# Monitoring the Ionosphere and Neutral Atmosphere with GPS


Richard B. Langley

Geodetic Research Laboratory
Department of Geodesy and Geomatics Engineering
University of New Brunswick
Fredericton, N.B.



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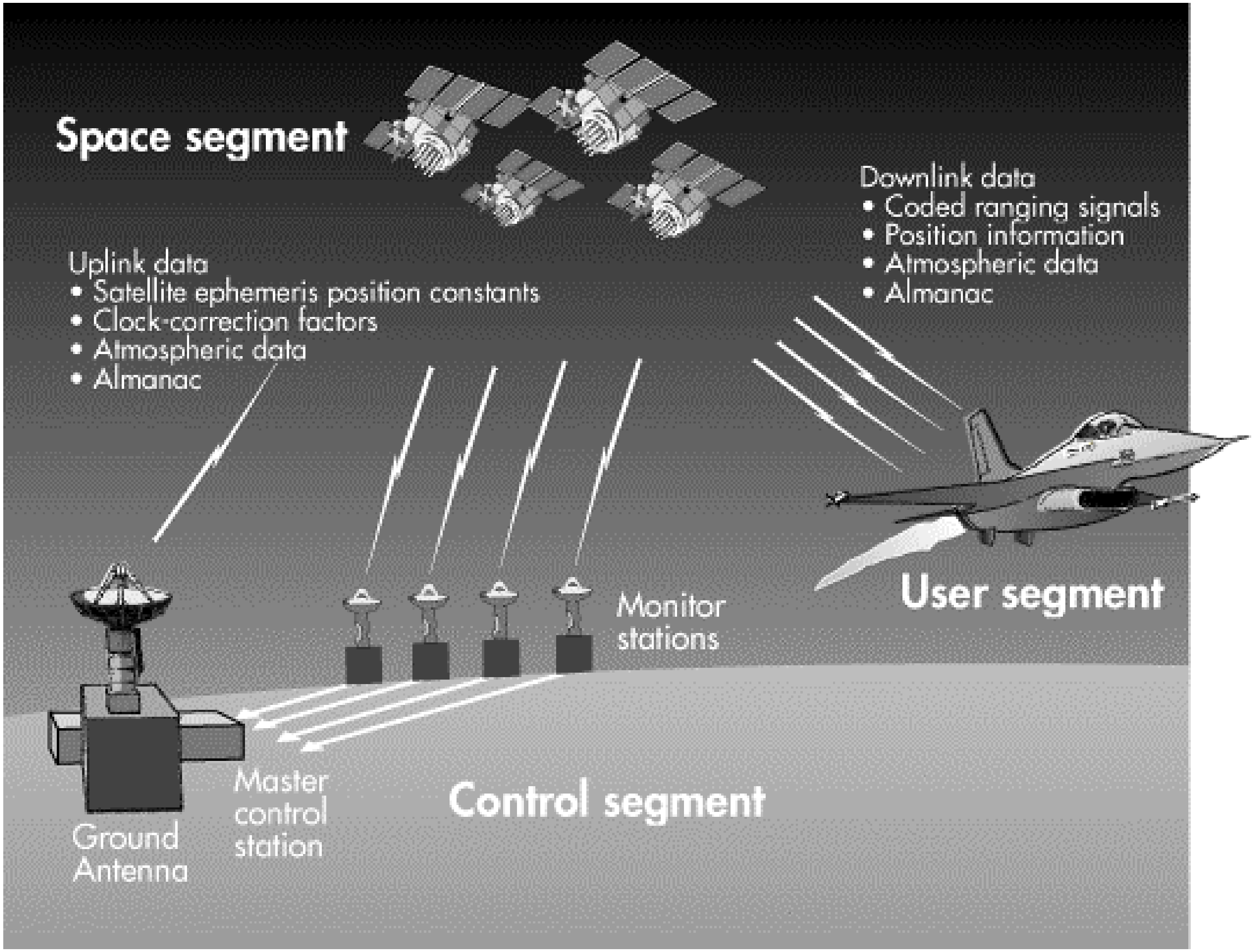
# Outline

- Introduction to GPS
- Current status
- Modernization
- The GPS Signals
- Atmospheric Propagation Delay
- Neutral Atmosphere
- Ionosphere
- Spaceborne GPS Limb Sounding
- Ionospheric Tomography
- Concluding Remarks

# GPS Segments

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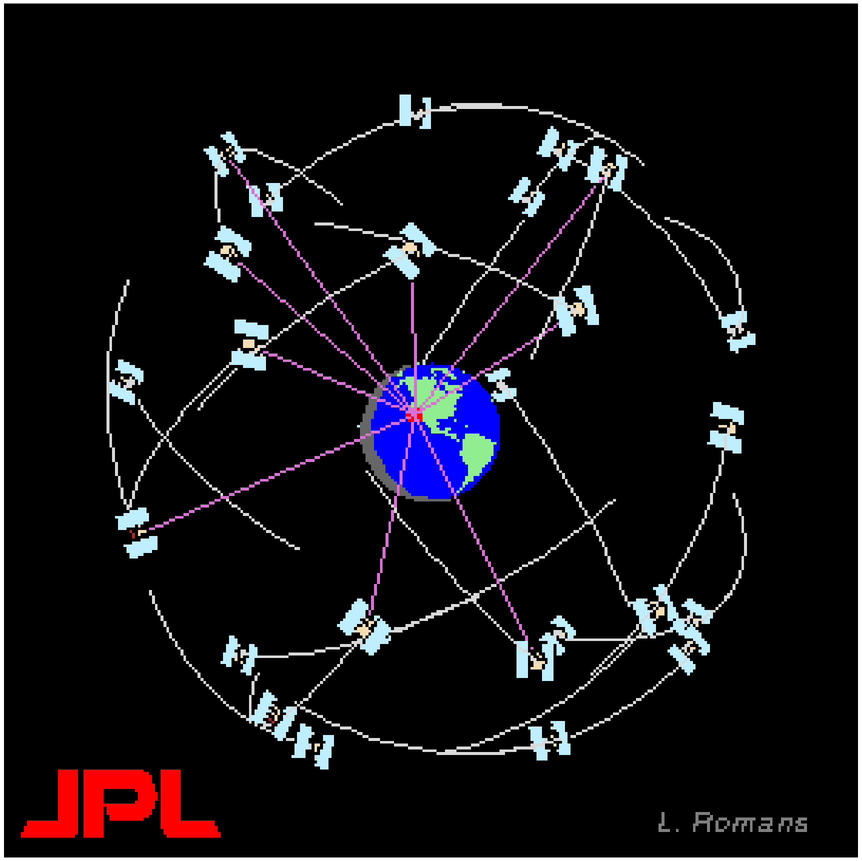
# GPS Constellation




