GNSS Meteorology - 1

GPS Observation Equation and Obtaining the Tropospheric Excess Phase

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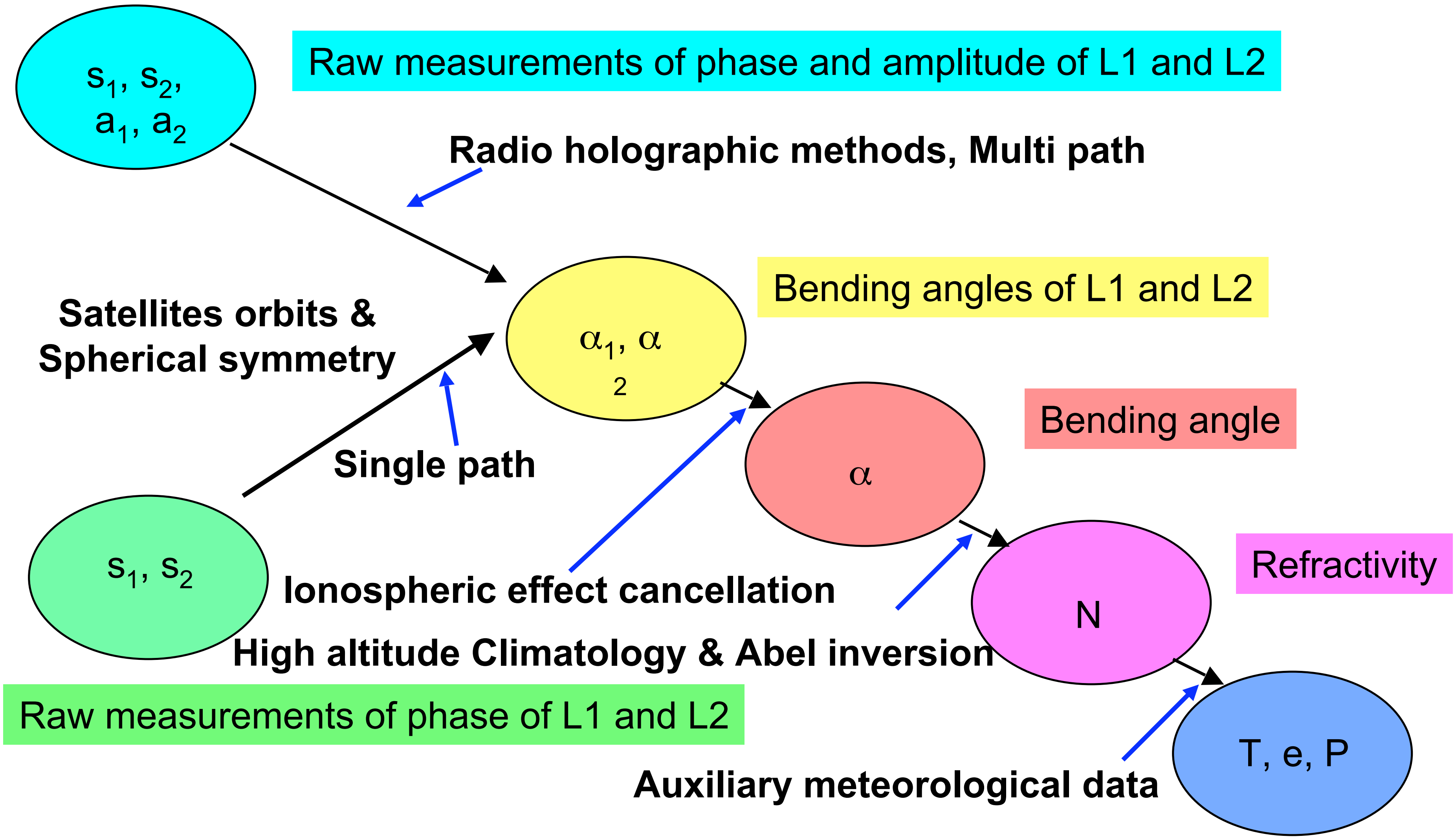
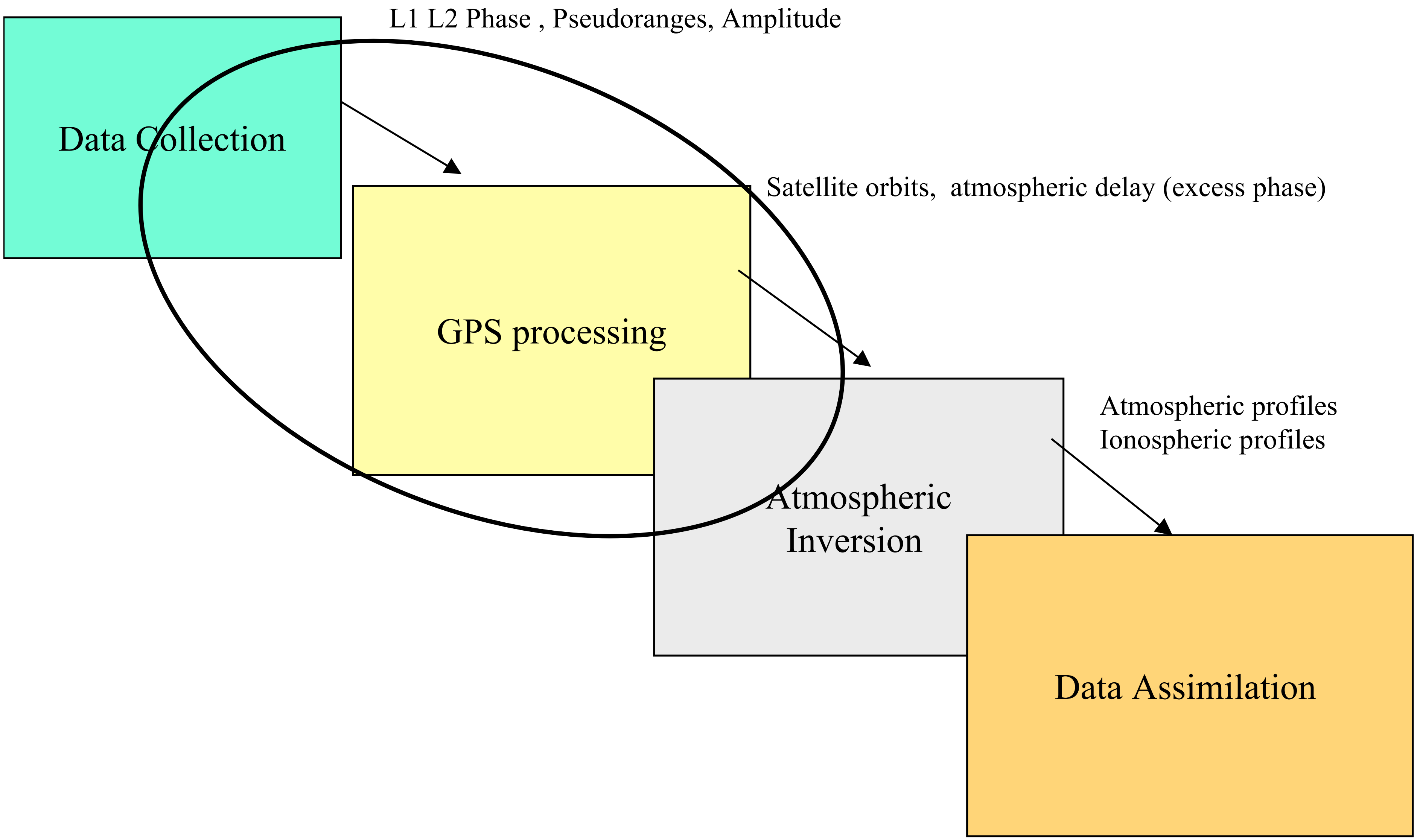
GPS radio occultation measurements & processing



