quartz crystal oscillator's role as a frequency standard in a GPS receiver and how certain characteristics of these mass-produced devices can limit performance for indoor use. Fundamentals. Systems Challenges. Requirements Overview (User dynamics). Receiver Sensitivity (GPS acquisition/track; Doppler window; Tracking thresholds; SNR; Acquisition sensitivity). Frequency Reference Anomalies (Microjump performance and E911; Conventional TCXO constraints). GPS Receiver Test Bed (The methodology overview; Temperature-induced gradient effects; Microjumps: How bad can they get? Temperature gradient profiles; Microjump profile). Test Results (Test results summary). Cost Trade: Silicon or Quartz? Choices (What's next?). Summary

14.12 [Showcase issue — no column]

15.01 Jamming Protection of GPS Receivers, Part I: Receiver Enhancements   Rounds

Rounds, S. (2004). Jamming protection of GPS receivers, Part I: Receiver enhancements. *GPS World*, January, Vol. 15, No. 1, pp. 54-59.

Innovation: The jamming of radio signals is almost as old as radio itself. In 1899, a rival newspaper attempted to jam the *New York Herald*'s ship-to-shore reporting of the America's Cup race results. Ever since, jamming has been used by governments, military forces, and others to deliberately interfere with radio communications to prevent their successful reception. Its use was perhaps most prevalent during the Cold War when shortwave broadcasts from the West were regularly jammed by Warsaw Pact countries. During military operations, jamming of an adversary's radio and radar signals is a common tactic and, in fact, is now an integral part of electronic warfare. In an attempt to thwart such jamming threats, military planners are continually developing antijamming techniques. Such is the case with GPS. Although its spread-spectrum nature affords it some protection from interfering signals, the signal is so weak that it can be readily overpowered by even a low-power nearby jammer or by a strong jammer at distances of up to many hundreds of kilometers. This month's column is the first installment of a two-part article about jamming protection for GPS receivers. In Part I, we look at enhancements to receiver design – primarily by integrating the GPS sensor with an inertial measuring unit. In next month's column, we will examine a variety of antenna enhancements. Stay tuned. Types of Enhancements. Receiver Enhancements (Integration Time Effects; Data Wipeoff; Limitations). Levels of Integration (Loose Coupling; Tight Coupling; Deep Integration).

15.02   Jamming Protection of GPS Receivers, Part II: Antenna Enhancements   Rounds

Rounds, S. (2004). Jamming protection of GPS receivers, Part II: Antenna enhancements. *GPS World*, February, Vol. 15, No. 2, pp. 38-45.

Innovation: This month's column features the second installment of a two-part article on jamming protection for GPS receivers. In Part I, we looked at enhancements to receiver design – primarily by integrating the GPS sensor with an inertial measuring unit. In this month's column, we examine a variety of antenna enhancements. Basic Antenna Enhancements (Cancellers; Polarimeters; Spectral Filters; Spatial Nulling). STAP. SFAP. STAP, SFAP Added Benefits (Beamforming; Self-Equalization; Other Benefits). Receiver Impacts (Phase Perturbations; RF Dynamic Range). Conclusions.

15.03   Applications for general aviation: Combining low-cost inertial systems with GPS
Soloviev, van Graas

Soloviev, A. and F. van Graas (2004). Applications for general aviation: Combining low-cost inertial systems with GPS. *GPS World*, March, Vol. 15, No. 3, pp. 38-45.

Innovation: Thanks to the development of micromachined sensors, the cost of some fairly sophisticated three-axis inertial navigation systems has dropped to a level where they can be seriously considered for use in a variety of demanding civil applications, including general aviation. Inertial systems have been used on commercial and military aircraft as primary navigation instruments for many years but these systems are very expensive and out of reach of most of the general aviation community. Low-cost inertial systems coupled with GPS could benefit general aviation in a number of ways, including: their use in attitude and heading reference systems (AHRS) for advanced perspective displays; aiding of GPS receiver code- and/or carrier-tracking loops to increase interference margins; bridging over short-term GPS outages; and as a stand-alone navigation system after the loss of GPS. However, the errors produced by low-cost inertial systems need to be carefully assessed and contained if these applications are to see the light of day. In this month's column, Drs. Andrey Soloviev and Frank van Graas of Ohio University's Avionics Engineering Center in Athens, Ohio, discuss the potential use of low-cost inertial systems by general aviation and, from a series of simulations and real-world tests, highlight the expected performance of the systems and the implementation challenges. Low-Cost System Performance (Flight Data; Calibration). Integration Options (Integration for AHRS; Inertial Aiding; Short-Term Inertial Coasting; Long-Term Inertial Coasting). Summary.

15.04   Robust integrity monitoring using GPS+Galileo: Navigation for precision approaches   Misra, Bednarz

Misra, P. and S. Bednarz (2004). Robust integrity monitoring using GPS+Galileo: Navigation for precision approaches. *GPS World*, April, Vol. 15, No. 4, pp. 42--49.

Innovation: The performance of any navigation system is characterized by its accuracy, availability, continuity, and integrity. From a safety point of view, integrity is arguably the most important factor. Without some assurance of a system's integrity, we have no way of knowing whether the navigation information we receive is correct: How are we to know whether a navigation system is actually achieving its advertised accuracy and not misleading us with faulty information? Although standalone GPS provides a certain level of integrity through self-monitoring by the GPS control segment, it is insufficient for aircraft conducting precision approaches to airport runways. The wide and local area augmentation systems offer a much higher level of integrity than standalone GPS. This is achieved, in part, by the aircraft

receiver computing a high-confidence upper bound on its position error from the data it receives from the augmentation signals. As long as the computed error bound in below a preset value, safe navigation is assured with an extremely high level of confidence. However, the error bound is based on the assumption that the errors are distributed according to a normal or Gaussian probability distribution. Unfortunately, the positions determined using corrections from the augmentation systems have errors which do not quite follow such a distribution. The current approach to handling this phenomenon is to overbound the errors with a protection limit which safely accounts for the occasional larger than "normal" errors. In this month's column, Pratap Misra, Ph.D., and Sean Bednarz from the Massachusetts Institute of Technology's Lincoln Laboratory discuss a promising alternative integrity monitoring technique that needs no assumption on the error distribution – a technique that will see a marriage of GPS with the eagerly anticipated Galileo system. Precision Approach. Integrity Monitoring (Gaussian Error Model). Redundant Measurements. Algorithm LGG1. Performance of LGG1. Summary.

15.05   Hyperboloidal range differencing: A new technique for deformation monitoring
Itani, et al.

Itani, K., M. Ueno, and R. B. Langley (2004). Hyperboloidal range differencing: A new technique for deformation monitoring. *GPS World*, May, Vol. 15, No. 5, pp. 34-39.
Innovation: The uses of GPS are myriad – from navigating a visitor around an unfamiliar city to determining a golf ball's distance to the next hole. Many applications of GPS involve safety of life such as locating mobile telephones through E-911 and E-112 services, tracking and dispatching emergency vehicles, and guiding aircraft to runway thresholds. GPS also is being used in another important safety-of-life service: monitoring the stability of landforms such as open-pit mines, the flanks of dormant volcanoes, and areas prone to landslides. Displacements smaller than 1 centimeter can be detected using the very precise carrier-phase observable. In many cases, devastating land ruptures are preceded by small, incipient deformations which, if detected, can help foretell their occurrence. Conventional GPS techniques for detecting such small displacements require good receiver-satellite geometry and a surfeit of observations. Unfortunately, many sites subject to deformation have poor satellite visibility. They might be near the base of a rock wall or on a north-facing slope. Conventional techniques have difficulty in detecting centimeter-level displacements at such sites in a timely fashion. Kenji Itani, a research engineer with Furuno Electric in Japan, recently devised a technique that uses observations from as few as two satellites over a period of minutes to detect sub-centimeter displacements. If the direction of the movement is predictable (such as along a slope of maximum inclination), then the actual size of the displacement can be estimated. In this month's column, Itani and his colleague, Mami Ueno, join me in describing the technique and the tests carried out to confirm its potential use in detecting incipient landslides. Hyperboloidal Method (The Misclosure). A Weighting Strategy. Field Tests. Conclusions.

15.06   Where's my bus? Radio signposts, dead reckoning, and GPS
El-Gelil, El-Rabbany

El-Gelil, M. A., and A. El-Rabbany. (2004). Where's my bus? Radio signposts, dead reckoning, and GPS. *GPS World*, June, Vol. 15, No. 6, pp. 68-72.
Innovation: There is nothing more irritating than walking to the bus stop on a windy sub-zero winter morning only to find that your bus is 15 minutes behind schedule. Wouldn't it be

nice if you could connect to the transit system's Web site from your computer or your mobile phone and find out the actual arrival time of the next bus – before you leave the house? Transit systems across North America and elsewhere are working towards such a service and, in fact, prototype systems are already being tested. To estimate arrival time at the next stop, current bus position, speed, and heading must be known. This information from an onboard positioning system is relayed to the fleet management center via a radio link. Updated arrival time can then be provided to transit users through a Web page, an automatic telephone answering system, or an electronic display at the bus stop. The transit system can also use the data to study effects of traffic and other factors on bus schedules, to increase efficiency. Onboard bus positioning systems typically take the form of a dead-reckoning system using an odometer coupled with an electronic compass or gyroscope. Errors of such a system grow with time and the system must be reset periodically using an accurate position fix. A radio signpost system with transmitters spaced along the bus route can perform this service. However, unless the density of signposts is sufficiently high, the dead-reckoned position error (and hence the error in the expected time or arrival at the next bus stop) will be unacceptably large. And should the bus detour from its scheduled route due to an accident or road works, the dead-reckoning system cannot be updated. This month's column describes a bus positioning system which integrates GPS with dead reckoning and radio signposts to significantly improve the system's accuracy. Dead-Reckoning System. Dead Reckoning Errors. Signpost System. Kalman Filter Design. Field Trails. Conclusions and Outlook.

15.07   Spacecraft formation flying: Relative positioning using dual-frequency carrier phase   Kroes, Montenbruck

Kroes, R., and O. Montenbruck. (2004). Spacecraft formation flying: Relative positioning using dual-frequency carrier phase. *GPS World*, July, Vol. 15, No. 7, pp. 36-42.

Innovation: On July 16, 1982, a Delta launch vehicle propelled the Landsat-4 remote sensing satellite into orbit. This satellite, the fourth in the United States' Landsat program, carried a new suite of sensors which produced data of such detail and clarity that its use represented a major advance in Earth observations from space. In addition, Landsat-4 carried the first GPS receiver into orbit. Although only a few of the prototype Block I GPS satellites were available at the time, Landsat-4's GPS receiver demonstrated that a spacecraft could be navigated with GPS to an accuracy better than 50 meters. Since that inaugural flight, dozens of GPS receivers have flown in space. These receivers have not only provided accurate positions and velocities of their host spacecraft but also determined spacecraft attitude and accurate time for spacecraft sensors, and profiled the atmosphere by observing GPS satellites as they are occulted by the Earth's limb. In this month's column, we look at yet another application of GPS in space: precisely determining the relative positions of cooperative spacecraft flying in formation. Simultaneous measurements by multiple formation-flying satellites can provide significant benefits to a wide variety of space missions. Such measurements can yield higher-resolution imagery and interferometry or information on small-scale spatial variations in atmospheric properties or gravity. The concept can also be extended to provide robust and redundant fault-tolerant spacecraft system architectures and complex networks dispersed over clusters of satellites. Some of these applications require knowing the precise location of each cooperating spacecraft. Dual-frequency GPS carrier-phase observations can provide the required precision. Strategy. Ambiguity (Re)initialization. Kinematic Positioning. Hardware Simulations (Testing; Results and Analysis). Summary and Conclusions.

15.08 [Showcase issue — no column]

15.09 **Revolution in GPS: Advanced spinning-vehicle navigation** **Doty**

Doty, J. H. (2004). Revolution in GPS: Advanced spinning-vehicle navigation. *GPS World*, September, Vol. 15, No. 9, pp. 48-55.

  Innovation: GPS-guided weapons played a key role during the recent war in Iraq. These air-dropped bombs and air- and sea-launched missiles achieved higher on-target success rates with reduced collateral damage compared to conventional weapons thanks, in part, to their use of GPS. The U.S. military would like to extend such capabilities to shells fired from artillery pieces and from the deck guns of naval vessels. Ongoing research and development will field such competent munitions within the next few years. These munitions are fitted with fins that are deployed in flight to de-spin the shell and correct its trajectory. An inertial measurement unit coupled to a GPS receiver computes the needed corrections. An unconventional receiver, it must fit within a shell's fuse and withstand 15,000 g acceleration on firing. In flight, it acquires satellite signals and starts determining shell course. Some GPS-guided munitions must be de-spun before the receiver can begin acquiring signals. This requirement results in a delayed trajectory correction and the possibility that the shell might miss its target. This article examines technological advances that will permit a GPS receiver to acquire satellite signals and compute the shell's position while it is still spinning. The jamming-resistant suite of Advanced Spinning-Vehicle Navigation (ASVN) technologies not only promises superior accuracy performance, but also can extend shell range, since the drag-causing control fins do not have to be deployed until later in the flight. ASVN technologies also can serve on rockets and satellites. Bottom Line Drivers. ASVN Technology Suite (GPS Roll Angle Determination; Interference-Aided Navigation; Temporal Beam Forming; Coriolis Pitch-and Yaw-Rate Sensing). GPS Roll-Angle Determination (GRAD Demonstration; Anti-Jamming Issues). Interference-Aided Navigation. Temporal Beam Forming. Pitch- and Yaw-Rate Sensing. Applications. Acknowledgements.

15.10 **Combating the perfect storm: Improving marine differential GPS accuracy with**
  a wide-area network **Skone, et al.**

Skone, S., R. Yousuf, and A. Coster (2004). Combating the perfect storm: Improving marine differential GPS accuracy with a wide-area network. *GPS World*, October, Vol. 15, No. 10, pp. 31-38.

  Innovation: Under normal operating conditions, marine differential GPS (DGPS) horizontal positioning accuracies on the order of several meters are achieved in North America. Such accuracies are well within the tolerance of 10 meters (95 percent confidence level) specified by the Canadian and United States Coast Guards, but under high levels of ionospheric activity, significant degradations in DGPS positioning accuracies can occur. Marine DGPS operations in North America are particularly susceptible to such effects, where a feature known as storm-enhanced density is observed during ionospheric storm events. It was previously thought that the mid-latitude North American ionosphere was reasonably benign, with minimal storm effects of relevance for marine DGPS users. However, during ionospheric storms in May and October, 2003, marine DGPS horizontal position accuracies were degraded by factors of 10-30. These degraded accuracies persisted for hours and were well beyond system tolerances specified for marine DGPS users. Such ionospheric activity is not unusual during the years following solar maximum, and is expected to persist for several years. In this month's column, we examine the impact of ionospheric storms on marine

DGPS users and look at a proposed wide-area approach for mitigating large storm-induced positioning errors. Storm Enhanced Density. Wide-Area DGPS. Data Set (Network 1; Network 2). Analyses and Results (Long-Term Data Set; May 29-30, 2003 Storm; Network 1; Network 2; October 29-31, 2003, Storm; Network 1; Network 2). Conclusion.

15.11   Time and frequency disseminations: Advances in GPS transfer techniques
<div align="right">Parker, Matsakis</div>

Parker, T. E., and D. Matsakis (2004). Time and frequency dissemination: Advances in GPS transfer techniques. *GPS World*, November, Vol. 15, No. 11, pp. 32-38.

Innovation: The atomic clock is one of the greatest inventions of the 20th century. When the first commercial atomic clocks based on the resonance of the cesium atom were introduced in 1958, available clock accuracy jumped by orders of magnitude. The new clocks would not gain or lose one second in a thousand years. Scientists used laboratory versions of the cesium atomic clock to define the atomic second and to establish and maintain a time scale to which all clocks could be set. But how do you set a clock, particularly one which is accurate to a microsecond or better? Or once set, how do you keep track of its error? Clocks are monitored and synchronized using a time and frequency dissemination technique. In the past, radio signals and traveling clocks were used for this purpose. But GPS, itself dependent on atomic clocks for its operation, has become the best technique for intercomparing clocks and for helping to maintain the world's time systems. In this month's column, scientists from the United States' two national time-keeping laboratories, the National Institute of Standards and Technology and the U. S. Naval Observatory, discuss the past, present, and future use of GPS for accurately disseminating time and frequency. Time Directly from GPS (Gentle Steering; Disciplined Oscillator; Cable Delays). GPS Common-View (Baselines). GPS Carrier Phase (Precise Point solutions; Biases; Discontinuities). Precise Calibration. Other Transfer Techniques. Summary.

15.12   [Showcase issue — no column]

16.01   Satellite navigation evolution: The software GNSS receiver   MacGougan, et al.

MacGougan, G., P.-L. Normark, and C. Stählberg (2005). Satellite navigation evolution: The software GNSS receiver. *GPS World*, January, Vol. 16, No. 1, pp. 48-55.

Innovation: More than twenty-five years have passed since the first GPS satellite was placed in orbit. During this time, there has been a remarkable evolution in the design and operation of global navigation satellite system (GNSS) receivers. What used to require a couple of 19-inch racks' worth of electronic equipment can now be done with a small module inside a mobile phone. The reduction in the size and power consumption of a GNSS receiver was made possible because of the general evolution of semi-conductor technology but also because more and more of the operation of a GNSS receiver could be accomplished with digital rather than analog circuitry. However, marvelous as modern GNSS receivers are, once built, most receivers are not readily adaptable to changes in frequency of operation, signal structure, or operating scenarios. While their firmware typically can be upgraded to accommodate changes in the algorithms for processing GNSS signals, changes are limited by the locked-in hardware design of the receiver. This limitation to the operation of a GNSS receiver will become increasingly important as new signals from modernized GPS satellites become available and as the Galileo system starts operation. In this month's column, we look at a further evolution of the GNSS receiver which offers the promise of flexibility,

adaptability, and cost-effectiveness: a receiver whose signal acquisition and processing is almost completely carried out by reprogrammable software rather than by hardware. Such software-defined GNSS receivers will serve a wide range of users from researchers developing novel GNSS applications and who need to tailor the receiver's operation to the users of mobile phones whose micro-processor could do double duty as a GNSS signal processor. Traditional Architectures (How it Works). Software Receivers (The Ideal; The Practical). SDR vs. ASIC (Flexibility vs. Processing Power; FPGA; Moore's Law; Upgradeability; Separation of Hardware; Acquisition; Tracking; Power Consumption; Cost Effectiveness). Software Gain (Multi-Mode; Multi-System; Multi-Sensor; Testing and Quality Control; Software Development). State of the Art (Bevy of Benefits; Research Product). Conclusion.