**Altitude: 20,200 km**

**Orbital Period: 12 hrs (semi-synchronous)**

**Orbital Plane: 55 degrees**

**Number of Planes: 6**

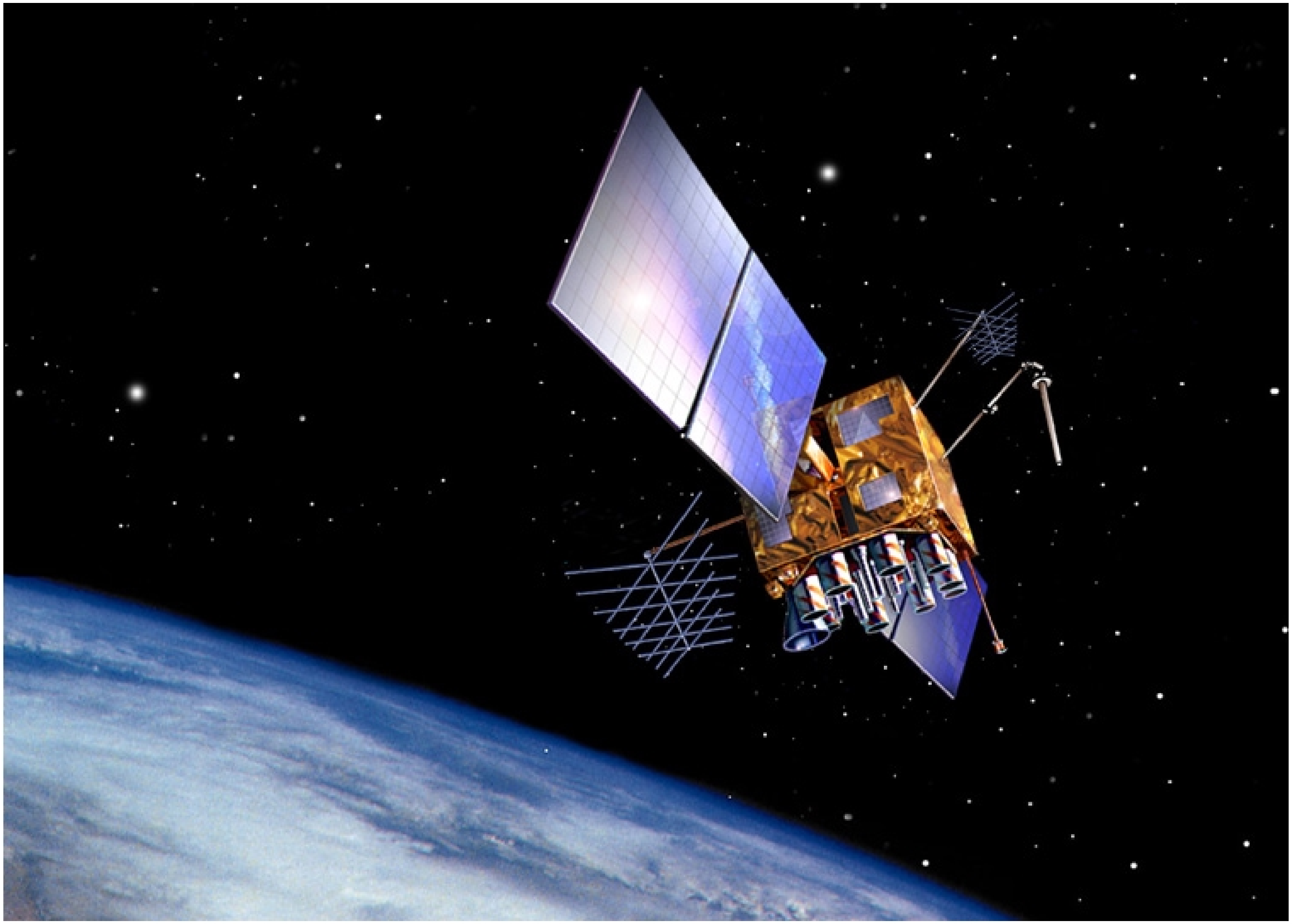
**Vehicles per plane: 4-5**

**Constellation size: >24 satellites (currently 28)**

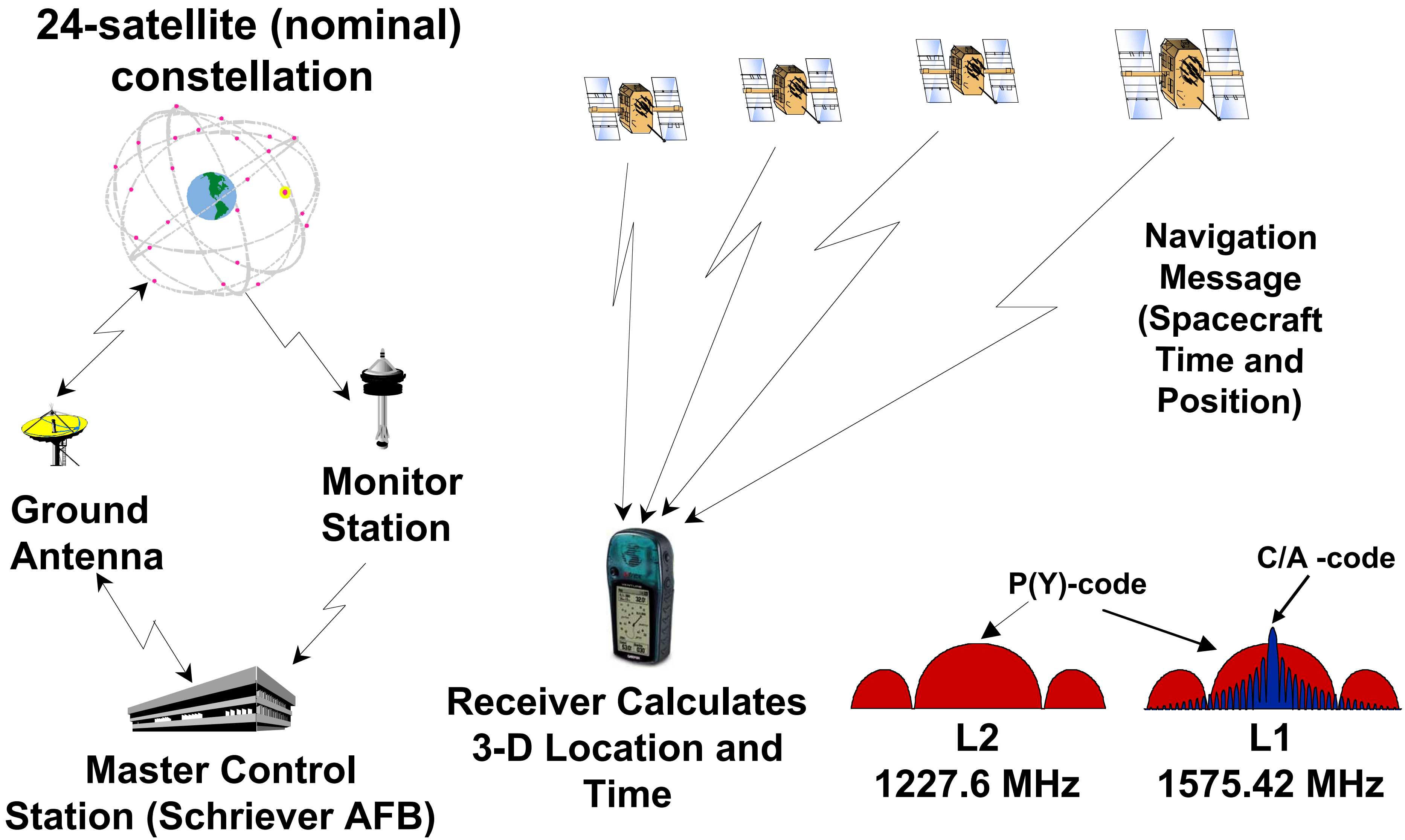
# Generations of Satellites

| | |
|---|---|
| Block I | Prototype (test) satellites. 10 launched between 1978 and 1985. All retired. |
| Block II | Initial operational satellites. 9 launched between 1989 and 1990. 4 still functioning. |
| Block IIA | Slightly modified Block IIs. 19 launched between 1990 and 1997. 18 still functioning. |
| Block IIR | Replenishment satellites. 6 orbited to date. First in 1997. C/A code on L2 plus higher power on last 12 satellites launched from 2003 onwards. |
| Block IIF | Follow-on satellites. New civil signal at 1176.45 MHz. First launch expected in 2005. |
| Block III | Conceptual. |

# Block IIR Satellite



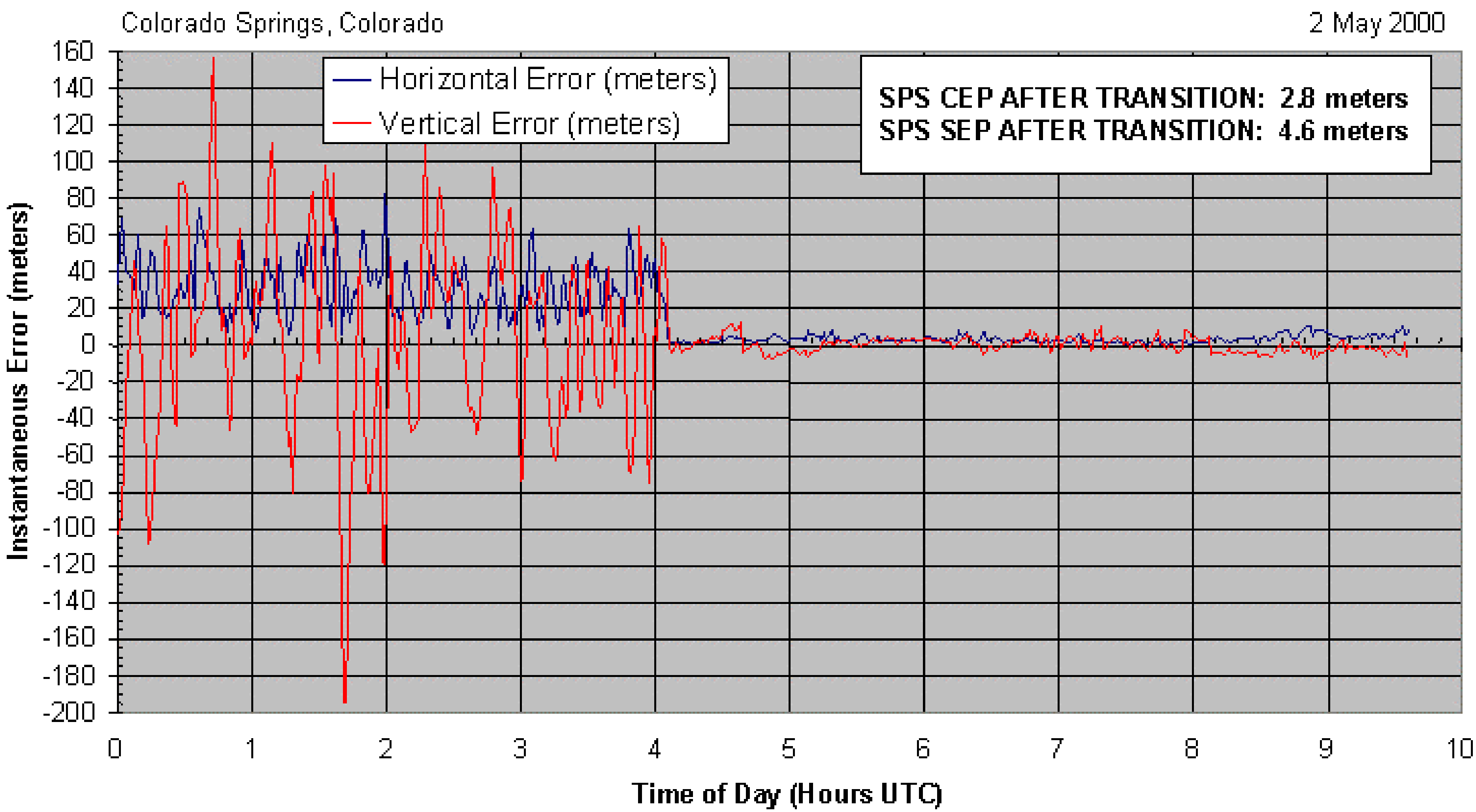
# GPS Operation



# GPS Modernization

- One goal is enhanced capabilities for civil users of GPS
- Civil benefits include:
  - Selective Availability (SA) turned off on 2 May 2000
  - Second civil frequency for ionospheric correction and redundancy
  - Third civil signal for “safety of life” applications in protected spectrum; more robust; also provides high accuracy and benefits real-time applications

# Selective Availability Switched Off

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# GPS Modernization Details

- Last 12 Block IIRs - Add second civil signal (C/A on L2) and new military signal (M-code). Provide more signal power.

  First modernized launch (Block IIR-M) - FY03

- First 6 Block IIFs ("IIF Lite") - All of above capabilities plus new third civil signal in protected band (L5).

  First Block IIF "Lite" launch - FY05

- At the current GPS satellite replenishment rate, all three civil signals (L1-C/A, L2-C/A, and L5) will be available for initial operational capability by 2010, and for full operational capability by approximately 2013.

# Block IIF Satellite

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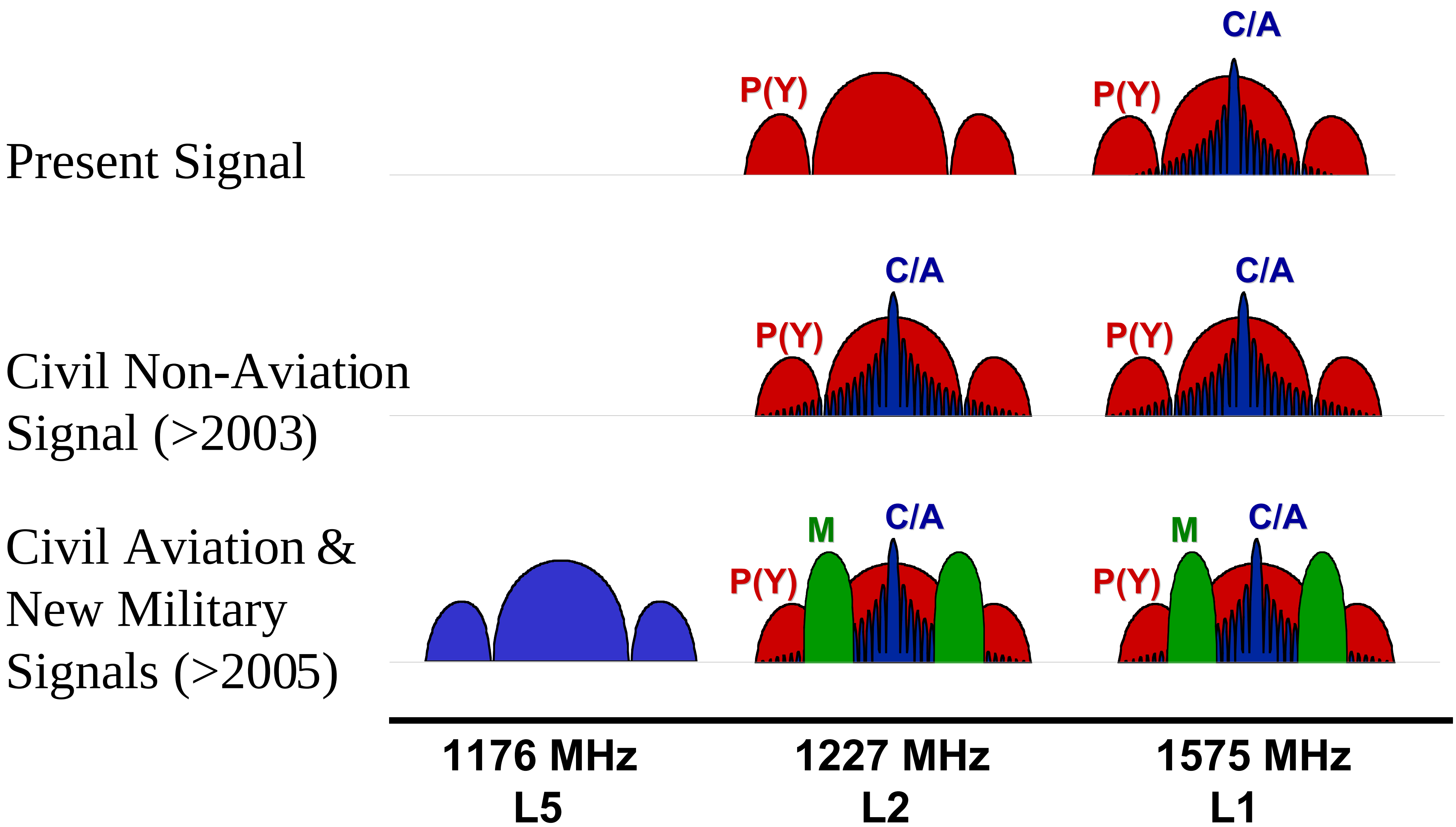
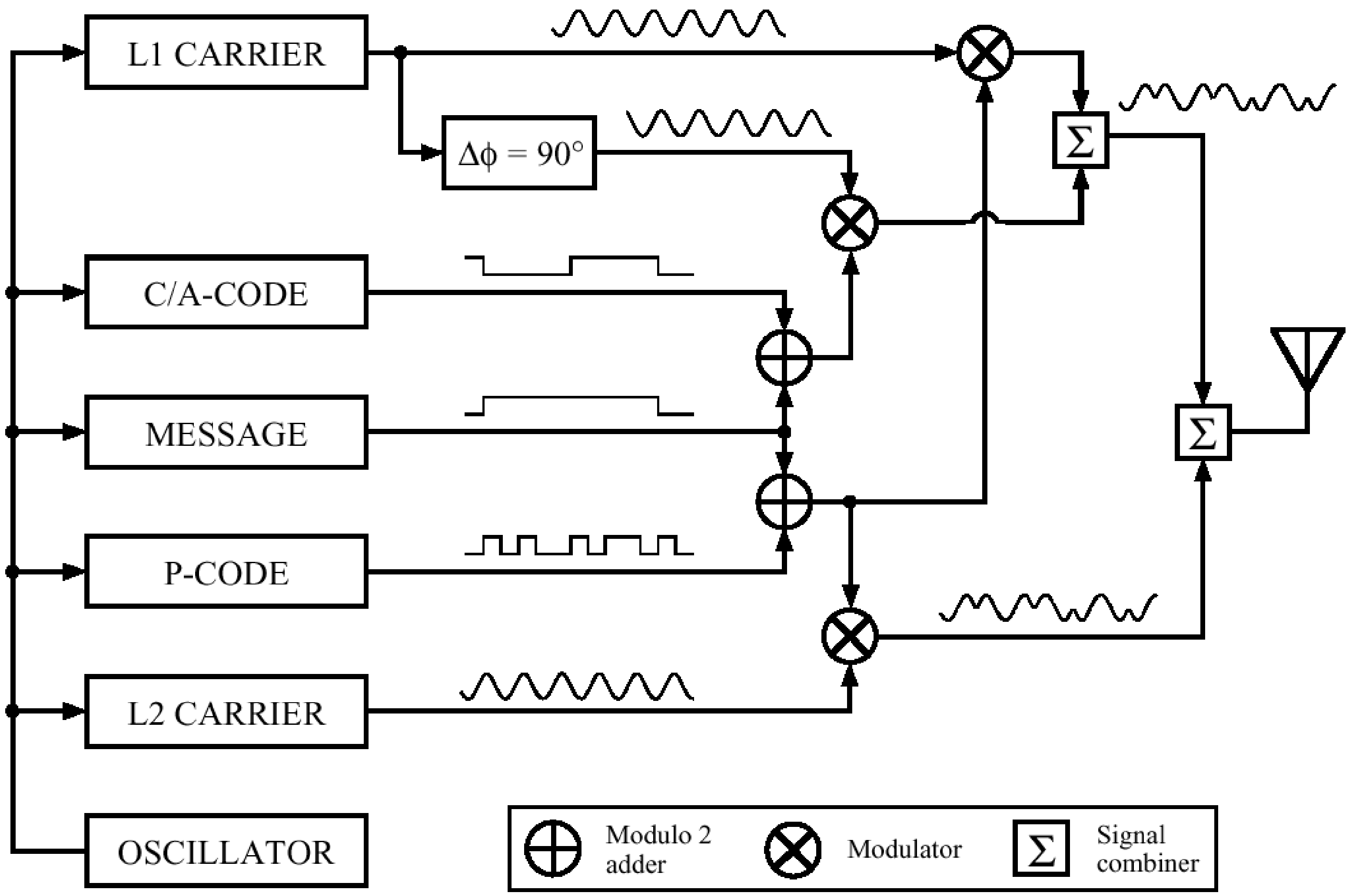
# Signal Modernization