GPS Meteorology Steps



Overview

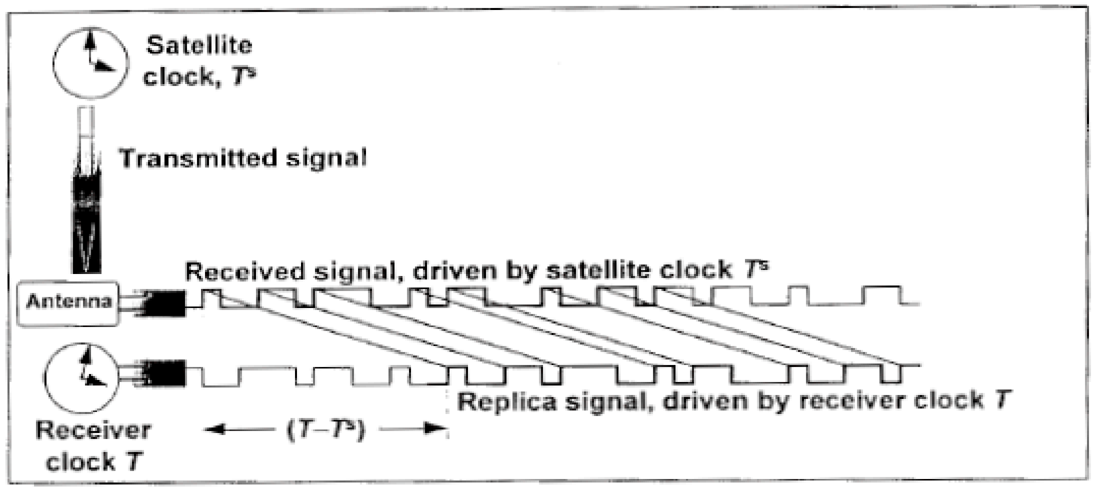
- GPS range and phase signals
- Ground Based GPS -concepts and results
- Space Based GPS - Radio Occultation
- Excess Phase Generation
  - » Clock error correction
  - » Geometric range correction
  - » Ionospheric correction
  - » Relativistic and multipath effects
  - » Tropospheric effects
- CDAAC excess phase file generation + format
- GNSS Modernization

Pseudorange/Code Measurement

- Actual **Pseudorange observation** P_r^s:

$$P_r^s = c\,(T_r - T^s)$$

- c : speed of light (in vacuum)
- No actual **"range"** (distance) because of clock errors



(Blewitt, 1996)

- Clock of receiver r reads T_r when signal is received (T_r in receiver clock time).
- Clock of satellite s reads T^s when signal is emitted (T^s in satellite clock time).
- **Measurement noise**: C/A-code $\sim$ **10 m**; P-code $\sim$ **1 m**

Pseudorange/Code Measurement (2)

$$
\begin{aligned}
P_r^s &= c\,(T_r - T^s) \\
&= c\,(t_r + \delta t_r - t^s - \delta t^s) \\
&= c\,(t_r - t^s) + c\,\delta t_r - c\,\delta t^s \\
&= \rho_r^s + c\,\delta t_r - c\,\delta t^s
\end{aligned}
$$

$t_r,\ t^s$	GPS time of reception and emission
$\delta t_r,\ \delta t^s$	Receiver and satellite clock error
ρ_r^s	Range (distance) between receiver and satellite

Simplified model for ρ_r^s: atmospheric delay missing, exactly 4 satellites, etc.

$$P_r^{s_1} = \sqrt{(x^{s_1} - x_r)^2 + (y^{s_1} - y_r)^2 + (z^{s_1} - z_r)^2} + c\,\delta t_r - c\,\delta t^{s_1} \qquad (1)$$

$$P_r^{s_2} = \sqrt{(x^{s_2} - x_r)^2 + (y^{s_2} - y_r)^2 + (z^{s_2} - z_r)^2} + c\,\delta t_r - c\,\delta t^{s_2} \qquad (2)$$

$$P_r^{s_3} = \sqrt{(x^{s_3} - x_r)^2 + (y^{s_3} - y_r)^2 + (z^{s_3} - z_r)^2} + c\,\delta t_r - c\,\delta t^{s_3} \qquad (3)$$

$$P_r^{s_4} = \sqrt{(x^{s_4} - x_r)^2 + (y^{s_4} - y_r)^2 + (z^{s_4} - z_r)^2} + c\,\delta t_r - c\,\delta t^{s_4} \qquad (4)$$

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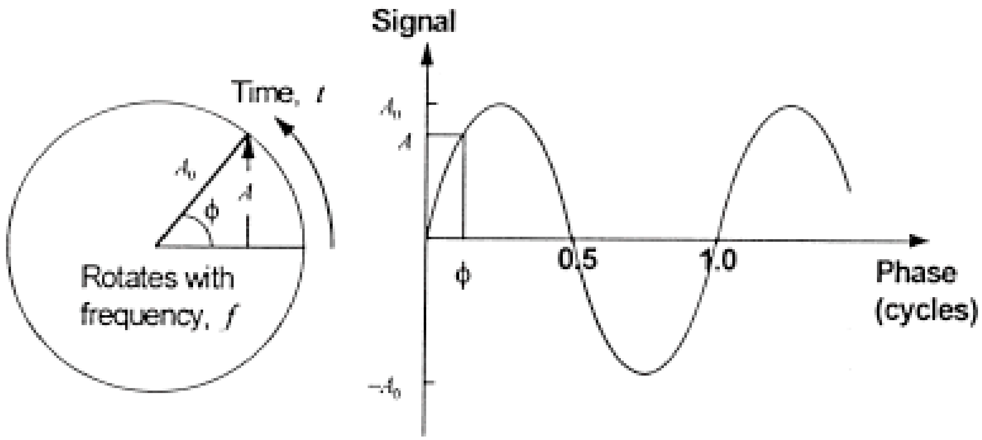
Carrier Phase Measurement



Phase Φ (in cycles) increases linearly with time t:

$$\Phi = f \cdot t$$

where f is the frequency.

The **satellite** generates with its clock the phase signal Φ^s. At emission time T^s (in satellite time) we have:

$$\Phi^s = f \cdot T^s$$

The same phase signal (e.g. a wave crest) propagates from the satellite to the receiver, but the receiver measures only the fractional part of the phase and doesn't know the **integer number of cycles** N_r^s (phase ambiguity):

$$\Phi_r^s = \Phi^s - N_r^s = f \cdot T^s - N_r^s$$

For details see "Description of GPS signal structure - How do GPS receivers work" by Larry Young
http://www.cosmic.ucar.edu/colloquium_2004/colloquium_schedule.html

M. Rothacher

Carrier Phase Measurement (2)

The **receiver** generates with its clock a **reference phase**. At time of reception T_r of the satellite phase Φ_r^s (in receiver time) we have:

$$\Phi_r = f \cdot T_r$$

The actual **phase measurement** is the difference between receiver reference phase Φ_r and satellite phase Φ_r^s:

$$\psi_r^s = \Phi_r - \Phi_r^s = f \cdot T_r - (f \cdot T^s - N_r^s) = f\,(T_r - T^s) + N_r^s$$

Multiplication with the wavelength $\lambda = c/f$ leads to the **phase observation equation** in meters:

$$\begin{aligned} L_r^s &= \lambda\,\psi_r^s = c\,(T_r - T^s) + \lambda\,N_r^s \\ &= \rho_r^s + c\,\delta t_r - c\,\delta t^s + \lambda\,N_r^s \end{aligned}$$

Difference to the pseudorange observation: **integer ambiguity term** N_r^s.