16.02   Calibrating antenna phase centers: A tale of two methods   Akrour et al.

Akrour, B., R. Santerre, and A. Geiger (2005). Calibrating antenna phase centers: A tale of two methods. *GPS World*, February, Vol. 16, No. 2, pp. 49-53.

Innovation: Often overlooked, the antenna is a vital component of any GPS receiver. Without it, a receiver simply would not work. The job of the antenna is to convert the miniscule energy in electromagnetic waves received from GPS satellites into an electrical current that can be processed by the receiver. The receiver then determines the coordinates of the antenna – or, more precisely, it determines the coordinates of the electrical phase center of the antenna. Typically, the phase center is near the physical center of the antenna and for many low-accuracy GPS applications, the exact location of the phase center is immaterial. However, for demanding applications such as monitoring the deformation of the Earth's crust, assessing the stability of bridges and buildings, for machine control, and for attitude determination, the relationship between the electrical phase center and the physical structure of the antenna is crucial – it should be known to the millimeter level. But try as they might, antenna designers have yet to create an antenna whose phase center is absolutely stable with respect to the physical structure of the antenna – there is always some movement of the phase center as the elevation angle and azimuth of an arriving electromagnetic wave changes. The movement can amount to millimeters or more. Such variation will contribute an error to positions computed using low-noise carrier-phase measurements. However, with the appropriate set-up, it is possible to measure the phase-center variation and calibrate an antenna. The mean phase center and its variation can then be used in software used to process collected carrier-phase data. In this month's column, we investigate two techniques for calibrating GPS antennas and examine how well they agree.   Calibration Beam (Temperature Compensation; Antenna Tests). Anechoic Chamber Calibration. Phase-Center Variations. Comparing the Two Methods (Mean Phase Center; Phase-Center Variations; Synergy). Conclusions.

16.03   Future GNSS performance: Predictions using GPS with a virtual Galileo
constellation   Feng

Feng, Y. (2005). Future GNSS performance: Predictions using GPS with a virtual Galileo constellation. *GPS World*, March, Vol. 16, No. 3, pp. 46-52.

Innovation: The Global Positioning System is a marvel of 20th century engineering. With it, we can find lost children, track shipping containers, and navigate aircraft. However, it has limitations such as the difficulty in acquiring signals in natural or concrete canyons. In such environments, too few satellites are visible for a receiver to determine a fix. However, once

the European Galileo system is in place in a few years' time, instead of having only about 30 satellites at our disposal, we'll have 60 – even more if we include the Russian GLONASS satellites. Positioning in areas with restricted sky visibility will be much easier using Galileo, and possibly GLONASS, along with GPS. Other benefits from use of a combined constellation will accrue such as more accurate positioning and time transfer and better determination of the atmosphere's behavior with the promise of improved weather forecasting. But can we determine how good positioning will actually be using a combined GPS and Galileo constellation before the Galileo satellites are in orbit? Neither Galileo signal simulators nor Galileo receivers are currently readily available, so it appears to be difficult for investigators to assess future Galileo performance using actual radio signals. However, given that Galileo will be compatible and interoperable with GPS and that the Galileo satellite orbits and signals have a lot in common with GPS, it is possible to get an idea of the potential performance of the combined constellation using just GPS alone. How? Read on. Galileo Pseudolites (Virtual Galileo Constellation). Single-Point Positioning (Performance Parameters). Differential Positioning (Single-Frequency Scenario; Dual-Frequency Scenario). Epoch Time Separation, Numerical Analysis. Conclusions.

16.04   Continuous navigation: Combining GPS with sensor-based dead reckoning
<div align="right">zur Bonsen et al.</div>

zur Bonsen, G., D. Ammann, M. Ammann, E. Favey, and P. Flammant (2005). Continuous navigation: Combining GPS with sensor-based dead reckoning. *GPS World*, April, Vol. 16, No. 4, pp. 47-54.

Innovation: "Can you hear me now?" This familiar question is asked countless times each day by mobile phone users attempting to improve their signal. Terrain, buildings, and foliage can block or seriously impede the propagation of cell-phone signals. Users of GPS receivers suffer the same problems. While there have been some advances in improving the sensitivity of GPS receivers and developing techniques such as assisted GPS that permit a GPS receiver to use attenuated signals, the antenna of a conventional receiver must have a direct line of sight to the GPS satellites. In urban canyons, it may not be able to "see" a sufficient number of satellites with good geometry to determine a three-dimensional position fix. And in tunnels or in parking garages, the receiver will see no satellites at all. Consequently, continuous navigation in many cities is impossible for conventional GPS-only navigation systems. In this month's column, we look at how GPS can be combined with other sensors to provide continuous navigation in even the most-challenging environments. Challenging Environments (Navigation with < 4 Satellites; SBAS; Sensor-Based Dead Reckoning; Distance Sensing; Direction Sensing). Sensing distance (Variable Reluctance; Hall Effect; Optical Sensors; Pulse Frequency; Data Recorders; Linear Accelerometers; Other Distance-Sensing Options). Sensing Direction (MEMS Gyroscopes; Linear Accelerometers; Car Control Sensors; Compass). Map Matching. GPS With Dead Reckoning (Switching Approach; Weighted-Mix Solution). Automatic Calibration (Odometer Pulse Calibration; Gyroscope Calibration). Test Drives. Conclusions by Application (In-Vehicle Navigation Systems; Automatic Vehicle Location and Fleet Management; GPS-Enabled Road Pricing; Homeland Security; Advanced Traffic Safety; Telecommunication Infrastructure).

16.05   Assisted GPS: Using cellular telephone networks for GPS anywhere   Bryant

Bryant, R. (2005). Assisted GPS: Using cellular telephone networks for GPS anywhere. *GPS World*, May, Vol. 16, No. 5, pp. 40-45.

Innovation: The first two articles to appear in the Innovation column in *GPS World* more than 15 years ago were entitled "GPS: A Multipurpose System" and "The Limitations of GPS." In the first article, GPS was trumpeted as a revolutionary positioning and navigation technique that could be used in all sorts of unexpected ways. This premise has stood the test of time with new uses for GPS still being discovered. The second article reminded readers that GPS may not be a panacea for all of our positioning needs – that there are some situations in which GPS fails us. In particular, it was noted that GPS signals are "blocked" by buildings, making indoor use of GPS impossible. But what was impossible 15 years ago is possible today. New designs have greatly improved the sensitivity of GPS receivers so they can make code-phase measurements even on the severely attenuated signals inside buildings. And if the signal is too weak for the receiver to extract the satellite navigation message itself, the necessary data can be sent to the receiver using a cellular telephone network, which also can supply timing information to help the GPS receiver acquire signals more quickly. In this month's column, we will investigate how this so-called "assisted GPS" works and why we can now say that GPS works (virtually) anywhere. System Considerations (Benefits of Assistance; Signal Levels; MS/UE Assisted; Time Assistance; Additional Assistance). CDMA vs. GSM (Precise Timing; Time Slots; Cell Sizes). AGPS Standards. Cell-Phone Interference (GSM Signal Blanking). Receiver Architectures (Limited Coherent Integration; Flexible Design; Memory and Hosting Constraints). Conclusions

16.06   Ionospheric modeling: The key to GNSS ambiguity resolution
Richert, El-Sheimy

Richert, T., and N. El-Sheimy (2005). Ionospheric modeling: The key to GNSS ambiguity resolution. *GPS World*, June, Vol. 16, No. 6, pp. 35-40.

Innovation: The GPS carrier-phase observable is more than 100 times more precise than the code-based pseudorange observable. Unfortunately, it is also ambiguous. If we want to use the carrier phase as a range measurement in positioning or navigation, we must account somehow for the unknown integer number of cycles or turns of phase in the initial phase measurement when a GPS receiver locks onto a satellite's L1 or L2 signal carrier. Mathematicians, scientists, and engineers have developed clever techniques for helping to resolve these integer ambiguities either in real time or in post-processing collected data. However, the success of these techniques in correctly determining the ambiguities depends on several factors including whether a point or relative positioning technique is employed, the length of the baseline in relative positioning, and how well a variety of errors afflicting the measurement can be mitigated. One source of such errors is the ionosphere. In this month's column, we examine how ionospheric modeling helps in the resolution of carrier-phase ambiguities and how the rate of success in correctly determining the ambiguities will be much improved when GPS observations are combined with those of the future Galileo system. Four Processing Scenarios. Ionospheric Delays (Ignoring the Ionosphere; Eliminating the Ionosphere; Modeling the Ionosphere; Ionospheric Estimation (Three frequencies; Fixed model; Float Model; Weighted Model). Pseudo-Observable Demo (Changing Satellites). Future GNSS Signals. Ambiguity Resolution (Weighted Model; GPS +Galileo; Ambiguity Validation; Effect of Future Signals). Conclusions.

16.07   Accurate time assistance: Synchronizing GSM mobile telephones to microseconds
Duffett-Smith, Hansen

Duffett-Smith, P., and P. Hansen (2005). Accurate time assistance: Synchronizing GSM mobile telephones to microseconds. *GPS World*, July, Vol. 16, No. 7, pp. 44-49.

Innovation: With the advent of assisted-GPS, location-based services (including emergency services) will be available anywhere within the coverage area of a cellular telephone network. Or will they? Although assisted-GPS, or A-GPS, permits a GPS receiver to operate with much weaker signals (such as those experienced indoors) there will be situations where even A-GPS will not provide a reasonably accurate position fix within an acceptable time interval. Users in locations with high multipath or extremely weak signals could experience long delays in achieving a position fix. And even if the fix is timely, it might have a large error. Network operators are therefore implementing fall-back methods that kick in when A-GPS fails, providing the user with a gracefully degrading position fix service. The simplest fall-back method is Cell ID, by which a user's position is assumed to coincide with the location of the cell tower handling the user's call or the centroid of the coverage of that particular cell. In either case, the assumed user's position could be wildly inaccurate, depending on the network's tower spacings. Researchers in the United Kingdom have invented a fall-back technique that uses network signal timings to provide a user's phone (terminal) with a synthetic clock, synchronized to GPS Time. With such an accurate clock, the terminal can be positioned using a similar technique to that used by GPS but by using the network signals themselves. In this month's column, the inventors describe their *Matrix* technique and how it promises to provide a high level of user satisfaction for location-based services. Positioning Terminals (Satellite Positioning; Network Positioning; Offsetting Weaknesses; Time-Synched Networks; Unsynched Networks; A-GPS Weaknesses; Cost and Complexity). Matrix Method. How Matrix Works. Solo Matrix. Test Results. Matrix-Enhanced GPS. Conclusion.

16.08   [Showcase issue — no column]

16.09   Prime time positioning: Using broadcast TV signals to fill GPS acquisition gaps
Martone, Metzler

Martone, M., and J. Metzler (2005). Prime time positioning: Using broadcast TV signals to fill GPS acquisition gaps. *GPS World*, September, Vol. 16, No. 9, pp. 52-60.

Innovation: Television. It features prominently in our living rooms and in our daily lives. It informs us, educates us, and entertains us. And now, thanks to a development at Rosum Corp. in Mountain View, California, TV will also position us. Researchers have devised a way to use terrestrial TV signals, both analog and digital, to determine positions. In a similar fashion to how GPS works, a special receiver can extract timing information from received TV signals to produce pseudoranges and, with additional transmitter clock offset information from a server, can determine the horizontal coordinates of the receiver. And since TV signals are quite strong, positions can be obtained inside buildings where conventional GPS and often assisted GPS does not work. In this month's column, we examine TV positioning. Authors from Rosum Corp. describe how the technique works, both standalone and in conjunction with GPS, discuss its advantages and limitations, and how the technique might provide added security for the global position, navigation, and timing infrastructure in these uncertain times. New Positioning channel. How it Works (Technology Trio). Error Mitigation (Transmitter Clock Instability; Multipath Mitigation). Hybridization with GPS (GPS Pseudoranges). Going Global (Cyclic Prefix; Gain). Field Test Results (Standalone TV Positioning; TV + GPS Hybrid). Further Advances. Conclusions.

16.10 Turn, turn, turn: Wheel-speed dead reckoning for vehicle navigation Hay

Hay, C. (2005). Turn, turn, turn: Wheel-speed dead reckoning for vehicle navigation. *GPS World*, October, Vol. 16, No. 10, pp. 37-42.

Innovation: Let us now consider an invention by no means useless, and delivered to us by the antients as of ingenuity, by means of which, when on a journey by land or sea, one may ascertain the distance travelled. It is as follows. The wheels of the chariot must be four feet diameter; so that, marking a certain point thereon, whence it begins its revolution on the ground, when it has completed that revolution, it will have gone on the road over a space equal to twelve feet and a half." So begins the description by the Roman engineer Marcus Vitruvius Pollio of a distance-measuring device based on the rotation of a wheel. This device is the ancestor of the odometer and wheel-speed sensors present in virtually every vehicle on the road today. Both odometers and wheel-speed sensors can be used for dead-reckoning navigation – determining a vehicle's position based on an initial position, the measured distance traveled in a given time interval, and the vehicle's heading. Compasses have traditionally supplied the heading information in a dead-reckoning navigation system. However, with wheel-speed sensors on each wheel, the system can determine not only the vehicles speed but also its heading by differencing the measurements from the left and right wheels. In this month's column, we take a look at the use of wheel-speed sensors for in-vehicle navigation systems. Such systems can provide continuous navigation even when GPS signals are blocked by buildings, tunnels, and other obstructions. (Road Obstacles; Inertial Sensors). Wheel-Speed Sensors (Data Distribution; Directional Accuracy). Design Challenges (Sensor Type; Sensor Tooth Count; Tire Size; LAN Variability; Vehicle Chassis; Wheel Slippage). Road Tests (Test Barriers). Simulations (NMEA Messaging; Motion Profile; Comparative Studies; Controlled Testing; Clean Data). Conclusion.

16.11 Map-aided GPS navigation: Linking vehicles and maps to support location-based services Syed, Cannon

Syed, S., and E. Cannon (2005). Map-aided GPS navigation: Linking vehicles and maps to support location-based services. *GPS World*, November, Vol. 16, No. 11, pp. 39-44.

Innovation: Installed GPS navigation systems are becoming popular options for new car buyers. And many aftermarket, portable, and PDA- or cell phone-based systems are available in the marketplace. A basic GPS navigation system can provide continuous, accurate navigation, except when the GPS signals are blocked by buildings, tunnels, or other obstructions or when multipath or interference reduces position accuracy. A factory-installed system might include additional sensors such as an odometer or gyroscope to provide dead-reckoning navigation when GPS signals are lacking. Another aid to accurate navigation is map-matching in which the computed position fix is snapped onto the nearest road. However, depending on the fix error and the density of the road network, the system may or may not snap the fix onto the correct road. In this month's column, guest authors Syed and Cannon examine a novel technique that tightly integrates information from accurate maps with raw GPS and gyro data to determine a vehicle's position. Using classic statistical theory and fuzzy logic algorithms, the technique improved vehicle navigation accuracy in an urban canyon setting by more than 30 percent. Challenges in Urban Canyons. Map Matching. Map-aided GPS. Map-Matching Framework (First-Fix Subalgorithm; Tracking Mode). MAGPS Measurement Model. Results. Conclusions.

16.12 [Showcase issue — no column]

17.01   OpenSource GPS: A hardware/software platform for learning GPS: Part I, Hardware   Kelley, Baker

Kelley, C., and D. Baker (2006). OpenSource GPS: A hardware/software platform for learning GPS: Part I, Hardware.   *GPS World*, January, Vol. 17, No. 1, pp. 58-62.

Innovation: I built my first crystal radio kit when I was 9 years old. I became hooked on radio technology and later went on to build other radios, even one using a razor blade and pencil lead! I learned how radios worked by building them and tinkering with them. Radio technology has advanced considerably since my youth and although it is still possible to buy a crystal radio kit, most modern radios are digital black boxes. It's not impossible for the radio enthusiast to learn how these devices work, just rather more difficult. And the difficulty comes, in part, from the inability to tinker with these radios – to learn by doing. The GPS receiver is no exception. A simple handheld GPS receiver costs less than $100 – within the budget of many students. But users of these digital wonders have very little control over their operation. After all, they were designed to be operated by virtually anyone with next to no training. So how can interested individuals on a budget learn how a GPS receiver works – not just superficially but at the level of the tracking loops and correlators? Can one actually tinker with the operation of a GPS receiver? Until recently this was difficult to do. Sure, you could try to build a GPS receiver from scratch using a chipset and program the controlling microprocessor but that is beyond the capabilities of many individuals who simply want to experiment with a receiver's operation. But thanks to a recent collaborative effort involving GPS technology enthusiasts from around the globe, it is now possible to learn GPS by doing. The OpenSource GPS project has developed an economical hardware and software platform specifically for educational purposes. In this month's column, two of the project's leaders, Clifford Kelley and Douglas Baker, present part one of a two-part article about the project. This month, they will discuss the hardware component, built around the Zarlink GP2015/GP2021 chipset. Next month, they will describe the platform software and the results of static and kinematic tests of this innovative tool for GPS education. Hardware (Current GPS Hardware; Frequency Plan). Software.

17.02   OpenSource GPS: A hardware/software platform for learning GPS: Part II, Software   Kelley, Baker

Kelley, C., and D. Baker (2006). OpenSource GPS: A hardware/software platform for learning GPS: Part II, Software. *GPS World*, February, Vol. 17, No. 2, pp. 52-57.