# Current GPS Signals



# Observation Equations

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## Pseudorange:

$$P(t) = \rho(t) + c[dt_r(t) - dt^s(t-\tau)] + I(t) + T(t) + \varepsilon_P(t)$$

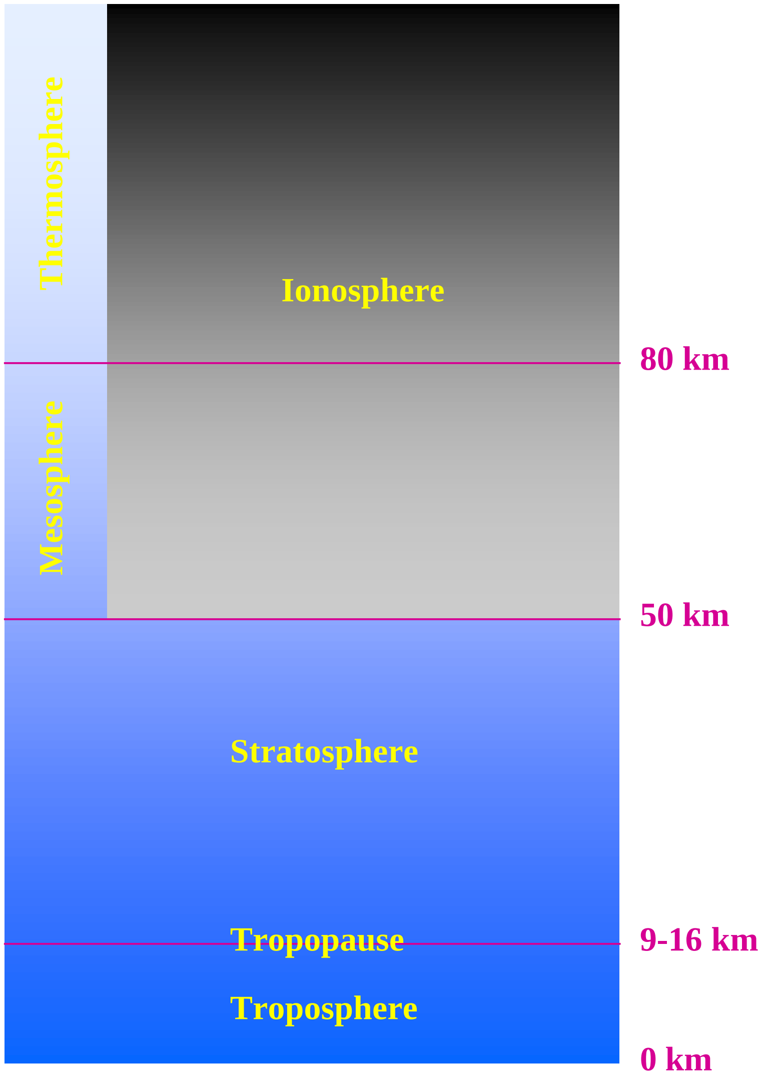
## Carrier phase:

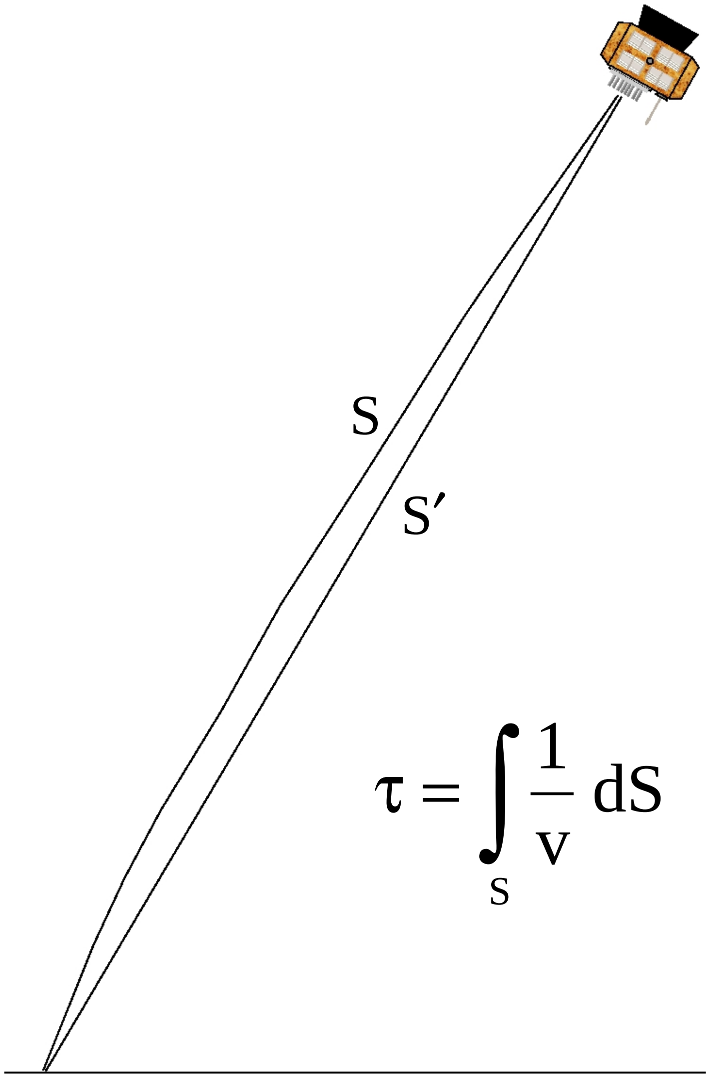
$$\Phi(t) = \lambda\,\phi(t)$$
$$= \rho(t) + c[dt_r(t) - dt^s(t-\tau)] - I(t) + T(t) + \lambda N + \varepsilon_\Phi(t)$$

$t$ - signal reception time
$\lambda$ - wavelength
$c$ - speed of light
$\rho$ - geometric range
$\tau$ - signal transit time
$dt_r$ - receiver clock offset

$dt^s$ - satellite clock offset
$I$ - ionospheric delay
$T$ - tropospheric delay
$N$ - integer ambiguity
$\varepsilon_P$ - pseudorange noise
$\varepsilon_\Phi$ - carrier phase noise

# Atmospheric Refraction




$$\tau = \int_S \frac{1}{v}\, dS$$

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# Phase and Group Delay

$$\Delta\tau = \int_S \frac{1}{v}\, dS - \int_{S'} \frac{1}{c}\, dS'$$

$$d\Phi = c\,\Delta\tau$$

$$= \int_S n\, dS - \int_{S'} dS'$$

$$= \int_S (n-1)\, dS + \left[ \int_S dS - \int_{S'} dS' \right]$$

$$dP = \int_S (n_g - 1)\, dS + \left[ \int_S dS - \int_{S'} dS' \right]$$

# Tropospheric Zenith Propagation Delay

Zenith Delay

$$T_z = \int [n(r) - 1]\, dr$$

$$= 10^{-6} \int N(r)\, dr$$

where refractivity of air is given by (ignoring compressibility factors)

$$N = \underbrace{K_1 \frac{P}{T}}_{Dry} + \underbrace{K_2 \frac{e}{T} + K_3 \frac{e}{T^2}}_{Wet}$$

or

$$N = \underbrace{K_1 \frac{M}{M_d} \frac{P}{T}}_{Hydrostatic} + \underbrace{\left( K_2 - K_1 \frac{M}{M_d} \right) \frac{e}{T} + K_3 \frac{e}{T^2}}_{\text{“}Wet\text{”}}$$