If the receiver looses the GPS signal (loss of lock), the continuous counting of the arriving wave cycles is interrupted: **jump** of an **integer** number of cycles in the phase (**cycle slip**).

Differences between Code and Phase Observation Equation

Phase:

$$L_r^s = \rho_r^s + c\,\delta t_r + c\,\delta t_{r,sys} - c\,\delta t^s - c\,\delta t^s_{sys} + \delta\rho_{trp} + \delta\rho_{ion}$$
$$+\delta\rho_{rel} + \delta\rho_{mul} + \lambda\,N_r^s + \ldots + \epsilon$$

Pseudorange/Code:

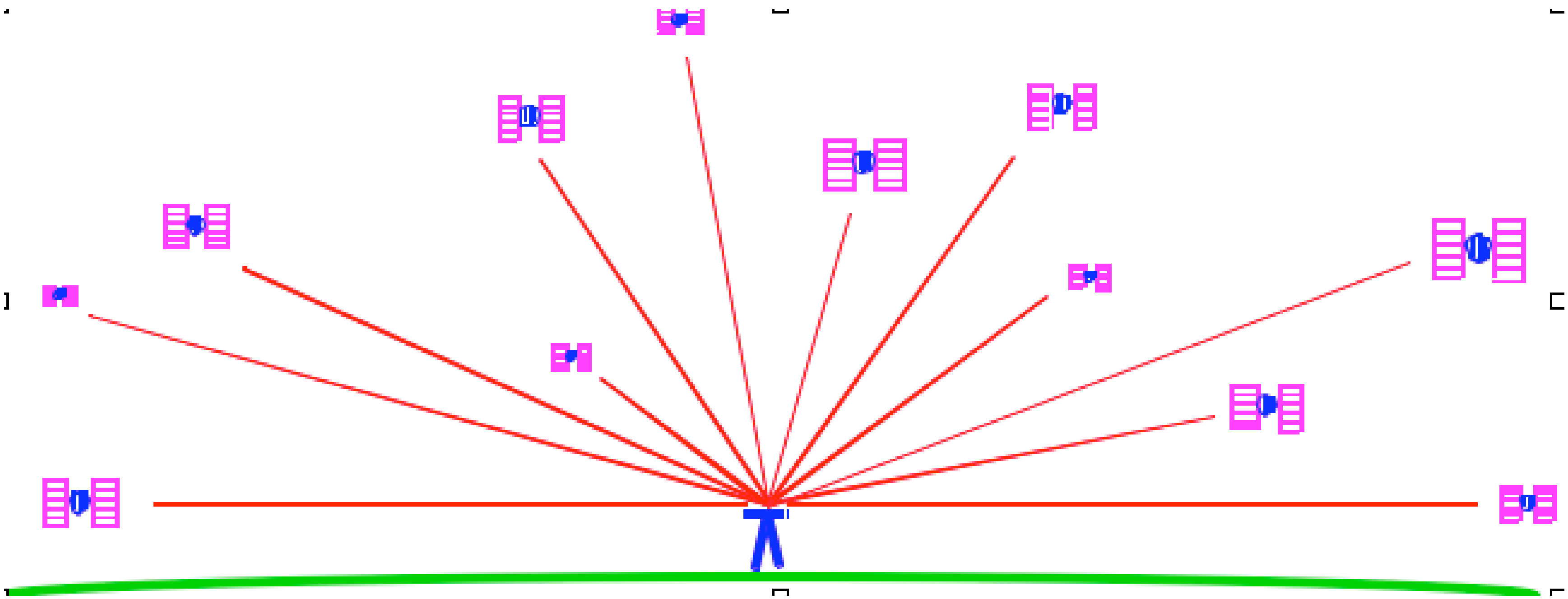
$$P_r^s = \rho_r^s + c\,\delta t_r + c\,\delta t_{r,sys} - c\,\delta t^s - c\,\delta t^s_{sys} + \delta\rho_{trp} - \delta\rho_{ion}$$
$$+\delta\rho_{rel} + \delta\rho_{mul} + \ldots + \epsilon$$

- The ionospheric refraction correction $\delta\rho_{ion}$ has the opposite sign for code measurements.
- There is no **ambiguity term** $\lambda\,N_r^s$ **for code measurements.**

The GPS Observation Equation

$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t^s_{sys} + \delta\rho_{trp} + \delta\rho_{ion} + \delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

ρ_r^s	Geometrical distance between satellite and receiver
c	Speed of light in vacuum
δt_r	Station clock correction: *receiver clocks* (time and frequency transfer)
$\delta t_{r,sys}$	Delays in receiver and its antenna (cables, electronics, . . .)
δt^s	Satellite clock correction: *satellite clocks*
$\delta t_{s,sys}$	Delays in satellite and its antenna (cables, electronics, . . .)
$\delta\rho_{trp}$	Tropospheric delay: *troposphere parameters* (meteorology, climatology)
$\delta\rho_{ion}$	Ionospheric delay: *ionosphere parameters* (atmosphere physics)
$\delta\rho_{rel}$	Relativistic corrections (Special and General Relativity)
$\delta\rho_{mul}$	Multipath, scattering, bending effects
λ	Wavelength of the GPS signal (L_1 or L_2)
N_r^s	Phase ambiguity: *ambiguity parameters* (ambiguity resolution)
ϵ	Measurement error



•GPS observes the "travel time" of the signal from the transmitters to the receiving antenna