Innovation: This month's column features the second installment of a two-part article about the OpenSource GPS project – an economical hardware and software platform developed specifically to allow students access to the inner workings of a GPS receiver. In Part I, we looked at the hardware component, built around the Zarlink GP2015/GP2021 chipset. In Part II, project leaders Clifford Kelley and Douglas Baker overview the project software and present results of static and kinematic testing of the OpenSource GPS platform. Software. Test Results. The Future.

17.03   GPS + modernized GPS + Galileo: Signal timing biases   Hegarty et al.

Hegarty, C., E. Powers, and B. Fonville (2006). GPS + modernized GPS + Galileo: Signal timing biases. *GPS World*, March, Vol. 17, No. 3, pp. 49-54.

Innovation: GPS timing and navigation user solutions are based on pseudorange measurements made by correlating user-receiver-generated replica signals with the signals broadcast by the GPS satellites. Any bias resulting from this correlation process within a user

receiver tends to be common across all receiver channels when the signal characteristics – code type, modulation type, and bandwidth – are identical. Such common biases will cancel out in the user navigation solution and appear as a fixed bias for timing solutions and some atmospheric signal analyses. New GPS signals and the future Galileo signals are somewhat different than the legacy signals broadcast by GPS satellites today, so new ways of accounting for biases will be needed. In this month's column, Chris Hegarty, Ed Powers, and Blair Fonville discuss this problem and quantify the timing biases of the different legacy and modernized GPS and Galileo signals broadcast on the L1 frequency and their dependencies on factors such as user-receiver filter bandwidth, filter transfer function, and delay-locked loop correlator spacing. Causes and Effects. Simulation Results. Hardware Measurements. Summary and Conclusions. Disclaimer.

17.04   Spacecraft navigator: Autonomous GPS positioning at high earth orbits
<div align="right">Bamford et al.</div>

Bamford, W., L. Winternitz, and C. Hay (2006). Spacecraft navigator: Autonomous GPS positioning at high earth orbits. *GPS World*, April, Vol. 17, No. 4, pp. 50-55.
Innovation: GPS receivers have been used in space to position and navigate satellites and rockets for more than 20 years. They have also been used to supply accurate time to satellite payloads, to determine the attitude of satellites, and to profile the Earth's atmosphere. And GPS can be used to position groups of satellites flying in formation to provide high-resolution ground images as well as small-scale spatial variations in atmospheric properties and gravity. Receivers in low Earth orbit have virtually the same view of the GPS satellite constellation as receivers on the ground. But satellites orbiting at geostationary altitudes and higher have a severely limited view of the main beams of the GPS satellites. The main beams are either directed away from these high-altitude satellites or they are blocked to a large extent by the Earth. Typically, not even four satellites can be seen by a conventional receiver. However, by using the much weaker signals emitted by the GPS satellite antenna side lobes, a receiver may be able [to] track a sufficient number of satellites to position and navigate itself. To initially acquire the GPS signals, a receiver also would have to search quickly through the much larger range of possible Doppler shifts and code delays than those experienced by a terrestrial receiver. In this month's column, William Bamford, Luke Winternitz, and Curtis Hay discuss the architecture of a receiver with these needed capabilities – a receiver specially deigned to function in high Earth orbit. They also describe a series of tests performed with a GPS signal simulator to validate the performance of the receiver here on the ground – well before it debuts in orbit. To initially acquire the GPS signals, a receiver also would have to search quickly through the much larger range of possible Doppler shifts and code delays than those experienced by a terrestrial receiver. (Extreme Conditions). Motivation. Acquisition Engine (Serial Search; Exceptional Navigator). Navigator Hardware. Integrated Navigation Filter. Hardware Test Setup. Simulation Results (Tracked Satellites; Acquisition Thresholds; Navigation Filter). Navigator's Future. Conclusion.

17.05   GNSS radio: A system analysis and algorithm development research tool for PCsRay et al.
Ray, J. K., S. M. Deshpande, R. A. Nayak, and M. E. Cannon (2006). GNSS radio: A system analysis and algorithm development research tool for PCs. *GPS World*, May, Vol. 17, No. 5, pp. 51-56.
Innovation: The GNSS community is forging a new era in positioning, navigation, and

timing. The first GPS satellite to transmit the civil L2 signal was launched in September 2005 with more to follow, and the first GPS Block IIF satellite with L5 signal capability will be launched in a couple of years. The first Galileo test satellite has been launched and the GLONASS constellation is to be renewed, with future satellites transmitting new signals. Also, several new augmentation systems under development will soon join the Wide Area Augmentation System. The plethora of new signals will require the development and testing of new methods for optimum acquisition and tracking, multipath mitigation, jamming resistance, and other aspects of receiver operation. Also, greater demands are being placed on the capabilities of GPS receivers using the legacy L1 signal, such as indoor operation and better performance under foliage, which require new signal processing approaches. Much of the work will center around the development of new signal correlators. To a certain extent, the design and development of a new correlator can be carried out using software signal simulation in a personal computer or workstation. However, software signal simulation does not emulate the actual GNSS signal conditions and therefore a platform which can work with either live or simulated radio-frequency (RF) signals is preferred. But the platform must still be as flexible and adaptable as that afforded by software simulation. A very efficient solution is to use an RF front end – a GNSS radio – to capture either live or simulated signals, down-convert and digitize the signals, preferably with user-selectable sampling frequencies, and stream the data to a personal computer where it can be stored for later processing or processed in real time. In this month's column, a team of researchers from India and Canada describe such a GNSS radio and how they have used it to develop and test algorithms for processing both legacy L1 GPS signals and the new L2C signal. The platform must still be as flexible and adaptable as that afforded by software simulation. (Hardware Simulators). L2C Signal Acquisition. L2C Signal Tracking. Weak Signal Techniques. Cross-Correlation Analysis. Interference Analysis. Summary.

17.06   Searching for Galileo: Reception and analysis of signals from GIOVE-A
Psiaki et al.

Psiaki, M. L., T. E. Humphreys, S. Mohiuddin, S. P. Powell, A. P. Cerruti, and P. M. Kintner, Jr. (2006). Searching for Galileo: Reception and analysis of signals from GIOVE-A. *GPS World*, June, Vol. 17, No. 6, pp. 66-72.

Innovation: At 05:19 UTC on December 28, 2005, the first Galileo test satellite blasted off from the Baikonur Cosmodrome atop a Soyuz-FG rocket. The rocket's Fregat upper stage placed the 649 kilogram satellite known as GIOVE-A (Galileo In-Orbit Validation Element-A) into a 29,635 kilometer circular orbit with an inclination of about 56 degrees. Built by Surrey Satellite Technology Ltd. of Guildford, England, GIOVE-A's role is to secure the Galileo system's frequencies allocated by the International Telecommunication Union, validate key technologies, and characterize the radiation environment of the orbits planned for the full constellation which is scheduled to be deployed by 2010. GIOVE-A carries a pair of redundant rubidium atomic clocks, a navigation signal generation unit, and a laser reflector. (Data from satellite laser ranging stations will help with analyses of satellite orbit and clock variations.) GIOVE-A can transmit two signals at a time from its L-band phased array antenna: either E2-L1-E1 (commonly called L1) and E5, or L1 and E6, using special pseudorandom noise (PRN) codes that are different from the planned Galileo codes. Furthermore, the navigation message broadcast by GIOVE-A is not representative of the structure or content ultimately to be used by Galileo. The GIOVE-A payload was activated on January 10, 2006, with the first signals broadcast on January 12. Official monitor sites of

the transmissions included the Rutherford Appleton Laboratory's Chilbolton Observatory in Hampshire, England, and the European Space Agency's Redu Station in the Ardennes region of Belgium. However, a number of researchers across the globe were interested in acquiring and studying the first Galileo signals. But because the PRN codes to be used by GIOVE-A had not been published, detection and tracking of the signals would not be easy. One could either use a very high gain dish antenna to lift the weak satellite signals out of the background noise or use clever signal manipulation techniques with stored signal samples acquired with a simple low gain antenna. In this month's column, Mark Psiaki and his colleagues at Cornell University describe how they used this latter approach to acquire and analyze the L1 signals transmitted by GIOVE-A. Researchers across the globe were interested in acquiring the first Galileo signals. Signal Data (Two Lobes). Signal Structure. Codeless Signal Acquisition (Acquisition Statistic; Search Strategy and Results). Code Breaking (In-Phase Accumulation; Approximate PRN Code Timing; Blind Alleys; Determination of Primary PRN Code Chips). Conclusions.

17.07 GPS + LORAN-C: Performance analysis of an integrated tracking system
Carroll

Carroll, J. (2006). GPS + LORAN-C: Performance analysis of an integrated tracking system. *GPS World*, July, Vol. 17, No. 7, pp. 40-47.

Innovation: Before GPS, even before satellites, there was LOng RAnge Navigation, or LORAN. Using terrestrial radio transmitters, it was developed during World War II for aircraft navigation. The wartime system evolved by the mid-1950s into the present day 100 kHz LORAN-C system. LORAN's standard principle of operation is hyperbolic positioning. A receiver measures the difference in times of arrival of pulses transmitted by a chain of three to six synchronized stations separated by hundreds of kilometers. The time-difference measurement derived from the signals of two stations, when multiplied by the speed of propagation of the signals, forms a line of position (LOP); the receiver could be anywhere on this line and give the same measurement. The geometrical form of this LOP is a hyperbola. Measurements using a third station provide another hyperbola, which intersects the first at the position of the receiver. There are many LORAN chains around the globe. The LORAN system is being modernized to enhance its accuracy, integrity, availability, and continuity. Vacuum-tube transmitters are being replaced with solid-state designs and new primary frequency standards are being installed at transmitting stations. Manufacturers have developed compact LORAN receivers able to track multiple transmitters simultaneously and to automatically apply propagation bias corrections. Some receivers are integrated with GPS or other sensors. Receivers also feature improved antenna designs. Collectively, these improvements are known as Enhanced LORAN or eLORAN for short. Additionally, LORAN signals can be used to convey differential GPS corrections. Such a system is already operational in Europe. Supported by the Coast Guard and the Federal Aviation Administration in the United States, a goal of eLORAN is to provide nonprecision approach for aviation users and harbor entrance and approach for marine users. Land users will benefit, too. Since LORAN has different signal characteristics from those of GPS, it can be used in locations where GPS cannot – by itself or in conjunction with GPS and other sensors. In this month's column, we look at a system that combines eLORAN with GPS and dead reckoning to overcome some of the problems in navigating in big cities. LORAN can help overcome some big-city navigation problems. LORAN-C (Legacy LORAN-C; eLORAN). Integrated Tracking System (GPS/LORAN System; Data Extraction). Performance Assessment (West-

Side Results; Loradd Receiver; Satmate Receiver; Wall Street Results; DR and Truth
Reference; GPS and LORAN Performance). Conclusions.

17.08   [Showcase issue — no column]

17.09   Phase wind-up analysis: Assessing real-time kinematic performance   Kim et al.
Kim, D., L. Serrano, and R. Langley (2006). Phase wind-up analysis: Assessing real-time
  kinematic performance. *GPS World*, September, Vol. 17, No. 9, pp. 58-64.
  Innovation: Many advances in GPS technology have occurred since the first test satellite was
  launched in February 1978. Perhaps the most significant for applications requiring very high
  accuracies in real time was the development of the technique known as RTK, or real-time
  kinematic. In RTK positioning and navigation, a reference station transmits carrier-phase and
  pseudorange data over a radio link to one or more roving stations. At a rover, the reference
  station data is combined with the rover data, resolving carrier –phase ambiguities, and the
  rover's position is determined in real time. Either single- or dual-frequency GPS receivers
  can be used, with the dual-frequency systems typically affording faster ambiguity resolution
  and higher positioning accuracies over longer distances. RTK systems, in common with other
  techniques, are susceptible to biases and errors such as ionospheric and tropospheric
  refraction along with line-of-sight-dependent phase-measurement effects including multipath,
  antenna phase-center variation, and carrier-phase phase wind-up. This latter phenomenon
  may not be familiar to all readers. It is a bias introduced into carrier-phase measurements by
  the rotation of a GPS receiver's antenna. There is also a contribution from the rotation of a
  GPS satellite's antenna as it orbits about the Earth. In developing an RTK-based vehicle
  navigation system at the University of New Brunswick (UNB), we have observed a few
  instances where the phase wind-up due to rotation of the rover receiving antenna can
  significantly degrade system performance. In this month's column, we'll look at carrier-phase
  wind-up introducing three wind-up observables that allowed us to perform qualitative
  assessments of its effects on the UNB RTK system. One motivation behind such an
  assessment is to determine whether or not we need to proceed to the next step of
  implementing algorithms to correct for the effects of phase wind-up. I am joined by Dr. Don
  Kim, the chief architect and developer of the UNB RTK system, and graduate student Luis
  Serrano. Phase wind-up can significantly degrade system performance. Observable Effects.
  Phase Wind-up Observables (Single-Difference Observable; Double-Difference Observable).
  Test Scenarios (3D Motion Table Test; Static-Rotating Antenna Pair; Two Co-Rotating
  Antennas; Vehicle Test). Concluding Remarks.

17.10   Dam stability: Assessing the performance of a GPS monitoring system
                                                                    Rutledge et al.
Rutledge, D. R., S. Z. Meyerholtz, N. E. Brown, and C. S. Baldwin (2006). Dam stability:
  Assessing the performance of a GPS monitoring system. *GPS World*, October, Vol. 17, No.
  10, pp. 26-33.
  Innovation: When the Global Positioning System was being designed back in the early 1970s,
  it was assumed that a GPS receiver's position would be determined from pseudorange
  measurements using the pseudorandom-noise-code modulation on the GPS satellite signals.
  In fact, that is how most GPS-based positioning and navigation is done even today. But the
  accuracy with which positions can be determined using pseudorange measurements is
  fundamentally limited by measurement noise and multipath which in turn is determined by

the effective wavelength of the code. However, it was realized around 1978 or so, that relative positions between pairs of GPS receivers could be determined with much higher accuracies by using the signal's carrier rather than its modulation. By differencing the phases simultaneously measured by a pair of receivers, essentially an interferometric technique, it was predicted that relative position accuracies equal to a small fraction of the carrier wavelength would be possible, although the instability of the receivers' clocks would be an issue. That issue was dealt with by forming a second measurement difference: differencing between satellites. Carrier-phase integer ambiguities also had to be dealt with by estimating them or eliminating them through a third differencing: differencing sequentially in time. And so by the early 1980s, the standard double and triple differencing carrier-phase approaches to high-accuracy relative positioning were in use. Since then, carrier-phase positioning has become a standard technique for both real-time and post-processed high accuracy positioning. In addition to many conventional applications, it has been used to detect slowly occurring or "silent" earthquakes, to control heavy machinery and to monitor the displacements of engineered structures such as suspension bridges, tall buildings, and as discussed in this month's column, dams. GPS vs. Plumb-Line Data (Pilot Project). GPS System Installation. Plumb-Line Correlation (Uncommon Displacement). Repeatability and Accuracy (Establishing Accuracy; 3D Motion). A Gaussian System. Performance Monitoring Plus.

17.11   GPS time transfer: Using precise point positioning for clock comparisons
Lahaye et al.

Lahaye, F., D. Orgiazzi, P. Tavella, and G. Cerretto (2006). GPS time transfer: Using precise point positioning for clock comparisons. *GPS World*, November, Vol. 17, No. 11, pp. 26-33. Innovation: One of the great technological accomplishments on [sic] the 18th century was the solution of "the longitude problem." Although latitude could be determined to high accuracy using astronomical observations and navigation tables alone, a determination of longitude additionally required knowing the time at Greenwich (Greenwich Mean Time or GMT) at the instant of the observations. Although astronomical techniques for determining GMT or time on some reference meridian had been developed as far back as the 1500s, they didn't provide sufficient accuracy and many marine disasters occurred because of inaccurately determined longitudes. The longitude problem was solved by John Harrison and his marine chronometers. He completed H4, his fourth and most portable chronometer (really a large watch) around 1760. Although not as accurate as large observatory clocks of its time, H4 was remarkably accurate for a portable clock. After a sea voyage lasting 147 days – its first real test – H4 had lost only 1 minute and 54.5 seconds, equivalent to less than 30 minutes of longitude! Ever since the birth of the marine chronometer, improvements in positioning accuracy have been tied to improvements in clock accuracy. Today we have clocks based on atomic phenomena with extraordinary accuracies. And GPS couldn't exist without its atomic clocks – both those carried by the satellites and those used at the system's monitoring stations. While GPS relies on atomic clocks for its operation, researchers at the world's time-keeping laboratories rely on GPS for intercomparing the behavior of their clocks and for maintaining global time scales. Over the past 20 years or so, researchers have developed a series of GPS-based techniques for clock measurements and comparisons. The latest technique to join the arsenal is precise point positioning (PPP), a technique initially developed for determining positions with sub-decimeter accuracy from single-receiver measurements. In this month's column, we take a look at how PPP has been used to monitor the behavior of clocks and what accuracies were obtained. The world's time-keeping

laboratories rely on GPS for intercomparing their clocks. Precise Point Positioning. Experiment Set-Up. PPP Processing Results (Constrained Solutions; Multi-Day Solutions; Comparison with IGS Products). Comparison with TWSTFT. Conclusions.