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# Slant Delay and PWV

zenith delays

$$T = T_h^z m_h(e) + T_w^z m_w(e)$$

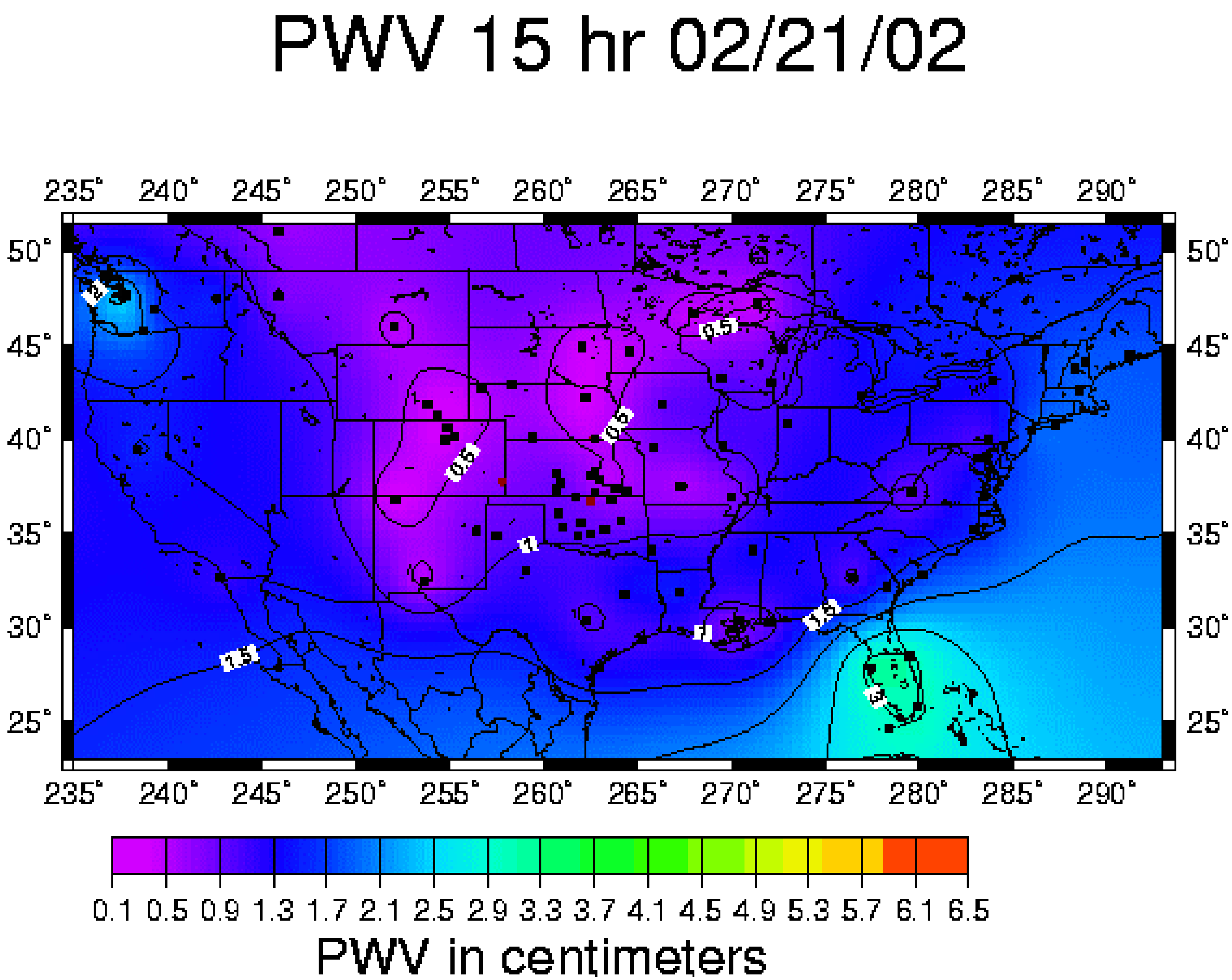
mapping functions

Zenith hydrostatic delay computed from accurate surface pressure

Zenith wet delay (ZWD) estimated from GPS data

Precipitable Water Vapour (PWV) $\approx$ ZWD $\div$ 6

# Precipitable Water Vapour from GPS

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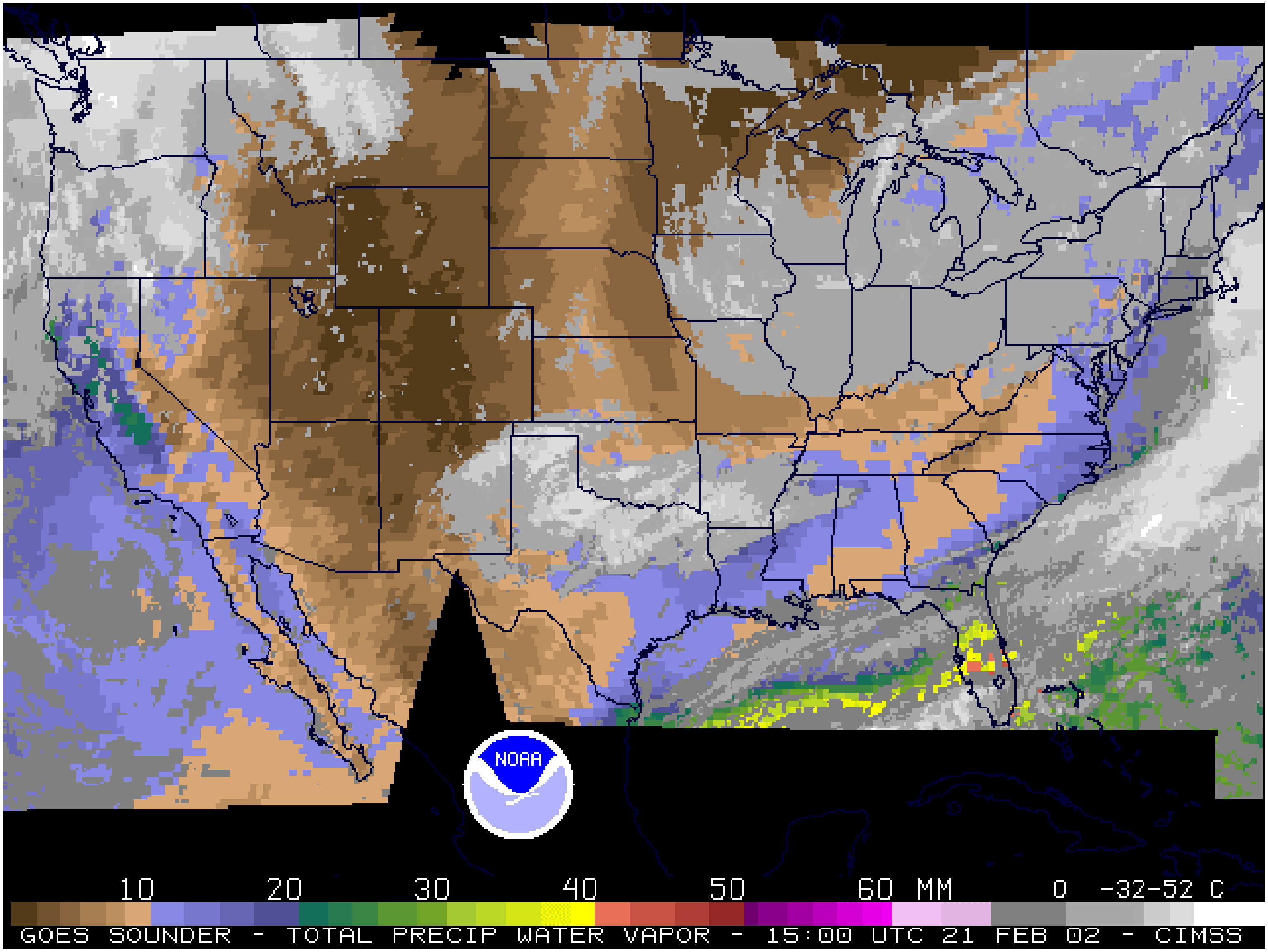
# PWV from GOES Sounder

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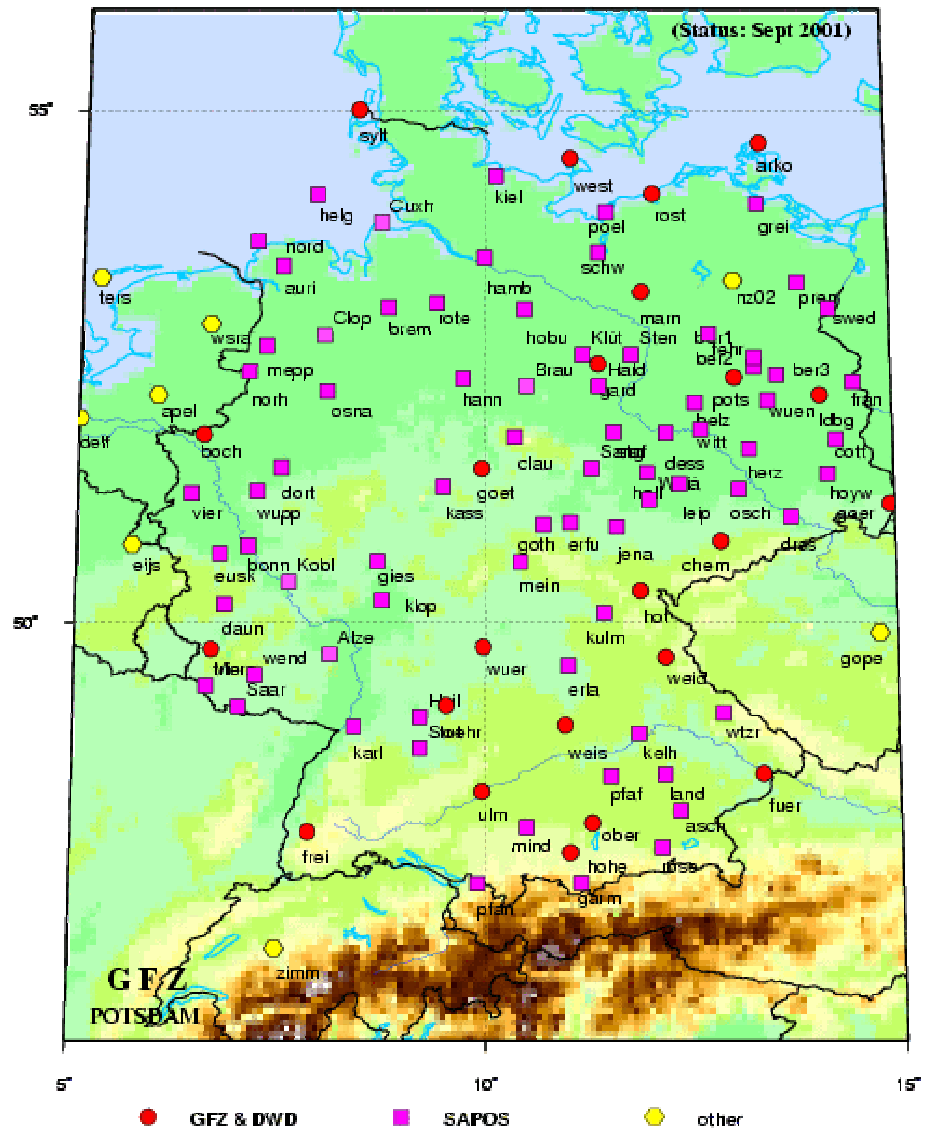
# German GPS Met Network

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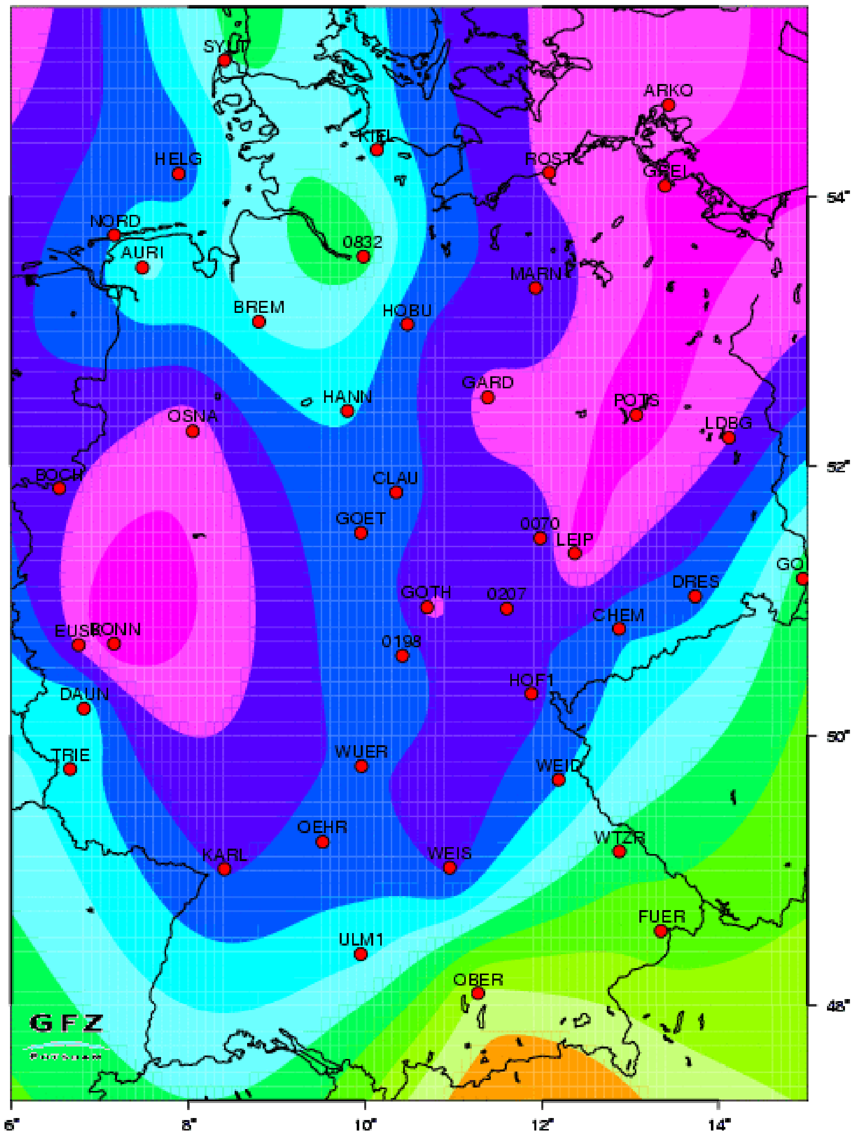
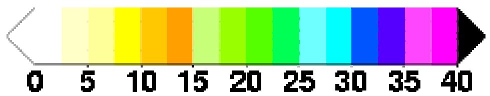
# Estimated Water Vapour Field




15 August 2000
12:00 UT




IWV(kg/m$^2$)

Integrated water vapour (IWV)
= PWV • density of $H_2O$

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# Ionospheric Refractive Index

$$n \cong 1 - \frac{1}{2}X \pm \frac{1}{2}XY|\cos\theta| - \frac{1}{8}X^2 - \frac{1}{4}XY^2\left(1+\cos^2\theta\right)$$

where

$$X = \frac{Ne^2}{4\pi^2\varepsilon_0 m}\frac{1}{f^2}, \quad Y = \frac{B_0|e|}{2\pi m}\frac{1}{f}$$

and $\theta$ is the angle between the direction of signal propagation and the geomagnetic field.