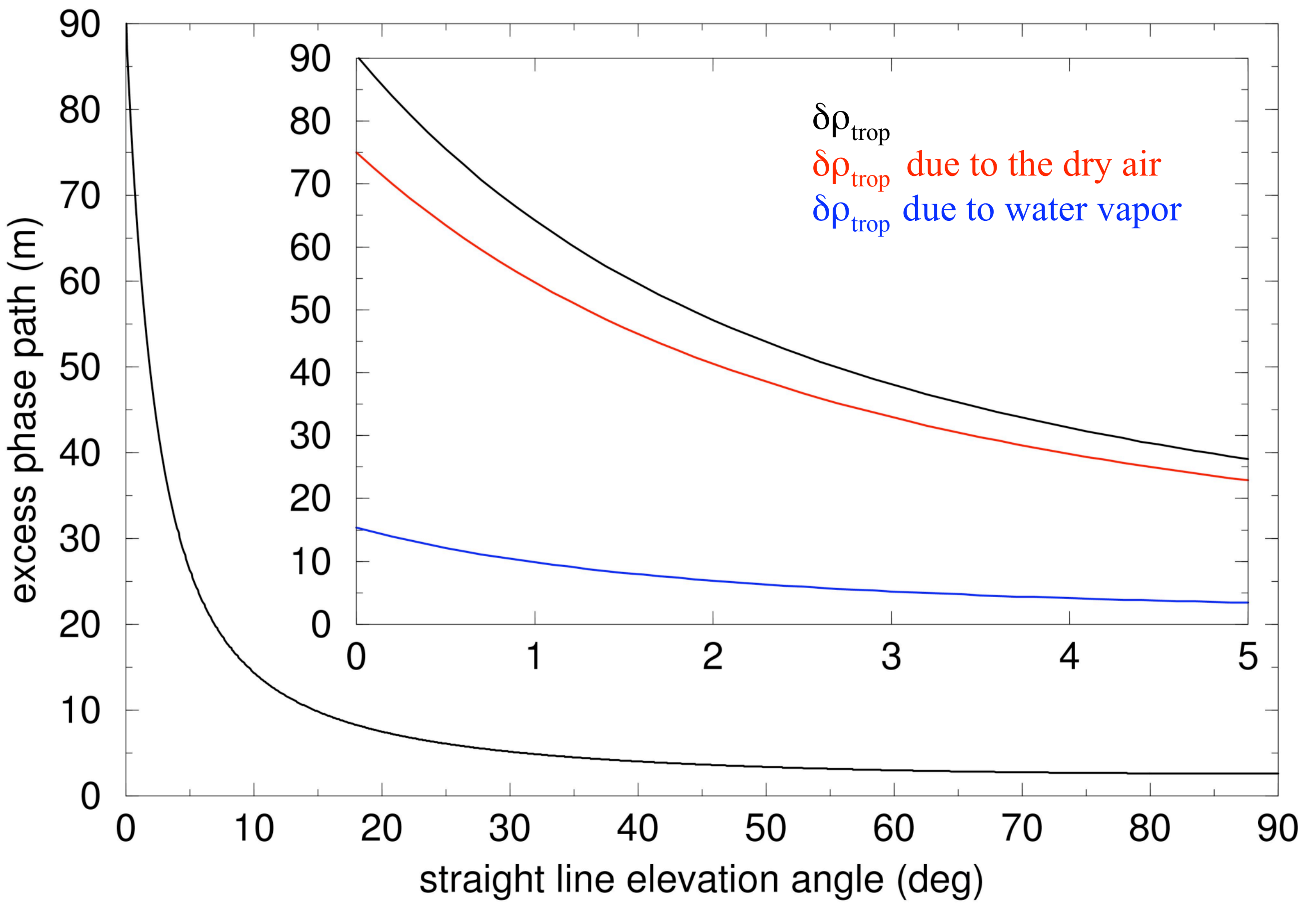
•It is possible to determine that part of the travel time due to the atmosphere: "atmospheric delay"

•From the "atmospheric delay" of the GPS signal the "zenith tropospheric delay" and "zenith precipitable water vapor" can be determined

$$\delta\rho_{trp} = L_E - G = \int_L n(s)\, ds - G = \int_L (n(s) - 1)\, ds + (S - G)$$

"*(S-G)*" is the effect of bending

Example size of tropospheric delay from CIRA+Q model atmosphere



Total zenith delay ~2.2 m

Delay at 5 degrees elevation is ~ 25 m

GPS phase measurement is precise to ~0.001 m

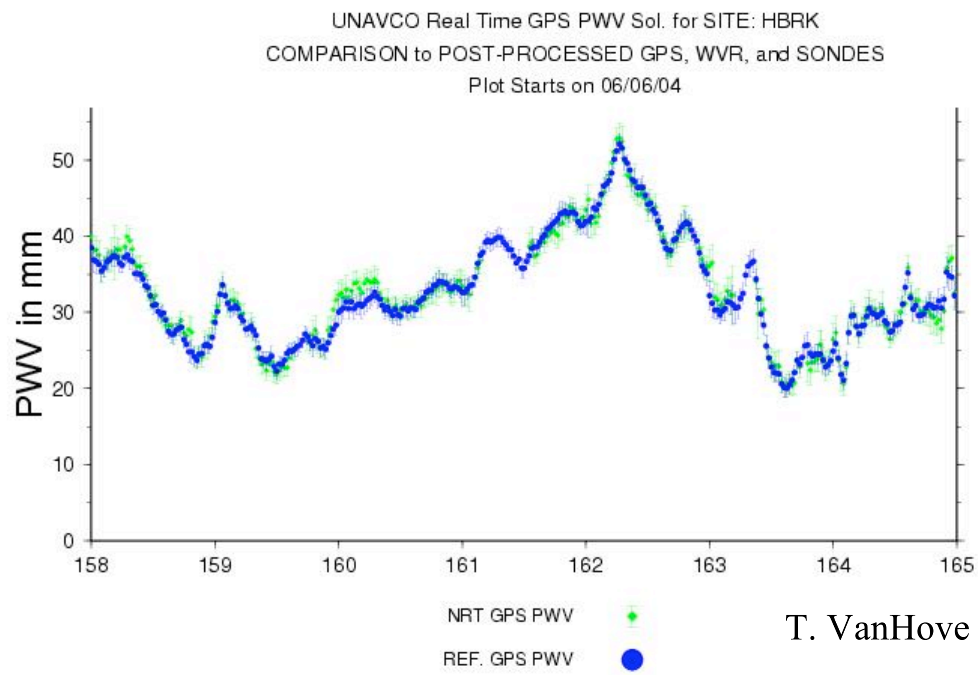
Orbits

GPS meteorology places some special requirements on the GPS orbits:

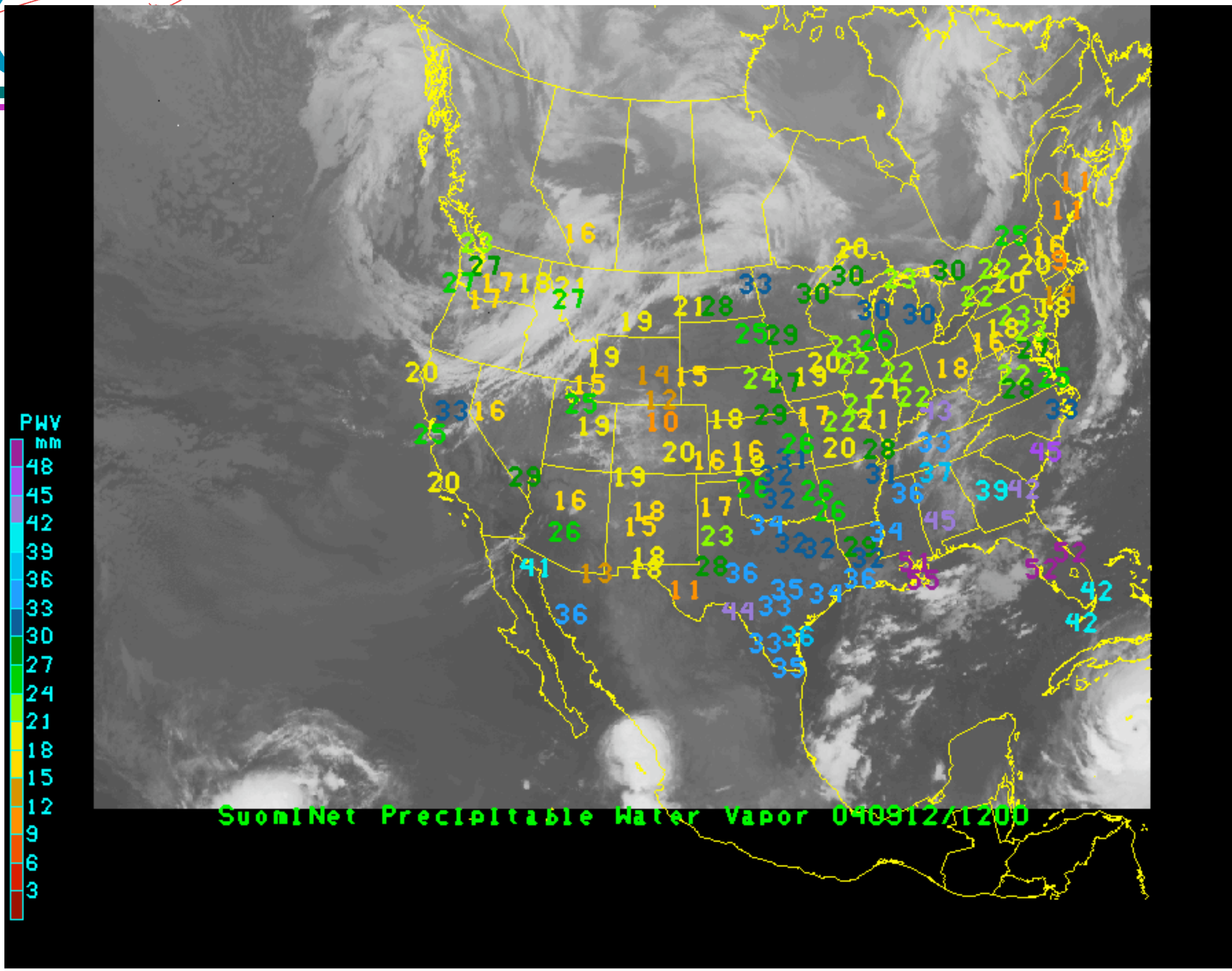
(a) Orbits need to be accurate (~10 cm orbit of IGU orbits causes only small tropospheric error)
(b) Orbits need to be available in real-time
(c) IGU orbits need to be tested for outliers. Orbit maneuvers cannot be predicted.

Estimation of how much the orbit error contributes to the tropospheric estimation error has not been done (to my knowledge and could be an interesting project.

Using recent 6-hour IGU orbits there is very little difference in the PWV estimates compared to IGS



T. VanHove


SuomiNet Precipitable Water Vapor 040912/1200
PWV
mm
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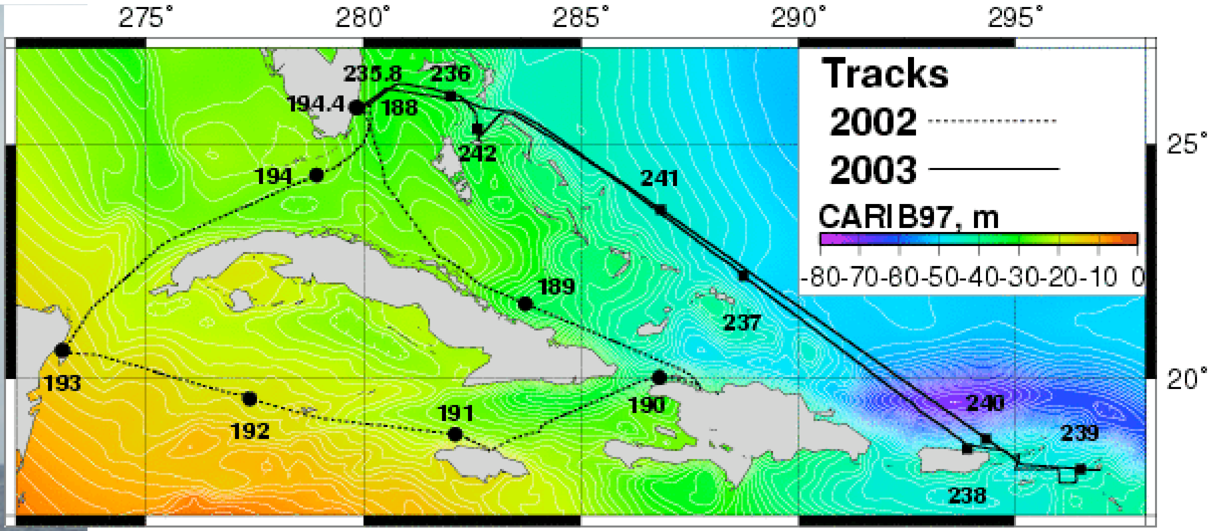
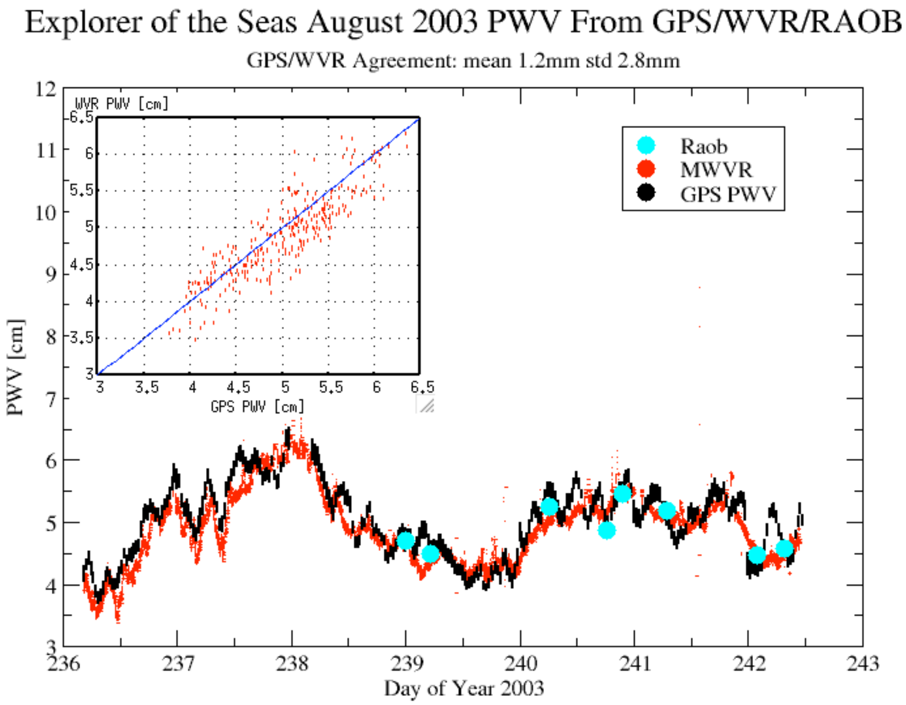
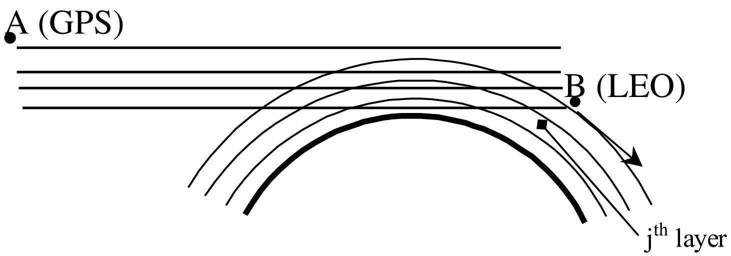
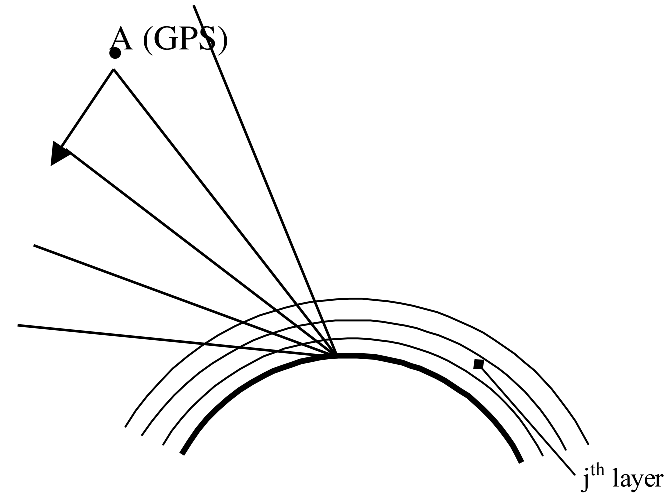