17.12   [Showcase issue — no column]

18.01   The International GNSS Service: Any Questions?   Moore
Moore, A. W. (2007). The International GNSS Service: Any Questions? *GPS World*, January, Vol. 18, No. 01, pp. 58-64.
Innovation: Collaboration is considered by many to be an inherent aspect of human society. It is through collaboration that society advances in different ways. In particular, progress in science depends on individuals and organizations collaborating with each other to develop theories, to test those theories using experimental data, to revise and enhance the theories on the basis of data analyses, and to test again. Looking on Wikipedia, we find the following traits necessary for successful collaboration: "shared objectives; sense of urgency and commitment; dynamic process; sense of belonging; open communication; mutual trust and respect; complementary, diverse skills and knowledge; intellectual agility." These words fittingly describe the International GNSS Service (IGS) and how it operates. The IGS was established in 1994 in order to provide the highest quality GNSS data and products in support of Earth science research, multidisciplinary applications, and education. It was and is still the aim of the IGS to advance scientific understanding of the Earth system components and their interactions, as well as to facilitate other applications benefiting society. The IGS consists of over 200 actively contributing organizations in more that 80 countries and a global network of over 370 stations. In addition to providing GPS and GLONASS raw measurements, the IGS contributes to the maintenance and improvement of the International Terrestrial Reference Frame, produces high accuracy GPS and GLONASS satellite orbit and clock data, and monitors the Earth's rotation and the state of its ionized and neutral atmospheres. Among other applications, IGS measurements and products help monitor the movement and flexure of the Earth's tectonic plates, assess sea-level variations, carry out precise time transfer, and determine accurate trajectories for low-Earth orbiting satellites. In this month's column, Angelyn Moore, the IGS Central Bureau's deputy director, overviews the organization's service, history, and future, demonstrating that the IGS is a model of scientific collaboration of which not just the GNSS community but the whole world should be proud. Just Wondering (What is the IGS?; How is the IGS Funded?; Are There Costs or Restrictions in Using IGS Data or Products?; What is an IGS Station?; What is the Relation of the IGS Network to Regional Networks?; May I Propose a New IGS Station?; What Equipment if Acceptable for Use in the IGS?; Does the IGS Endorse Equipment?; Does the IGS Certify Equipment as Meeting the Guidelines?; What Standards Apply to Reference Frame Stations?; What Kind of Support from Equipment Manufacturers do IGS Users Expect?; What Should Equipment Manufacturers Keep in Mind in Product-Planning Stages?). IGS Activity Areas (Contribution of the IGS to Reference Frame Determination; GNSS; Low-Latency/Real Time). Summary.

18.02   Stochastic Models for GPS Positioning: An empirical approach

Leandro, Santos
Leandro, R. F., and M. C. Santos (2007). Stochastic models for GPS positioning: An empirical approach. *GPS World*, February, Vol. 18, No. 2, pp. 50-56.

Innovation: When we process a set of measurements – say a series of pseudoranges output by a GPS receiver – we attempt to characterize or model all of the effects that have conspired to produce those particular values. In the case of GPS pseudoranges, this includes the geometric distance between the antennas of the satellites and the receiver, the offsets of the satellite and receiver clocks from GPS System Time, the atmospheric delays, and so on. Most of the effects can be modeled using parameters whose values are constant or changing relatively slowly with time, and either we can obtain the values of these parameters from an external source (such as satellite position coordinates) or estimate them from the receiver data itself (such as the receiver's antenna coordinates). We refer to these components of the model as deterministic as their values are determined primarily in a fixed predictable fashion. However, a receiver's measurements are also affected by non-deterministic causes such as the thermal noise generated in the receiver and its antenna preamplifier. Also included would be effects that typically we cannot model well such as multipath and the residual errors of chiefly (but not completely) deterministic effects. As these effects have a random nature producing values governed by the laws of probability, we refer to them as stochastic, which comes from the Greek word *stokhazesthai*, which means "aim at or guess." When processing GPS data, we should not only try to model the deterministic part of the measurements; we should also try to account for their stochastic behavior. We can do this through the use of the measurement variance-covariance matrix, often just called the covariance matrix, with the measurement variances along the matrix's main diagonal and the covariances (related to how measurements are correlated with each other) along the adjacent diagonals. In this month's column, two of my UNB colleagues review the basics of stochastic modeling of GPS measurements and introduce a new approach for constructing the covariance matrix. A receiver's measurements are also affected by non-deterministic causes. Stochastic Processes. ESto Model. Data Processing Example. Conclusions and Future Work.

18.03   Photogrammetry for mobile mapping: Bridging degraded GPS/INS performance in urban centers   Hassan et al.

Hassan, T., C. Ellum, S. Nassar, W. Cheng, and N. El-Sheimy (2007). Photogrammetry for mobile mapping: Bridging degraded GPS/INS performance in urban Centers. *GPS World*, March, Vol. 18, No. 3, pp. 44-48.

Innovation: The mapping of our world – its towns, countries, continents, and oceans – has preoccupied humankind for millennia. Thanks to scientific and technological developments, the speed and accuracy with which we can do the task has improved through the years. One of the oldest techniques still used for mapping is photogrammetry – the science, art, and technology of obtaining reliable measurements from images to determine the geometric properties of objects. It is virtually as old as photography itself. In 1849, just 10 years after the development of the daguerrotype, a French military engineer, Colonel Aimé Laussedat, began work to show that photographs could be used in the preparation of topographic maps. Using images taken from the tops of buildings and mountains and later – initiating aerial photogrammetry – from kites and balloons, he developed the necessary graphical constructions to extract spatial information. Later on, measuring engines and plotters were developed for more accurately transforming image details into maps. Digital imaging and computer analysis have more or less replaced photographic emulsions and mechanical measuring engines in the practice of photogrammetry, resulting in a more accurate and more efficient tool. And still, the principal application of photogrammetry is in mapping – determining the spatial position of the natural and human-made features on the Earth's

surface. However, it is also used as a measuring tool in architecture and industrial design, studying the deformation of structures, accident investigation, and even medicine. While photogrammetry is often used as a mapping tool on its own, GPS (perhaps with an integrated inertial navigation system, or INS) typically comes to the aid of the technique by supplying accurate coordinates for the cameras. The accuracy of those coordinates are subsequently transferred to features in the images. Such a system is used, for example, in mobile mapping scenarios where vans outfitted with the necessary equipment can be used to map our city streets, buildings, telephone poles, and so on. But in this month's column, a team of University of Calgary researchers shows us how photogrammetry can come to the aid of a GPS/INS positioning system by bridging the gaps in good GPS/INS positions, which frequently occur in urban environments. Mathematical Model. Mapping Procedures. Photogrammetric Bridging. Hybrid Simulation. Results. Summary and conclusions

18.04   Network RTK: Getting ready for GNSS modernization   Landau et al.

Landau, H., X. Chen, A. Kipka, and U. Vollath (2007). Network RTK: Getting ready for GNSS modernization. *GPS World*, April, Vol. 18, No. 4, pp. 50-55.

Innovation: Surveyors and geodesists pioneered the use of GPS carrier-phase positioning in the early 1980s when only a few Block I test satellites were in orbit. Receiver measurements were recorded simultaneously at project or rover sites and a reference site and, after collection, the data were postprocessed back at the office. Postprocessing of differenced carrier phases became a standard high-accuracy positioning technique and is still frequently used today. However, some high-accuracy positioning and navigation tasks require real-time operations. In the mid-1990s, real-time kinematic (RTK) positioning was developed. In RTK positioning, a receiver at a reference site makes pseudorange and carrier-phase measurements, which are transmitted over a radio link to one or more rover receivers in the field. A rover receiver combines its measurements with those received over the radio link and, resolving the carrier-phase ambiguities, accurately determines its coordinates. Because atmospheric and satellite-positioning errors decorrelate with increasing distance between reference and rover receivers, the ability to perform successful ambiguity resolution decreases with distance as well. This limits the effective distance between reference stations and rovers. To overcome this limitation efficiently, the concept of network RTK was developed where data from a number of reference stations are used in a filter to determine the measurement errors across the network and then to provide corrections to rover or to synthesize data for a virtual reference station (VRS) in the vicinity of a particular rover. As the number of stations in a network grows, the more processing is required to generate corrections and VRS data streams. And as more satellite signals are observed by reference and rover receivers, even higher demands are placed on the network RTK filter processing. In this month's column we look at an innovative filter technique for significantly extending the number of reference stations that can be supported for network RTK positioning under modernized GNSS. As a network grows, more processing is required to generate corrections. Geometry Filter (Centralized Filter; Federated Filter; Performance Analysis; Post-Processing Performance; Real-Time Performance). Improving Rover Performance (Terrasat Network; Land Survey Network; Initialization Performance). Summary.

18.05   Time for GIOVE-A: The onboard rubidium clock experiment   Hahn et al.

Hahn, Jörg, D. Navarro-Reyes, F. Gonzalez, P. Waller, and G. Mandorlo (2007). Time for GIOVE-A: The onboard rubidium clock experiment. *GPS World*, May, Vol. 18, No. 5, pp.

64-69.

Innovation: Apart from the ability to launch satellites, what was the single greatest technological development which has made global navigation satellite systems possible? Time's up (that should give you a hint). It is the atomic clock. GNSS receivers work by accurately timing how long it takes signals to travel from the satellites' antennas to the receiver's antenna and converting the time delays to ranges using the speed of light. Each delay is essentially the difference between the time a particular signal transition was received, as measured with the receiver's clock, and the time that same transition left a satellite, as measured with the satellite's clock. The delays must be measured very accurately since a timing error of just 10 nanoseconds is equivalent to a ranging error of about 3 meters. One of the clocks must be a highly stable reference clock. The demands on the timekeeping ability of the other clock is much less since its timing error can be estimated from measurements. The only practical approach for a GNSS is to place reference clocks in the satellites, permitting receivers to operate with a low-cost clock whose error is estimated along with the receiver's coordinates from the simultaneous measurements made on four or more satellites. Only atomic clocks have the required accuracy and stability to be used as reference clocks. Scientists have developed three basic kinds of atomic clock, each based on a different element; cesium, rubidium, and hydrogen. The GPS Block II and IIA satellites each carried four clocks: two cesium and two rubidium whereas the Block IIR and IIR-M satellites each carry three rubidium clocks. GLONASS satellites carry three cesium clocks. The European Galileo system will also use redundant atomic clocks onboard its satellites. One candidate clock for the future Galileo satellites is the European Rubidium Atomic Frequency Standard. Two of these clocks are flying onboard the GIOVE-A test satellite which was launched on December 28, 2005. In this month's column, the GIOVE clock experiment team discusses the tests which have been conducted to assess the performance of the satellite's active clock and their future plans for onboard clock assessment including the passive hydrogen maser to be flown on GIOVE-B. A timing error of just 10 nanoseconds is equivalent to a ranging error of about 3 meters. ODTS Results. Quality Control. Clock Telemetry. Where do we go next?

18.06   Ubiquitous Positioning: Anyone, anything: anytime, anywhere   Meng et al.

Meng, X., A. Dodson, T. Moore, and G. Roberts (2007). Ubiquitous positioning: Anyone, anything: anytime, anywhere. *GPS World*, June, Vol. 18, No. 6, pp. 60-65.

Innovation: Mark Weiser is not exactly a household name. He was a chief technology officer at the Xerox Corporation's famous Palo Alto Research Center. This is the same outfit which brought us laser printing, Ethernet communications, the graphical user interface paradigm (including the mouse), and object-oriented programming. Like many of those who make a significant difference in technical fields, Mark Weiser's contributions are well known but his name is not. Dr. Weiser introduced the concept of "ubiquitous computing." He coined this term in 1988 to describe a new generation of the computer era, where the first two generations, that of the mainframe and the personal computer, would be superseded by one in which computers would disappear into the objects that surround us in our daily life both at the office and at home. He further posited that the best computer is a quiet, invisible servant whose "calm technology" informs us but doesn't demand our focus or attention. His idea, often tagged "UbiComp," has borne fruit and we now have smart coffee pots, smart printers, smart copy machines and the like, all connected via a wired or wireless network. Users of some of the smart devices in our UbiComp world, such as mobile telephones, personal digital assistants, cameras, and camcorders, would benefit by knowing their location wherever they

might be – whether it's in an open field, on a street surrounded by skyscrapers, or inside an apartment building. As we all know, conventional GPS receivers don't always work where we would like them to. In order for a UbiComp device to know its position anywhere and anytime, we need "ubiquitous positioning" or UbiPos. And like UbiComp, UbiPos should inform us but not demand our focus or attention. In this month's column, we take a look at the available technologies that might be used to supplement conventional GPS positioning and some initial testing that will eventually lead to a UbiPos world, one in which we can locate anyone, anything, anytime, anywhere. Like UbiComp, UbiPos should inform us but not demand our focus or attention. Technologies for UbiPos (GNSS; Augmented GNSS; High Sensitivity GNSS; Assisted GPS; Inertial Navigation Systems; Pseudolites; Ultra-Wideband; Other Approaches). Network RTK Testbed. Instantaneous Error Indexing. NRTK GPS Facility. Conclusions.

18.07   Opportunistic navigation: Finding your way with AM signals of opportunity
<div align="right">McEllroy et al.</div>

McEllroy, J., J. F. Raquet, and M. A. Temple (2007). Opportunistic navigation: Finding your way with AM signals of opportunity. *GPS World*, July, Vol. 18, No. 7, pp. 44-49. Innovation: In last month's column, we took a brief look at some of the technologies that might be used for UbiPos – ubiquitous positioning – to supplement conventional GPS in environments where it performs poorly or not at all such as in concrete canyons and inside buildings. One of the technologies mentioned involves using signals of opportunity – radio signals whose primary purpose is for communications or broadcasting but which could be used for positioning and navigation. Potential signals of opportunity include the amplitude modulation (AM) broadcast stations in the medium wave band. Invented just over 100 years ago by the Canadian radio pioneer Reginald Fessenden, AM broadcasting covers large parts of the globe. Despite the recent tendency of AM stations to move to the FM band, most large metropolitan areas still boast a dozen or more stations on the "AM dial." The signals from AM stations can be used to determine the position of a mobile receiver with respect to a reference receiver using time difference of arrival (TDOA) measurements and a supplementary link between the two receivers. Measurements on one transmitter establish a hyperbolic line of position for the mobile receiver and the intersection of this line with another from measurements on a second transmitter establishes the receiver's position. Measurements on additional transmitters can improve the position accuracy and estimate unsynchronized receiver clock differences through a multi-lateration approach. It matters not whether the stations are "talk radio" or "country and western," as it is the carrier phase of the signals which provides the TDOA measurements. Of course, the proposed use of AM radio broadcasts for positioning and navigation is not a new idea. Measurements of the angle of arrival of AM broadcasts have long been used for position fixing in marine and other environments. In this month's column, a team of authors from the U.S. Air Force Institute of Technology describe the simulations and real-world experiments they carried out using a software-defined radio receiver to test the feasibility of AM radio TDOA measurements for positioning and navigation. The signals from AM stations can be used to determine the position of a mobile receiver. TDOA Calculation Methods (Raw Max Peak; Quad-Sample Linear Fit; Raw Sine Wave Fit; High-Sample Max Peak). Simulated Results. Data Acquisition System (Software; Hardware). Field Test Results. Cross-Correlation Alternatives. Conclusions. Future Work.

18.08   [Showcase issue — no column]

18.09   Brainy positioning: Processing GPS data with neural networks   Leandro et al.
Leandro, R. F., C.A.U. da Silva, P. C. L. Segantine, and M. C. Santos (2007). Brainy
    positioning: Processing GPS data with neural networks. *GPS World*, September, Vol. 18,
    No. 9, pp. 60-65.
    Innovation: The brain is a fascinating organ. How it works or, more specifically, how it learns
    and how it processes information, has intrigued us for centuries. Towards the end of the 19th
    century, neuroscientists had established the "neuron doctrine" to explain in broad terms how
    our brains work. In this theory, the fundamental processing unit of the brain is the neuron, a
    specialized type of cell. At birth, our brains contain about 100 billion neurons and although
    many of these die as we age and are not replaced, we continue to think and learn. Neurons
    communicate with each other using electrochemical signals with each neuron being
    connected to as many as 100,000 other neurons. In an effort to better understand how the
    brain works, neuroscientists team up with computer scientists to develop mathematical
    models to describe how networks of interconnected neurons process information. By the late
    1950s, they had arrived at a basic model which has been improved on over the years. Each
    neuron in the network performs a simple computation; it receives signals from its input links,
    which it weights and then uses to compute its activation level (or output). The success of
    neural network models to mimic the basic operation of brain cells led computer scientists to
    the idea that artificial neural networks could be used to solve mathematical problems. They
    were able to show that, through a training or learning process, such networks are capable of
    solving virtually any problem that involves mapping input data to output data. Artificial
    neural networks have served as the basis for a variety of a [sic] tasks ranging from intelligent
    simulation, to real-time adaptation, to data analysis. While not a direct replacement for our
    traditional least-squares and Kalman filtering techniques, artificial neural networks have been
    used effectively for a number of applications in geodesy and navigation, including the
    processing of GPS data. But the handling of GPS data for use in a neural network processor
    is not without problems. In this month's column, we take a look at how artificial neural
    networks can be used as a tool in GPS applications, including the preprocessing necessary to
    successfully ingest the data. Networks are capable of solving any problem that involves
    mapping input data to output data. Neural Network Models (Training; Applications). Neural
    Networks for Geodesy, Predicting L2 Observables. Feeding Neural Networks
    (Normalization). Conclusion.

18.10   Reflecting on GPS: Sensing land and ice from low earth orbit   Gleason
Gleason, S. T. (2007). Reflecting on GPS: Sensing land and ice from low Earth orbit. *GPS
    World*, October, Vol. 18, No. 10, pp. 44-49.
    Innovation: GPS is not your parents' positioning system. Today, GPS is being used in a
    variety of unconventional ways, likely unthought of when the system was being designed
    back in the early 1970s. With data from a network of geodetic-quality receivers, geodesists
    are monitoring the small fluctuations in the Earth's spin and the wobble of the Earth on its
    axis. Other scientists use GPS data to measure the drift and flexure of the Earth's tectonic
    plates and the rise of sea level due to global warming and other causes. These applications
    rely on GPS to produce extremely accurate antenna positions – to better than a centimeter.
    Other unconventional uses of GPS include studies of the Earth's atmosphere from the ground
    and from low-Earth-orbiting satellites. The radio signals emanating from the GPS satellites

must travel through the ionosphere and the neutral atmosphere on their way to receivers on and near the Earth. The propagation velocity variations the signals suffer due to the electrons and electrically neutral atoms and molecules they encounter allows scientists to determine ionospheric electron density for space weather studies and water vapor concentrations in the troposphere for moisture forecasts. In this month's column, we look at yet another out-of-the-ordinary application of GPS; using signals reflected off the Earth's surface to sense land and ice, as well as the ocean surface, from low Earth orbit. Such reflected signals, weaker and with less coherence than light [sic]-of-sight signals and with predominantly left-handed polarization, have been intercepted by a special receiver on the United Kingdom's Disaster Monitoring Constellation satellite. Analysis of these and other reflected signals holds great promise for measuring ocean roughness, ice conditions, vegetation cover, and even soil moisture from orbiting satellites! And you thought GPS was just a positioning, navigation, and timing tool. Read on. Analysis of reflected signals holds great promise for measuring ocean roughness, ice conditions, vegetation cover, and even soil moisture. Land Applications. Ice Applications. Signals Processing. Land Sensing (Example Data Collection; Variations in the Signal Magnitude). Ice Sensing (Example Data Collections; Signal Response). Conclusions and Future Work.