At the GPS L1 frequency, assuming $N=10^{12}$, $B_0=0.5\text{x}10^{-4}$, $\theta=0$,

$$n \cong 1 - 1.6\times10^{-5} \pm 1.6\times10^{-8} - 1.3\times10^{-10} - 1.6\times10^{-11}$$

And so, to a good approximation: $n = 1 - \alpha N/f^2$ and $n_g = 1 + \alpha N/f^2$

# Phase Advance and Group Delay

$$\rho_{\Phi} = \int_S (n\, dS) = \int_S \left(1 - \frac{\alpha N}{f^2}\right) dS = \rho - I$$

and

$$\rho_{P} = \int_S (n\, dS) = \int_S \left(1 + \frac{\alpha N}{f^2}\right) dS = \rho + I$$

where $\quad I = \dfrac{\alpha}{f^2} \displaystyle\int_S N\, dS \cong 40.28 \frac{TEC}{f^2}$

# Ionospheric Propagation Delay

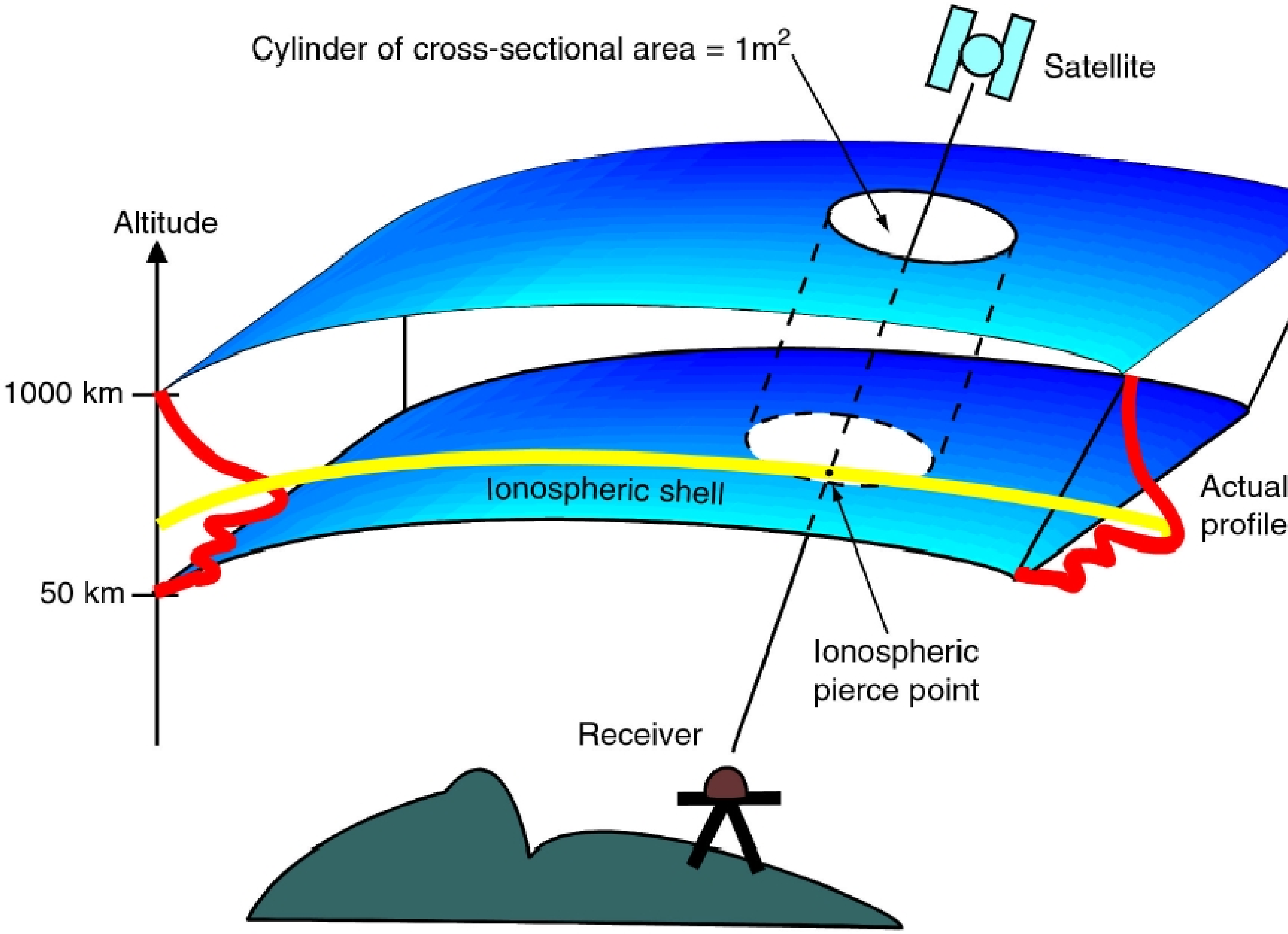
$$I_{L1(P)} = \frac{f_2^2}{f_2^2 - f_1^2}\left[P_{L1} - P_{L2}\right] + \varepsilon_{P(L1+L2)}$$

$$I_{L1(\Phi)} = \frac{f_2^2}{f_2^2 - f_1^2}\left[\left(\lambda_1 N_1 - \lambda_2 N_2\right) - \left(\Phi_1 - \Phi_2\right)\right] + \varepsilon_{\Phi(L1+L2)}$$

Phase levelling:

$$I = I_\Phi - \frac{\sum_{j=-\frac{n}{2}}^{\frac{n}{2}} w_j\left[I_{\Phi,j} - I_{P,j}\right]}{\sum_{j=-\frac{n}{2}}^{\frac{n}{2}} w_j}$$

# Ionospheric Shell Model



# Ionospheric Shell Model

observable

stochastic parameters

receiver bias

$$I_r^s(t) = M\left(e_r^s\right)\left[a_{0,r}(t) + a_{1,r}(t)\, d\lambda_r^s + a_{2,r}(t)\, d\phi_r^s\right] + b_r + b^s$$

mapping function

difference in longitudes of pierce point and Sun

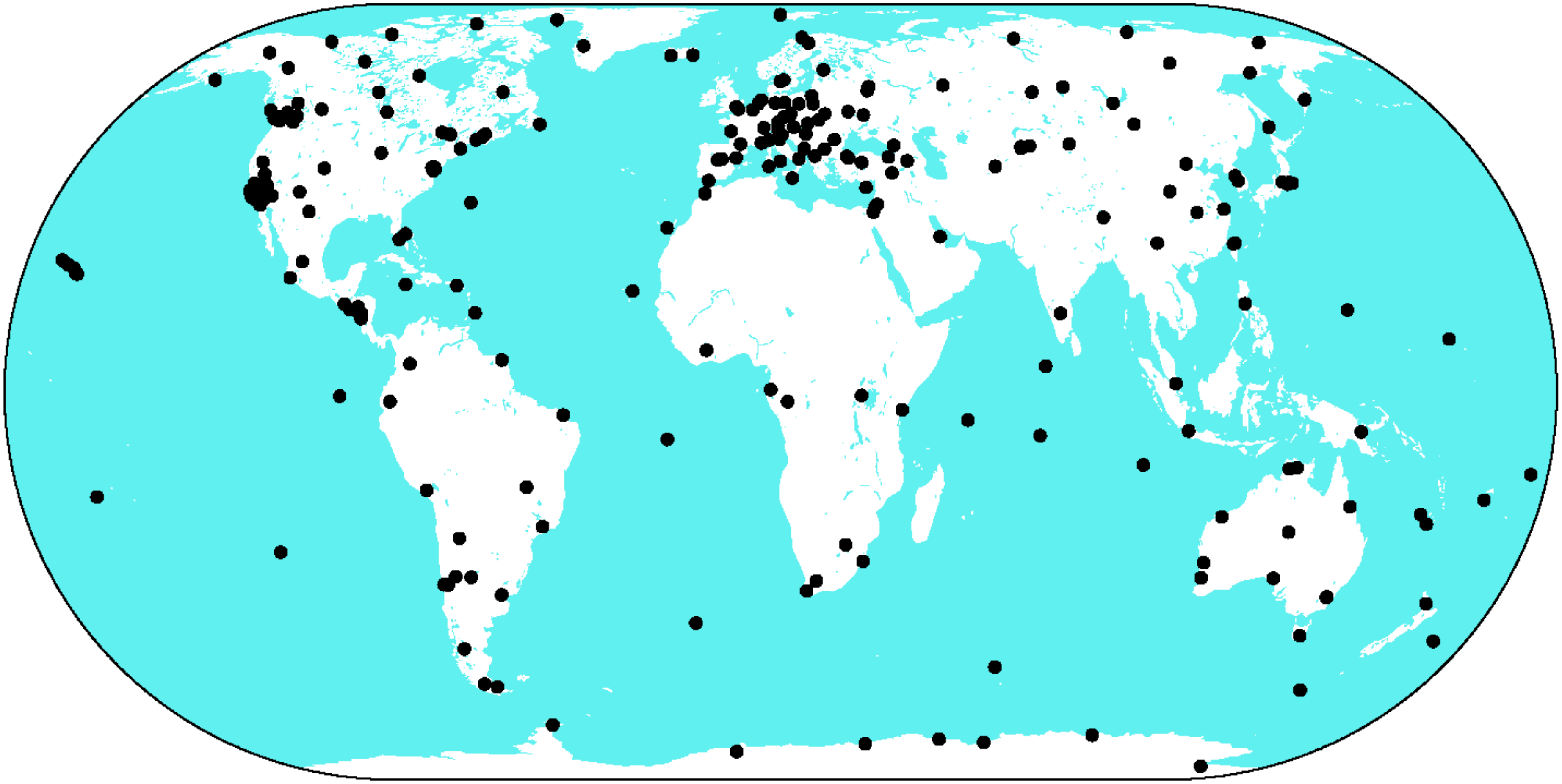
difference in geomagnetic latitudes of pierce point and receiver

satellite bias

$$M(e) = \left[1 - \frac{r_E^2 \cos^2 e}{\left(r_E + h\right)^2}\right]^{-\frac{1}{2}}$$