GPS Meteorology at Sea



Radio Occultation and Ground based GPS meteorology





Space-based: Profiling

Onion-peeling one layer at a time - thus this problem is well-posed and can be solved with the Abel transform

Total phase delay effect up to 3 km (geometric amplification)

Takes 1-2 minutes for entire profile

Bending angle computed from Doppler rate

Refractivity profile computed from bending

Global coverage

Ground-based: Integrated Delay

All layers affect each observation - good for estimation of integrated quantities ill-posed for profiling

Total phase effect 2.5m zenith, ~100 m at horizon

Takes 30 minutes for GPS to set 15 degrees

Total delay along rays can be determined

Delay due to water vapor can be determined **

Bending angle can be computed from Doppler rate

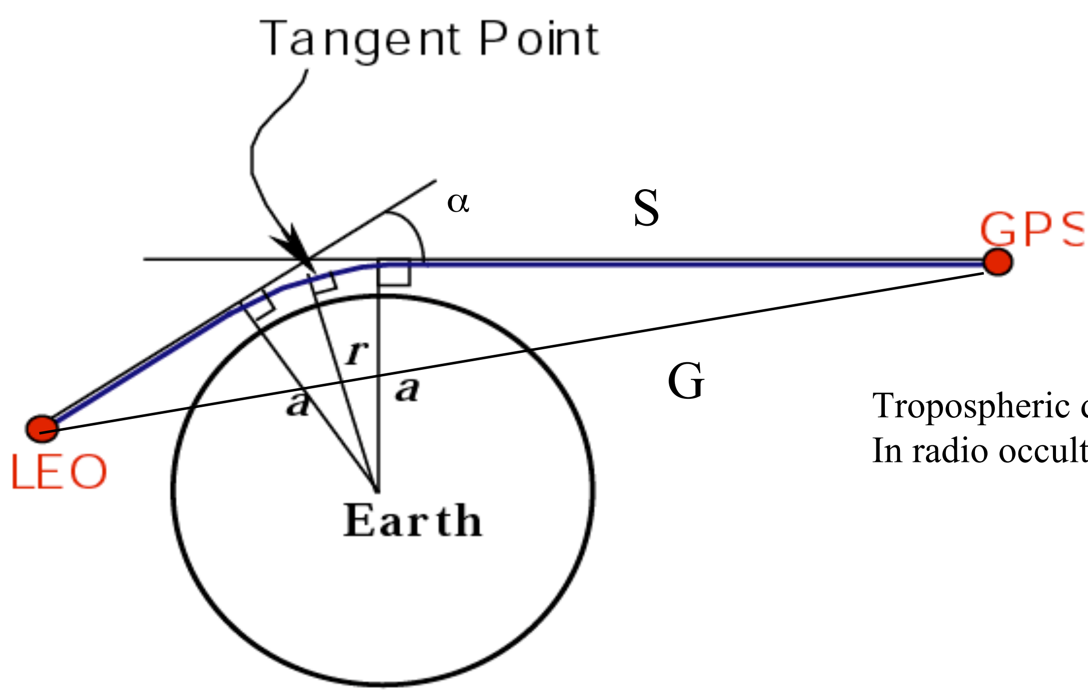
Application in the oceans is challenging

$$L_E = \int_L n(s)\, ds$$

L_E is the path length along the path L and $n(s)$ is the index of refraction which is a function of position s along the path L

$$\delta\rho_{trp} = L_E - G = \int_L n(s)\, ds - G = \int_L (n(s) - 1)\ ds + (S - G)$$

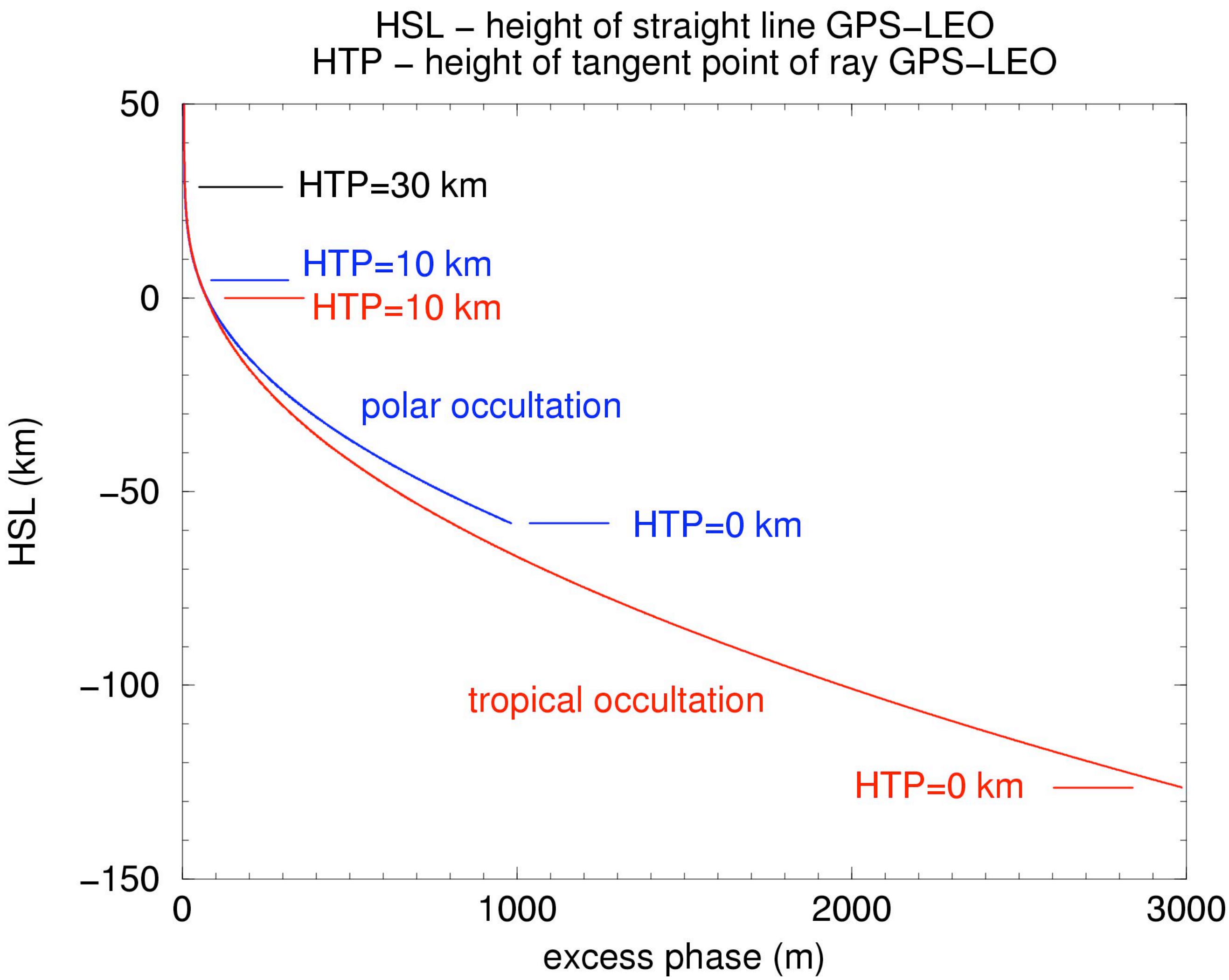
Bending effect is $(S\text{-}G)$ and refractivity is defined as $N = (n-1)\ 10^6$