18.11   Time for a better receiver: Chip-scale atomic frequency references   Kitching

Kitching, J. (2007). Time for a better receiver: Chip-scale atomic frequency references. *GPS World*, November, Vol. 18, No. 11, pp. 52-57.

Innovation: Clockmakers down through the ages have toiled long and hard to improve clock stability – to try to make a clock which keeps constant time, or as constant as possible. The need for such a clock to improve 18th-century navigation led John Harrison to develop a series of marine chronometers, each more stable than the previous. He finally produced the H4, which permitted longitude to be determined with an error of no more than 30 minutes, even after a sea voyage lasting almost half a year. All clocks contain an oscillator or frequency reference. How well a clock keeps time depends on the stability of this reference. Harrison's oscillating springs and escapements gave way to more accurate quartz crystals and electronic circuitry. Mass-produced quartz-crystal oscillators now are found in virtually every piece of electronic equipment, from wristwatches to GPS receivers. But they are susceptible to environmental factors such as a changing ambient temperature. The quartz-crystal oscillators in GPS receivers, even if temperature compensated, still have instabilities leading to clock errors that must be estimated by the GPS receiver when computing its fix or otherwise eliminated. What if a GPS receiver's clock was sufficiently error-free that it did not perturb the position fix? The fix could then be obtained with fewer satellite signals – as few as three for a complete three-dimensional fix. Atomic frequency references significantly outperform quartz-crystal oscillators but they are bulky and consume lots of power – hardly an option for a handheld GPS receiver. But just as John Harrison worked to develop a portable clock with a stability approaching that of observatory clocks of his day, so are modern-day John Harrisons working to miniaturize atomic clocks – down to the size of a [sic] chip on a printed circuit board – so that they can be used in handheld devices such as GPS receivers. In this month's column, we look at the fabrication and performance of chip-scale atomic frequency references. These new marvels of miniaturization will be moving from the lab to the factory any day now. Modern-day John Harrisons are miniaturizing atomic clocks. Clock Physics Package. Alkali Vapor Cells. CSAC Physics Package. Local Oscillator and Control System. Performance. Applications to GNSS. Conclusion.

18.12   [Showcase issue — no column]

19.01   Good, better, best: Expanding the Wide Area Augmentation System

Schempp

Schempp, T. R. (2008). Good, better, best: Expanding the Wide Area Augmentation System. *GPS World*, January, Vol. 19, No. 1, pp. 62-67.

Innovation: Air travel promises to become safer and cheaper thanks to the Wide Area Augmentation System (WASS). It assists or augments GPS by providing the increased accuracy, availability, continuity, and integrity necessary for aircraft navigation. Unaugmented, or standalone, GPS isn't accurate enough for some types of runway approach procedures. Using Geostationary Earth orbit (GEO) communications satellites, WAAS provides corrections to the GPS satellite orbit and clock information in a satellite's navigation message as well as ionospheric delay information. These corrections permit a user's receiver to compute a more accurate position, often to better than 1 meter horizontally and 2 meters vertically, with a 95% confidence. WAAS also increases the availability and continuity of GPS for aircraft navigation by requiring fewer redundant observations for determining a valid position. Availability is also increased through the provision of the additional GEO ranging signals. But perhaps most importantly, WAAS provides the increased integrity needed for a safety-of-life navigation system. Within 6 seconds of a fault detection, an alarm message corrects the error or allows a safe transition to an alternative navigation procedure. The advantages of WAAS for aviation include greater runway capability, reduced separation standards which allow increased capacity in a given airspace without increased risk, more direct enroute flight paths, new precision approach services, reduced and simplified equipment onboard aircraft, and significant government cost savings due to the elimination of maintenance costs associated with older, more expensive ground-based navigation aids. But WAAS not only benefits GPS users in the sky. Many GPS users on terra firma are making use of the increased accuracy and availability afforded by WAAS. For example, according to the FAA, OnStar has added WAAS capability to the GPS receivers in General Motors 2008 product year vehicles. And even surveyors are making use of the WAAS ranging signals for improving real-time kinematic survey operation. While WAAS was already a much-valued addition to standalone GPS, significant improvements were made to WAAS over the past three years, including expansion of the reference station network and the commissioning of two new GEOs. 2008 will see even more enhancements. In this month's column, we take a look at WAAS's recent upgrades and take a peek into its future. WAAS also benefits GPS users on the ground. The System (Redundancy). Enhancements (New Satellites; New Stations). WAAS Shadows. Stormy (Space) Weather. Current Performance and Future.

19.02   Tsunami detection by GPS: How ionospheric observations might improve the global warning system

Occhipinti et al.

Occhipinti, G., A. Komjathy, and P. Lognonné (2008). Tsunami detection by GPS: How ionospheric observations might improve the global warning system. *GPS World*, February, Vol. 19, No. 2, pp. 50-56.

Innovation: The tsunami generated by the December 26, 2004 earthquake just off the coast of the Indonesian island of Sumatra killed over 200,000 people. It was one of the worst natural disasters in recorded history. But it might have been largely averted if an adequate warning system had been in place. A tsunami is generated when a large oceanic earthquake causes a

rapid displacement of the ocean floor. The resulting ocean oscillations or waves, while only on the order of a few centimeters to tens of centimeters in the open ocean, can grow to be many meters even tens of meters when they reach shallow coastal areas. The speed of propagation of tsunami waves is slow enough, at about 600 to 700 kilometers per hour, that if they can be detected in the open ocean, there would be enough time to warn coastal communities of the approaching waves, giving people time to flee to higher ground. Seismic instruments and models are used to predict a possible tsunami following an earthquake and ocean buoys and pressure sensors on the ocean bottom are used to detect the passage of tsunami waves. But globally, the density of such instrumentation is quite low and, coupled with the time lag needed to process the data to confirm a tsunami, an effective global tsunami warning system is not yet in place. However, recent investigations have demonstrated that GPS might be a very effective tool for improving the warning system. This can be done, for example, through rapid determination of earthquake magnitude using data from existing GPS networks. And, incredible as it might seem, another approach is to use the GPS data to look for the tsunami signature in the ionosphere: the small displacement of the ocean surface displaces the atmosphere and makes it all the way to the ionosphere, causing measurable changes in ionospheric electron density. In this month's column, we look in detail at how a tsunami can affect the ionosphere and how GPS measurements of the effect might be used to improve the global tsunami warning system. There would be enough time to warn coastal communities. Ionospheric Perturbation. Some Background. Modeling TEC Perturbations (Tsunami Propagation; Neutral Atmosphere Coupling; Neutral-Plasma Coupling). GPS Data Processing (High-Precision Processing). Ionospheric Warning System. Conclusions.

19.03   Improving long-range RTK: Getting a better handle on the biases
Kim, Langley

Kim, D., and R. B. Langley (2008). Improving long-range RTK: Getting a better handle on the biases. *GPS World*, March, Vol. 19, No. 3, pp. 50-56.

Innovation: Scientists and engineers continue to improve high-accuracy GPS positioning techniques – techniques pioneered a quarter of a century ago. The first GPS satellite, SVN01/PRN04, was launched from Cape Canaveral on February 22, 1978. And between 1978 and 1985, the U. S. Air Force orbited nine more prototype or Block I satellites to test key technologies before deploying the operational constellation. Surveyors and geodesists were among the earliest users of the Block I satellites. Using the satellite signals, they developed accurate positioning techniques based on the use of carrier-phase observations – about two orders of magnitude more precise than code measurements. To reduce the effect of biases and errors in the measurements, they developed the concepts of between-satellite and between-receiver single differencing of the carrier-phase data as well as double and triple differencing. Raw measurements were recorded by receivers and then post-processed to obtain receiver coordinates. Clever approaches were developed to handle the integer ambiguity of the carrier phases. With the launch of the Block II satellites beginning in 1989, further improvements in positioning accuracy and efficiency became possible, including real-time carrier-phase-based positioning with a radio link between a reference receiver and a remote receiver. This technique became known as real-time kinematic or RTK, as it permitted the remote receiver to rove and occupy different points in a single positioning exercise. But carrier-phase ambiguity resolution issues coupled with inaccurately modeled satellite orbit and atmospheric effects has limited consistent single-baseline RTK operation between reference and rover receivers to tens of kilometers. On longer baselines, inaccurate

modeling can result in significant positioning errors. Network RTK, using simultaneously operating reference stations to better determine error corrections, can extend the area of coverage of RTK but it, too, has limitations. In this month's column, I am joined by my colleague Don Kim who has developed an innovative approach to long-range RTK. We describe how accurate modeling of atmospheric effects coupled with an ionosphere-free ambiguity resolution process results in successful long-range RTK that can be implemented in either single-baseline or network mode. Has the ultimate RTK approach been developed? Probably not. But we're getting closer. New Approach Considerations (The Observation Model; The Objective Function; Satellite Orbit Errors; Ionospheric Delays; Tropospheric Delays). Estimation Model (Adaptive Estimator; Ionosphere Nullification). Test Results (Ionosphere Nullification; Tropospheric Delay Estimation; Static Results; Kinematic Results). Conclusions.

19.04   A GNSS odometer: How far have we come?   Wieser

Wieser, A. (2008). A GNSS odometer: How far have we come? *GPS World*, April, Vol. 19, No. 4, pp. 50-55.

Innovation: What do the Greek mathematician Archimedes of Syracuse, the American statesman and polymath Benjamin Franklin, and the Mormon pioneer William Clayton all have in common? They each invented an odometer – a mechanical device for measuring distance. Whether we be military engineers, mail-route mappers, wagon masters, or just automobile drivers, we often want to know not just where we are but how far we have come. The odometer was likely first invented by Archimedes during the First Punic War when Syracuse got in the way of Rome during its battle with Carthage. A Greek origin is fitting as the word odometer derives from the Greek words *hodós*, meaning "path" or "way" and *métron*, meaning "measure". The device was reinvented many times over the years but its use was not widespread until the development of the automobile, and now virtually every vehicle sports one. Mechanical odometers gave way to electronic ones but the distance traveled was and is still determined by counting wheel revolutions. But just how accurate are the odometers in our modern vehicles? Not very, it seems. The odometer reading is affected by tire pressure, tire slip, and incorrect calibration. And while in many countries there is no regulation covering odometer accuracy, the Society of Automotive Engineers' voluntary standard and that of the European Commission is only plus or minus 4 percent, or as much as a 4-kilometer error in every 100 kilometers. Does this matter? Well, in effort to reduce the cost to the general tax payer of maintaining roads or reducing conjestion [sic], many administrations have implemented "road pricing," where a flat charge is levied for using a particular stretch of road or for entering a city center. But some administrations are charging per kilometer of travel with data coming from an odometer recording. Automobile insurance companies have also implemented plans where the premium is based on the distance traveled by the vehicle ("pay as you drive"). To fairly implement such schemes, governments should require more accurate odometers in vehicles. Could an odometer based on GNSS be a solution? In this month's column, we take a look at how distance traveled can be computed from GNSS observations and just how accurate those computations are. Could an accurate odometer be based on GNSS? Computing Distance Traveled. Attainable Accuracy (Numerical Integration Error; Estimated Speed Random Noise; Speed Bias; Total Error). Experimental Results. Conclusion.

19.05   Making a difference with GPS: Time differences for kinematic positioning with low-cost receivers   Traugott et al.

Traugott, J., D. Odijk, O. Montenbruck, G. Sachs, and C. Tiberius (2008). Making a difference with GPS: Time differences for kinematic positioning with low-cost receivers. *GPS World*, May, Vol. 19, No. 5, pp. 48-57.

Innovation: Let's review. Most radio signals consist of a carrier wave that is modulated in some way. This includes the GPS satellite signals. The pseudorandom-noise ranging codes and the navigation message are modulated onto the L-band carriers using binary biphase modulation. A GPS receiver uses the ranging codes to determine its distance from multiple satellites and then, through the process of multilateration, its position. But what about the carrier phase? Is it just a means to convey the ranging codes and navigation message? Definitely not. A GPS receiver determines its velocity as well as its position and it does this not by differencing sequential code-based positions, which would not be very accurate, but rather by measuring the Doppler shift of the received carrier. But the carrier can be used in other ways too. In fact, it can be used for determining positions, just like the code, but with much higher precision. Over 20 years ago, surveyors and geodesists devised ways to make use of recorded measurements of the phase of the received carriers to determine accurate relative positions between a roving receiver and a base or reference receiver at a known location. The technique was enhanced over the years, evolving into an approach known as RTK or real-time kinematic positioning. As its name suggests, RTK is usually employed in real time using auxiliary radio communications (often cell-phone-based) between the base and rover receivers. However, RTK-style positioning can also be used to postprocess collected data, achieving the same high-accuracy standards. But one of the difficulties with the RTK approach is resolving the so-called carrier-phase ambiguities. One cycle of the carrier looks just like the next, so how can you determine the exact number of cycles in the carrier between the satellite's antenna and the receiver's antenna? Well, it can be done, but even with increasingly sophisticated techniques, there is a limit to how far away a rover can be from the base station. Isn't there a way to get rid of the integer ambiguity problem? There is. If you time-difference sequential carrier-phase measurements, the ambiguity actually disappears! As we'll see in this month's column, you can determine accurate relative positions using time-differenced carrier-phase measurements. But there are some caveats. Read on. The Concept (The Observable; Applications; Kinematic Time Differences; Quality of Results). Practical Validation (Static Test; Vehicle Test; Flight Test). Conclusions.

19.06   Interference heads-up: Receiver techniques for detecting and characterizing RFI   Ward

Ward, P. W. (2008). Interference heads-up: Receiver techniques for detecting and characterizing RFI. *GPS World*, June, Vol. 19, No. 6, pp. 64-73.

Innovation: As we all know, GPS signals are weak. At a receiver's antenna, in the open air, their strength is about -160 dBW or 1×10^{-16} watts. Compare this to a cell-phone signal, which might be -60 dBW or 1×10^{-6} watts – 10 billion times stronger! While code correlation in the receiver lifts the GPS signals above the background noise floor, the signals are still relatively fragile, and building walls and other obstructions can significantly attenuate the received signal power so that they cannot be tracked by a conventional receiver. It is the ratio of the signal power to the noise power per unit bandwidth that determines the trackability of the signals. Accordingly, if the receiver's noise floor should increase sufficiently, even in an outdoor environment, the signals may also become untrackable. This

can happen when the receiver is subjected to intentional or unintentional radio-frequency interference (RFI) by a transmitter operating on or near GPS frequencies. If the interference is strong enough, it can jam the receiver. Although intentional jamming is typically of concern only to military GPS users, unintentional jamming can occur anywhere and anytime and can affect large numbers of users within the range of the jamming transmitter. The jamming incident in San Diego harbor in January 2007, for example, affected all GPS users within a range of about 15 kilometers including a medical services paging network. Such jamming renders a GPS receiver inoperable. But how do users know that their receivers are being jammed and not suffering some other type of malfunction? Clearly it would be advantageous for users to receive a heads-up when jamming signals are present and, if possible, for the receiver to take corrective action automatically. In this month's column, we look at some simple techniques, which can be easily incorporated into the design of a GNSS receiver, to detect, characterize, and actually mitigate RFI. Such receiver enhancements will benefit civilian and military users alike. Unintentional jamming can occur anywhere and anytime. J/N Meter Design. RF Front End. Estimating J/S from J/N. Adaptive Initial Search Using J/N Meter. Removing CW and NB RFI. RFI Characterization (Simple CW RFI Effect Minimization; Simple CW Detector Design; Mitigation Techniques). Conclusions.

19.07   The future is now: GPS + GLONASS + SBAS = GNSS   Wanninger
Wanninger, L. (2008). The future is now: GPS + GNSS + SBAS = GNSS. *GPS World*, July, Vol. 19, No. 7, pp. 42-48.

Innovation: We are on the brink of a new era in satellite positioning and navigation. The excitement that was felt 30 years ago when the first GPS satellite was launched is beginning to be felt again. Back then, instantaneous three-dimensional satellite-based positioning was an entirely new concept. Yes, we did have satellite-based positioning before GPS, but it wasn't instantaneous and it wasn't fully 3D – nor was it very accurate. Over the past 30 years, thousands of scientists and engineers have developed an amazing range of GPS applications providing positioning accuracies all the way down to the millimeter level. However, some would argue that many of the recent developments, especially in the area of high-accuracy positioning, are just minor enhancements to existing techniques first introduced or foretold years ago. Been there; done that. But that situation is about to change – and in a big way! New signals and new satellites herald a new era in satellite-based positioning and navigation. Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) is being revitalized after many years of neglect. With its first launch in 1982, this second global navigation satellite system gave rise to the generic term for all such systems: GNSS. In addition to GLONASS and a modernized GPS featuring new civil and military signals along with new constellations of satellites, we will have Europe's Galileo system (with two GIOVE test satellites already in orbit) and China's Beidou/Compass system (with five satellites already in orbit). Receivers and data-processing techniques will be developed to allow use of all available signals and satellites. The future promises to be just as exciting for GNSS scientists and engineers as the early days of GPS. But do we have to wait for these new or enhanced systems to be in place before benefiting from a multi-signal, multi-constellation global navigation satellite system? Definitely not. As this month's column describes, we can sample the future today. The existing GPS satellites, along with the revitalized GLONASS constellation and the satellites of the various geostationary satellite-based augmentation systems, already constitute a system of systems. And receivers currently on the market provide the necessary raw measurement data to yield positioning solutions from this system

of systems with potentially more continuity and greater accuracy than those obtained using GPS along. Listen up: the future is now. Orbit Accuracy. Code Ranging. Carrier-Phase Equations. Stability of GLONASS Inter-Channel Biases. Combined Results. Conclusions and Outlook.