e - elevation angle
$r_E$ - mean Earth radius
h - shell height

# IGS Tracking Network



288 stations on 20 February 2002

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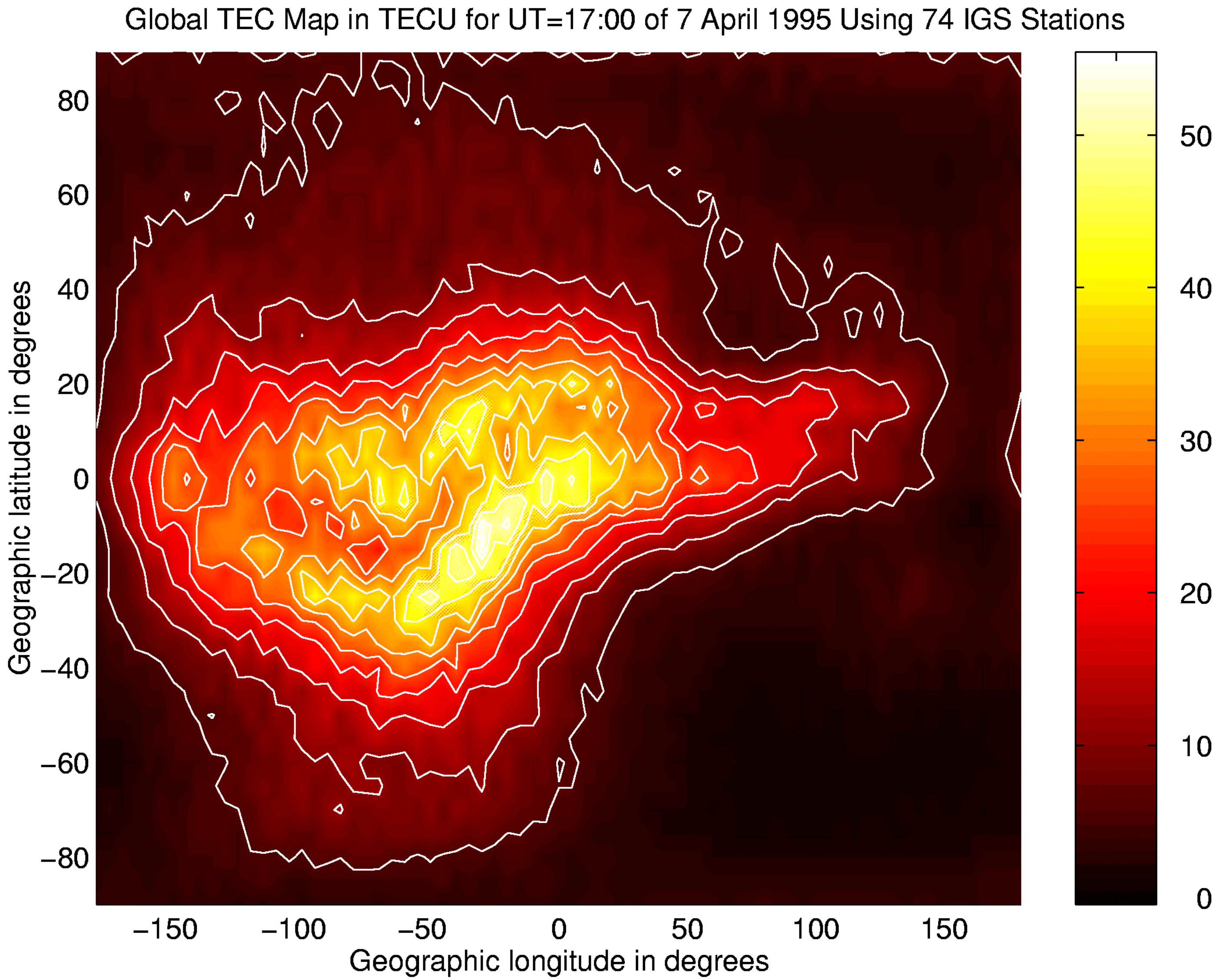
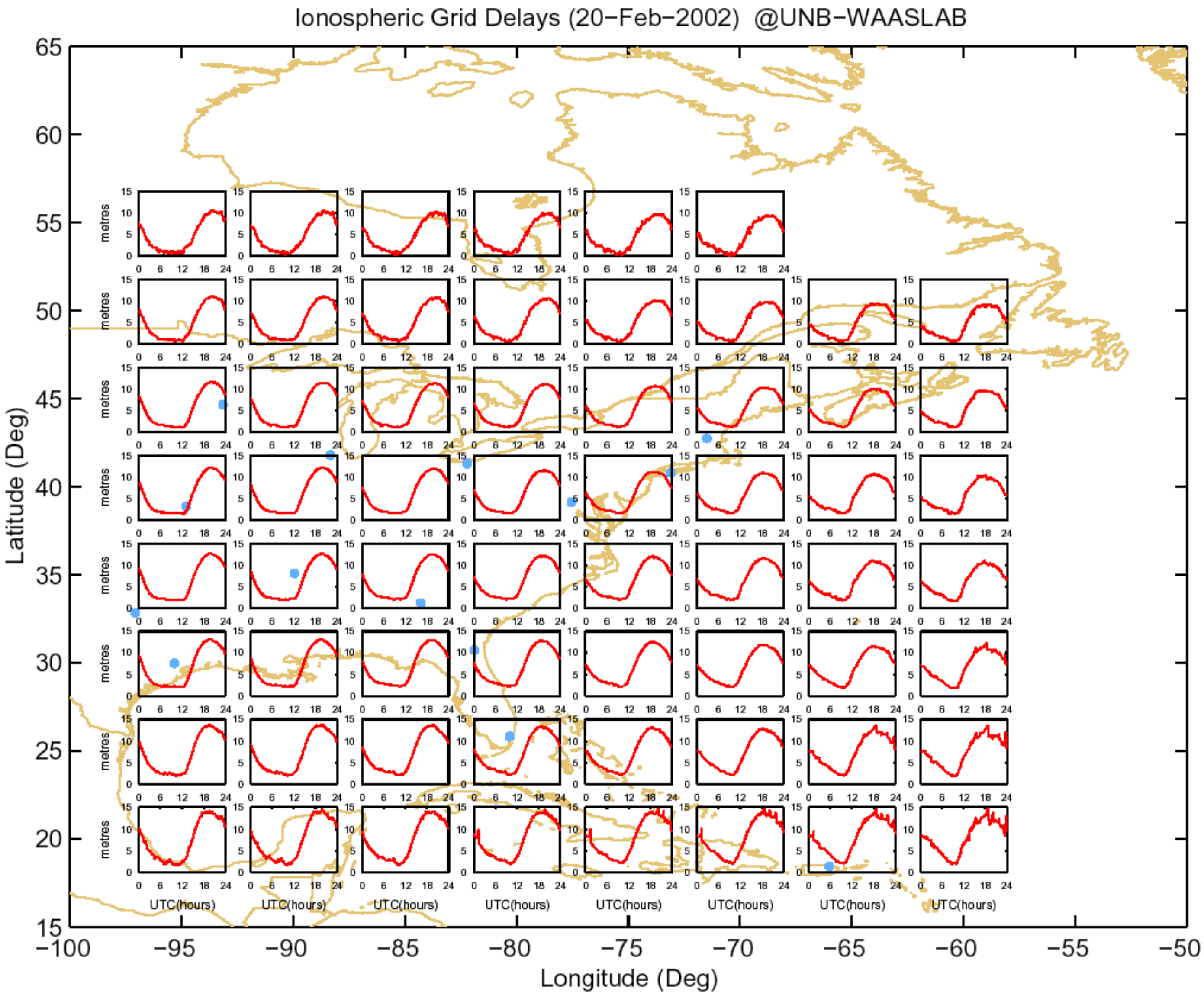
# Global TEC Map from IGS Data



# WAAS Ionospheric Grid

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# Low Latitude Ionosphere Studies


## South American Network

- 37 stations from the IGS and RMBC (Brazilian Network for Continuous Monitoring of GPS)
- Map shows 23 of the stations

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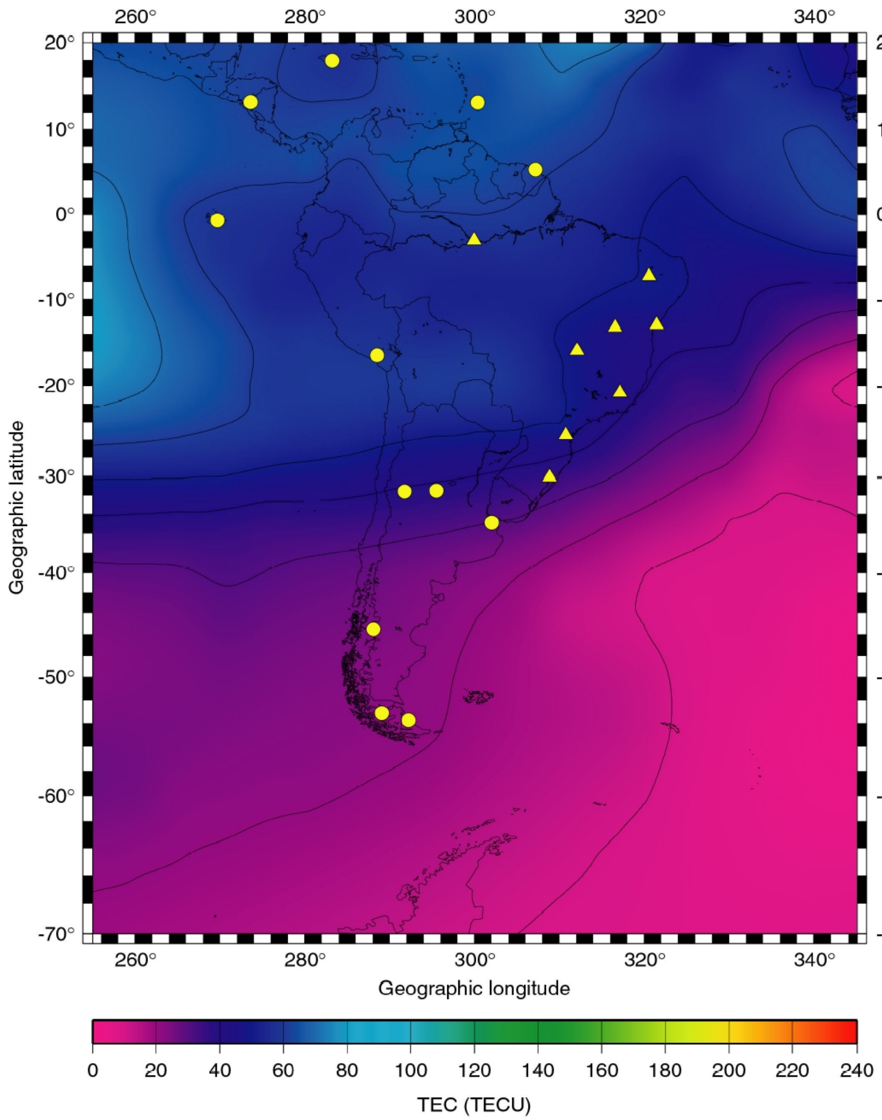
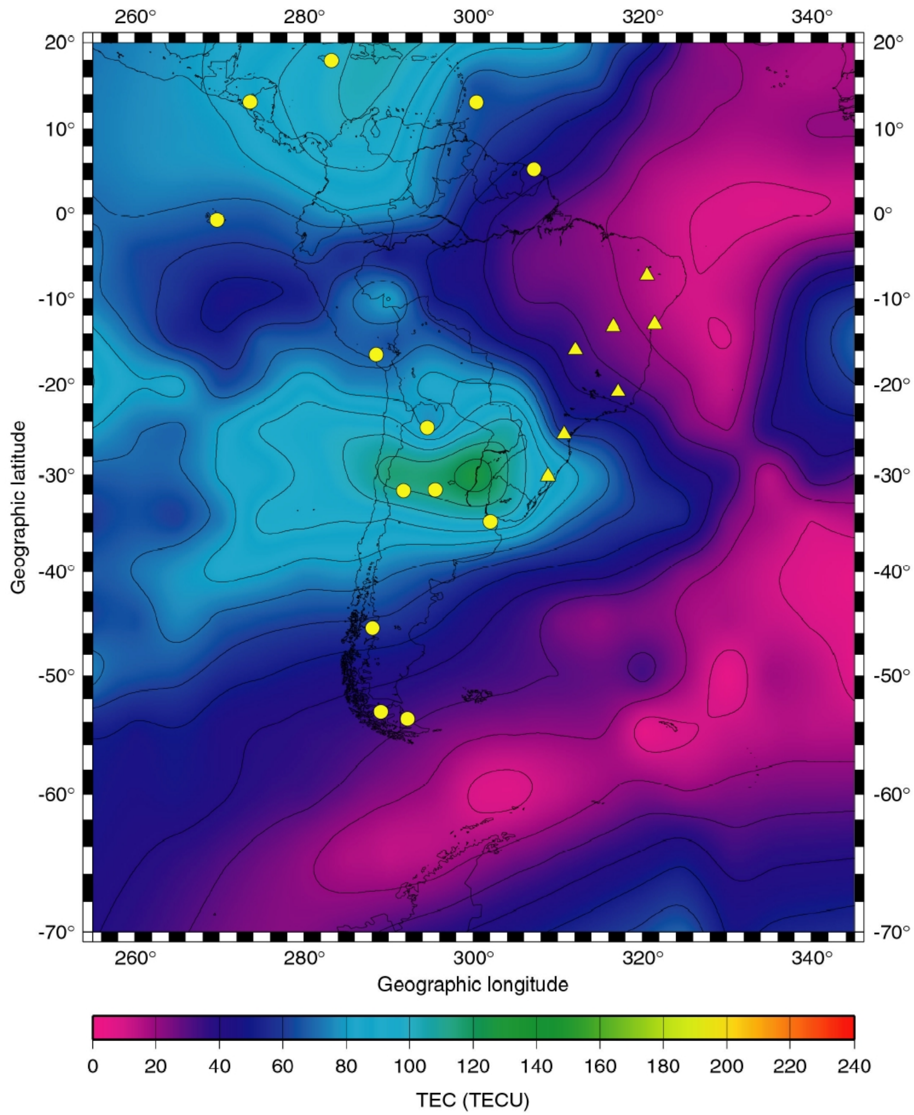
# TEC Maps - St. Swithin's Day Storm