Tropospheric delay
In radio occultation

$$\delta\rho_{trp} = L_E - G = \int_L n(s)\, ds - G = \int_L (n(s) - 1)\, ds + (S - G)$$

"*(S-G)*" is the effect of bending



Excess phase starts at 0 meters

Reaches about 1000 m in dry polar conditions

Reaches about 3000 m in moist tropical conditions

There are several ways to obtain $\delta\rho_{trp}$ from the GPS observations

$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta\rho_{trp} + \delta\rho_{ion}$$
$$+\delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

(1) Remove all other components from $L^s{}_r$
This is done for estimating the "atmospheric delay for radio occultation observations where all other components must be known from separate processing steps

(2) Model it and estimate as a parameter
This is done for ground based GPS and will be explained in more detail in this lecture

Ionospheric free linear combination

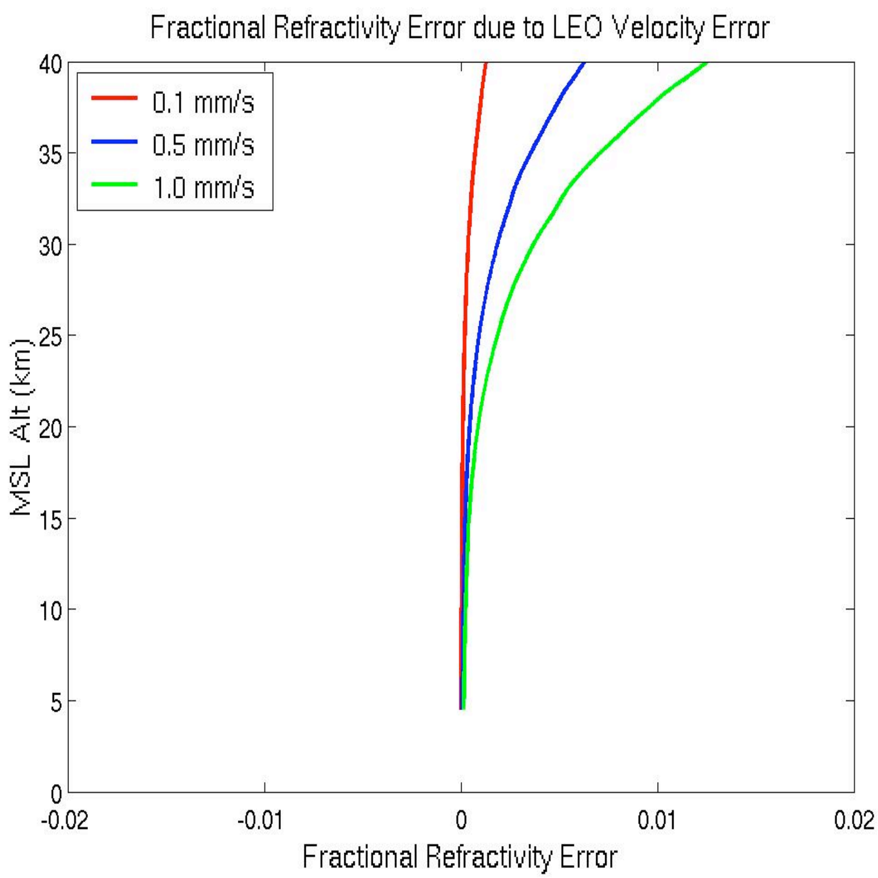
Form double difference

$$\frac{d(\delta_{trp})}{dt}$$

Radio occultation is only sensitive to rate of change

Orbit and Clock Drift Error Impact on RO Retrieval Accuracy

- Velocity errors added to excess atmospheric phase delay of actual CHAMP occultation
- Perform RO inversions and compare with actual retrieval
- Retrievals used Statistical Optimization of bending angles which reduces impact of orbit error.



•To keep refractivity error < 0.2% up to 40 km excess Doppler must be good to 0.2 mm/sec

•This 0.2% error is comparable to the lowest level of uncalibrated ionospheric noise at 40 km

•At lower altitudes this requirement is much less strict

Elimination of Clock effects

$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta\rho_{trp} + \delta\rho_{ion}$$
$$+\delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

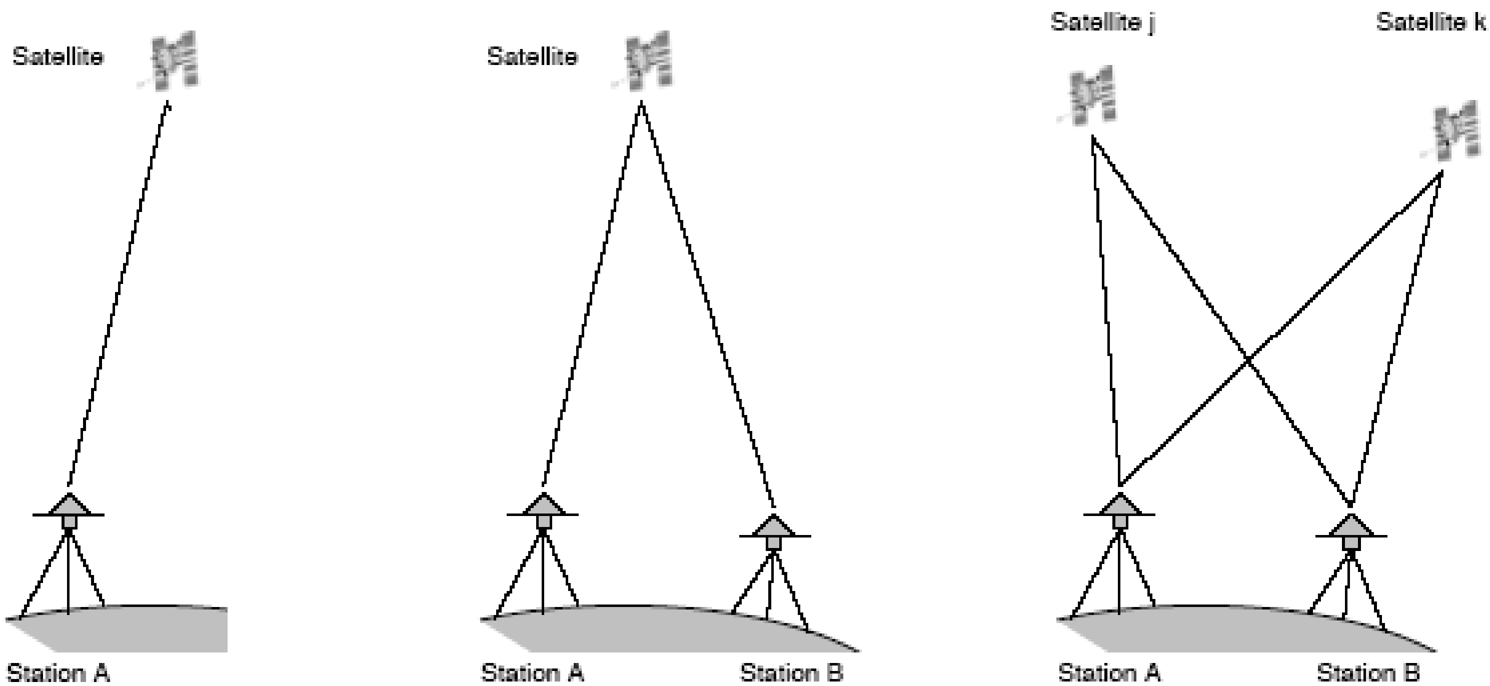
•To meet the 0.2 mm/sec requirement - clocks good to better than 6 parts in 10^{13} are needed