19.08   [Showcase issue — no column]

19.09   Online precise point positioning: A new, timely service from Natural Resources Canada   Mireault et al.

Mireault, Y., P. Tétreault, F. Lahaye, P. Héroux, and J. Kouba (2008). Online precise point positioning: A new, timely service from Natural Resources Canada. *GPS World*, September, Vol. 19, No. 9, pp. 59-64.

Innovation: Meliora Sequamur – let us strive to improve. The words that the Roman poet Virgil wrote some 2,000 years ago could well be the watchwords of those scientists and engineers who today work to improve the accuracy, coverage, and timeliness of GPS-based positioning. They are particularly appropriate for those seeking to improve the technique of precise point positioning or PPP. PPP is a single-receiver positioning technique just like conventional pseudorange-based positioning, which takes place inside a receiver. However, the similarity stops there. PPP uses the receiver's very precise undifferenced carrier-phase observations together with very precise (and accurate) satellite orbits and clocks to achieve positioning accuracies at the few centimeter level or better. And unlike differential techniques such as real-time kinematic (RTK) positioning, all of the physical phenomena affecting the measurements must be very accurately modeled. These include solid earth tides, ocean-tide loading, transmitting and receiving antenna phase-center offsets and variations, carrier-phase wind-up, relativistic effects, and so on. With differential techniques, such effects are greatly reduced and typically become insignificant, especially on short baselines. PPP can be used to process data collected at a fixed (static) site or along a trajectory in kinematic mode or a mixture of the two – "stop and go" PPP. Although introduced in the late 1990s, PPP has only become more commonplace in the past few years, thanks, in part, to continued PPP development in government and university research labs. Several PPP processors are even available online. The precise satellite orbits and clocks required are provided by the International GNSS Service (IGS) and its worldwide tracking network and analysis centers. These produces are supplied with some latency resulting in PPP normally being used as a post-processing technique with observations being processed some time after they are collected. However, over the past year or so efforts have been made to reduce the latency of some high-precision products. In particular, the ultra-rapid orbit and clock product of the Geodetic Survey Division of Natural Resources Canada (NRCan) is now being produced with a delay of only 90 minutes. Coupled with NRCan's online PPP engine, it provides positioning accuracies almost as good as the IGS final product, which is only available with a delay of about two weeks. This month's column takes a look at this new, timely service from the Great White North. PPP uses undifferenced carrier-phase observations. CSRS-PPP (Geodetic Control Products; NRCan Ultra-Rapid Products; Orbit Products; Clock Products). CSRS-PPP Accuracy Evaluation. Summary.

19.10   The GPS L2C signal: A preliminary analysis of data quality   Leandro et al.

Leandro, R. F., R. B. Langley, L. Sükeová, T. Thirumurthi, and M. C. Santos (2008). The GPS L2C signal: A preliminary analysis of data quality. *GPS World*, October, Vol. 19, No. 10, pp.

42-47.

Innovation: Fifty-six and counting. That's the number of GPS satellites that have been launched over the past thirty years beginning with the first prototype (Block I) satellite, space vehicle number 1, in February 1978. Ten Block I satellites were successfully launched between 1978 and 1985 to demonstrate the feasibility of GPS. The first satellite of the Block II operational constellation was launched in February 1989. The four-year hiatus in launches was due, in part, to the Space Shuttle Challenger disaster as it had been planned to launch the operational satellites using the Shuttle. Following the accident, it was decided to continue with expendable rockets for GPS launches but to switch to the newly designed Delta II rocket. The pace of Block II launches was rapid with five launches of the original Block II design in 1989 and four in 1990. A modified version of the Block II satellite — the IIA — was developed and between 1990 and 1997, 19 Block IIAs were launched. The Block II and IIA satellites established the operational GPS constellation. Full operational capability was declared on April 27, 1995. A new satellite was developed for replenishing the constellation as the earlier satellites were retired. Following an initial launch failure, twelve of the Block IIR satellites were launched between 1997 and 2004. All of the satellites in the Block I, Block II, Block IIA, and Block IIR constellations transmitted what are now called the legacy signals: the C/A-code on the L1 frequency of 1575.42 MHz and the P-code on L1 and the L2 frequency of 1227.60 MHz. The P-code has been encrypted to yield the Y-code since January 1994, denying its direct access by most civil users. Since the C/A-code was only transmitted on the L1 frequency, civil users have had to rely on suboptimal semi-codeless techniques for the dual-frequency operation necessary for direct cancellation of ionospheric biases. In 1998, Vice-President Al Gore announced that a new civil signal on L2 would be transmitted by future GPS satellites. This new signal–L2C–joined the legacy signals beginning with the launch of modernized Block IIR satellites. Six of these Block IIR-M satellites have been launched to date. This month's column gives an overview of the characteristics of the new L2C signal and takes a look at some of the analyses of received signals carried out by a team of researchers from the University of New Brunswick. Signal Structure. L2C Signal Tracking. Handling L2C Data. L2C Code Measurement Analysis. Additional Quality Measurements. Impact of L2C on Positioning. Conclusions and Future Work.

19.11   First AGPS — Now BGPS: Instantaneous precise positioning anywhere
Petrovski et al.

Petrovski, I., H. Hojo, and T. Tsujii (2008). First AGPS — Now BGPS: Instantaneous precise positioning anywhere. *GPS World*, November, Vol. 19, No. 11, pp. 42-48.

Innovation: BGPS can produce first fixes within one second. Good news, everyone! Instant GPS positioning appears to be at hand. For better or worse, we live in fast-paced society with its fast food, fast communications, and fast cars, and have come to expect instant responses when we want something. Our TVs now turn on instantly. We push a single key on our mobile phones for speed dial or instant push-to-talk service. We press the shutter on our digital cameras to capture and view images instantly. But GPS? Not so fast. After switching on our receiver, we typically have to wait for some time before we can start navigating. This time to first fix (TTFF) depends on the quality of the received signals and the age of the receiver's stored almanac and ephemerides used to determine the positions of the satellites. It's also affected by how well the receiver knows the exact time. So there are several kinds of TTFF. If a receiver has no knowledge of its last position, doesn't know the approximate time, and has no almanac, it starts searching for signals blindly. This is called a cold start.

Depending on signal quality and the design of the receiver, it can take anywhere from 60 seconds to 12 minutes or more before the receiver acquires signals, obtains ephemeris data, measures pseudoranges, and gets its first position fix. If the receiver knows the approximate time as well as its approximate position and has a recent almanac but not a current ephemeris, it can produce a position fix within about 30 seconds or so after it is switched on — the time required to receive orbit and clock data from the tracked satellites. This is called a warm start. A hot start occurs when a receiver is powered on with a current ephemeris (received within the past four hours). It can take up to 6 seconds or more before the first fix as the receiver must typically acquire time marks from the satellite navigation messages to resolve the pesudorange ambiguities. Assisted GPS, or AGPS, can reduce TTFF by supplying current ephemeris data and accurate time over a mobile phone network. In some situations, TTFF can be reduced to just a second or two. However, the receiver does need to be connected to an AGPS network and so cannot operate autonomously. Enter BGPS. In this column we learn about an innovative approach that can produce accurate first fixes within one second without a network connection. Within one second and without a network connection? Oh my, yes. Convergence of Geodesy, Mobile Applications. BGPS (Test Results). Seamless Positioning Across Applications. Private vs. International GNSS Services. Advantages of BGPS.

19.12   [Showcase issue — no column]

20.01   Counting equivalent correlators: Quantifying the number for GNSS acquisition engine architectures   Genghi et al.

Genghi, A., J. Brenner, F. Pisoni, and F. Spalla (2009). Counting equivalent correlators: Quantifying the number for GNSS acquisition engine architectures. *GPS World*, January, Vol. 20, No. 1, pp. 39-43, 64-65.

Innovation: Different manufacturers use different ways of counting the effective correlators in their devices. With this issue, *GPS World* and the Innovation column begin their 20th year of publication. The magazine's first issue in January/February 1990 carried advertisements from a number of GPS receiver manufacturers touting their latest products. Most of these receivers had only a few correlator channels. Some had only one or two, having to sequence through the visible satellites in order to make their measurements. One manufacturer introduced a receiver with an amazing 12-channel sophistication—acquiring and tracking all GPS satellites in view. These days, most conventional GPS receivers have at least a dozen channels; some have even 50 or more. But these receivers must still dedicate at least one channel to each satellite being searched—sequentially offsetting the Doppler frequency and code phase of the replica signal until the satellite is found and then coherently integrating the detected signal. With this approach, there are limitations to the sensitivity of the receiver (and, to some degree, the time to first fix). And, as a result, GPS signals cannot be readily tracked indoors or in other locations with challenging signal conditions. For GPS to work indoors and downtown, receivers need to acquire weak signals quickly and to collect enough signal power to produce reliable measurements for a position fix. This can be achieved by designing a GPS receiver's baseband processor with more full correlator channels, each of which could search simultaneously for a satellite using different Doppler-frequency and code-phase offsets and, when a signal is detected, could coherently integrate it with the coherent integrations then being combined through a noncoherent integration. However, a much more efficient and less costly approach is to use the concept of correlator "fingers" or "taps" where certain features of a correlator channel are shared amongst the taps, resulting in a large

number of effective correlators. Such designs have produced processing engine architectures with tens to hundreds of thousands of effective correlators. But different chip and receiver manufacturers have approached the task of designing such engine architectures differently and use different ways of counting the number of effective correlators in their devices. In this column, a team of engineers from one of these manufacturers reviews the concept and performance of effective-correlator baseband processors and proposes a benchmark definition of the number of effective correlators in a particular architecture that is meaningful and easy to apply. Number of Correlators. Proposed Definition. Pipelined Architecture (Skimmers and Distillers. Ranking. Performance and Equivalent Correlators. Extensions for Galileo Signals. Conclusions.

20.02   GNSS antennas: An introduction to bandwidth, gain pattern, polarization, and all that   Moernaut, Orban

Moernaut, G. J. K., and D. Orban (2009). GNSS antennas: An introduction to bandwidth, gain pattern, polarization, and all that. *GPS World*, February, Vol. 20, No. 2, pp. 42-48. Innovation: A well-designed antenna is important for reliable GNSS signal reception. The antenna is a critical component of a GNSS receiver setup. An antenna's job is to capture some of the power in the electromagnetic waves it receives and to convert it into an electrical current that can be processed by the receiver. With very strong signals at lower frequencies, almost any kind of antenna will do. Those of us of a certain age will remember using a coat hanger as an emergency replacement for a broken AM-car-radio antenna. Or using a random length of wire to receive shortwave radio broadcasts over a wide range of frequencies. Yes, the higher and longer the wire was the better, but the length and even the orientation weren't usually critical for getting a decent signal. Not so at higher frequencies, and not so for weak signals. In general, an antenna must be designed for the particular signals to be intercepted, with the center frequency, bandwidth, and polarization of the signals being important parameters in the design. This is no truer than in the design of an antenna for a GNSS receiver. The signals received from GNSS satellites are notoriously weak. And they can arrive from virtually any direction with signals from different satellites arriving simultaneously. So we don't have the luxury of using a high-gain dish antenna to collect the weak signals as we do with direct-to-home satellite TV. Of course, we get away with weak GNSS signals (most of the time) by replacing antenna gain with receiver-processing gain, thanks to our knowledge of the pseudorandom noise spreading codes used to transmit the signals. Nevertheless, a well-designed antenna is still important for reliable GNSS signal reception (as is a low-noise receiver front end). And as the required receiver position fix accuracy approaches centimeter and even sub-centimeter levels, the demands on the antenna increase, with multipath suppression and phase-center stability becoming important characteristics. So, how do you find the best antenna for a particular GNSS application, taking into account size, cost, and capability? In this month's column, we look at the basics of GNSS antennas, introducing the various properties and trade-offs that affect functionality and performance. Armed with this information, you should be better able to interpret antenna specifications and to select the right antenna for your next job. GNSS Antenna Properties (Frequency Coverage; Gain Pattern; Circular Polarization; Multipath Suppression; Phase Center; Impact on Receiver Sensitivity; Interference Handling). GNSS Antenna Types (Geodetic Antennas; Rover Antennas; Handheld Receiver Antennas; Summary of Antenna Types). Conclusion.

20.03   Comb filtering: Improving acquisition and tracking in GNSS receivers
<div align="right">Dempster</div>

Dempster, A. G. (2009). Comb Filtering: Improving acquisition and tracking in GNSS receivers. *GPS World*, March, Vol. 20, No. 3, pp. 44-49.

Innovation: The filter's frequency response has passbands resembling a comb's teeth. Our world is inherently noisy. Of course, we are all familiar with the sounds that assault our ears when we're walking down a busy street or the vibration of a hotel air conditioner that might keep us awake on a hot summer evening. But the concept of noise can be extended to any process or activity if we think of it as something whose presence usually results in a less than ideal outcome. So we talk about the off-topic noise in an online discussion group, for example. In the electronic world, we are often faced with noisy signals. Fluctuating electrical currents or electromagnetic waves have two components: one of interest, called the desired signal, and one which is not, called the noise. The noise typically is unwanted and we usually seek ways to reduce its presence or level compared to that of the desired signal. The noise may or may not be random. The 50 to 60 Hz power-line hum picked up by an improperly grounded amplifier is an example of the latter, whereas the static on a weak radar return is an example of the former. We can reduce an undesirable component in a signal, analog or digital, by using a filter. A filter enhances or attenuates a particular frequency or range of frequencies in the input signal to produce the desirable output signal. There are a wide variety of filters, each designed to operate on a given input to produce a desired output. Common generic filters are the lowpass, highpass, and bandpass filters where the designations indicate the frequency range of the output signal. A special type of filter can be used where the desired signal or the noise has equally spaced frequency components. This filter has a frequency response with equally spaced passbands or stopbands resembling the teeth of a comb. Accordingly, it is called a comb filter. Comb filters are used in analog and digital televisions, for example, to reduce picture artifacts that otherwise result from incomplete separation of the luminance and chrominance signals in composite video. Comb filters have also been used to attenuate the power-line fundamental and its harmonics in audio signals and to separate solar and lunar variations in electron-content data. The pseudorandom noise codes transmitted by GNSS satellites repeat in the time domain, which results in equally spaced spectral components in the frequency domain. So, could comb filters in GNSS receivers enhance acquisition and tracking of satellite signals? In the column, we find out. Line Spectrum. Digital Comb Filters (Unique Dopplers; Filter Alignment; Millisecond Delays). Characterizing Filter Effect. Acquisition (Sequential Hardware Acquisition; The Algorithm; Parallel Hardware Acquisition (Search Engine); Software Acquisition). Tracking (Code Loop; Carrier Loop). Conclusion.

20.04   Precise point positioning: A powerful technique with a promising future
<div align="right">Bisnath, Gao</div>

Bisnath, S., and Yang Gao (2009). Precise point positioning: A powerful technique with a promising future. *GPS World*, April, Vol. 20, No. 4, pp. 43-50.

Innovation: Is there a viable alternative to RTK? More than 10 years ago in an Innovation column, I wrote, "Although RTK is the latest word, or should we say acronym, in GPS positioning, it will not be the last. Scientists and engineers will continue to invent faster, more accurate, more convenient, and more reliable ways to use GPS in navigation, surveying, and a host of other areas, some of which we haven't even dreamt of yet." In the intervening decade, RTK—or real-time kinematic—positioning has become an industry standard

procedure in surveying, machine control, and other high-precision applications. RTK makes use of carrier-phase and pseudorange measurements recorded at a (usually) fixed reference location with known coordinates and transmitted in real time to a user's rover receiver using a radio link of some kind. The rover processes the double differences of observations between satellites and receivers to determine its coordinates with better than 10-centimeter accuracy. It can do this successfully if it can resolve the integer ambiguities in the carrier-phase measurements. Ambiguities are the bane of carrier-phase positioning. They must be resolved to turn carrier-phase measurements into unbiased range measurements. In RTK positioning, the ability to resolve ambiguities is determined by many factors, such as the distance between the reference station and the rover and atmospheric effects. RRK is a much more efficient technique than the earlier developed (but sometimes still used) post-processing surveying techniques. However, it does require an investment in reference station infrastructure or the purchase of commercial RTK services. Is there a viable alternative to RTK? In the column, we take a look at the technique of precise point positioning (PPP). Like RTK, PPP makes use of ambiguous carrier-phase measurements but only from the user's receiver. Rather than measurements from a reference receiver, it needs ultra-precise (and accurate) satellite orbit and clock information such as that provided by the International GNSS Service. Currently, there are issues with how long solutions take to converge and the difficulty in resolving the ambiguities, for example, but research is targeting these and other practical issues. How close is PPP to prime time? Read on.

20.05   The WAAS L5 signal: An assessment of its behavior and potential end use
<div align="right">Rho, Langley</div>

Rho, H., and R. B. Langley (2009). The WAAS L5 signal: An assessment of its behavior and potential end use. *GPS World,* May, Vol. 20, No. 5, pp. 42-50.

Innovation: L5 signals have been continuously transmitted by a pair of satellites for the past several years. The recent launch of the GPS Block IIR-20(M) satellite and the commissioning of its L5 demonstration payload herald the beginning of a bright new era in space-based positioning, navigation, and timing. The new satellite signal is anticipated to provide better-quality range measurements and possibly improve the tracking performance of a GPS receiver compared with current civil L1 and L2 signals through use of improved signal structures. The L5 signal will be standard on the future Block IIF and Block III satellites. However, some readers may be surprised to learn that L5 signals have been continuously transmitted by a pair of satellites for the past several years. The geostationary Earth-orbiting (GEO) satellites used by the U.S. Federal Aviation Administration's (FAA's) Wide Area Augmentation System to provide enhanced integrity and accuracy include not only an L1 payload but an L5 payload as well. While the WAAS L5 signals have been broadcast from space for some time, they did not come from a satellite in medium Earth orbit, and so it was necessary to include the demonstration payload on the GPS Block IIR-20(M) satellite to guarantee the L5 frequency filing with the International Telecommunication Union. There are some differences between the WAAS L5 signals and the future fully fledged GPS L5 signals. The WAAS L5 signals only use a single-channel carrier (there is no quadrature or Q channel) and the data rate is 250 bits per second (bps) rather than 50 bps. The WAAS signals are actually generated on the ground and relayed through the GEOs using a "bent pipe" approach. The FAA uses the L5 signals, in conjunction with the L1 signals, to compute ionospheric delays as part of the closed-loop control of the broadcast signals. Although the WAAS L5 signals are not yet intended for end users, can they be used now for positioning and

navigation and, if so, are there any caveats? In this column, I am joined by one of my graduate students, Hyun-ho Rho, who has looked at the WAAS L5 transmissions, examining their signal strengths, multipath characteristics, and instrumental bias issues. Precise positioning performance of WAAS pseudoranges has also be assessed as an independent check on instrumental bias compensation by the WAAS control segment. The favorable results point to a future of the L5 signal, on both the WAAS satellites and the next-generation GPS satellites, which is bright indeed. Observability of L5 Signals at UNB. Test Results and Analyses (Carrier-Power-to-Noise-Density Ratio; Code Multipath and Noise Level Analysis; Satellite and Receiver Differential Code Bias; Positioning Domain Results). Conclusions.