Mean TEC 22:00 UT, 14 July 2000




Mean TEC 22:00 UT, 15 July 2000

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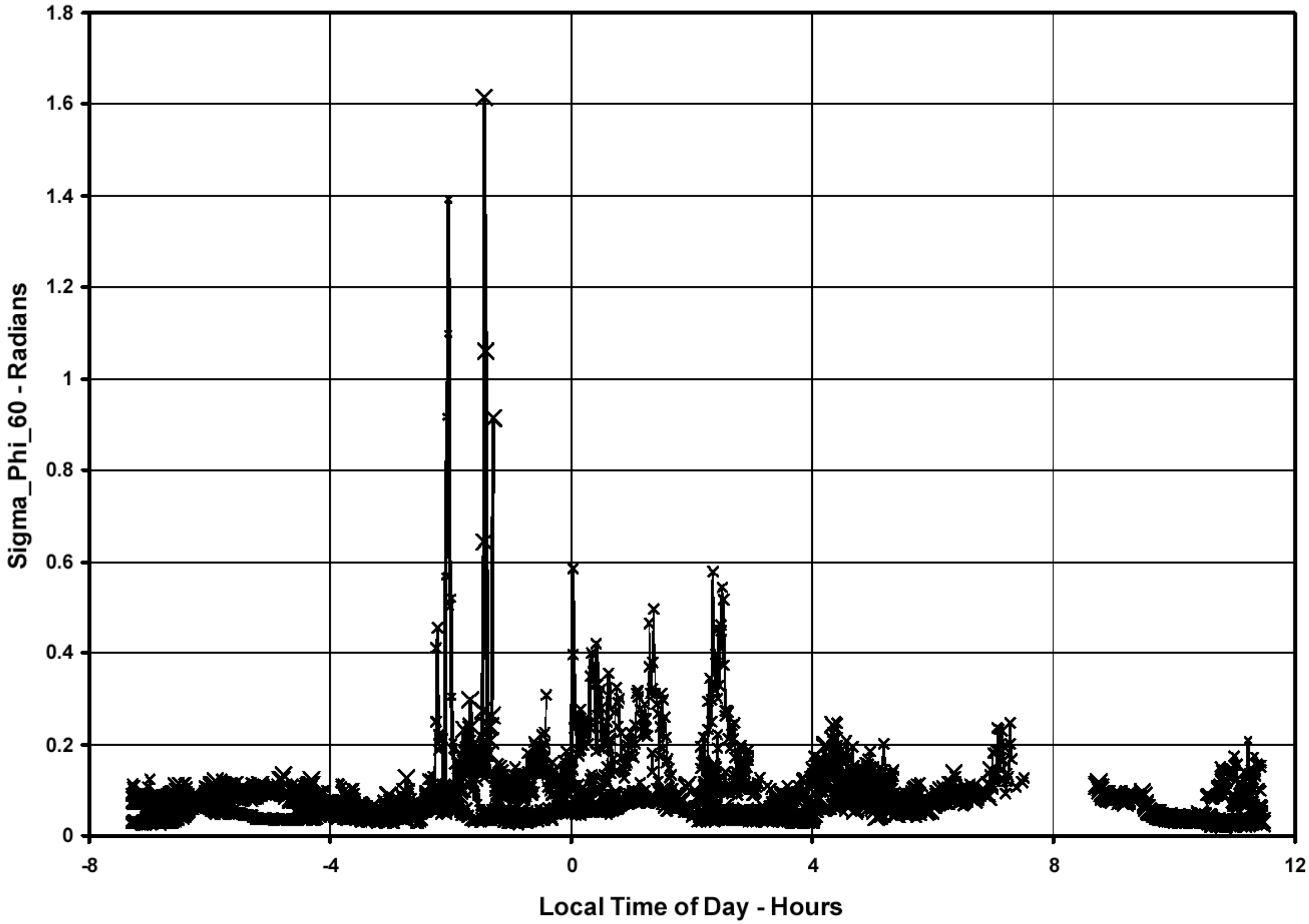
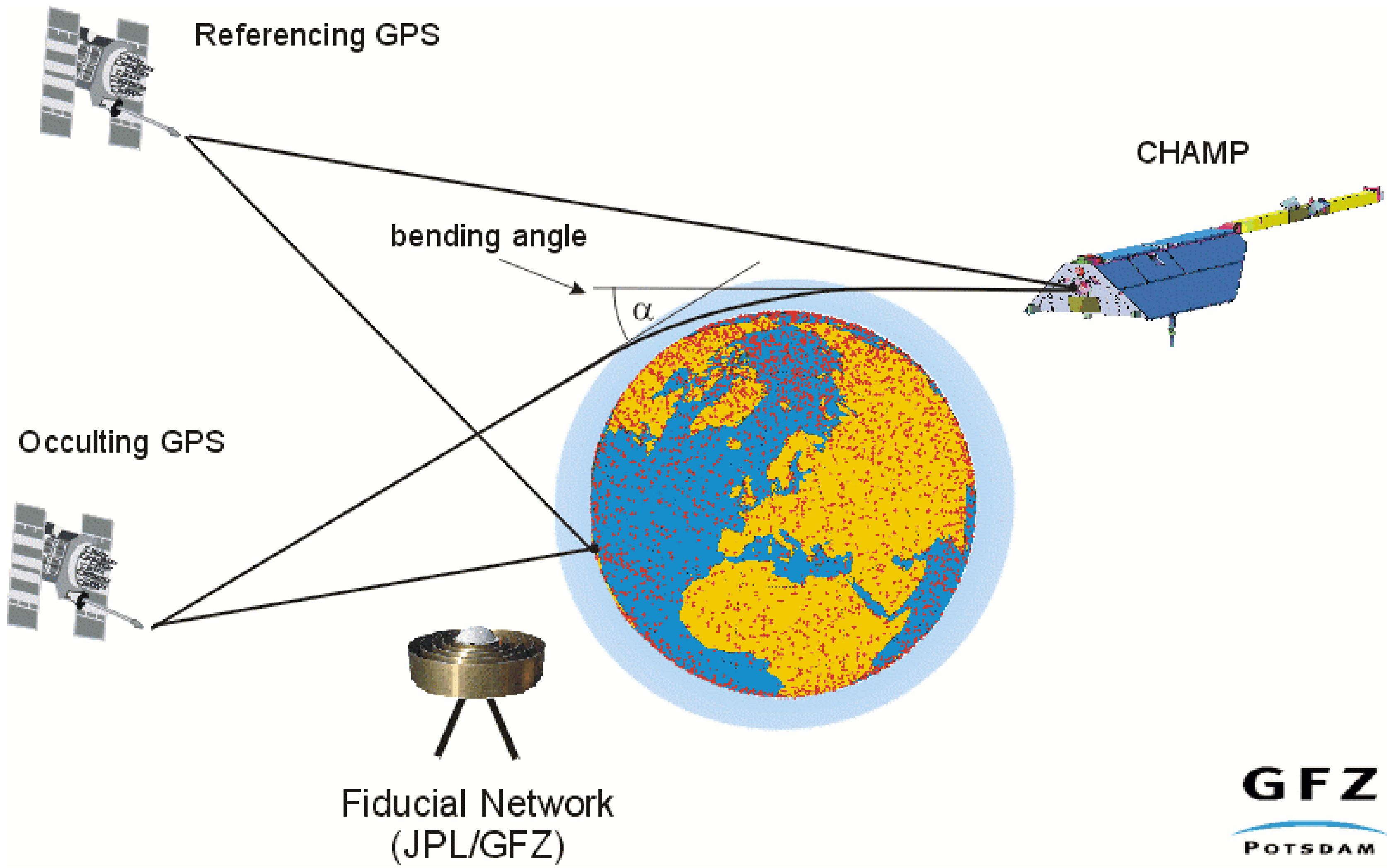
# Ionospheric Scintillation Monitoring