20.06   GPS L5 first light: A preliminary analysis of SVN49's demonstration signal
<div align="right">Meurer et al.</div>

Meurer, M., S. Erker, S.Thölert, O. Montenbruck, A. Hauschild, and R. B. Langley (2009). GPS L5 first light: A preliminary analysis of SVN49's demonstration signal. *GPS World,* June, Vol. 20, No. 6, pp. 49-58.

Innovation: On April 10, a new type of radio signal was transmitted from space. I am referring, of course, to the L5 demonstration signal from the Block IIR-M satellite SVN49, launched on March 24. The L5 signal, the second of two new civil GPS signals, will be standard on the next generation of GPS signals—the Block IIFs—and its frequency band was duly registered with the International Telecommunication Union (ITU) back in 2002. But satellite operators only have seven years after filing a frequency application to start transmitting signals from the designated orbit, and delays in launching the first Block IIF satellite meant that GPS could lose the allocation. The GPS Wing and its contractors determined that the best way to secure the L5 frequency was to add an L5 demonstration payload to one of the remaining modernized Block IIR satellites. And so SVN49 made history with the inaugural broadcast of L5 with just a few months to spare before the clock ran out on the ITU filing. Great excitement always surrounds the first photons captured by a new telescope or other detectors of electromagnetic signals. Or when a transmitter is activated for the first time. Just as we do for the dawning of a new day, we call this occasion *first light.* Research groups around the globe joined the GPS Wing in monitoring and analyzing the first L5 signals from space, including a group of scientists and engineers from Germany and Canada. This month the group describes the equipment and procedures used to capture and analyze SVN49's signals and gives an assessment of their characteristics. The L5 Signal Structure (Two-Component Signal; Code Structure; Improved Cross-Correlation). Demo Signal Verification (Time and Frequency; Signal Code Sequence; Power of Received Signals). Signal Tracking (Legacy Signal Anomaly). Conclusions.

20.07   Where is GIOVE-A exactly? Using microwaves and laser ranging for precise orbit determination
<div align="right">Schönemann et al.</div>

Schönemann, E., T. A. Springer, M. Otten, and Matthias Becker (2009). Where is GIOVE-A exactly? Using microwaves and laser ranging for precise orbit determination. *GPS World,* July, Vol. 20, No. 7, pp. 42-50.

Innovation: SLR is unaffected by satellite electronics. We use them for listening to music, for routine surgeries, for making a point in a presentation, and even for hanging pictures straight. Of course, I'm talking about lasers. Invented in 1960, the laser (an acronym for light amplification by the simulated emission of radiation) has become ubiquitous in modern society. Every CD and DVD player has one. Many printers use them. But lasers are also used

in a wide range of industrial and scientific applications including determining the orbits of satellites through satellite laser ranging (SLR). In the SLR technique, pulses of laser light from a ground reference station are directed at satellites equipped with an array of corner-cube retroreflectors, which direct the pulses back towards a collocated receiving telescope. By accurately measuring the two-way travel times of the pulses and knowing the location of the station and other operating parameters, the positions of the satellites can be determined. A network of SLR reference stations around the globe is used to monitor the orbits of satellites over time and their variations have been used by scientists to improve our knowledge of the Earth's gravity field; to study the long term dynamics of the solid Earth, oceans, and atmosphere; and even to verify predictions of the General Theory of Relativity. The first SLR measurements were obtained from the Beacon Explorer-B satellite, which was launched in October 1964. Since then, dozens of satellites equipped with corner-cube retroreflectors have been launched including a number of radio-navigation satellites. Every GLONASS satellite is equipped with retroreflectors and two GPS satellites have been equipped—SVN35/PRN05 and SVN36/PRN06. The COMPASS-M1 satellite in medium Earth orbit carries retroreflectors, as do both GIOVE-A and –B, the Galileo test satellites. Precise orbit determination of radio-navigation satellites using SLR has the advantage of being unaffected by any onboard satellite electronics and associated signal biases. Radiometric observations of a satellite's microwave signals, on the other hand, are influenced by the satellite's clock, for example, and its effect must be estimated to obtain precise (and accurate) satellite orbits for navigation and positioning. Therefore, a comparison of SLR- and microwave-derived orbits can be very useful for studying the performance of the data measurement and orbit-determination processes of both techniques. In this column, we take a look at some work being carried out to precisely determine the orbit of the GIOVE-A test satellite using SLR and microwave observations. This preliminary investigation will benefit the procedures to be implemented for the future Galileo constellation. Data Analysis (Microwave Analysis). Satellite Laser Ranging (Combined Microwave and SLR Analysis). Microwave Data Quality (Signal-to-Noise Ratio; Code-Tracking Noise; Code Multipath; Carrier-Phase-Tracking Noise Analyses; Carrier-Phase Residuals; Phase and Code Validation in Processing). Orbit Quality (Internal Orbit Consistency; SLR Validation; Orbit Comparison). Conclusion.

20.08   [Showcase issue — no column]

20.09   One year in orbit: GIOVE-B E1 CBOC signal quality assessment
                                                                Söllner et al.

Söllner, M., C. Kurzhals, W. Kogler, S. Erker, S. Thölert, M. Meurer, M. Malik, and M. Rapisarda (2009). One year in orbit: GIOVE-B E1 CBOC signal quality assessment. *GPS World,* September, Vol. 20, No. 9, pp. 28-38.
Innovation: GIOVE-B transmits a more versatile modulation type. The second Galileo test satellite, GIOVE-B, was launched on April 27, 2008, and began transmitting navigation signals a few days later. It joined its older sibling, GIOVE-A, which was placed in orbit over two years earlier. Standing for Galileo In-Orbit Validation Element, the GIOVE satellites constitute the first in-orbit test phase of the development of the Galileo navigation system. In addition to securing the frequencies for the system, the satellites are being used to assess key technologies for the full Galileo constellation. The GIOVE test phase will be followed by the In-Orbit Validation (IOV) phase during which four IOV satellites will be launched, two at a time, aboard Soyuz rockets from Europe's spaceport in French Guiana. Together with a

preliminary ground network, the IOV satellites will be used to validate the Galileo system as a whole, using advanced system simulators. The launches are expected to occur by the end of 2010. But before the IOV phase can begin, a thorough analysis of the performance of the GIOVE satellites must be carried out to minimize any difficulties with the IOV satellites. This includes monitoring and assessing the different signals broadcast by the satellites. The GIOVE satellites can transmit on all three Galileo frequencies, E5, E6, and E1 (also known as L1) but only on two simultaneously (either E1-E5 or E1-E6). A variety of modulation types can be transmitted on the different frequencies by both satellites to test their use for the different Galileo services to be implemented for the operational constellation. These include alternative binary offset carrier (BOC) and quadrature phase shift keying on E5 and cosine BOC (BOCc) and binary phase shift keying on E6. On E1, the satellites have different capabilities. Although both satellites can transmit BOCc on this frequency, GIOVE-A can additionally transmit a single BOC signal with a subcarrier frequency of 1.023 MHz and a spreading code chipping rate of 1.023 MHz (BOC(1, 1)) whereas GIOVE-B transmits a more versatile multiplexed composite BOC or CBOC, which linearly combines BOC(1, 1) and BOC(6, 1). The CBOC signal is being transmitted by GIOVE-B to explore its performance, usability, and any possible side effects including its use in receivers designed to track a BOC(1, 1) signal. GIOVE-B has now been in orbit for just over one year. How well is it performing? In particular, what can we say about one of GIOVE-B's pioneering features: its E1 CBOC signal? This month we take a detailed look at a particular monitoring and assessment program set up to examine the CIOVE-B signals and discuss some of its initial CBOC results. The successful operation of this program bodes well for its use in future validation campaigns. GIOVE-B E1 Signal. Signal Quality and Relevance. Evaluation Parameters (Correlation Loss; S-Curve Bias). Weilheim Measurement Setup. Measurement Calibration. Power Measurement Results. Signal Quality Results. Conclusions.

20.10   It's not all bad: Understanding and using GNSS multipath   Bilich, Larson

Bilich, A., and K. M. Larson (2009). It's not all bad: Understanding and Using GNSS multipath. *GPS World,* October, Vol. 20, No. 10, pp. 31-39.

Innovation: SNR fluctuations are a telltale sign of multipath. Cast your mind back 30 or 40 years. (Sorry, students, this exercise is for the older folks.) What was one of the most striking features of the suburban landscape? Virtually every house was topped with a Yagi TV antenna. The only way to receive TV signals before cable and satellite TV was directly from the transmitter tower. And, unless you had one of those fancy antenna rotors, reception wasn't always that great. Not only did we have to put up with weak signals, there was the problem of multipath. Besides a direct signal from the transmitter, the antenna could pick up a signal reflected off a nearby building, say, resulting in a delayed ghost image to the right of the main image on the TV screen. Even those out in the country weren't immune from multipath as a fluttery image might be seen caused by reflections from passing aircraft. These days, with TV signals primarily delivered by cable and satellite, we don't *see* multipath much anymore. But we do hear it in our cars, from time to time, while listening to FM radio. (Students can tune back in now.) Although the FM "capture effect" provides some margin against multipath, it is not uncommon to lose stereo reception or to experience fading out of the signal while driving in built-up areas as a result of reflections. This same multipath phenomenon also affects GNSS signals. Unlike satellite TV antennas, the antennas feeding our GNSS receivers are omnidirectional. So we have the possibility of not only receiving a direct, line-of-sight signal from a GNSS satellite but also any indirect signal from the satellite

that gets reflected off nearby buildings or other objects or even the ground. GNSS antenna and receiver manufacturers have developed techniques to minimize the impact of multipath on the GNSS observables. Nevertheless, there is typically some residual multipath afflicting the pseudorange and carrier-phase observables that limits the precision and accuracy of position determinations. Telltale signs of multipath are the quasi-periodic fluctuations in the signal-to-noise ratios (SNRs) reported by some GNSS receivers, and this month we learn how an analysis of SNR values can be used to map and better understand the multipath environment surrounding an antenna. And, although an annoyance for most GNSS users, it turns out that multipath is not all bad. By analyzing the SNR fluctuations due to multipath, characteristics of the reflector can be deduced. If the reflector is the ground, then the amount of moisture in the soil can be measured. GNSS for measuring soil moisture? Who would have thought? Simplified Multipath Model. SNR Multipath Applications (Multipath Corrections; Power Spectral Maps; Soil Moisture). Conclusions.

20.11   Improving dilution of precision: A companion measure of systematic effects
<div align="right">Milbert</div>

Milbert, D. (2009). Improving dilution of precision: A companion measure of systematic effects. *GPS World,* November, Vol. 20, No. 11, pp. 38-47.

Innovation: The simple geometrical relationship breaks down if model errors are systematic. We live in an imperfect world. We know this all too well from life's everyday trials and tribulations. But this statement extends to the world of GPS and other global navigation satellite systems, too. A GPS receiver computes its three-dimensional position coordinates and its clock offset from four or more simultaneous pseudoranges. These are measurements of the biased range (hence the term pseudorange) between the receiver's antenna and the antenna of each of the satellites being tracked. The receiver processes these measurements together with a model describing the satellite orbits and clocks and other effects, such as those of the atmosphere, to determine its position. The precision and accuracy of the measured pseudoranges and the fidelity of the model determine, in part, the overall precision and accuracy of the receiver-derived coordinates. If we lived in an ideal world, a receiver could make perfect measurements and model them exactly. Then, we would only need measurements to any four satellites to determine our position perfectly. Unfortunately, the receiver must deal with measurements and models that have some degree of error, which gets propagated into the position solution. Furthermore, the geometrical arrangement of the satellites observed by the receiver—their elevation angles and azimuths— can significantly affect the precision and accuracy of the receiver's solution, typically degrading them. It is common to express the degradation or dilution by dilution of precision (DOP) factors. Multiplying the measurement and model uncertainty by an appropriate DOP value gives an estimate of the position error. These estimates are reasonable if the measurement and model errors are truly random. However, it turns out that this simple geometrical relationship breaks down if some model errors are systematic. If that systematic error is a constant bias and if it is common to all pseudoranges measured simultaneously, then the receiver can easily estimate it along with its clock offset, leaving the position solution unaffected. But if the errors are systematically different for the different simultaneous pseudoranges, as is typically the case when trying to correct for ionospheric and tropospheric effects, these errors propagate into the receiver solution in a way that is fundamentally different from the way that random errors propagate. This means that in addition to DOP, we need a companion measure of systematic effects. This month Dennis Milbert introduces just such a measure—the error scale factor or

ESF. ESF, combined with DOP, forms a hybrid error model that appears to more realistically portray the real-world GPS precisions and accuracies we actually experience. Random Error Propagation. Systematic Error Propagation (Ionosphere Error Scale Factor; Systematic Range Error and Height; Tropospheric Error Scale Factor; Cutoff Angle). GPS Error Models.

20.12   [Showcase issue — no column]

21.01   Collective detection: Enhancing GNSS receiver sensitivity by combining signals from multiple satellites   Axelrad et al.

Axelrad, P., J. Donna, M. Mitchell, and S. Mohiuddin (2010). Collective detection: Enhancing GNSS receiver sensitivity by combining signals from multiple satellites. *GPS World,* January, Vol. 21, No. 1, pp. 58-64.

Innovation: Poor signal reception in difficult environments is still a problem. Although I have managed the Innovation column continuously since *GPS World*'s first issue, it wasn't until the second issue that I authored a column article. That article, co-written with Alfred Kleusberg, was titled "The limitations of GPS." It discussed some of the then-current problems of GPS, including poor signal reception, loss of signal integrity, and limited positioning accuracy. In the ensuing 20 years, both signal integrity and positioning accuracy have improved significantly. Advances in the GPS control segment's capabilities to continuously monitor and assess signal performance, together with receiver-autonomous integrity monitoring and integrity enhancement provided by augmentation systems, have reduced worries about loss of signal integrity. The removal of Selective Availability and use of error corrections provided by augmentation systems, among other approaches, have improved positioning accuracy. But the problem of poor reception due to weak signals is still with us. In that March/April 1990 article, we wrote "[GPS] signals propagate from the satellites to the receiver antenna along the line of sight and cannot penetrate water, soil, walls, or other obstacles very well. … In surface navigation and positioning applications, the signal can be obstructed by trees, buildings, and bridges. … [In] the inner city streets of urban areas lined with skyscrapers, the 'visibility' of the GPS satellites is very limited. In such areas, the signals can be obstructed for extended periods of time or even [be] continuously unavailable." Poor signal reception in other than open-sky environments is still a problem with conventional GPS receivers. However, extending signal integration times and using assisted-GPS techniques can give GPS some degree of capability to operate indoors and in other restricted environments, albeit typically with reduced positioning accuracy. An antenna with sufficient gain is needed and capable systems are available on the market. The pilot channels of modernized GNSS signals will also benefit signal acquisition and tracking in challenging environments. In this column, we look at a completely different approach to enhancing signal sensitivity. Rather than requiring each satellite's signal to be acquired and tracked before it can be used in the navigation solution, the new approach—dubbed "collective detection"—combines the received signals power from multiple satellites in a direct-to-navigation-solution procedure. Besides providing a quick coarse position solution with weak signals, this approach can be used to monitor the signal environment, aid deeply-coupled GPS/inertial navigation, and assist with terrain and feature recognition. Acquisition Theory and Methods. Collective Detection. Applications. Simulation and Processing. Results and Discussion (Impact of Reduced Geometry; Focusing on Clock Errors; Live Satellite Signals). Conclusions.

21.02   Mobile-phone GPS antennas: Can they be better?   Haddrell et al.

Haddrell, T. M. Phocas, and N. Ricquier (2010). Mobile-phone GPS antennas: Can they be better? *GPS World,* February, Vol. 21, No. 2, pp. 29-35.

Innovation: GPS units in mobile phones don't work everywhere. What three things matter most for a good GPS signal? Antenna, antenna, antenna. The familiar real-estate adage can be rephrased for this purpose, although the original – location, location, location – is valid here, too. GPS satellite signals are notoriously weak compared to familiar terrestrial signals such as those of broadcast stations or mobile-phone towers. However, if an appropriate antenna has a clear line-of-sight to the satellite, excellent receiver performance is the norm. But what constitutes an appropriate antenna? The GPS signals are right-hand circularly polarized (RHCP) to provide fade-free reception as the satellite's orientation changes during a pass. A receiving antenna with matching polarization will transfer the most signal power to the receiver. Microstrip patch antennas and quadrifilar helices, two RHCP antennas commonly used for GPS reception, have omnidirectional (in azimuth) gain patterns with typical unamplified boresight gains of a few dB greater than that of an ideal isotropic RHCP antenna. But what happens when signals are obstructed by trees or buldings or, worse yet, when we move indoors? Received signal strength plummets. A conventional receiver, even with a good antenna, will then have difficulty acquiring and tracking the signals, resulting in missed or even no position fixes. However, thanks in large part to massive parallel correlation, receivers have been developed with 1,000 times more sensitivity than conventional receivers, permitting operation in restricted environments, albeit usually with reduced positioning accuracy. But such operation requires a standard antenna. So, do the GPS receivers in our mobile phones now work everywhere? Sadly, no. Consumers demand that their phones not only provide voice communications and GPS but also Bluetooth connectivity to headsets, Wi-Fi, and even an FM transmitter, all in a small form factor at reasonable cost. This requires miniaturizing the GPS antenna and possibly integrating it with the other radio services on the platform. Such compromises can, if the designer is not careful, significantly reduce receiver effectiveness with dramatically reduced antenna gain and distorted antenna patterns. Here we look at some antenna designs providing GPS functionality to mobile phones and examine why most phones still do not provide GPS operation indoors or in other challenging environments. We also find out what it will take to make them better. Theory, Performance. Size of the Problem (Vanishing Space; Interference and Isolation). Requirements (Coexistence and Cohabitation). Real-Life Testing (Differential vs. Single-Ended Antennas; Testing Some Commercial Parts). Novel Approaches, Validation.

21.03   Hybrid positioning: A prototype system for navigation in GPS-challenged environments   Rizos et al.

Rizos, C., D. A. Grejner-Brzezinska, C. T. Toth, A. G. Dempster, Y. Li, N. Politi, J. Barnes, H. Sun, and L. Li. (2010). Hybrid positioning: A prototype system for navigation in GPS-challenged environments. *GPS World,* March, Vol. 21, No. 3, pp. 42-47.

Innovation: A new ground-based system works in a similar way to GPS. GPS has its limitations. Although it is a 24/7 global system, it doesn't work everywhere. The microwave radio signals transmitted by the satellites are rather weak, and although they can provide excellent positioning performance when a receiver's antenna has a direct line-of-sight view of a sufficient number of satellites well spread out in the sky, positioning accuracy degrades or becomes impossible when the signals are effectively blocked by obstacles such as trees, rock faces, and buildings outdoors and by roofs, ceilings, and walls indoors. In many obstructed

environments, the signals aren't completely blocked but rather their power is severely attenuated so that they are no longer strong enough to be acquired and tracked by a conventional GPS receiver. Remarkable progress has been made in the development of super-sensitive receivers that, in conjunction with an appropriate antenna and assistance information provided over a mobile phone network, can provide position fixes in such environments. However, the precisions and accuracies of these pseudorange-based positions are often very poor – perhaps as low as 100-meters or more. So, is it possible to obtain precise and accurate positions in obstructed environments? Well, we could add measurements from GLONASS (or other satellites) to GPS measurements, but GLONASS suffers the same problem as GPS, and while the additional satellites could be an advantage in some partially obscured areas there are many places where we won't be any better off. We could use an inertial navigation system (INS), but such devices have their own weaknesses such as the requirement of initial calibration and the accumulation of position error with time. Are there any other technologies available? We know GPS works very well when there is a direct line-of-sight view between the satellite transmitters and the receivers and carrier-phase measurements can provide decimeter- and even centimeter-accuracies. So why not develop a ground-based system that works in a similar way to GPS, which would allow you to place the transmitters wherever you like? Well, such a system has indeed been developed and this month, a team of Australian and U.S. researchers describes how they integrated the ground-based system together with GPS and INS to create a hybrid system that provides precise and accurate position information continuously in a variety of environments where GPS alone comes up short. Locata Technology. Triple Integration. Field Tests (Test 1: NTF; Test 2: Electric Car). Concluding Remarks.

21.04   GPS by the numbers: A sideways look at how the Global Positioning System works   Langley

Langley, R. B. (2010). GPS by the numbers: A sideways look at how the Global Positioning System works. *GPS World,* April, Vol. 21, No. 4, pp. 42-48.

Innovation: Welcome to Innovation column number 200. I have managed this column continuously since the first issue of *GPS World* magazine, which appeared back in 1990. From the outset, we established that the column should deal with issues that have broad application and interest and are presented in terms that are accessible to as wide a range of readers as possible. Since 1990, we have covered a wide range of topics, some of them at the leading edge of GPS development and some of them receiving the basics of GPS operation in tutorial fashion. The column has appeared 199 times and now we come to number 200. So clearly 200 is an important number for me and, I hope, for you. But the number 200 is interesting for other reasons, too. It is the smallest base 10 unprimeable number—you can't turn it into a prime number by changing just one of its digits to any other digit. It's how many dollars you get when you pass G in Monopoly. And in 2012, it will be how many years have elapsed since The War of 1812—the last time Canada and the United States had a serious quarrel (other than in hockey). But more to the point of this column, it is the designation of the basic reference document that describes how GPS works: IS-GPS-200. Formerly known as an Interface Control Document or ICD, it has gone through several revisions since its first public release in July 1991. It is full of numbers. Numbers that tell us how the GPS signals are generated and how a receiver is to interpret the signals to provide a position fix. If you are a regular reader of the Innovation column, then likely you have an inquisitive bent. You like to know how things work — GPS in particular. And you don't have to be convinced about

the importance of numbers and their role in understanding the world around us. As Sir William Thomson, a.k.a. Lord Kelvin, said in one of his lectures, "*I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.*" So in this column, the 200th, we're going to look at GPS by the numbers, getting a sense of how GPS works by examining some of the key numbers that govern its remarkable capabilities, from the smallest to the largest. I'll draw heavily on material from the past 199 columns. Let's get started. 0 Zero. 0.00000000000001 (or 1 x 10^{-14} in scientific notation). 0.77922077922… The rational number 60/77. 1 The loneliest number. 2.4 The approximate delay, in meters. 3.1415926…π. Every nerd's favorite number. 4. This is the minimum number of satellites… . 10.23. The frequency of a GPS satellite… . 12.5 The length of the full navigation message… . 24. The number of satellites in the current GPS baseline constellation. 40.3. The scaling factor … . 1023. This is the number of chips in the C/A-code. 1176.45. The L5 carrier frequency in megahertz. 1227.60. The L2 carrier frequency in megahertz. 1381.05. The L3 carrier frequency in megahertz. 1575.42. The L1 carrier frequency in megahertz. 403199. The maximum value of the GPS time of week count. 299,792,458. The speed of light in meters per second. 235,469,592,765,000. (Or 2.35469592765000 x 10^{14} in scientific notation.) $\sqrt{-1}$. The square root of -1.

21.05   Accuracy versus precision: A primer on GPS truth   Rutledge

Rutledge, D. (2010). Accuracy versus precision: A primer on GPS truth. *GPS World*, May, Vol. 21, No. 5, pp. 42-49.

Innovation: All measurements contain errors. Jacques-Bénigne Bossuet, the 17th century French bishop and pulpit orator, once said, "Every error is truth abused." He was referring to man's foibles, of course, but this statement is much more general and equally well applies to measurements of all kinds. As I am fond of telling the students in my introduction to adjustment calculus course, there is no such thing as a perfect measurement. All measurements contain errors. To extract the most useful amount of information from the measurements, the errors must be properly analyzed. Errors can be broadly grouped into two major categories: biases, which are systematic and which can be modeled in an equation describing the measurements, thereby removing or significantly reducing their effect; and noise or random error, each value of which cannot be modeled but whose statistical properties can be used to optimize the analysis results. Take GPS carrier-phase measurements, for example. It is a standard approach to collect measurements at a reference station and a target station and to form the double differences of the measurements between pairs of satellites and the pair of receivers. By so doing, the biases in the modeled measurements that are common to both receivers, such as residual satellite clock error, are canceled or significantly reduced. However, the random error in the measurements due to receiver thermal noise and the quasi-random effect of multipath cannot be differenced away. If we estimate the coordinates of the target receiver at each epoch of the measurements, how far will they be from the true coordinates? That depends on how well the biases were removed and the effects of random error. By comparing the results from many epochs of data, we might see that the coordinate values agree amongst themselves quite closely; they have high precision. But, due to some remaining bias, they are offset from the true value; their accuracy is low. Two different but complementary measures for assessing the quality of the results. Here we will examine the differences between the precision and accuracy of GPS-determined positions and, armed with a better understanding of these often confused terms,

perhaps be less likely to abuse the truth in the business of GPS positioning. The GPS Signal. Frequency Distribution. Internal vs. External Accuracy. Final Notes.

21.06   GPS, GLONASS, and more   Springer and Dach

Springer, T. and R. Dach (2010). GPS, GLONASS, and more. *GPS World,* June, Vol. 21, No. 6, pp. 48-58.

Innovation: GLONASS was reborn. Are we there yet—at a multiple-constellation GNSS world? The European Galileo system only has two test satellites in orbit, with constellation completion not scheduled until 2014. The Chinese Beidou/Compass system has launched some test satellites, but global coverage is not promised until 2020. And the first Japanese Quasi-Zenith Satellite System space vehicle is scheduled for launch this year with the system not fully operational until 2013. So, does this mean GPS is still the only game in town? No, not by a long shot. We have overlooked Russia's GLONASS. Standing for *Global'naya Navigatsion-naya Sputnikova Sistema*, GLONASS was conceived by the former Soviet Ministry of Defence in the 1970s, perhaps as a response to the announced development of GPS. The first satellite was launched on October 12, 1982, But because of launch failures and the characteristically brief lives of the satellites, a further 70 satellites were launched before a fully populated constellation of 24 functioning satellites was achieved in early 1996. Unfortunately, the full constellation was short-lived. Russia's economic difficulties following the dismantling of the Soviet Union hurt GLONASS. Funds were not available, and by 2002 the constellation had dropped to as few as seven satellites, with only six available during maintenance operations! But Russia's fortunes turned around, and with support from the Russian hierarchy, GLONASS was reborn. Longer-lived satellites were launched, as many as six per year, and slowly but surely the constellation has grown to 21, with two in-orbit spares. But are there any users outside Russia? Although dual-system GPS/GLONASS receivers have been around for at least a decade, manufacturers have taken notice of GLONASS's recent phoenix-like rebirth. All of the high-end manufacturers now offer receivers with GLONASS capability. Does combining GPS and GLONASS observations make a difference? You bet—just ask any surveyor who uses both systems in the real-time kinematic (RTK) approach. Scientific applications requiring high-accuracy satellite orbit and clock data also benefit. The International GNSS Service (IGS) has been providing such data for several years, and in this article representatives from two IGS analysis centers discuss the past, present, and future of IGS GNSS monitoring and product development. So getting back to our question, are we there yet? Many early adopters of GPS plus GLONASS data and products would reply with a resounding "yes." Why GNSS? IGS GNSS Analysis Centers. GLONASS Tracking Network. GLONASS Constellation. Orbit and Clock Accuracy. Conclusions and Outlook.

21.07   Better weather prediction using GPS: Water vapor tomography in the Swiss Alps   Lutz et al.

Lutz, S., M. Troller, D. Perler, A. Geiger, and H.-G. Kahle (2010). Better weather prediction using GPS: Water vapor tomography in the Swiss Alps. *GPS World,* July, Vol. 21, No. 7, pp. 40-47.

Innovation: GPS can estimate the atmosphere's moisture content. Weather forecasting is still an imperfect art. Humankind has been trying to predict the weather for millennia. But it was only with advances in scientific thought and the invention of measuring devices, such as the mercury barometer, that specific prediction could be made. Towards the end of the 18th

century, the father of modern chemistry, Antoine Laurent Lavoisier, said, "It is almost impossible to predict one or two days in advance, within a rather broad range of probability, what the weather is going to be; it is even thought that it will not be impossible to publish daily forecasts, which would be very useful to society." Forecasting ability has improved as measurement technology, communications, and the understanding of atmospheric processes have improved. Meteorologists use measurement from various types of sensors and mathematical models to predict its future state. Yet better sampling of the current state of the atmosphere, particularly water vapor, is needed to produce more accurate and more timely forecasts. GPS can help. The signals from the GPS satellites must transit the atmosphere on their way to a receiver on the Earth's surface. The atmosphere's atoms and molecules slow down the signals so that they arrive slightly later than they would if the Earth was surrounded by a vacuum, and this effect shows up in the GPS receiver measurements. The receiver or measurement processing software needs to remove or model the effect to obtain accurate receiver positions. On the other hand, if all parameters affecting GPS measurements such as satellite and receiver coordinates are well known, then the delay imparted by the atmosphere can be estimated. It is possible to separate the effect of water vapor from that of the dry gasses such as nitrogen, oxygen, and carbon dioxide and to provide a measure of the atmosphere's moisture content. Several national weather agencies are ingesting such estimates from networks of GPS receivers into experimental or operational numerical weather forecast models. But these values represent an integrated measure of moisture above a receiver. Profiles of how moisture is distributed with height would be more useful and might lead to better weather forecasts. Here a team of Swiss researchers discuss how they use data from a network of GPS receivers and the technique of tomography to obtain such profiles.   Theoretical Background (Radio Wave Refractivity; The Tomographic Voxel Model; Double-Difference GPS Tomography). Data Description (The Project Area; GPS Network and Meteorological Data; The Numerical Weather Model COSMO-7). Results (GPS Data Processing; Comparison of ZTD Time Series; Effect of Voxel Model Resolution; Effect of Temporal Resolution; Implications). Conclusions.

21.08   [Showcase issue — no column]

21.09   Friendly reflections: Monitoring water level with GNSS   Egido and Caparrini
Egido, A., and M. Caparrini (2010). Friendly reflections: Monitoring water level with GNSS. *GPS World,* September, Vol. 21, No. 9, pp. 50-56.
   Innovation: Why is the sky blue? This is an age-old question, interesting to anyone with a curiosity about his or her surroundings. But what has it got to do with global navigation satellite systems? Believe it or not, there is a connection. Some of you might remember the explanation of the sky's color from your Physics 101 course but to bring everyone up to the same level, let's review. Everything we see is the result of the interaction of light and matter. And by matter, we mean the atoms, molecules, and particles making up matter. Light causes matter to vibrate. And vibrating matter (due to its electrical charges) in turn emits light, which combines with the original light. But matter not only re-emits light in the forward direction, it re-emits light in all other directions. This is called scattering. Now, the light from the sun includes all colors and so if look [*sic*] directly at the sun when it is high in the sky (don't try this at home), it looks white or slightly yellowish. We are seeing the light propagating directly toward our eyes. When we look at the sky away from the sun, we are seeing scattered light. And this scattered light is predominantly blue. Why? It turns out that

scattering is proportional to the fourth power of frequency. Light that is of a higher frequency, say a factor of two, is sixteen times more intensely scattered. So, blue light, which has about twice the frequency of light from the red end of the visible spectrum, is scattered much more than red light. Violet light is scattered even more but our eyes are not as sensitive to violet light as they are to blue light. Hence the sky looks blue. So what has this got to do with GNSS? As we know, for the best positioning and navigation results, we need the satellite signals to travel along a direct path to the receiver's antenna. There may be slight changes in the speed and direction of propagation of these direct-path signals caused by the interaction of the electromagnetic waves with the matter making up the ionosphere and the neutral atmosphere, but these are readily accounted for in the position fixes. However, once they reach the Earth's surface, the signals can be reflected by buildings, vegetation, the ground, water surfaces, and so on. The signals are actually being scattered by the matter they encounter. A receiver can selectively acquire the scattered signals and the resulting measurements can be interpreted to reveal certain characteristics of the source of the scattering. In this column, we learn about the design and application of a GNSS instrument that uses scattered signals for monitoring the level and roughness of inland and coastal water surfaces—yet one more use of GNSS signals for the betterment of planet Earth. Our Instrument. GNSS-R Altimetry Algorithms. Measuring the Level of a Water Reservoir (La Baells Experiment; Lake Laja Experiment). Measuring Sea Level (Scheveningen Pier Experiment). Conclusion and Outlook.

21.10   Record, replay, rewind: Testing GNSS receivers with record and playback techniques   Hall

Hall, D. A. (2010). Record, replay, rewind: Testing GNSS receivers with record and playback techniques. *GPS World,* October, Vol. 21, No. 10, pp. 28-34.

Innovation: Is there a way to perform repeatable tests on GNSS receivers using real signals? This column looks at how to use an RF vector signal analyzer to digitize and record live signals, and then play them back to a GNSS receiver with an RF vector signals generator. As a professor, I'm quite familiar with testing—of students, that is. It's how we check their performance—how well they have mastered the course material. Outside academia, testing is also quite common. We have to pass a driving test before we can get a license. We might have to pass a physical fitness test before starting a job. And manufacturers have to test or stress their products to make sure they are fit for purpose. As David Ogilvy, the father of advertising once quipped, "Never stop testing, and your advertising will never stop improving." But it's not just manufacturers who should test products. Consumers, or their representatives, should test products on offer—not only to corroborate (or dispute) manufacturers' claims but also to compare one manufacturer's product against another. There's a whole slew of magazines, television programs, and web resources devoted to testing and comparing everything from laundry detergent to automobiles. And GNSS receivers are no exception. When we conduct tests, we are usually trying to get answers to certain questions—just like those posed to students on their exams. In testing GNSS receivers, what are some appropriate questions? When a receiver is turned on, how long does it take until the position of the receiver is determined? When a weak signal area is encountered, can the receiver still determine its position? If the signal is interrupted and then restored, how long does it take for the receiver to recover and resume calculating its position? And what is the position accuracy under different situations? While we can certainly hook up an antenna to a receiver to get answers to these questions in a certain environment on a

certain day at a certain time with certain signals, the scenario cannot be repeated—not exactly. If we tweak a receiver operating parameter, for example, we don't know for certain whether any observed change is due to the tweaking or a change in the scenario. We could use a radio-frequency (RF) simulator—a device for mimicking the radio signals generated by the satellites. This would allow us to define scenarios, including receiver trajectories, and to replay them as many times as necessary while varying the operating parameters of the receiver. Or we could modify the scenario from run to run. Such test scenarios could include those difficult to carry out with live signals such as determining how a receiver would perform in low Earth orbit. While extremely useful, these are tests with simulated signals. Is there a way to perform repeatable tests on GNSS receivers using real signals? In this column, we learn how to use an RF vector signal analyzer to digitize and record live signals, and then play them back to a GNSS receiver with an RF vector signal generator—a procedure we can repeat as often as we like. Setting up the RF Front End. Hardware Connections (Method 1: Active Antenna Powered by GPS Receiver; Method 2: Active GPS Antenna Powered by Receiver). Selecting the Right LNA. Saving Data to Disk. Receiver Performance. Conclusion.

21.11   [no column]

21.12   [Showcase issue — no column]