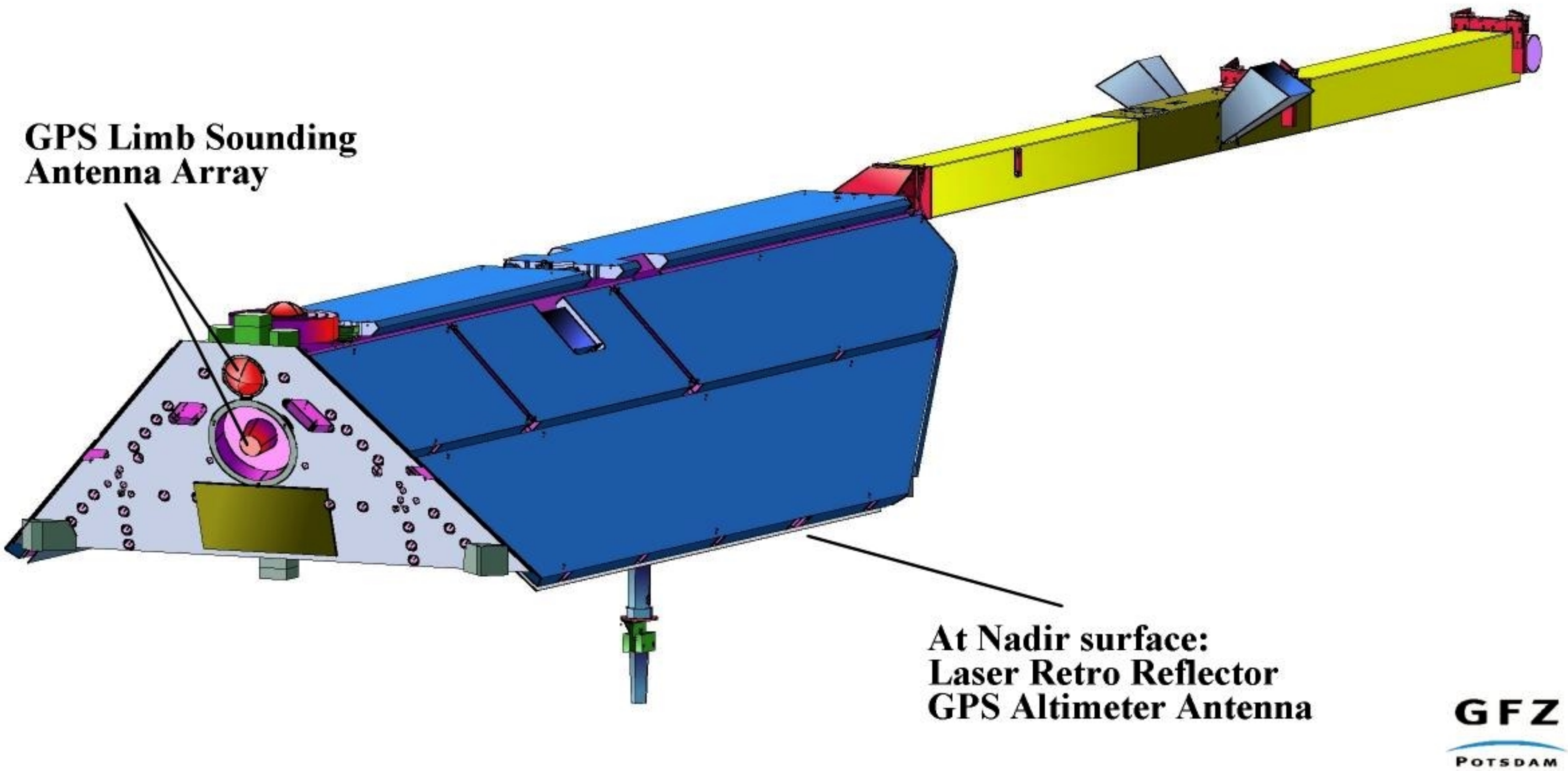



Phase scintillation at Calgary on 22 March 2001

# Spaceborne GPS Limb Sounding



# CHAMP

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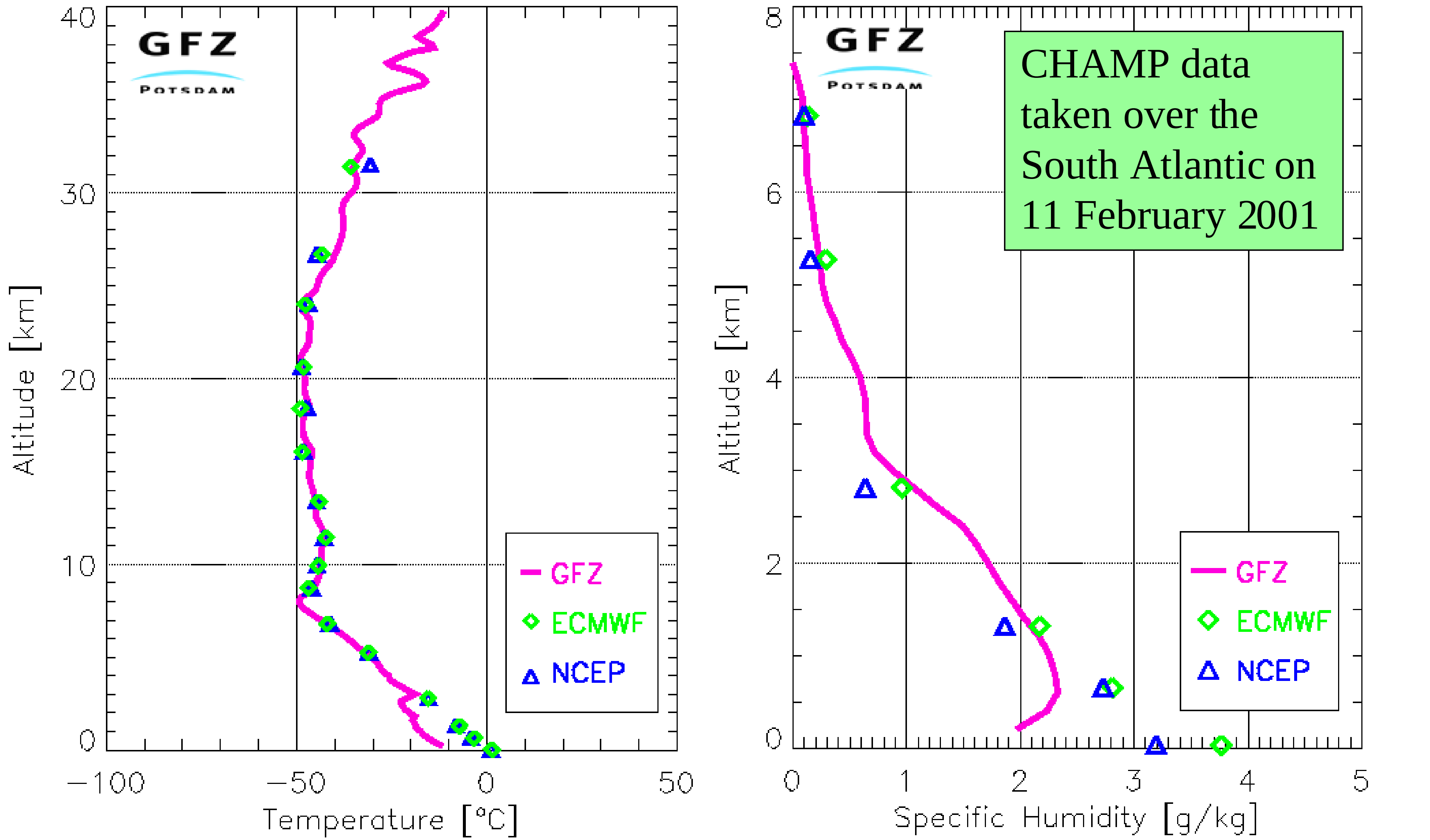
# Initial CHAMP Neutral Atmosphere Results



# Initial CHAMP Ionosphere Profile

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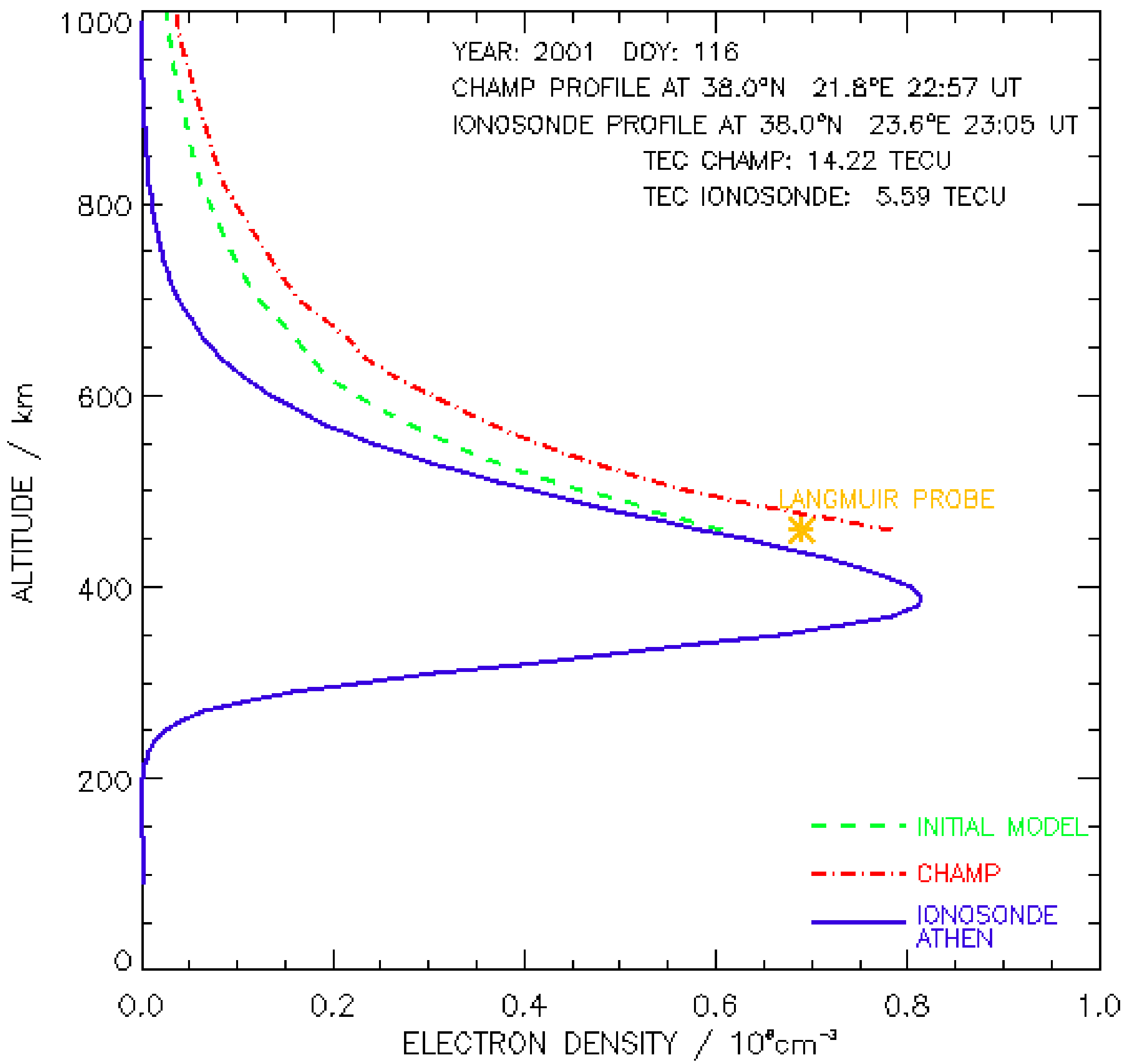


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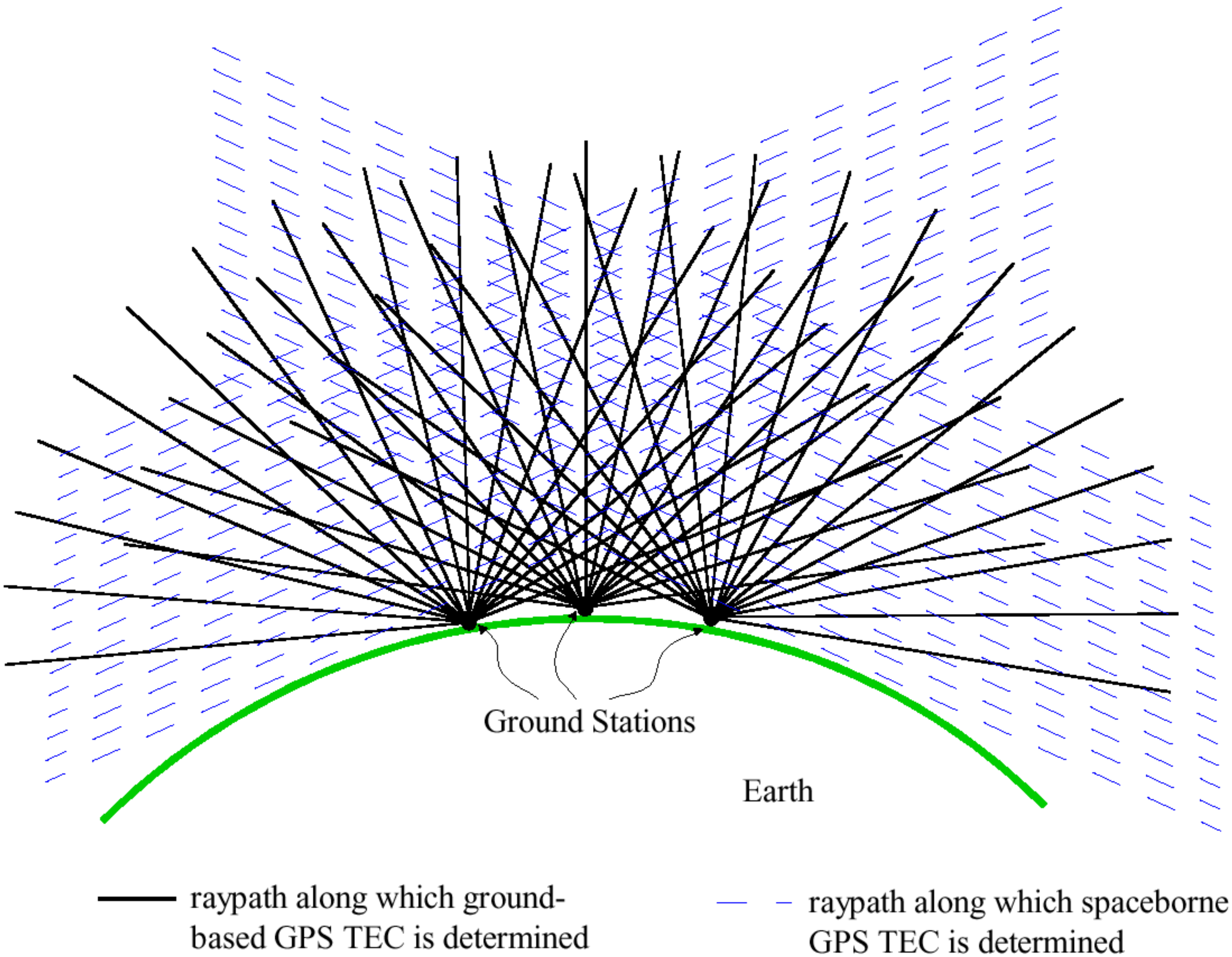
# Ionospheric Tomography

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# Concluding Remarks

• Monitoring and mapping the atmosphere is yet another application of GPS

• Regional GPS networks are being established with the expressed purpose of measuring atmospheric properties with the aim of introducing GPS-derived parameter values into weather models

• GPS techniques can contribute to our understanding of space weather

• Several GPS limb-sounding satellite missions have flown with more in the planning stages including e-POP

• GPS modernization as well as other global navigation satellite systems (GLONASS, Galileo) will further enhance radiometric techniques for studying the Earth's atmosphere

# Acknowledgements


| Slide | Organization |
|---|---|
| 3 | The Aerospace Corporation |
| 4 | Jet Propulsion Laboratory |
| 6 | Lochheed Martin Space Systems |
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| 12 | A.J. Van Dierendonck |
| 19 | University Corporation for Atmospheric Research |
| 20 | National Oceanic and Atmospheric Administration |
| 21 | GeoForschungsZentrum Potsdam |
| 22 | GeoForschungsZentrum Potsdam |
| 28 | Jet Propulsion Laboratory |
| 33 | A.J. Van Dierendonck and Q. Hua |
| 34 | GeoForschungsZentrum Potsdam |
| 35 | GeoForschungsZentrum Potsdam |
| 36 | GeoForschungsZentrum Potsdam |
| 37 | National Observatory of Athens |