•Typical GPS receiver clock stabilities are generally much worse

•Even GPS satellite clocks are generally not that good

•Therefore - clock errors need to be differenced or clocks need to be estimated as parameters

Zero, Single, Double Difference



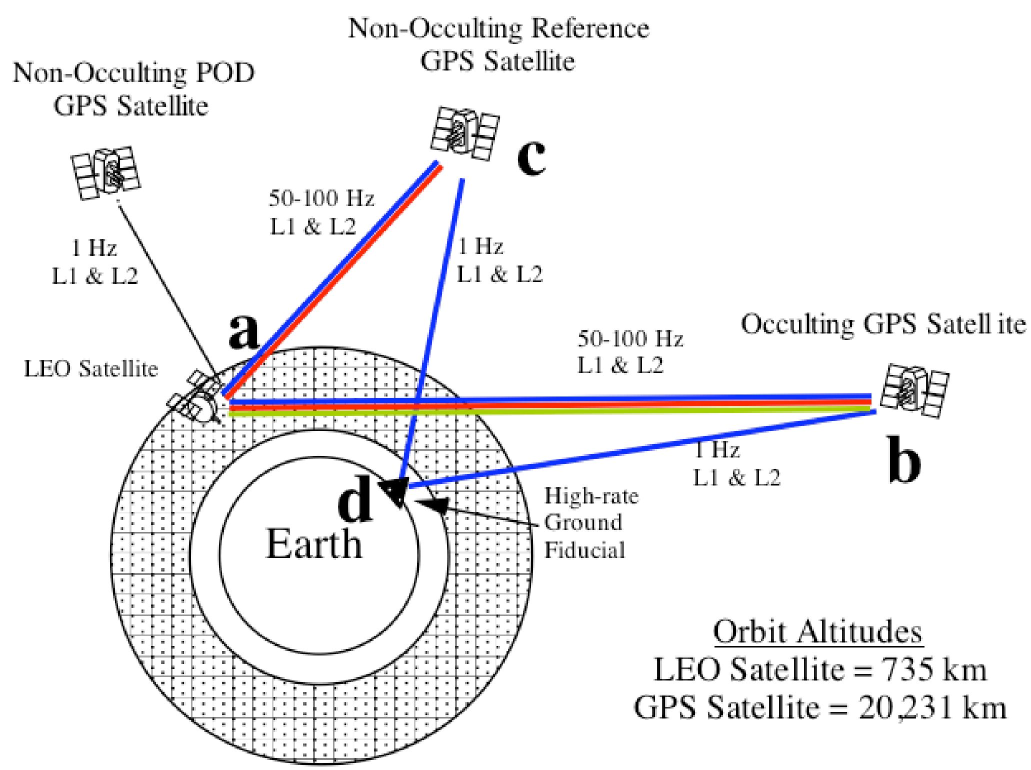
- **Zero** differences

- **Single** differences
- Between 2 **sites**
- Elimination: **satellite clock** errors

- **Double** differences
- Between 2 **satellites**
- Elimination: **receiver clock** errors

Computation of excess atmospheric delay

- Double Difference
  - Advantage: Station clock errors removed, satellite clock errors mostly removed (differential light time creates different transmit times), general and special relativistic effects removed
  - Problem: Fid. site MP, atmos. noise, thermal noise
- Single Difference
  - LEO clock errors removed
  - use solved-for GPS clocks
  - Main advantage: Minimizes double difference errors



Double-Difference Processing Description

Neglecting ambiguities, multipath, and thermal noise, the observed occulting-link L1 phase path and the non-occulting L3 (ionosphere-free) phase paths can be written as

$$L1_a^b(t_r) = \rho_a^b(t_r) + c\cdot\delta t_a(t_r) - \delta t_{a,rel}(t_r) - c\cdot\delta t^b(t_r - \tau_a^b) + \delta t_{rel,1}^b(t_r - \tau_a^b) + \delta\rho_{a,ion}^b(t_r) + \delta\rho_{a,trop}^b(t_r) + \delta\rho_{a,rel,2}^b(t_r)$$

$$L3_a^c(t_r) = \rho_a^c(t_r) + c\cdot\delta t_a(t_r) - \delta t_{a,rel}(t_r) - c\cdot\delta t^c(t_r - \tau_a^c) + \delta t_{rel,1}^c(t_r - \tau_a^c) + \delta\rho_{a,rel,2}^c(t_r)$$

$$L3_d^c(t_r) = \rho_d^c(t_r) + c\cdot\delta t_d(t_r) - \delta t_{d,rel}(t_r) - c\cdot\delta t^c(t_r - \tau_d^c) + \delta t_{rel,1}^c(t_r - \tau_d^c) + \delta\rho_{d,rel,2}^c(t_r) + \delta\rho_{d,trop}^c(t_r)$$

$$L3_d^b(t_r) = \rho_d^b(t_r) + c\cdot\delta t_d(t_r) - \delta t_{d,rel}(t_r) - c\cdot\delta t^b(t_r - \tau_d^b) + \delta t_{rel,1}^b(t_r - \tau_d^b) + \delta\rho_{d,rel,2}^b(t_r) + \delta\rho_{d,trop}^b(t_r)$$

where $\delta t_{d,rel}(t_r)$ and $\delta t_{a,rel}(t_r)$ are the combined oscillator effects of general and special relativity at the ground station (constant) and LEO receiver, respectively, and ρ is the geometric distance and τ is the signal travel time. The desired L1 excess phase path is shown in **GREEN**, and quantities computed from previous POD and ZTD estimates are shown in **BLUE**.

Forming the Double-Difference and subtracting known quantities leaves the desired excess phase path and an error term of small magnitude due to incomplete cancellation of the GPS satellite clocks because each observation has a slightly different signal transmission time.

$$\Delta\Delta L1_a^b = \delta\rho_{a,ion}^b(t_r) + \delta\rho_{a,trop}^b(t_r) - c\cdot(\delta t^b(t_r - \tau_a^b) - \delta t^b(t_r - \tau_d^b)) + c\cdot(\delta t^c(t_r - \tau_a^c) - \delta t^c(t_r - \tau_d^c))$$

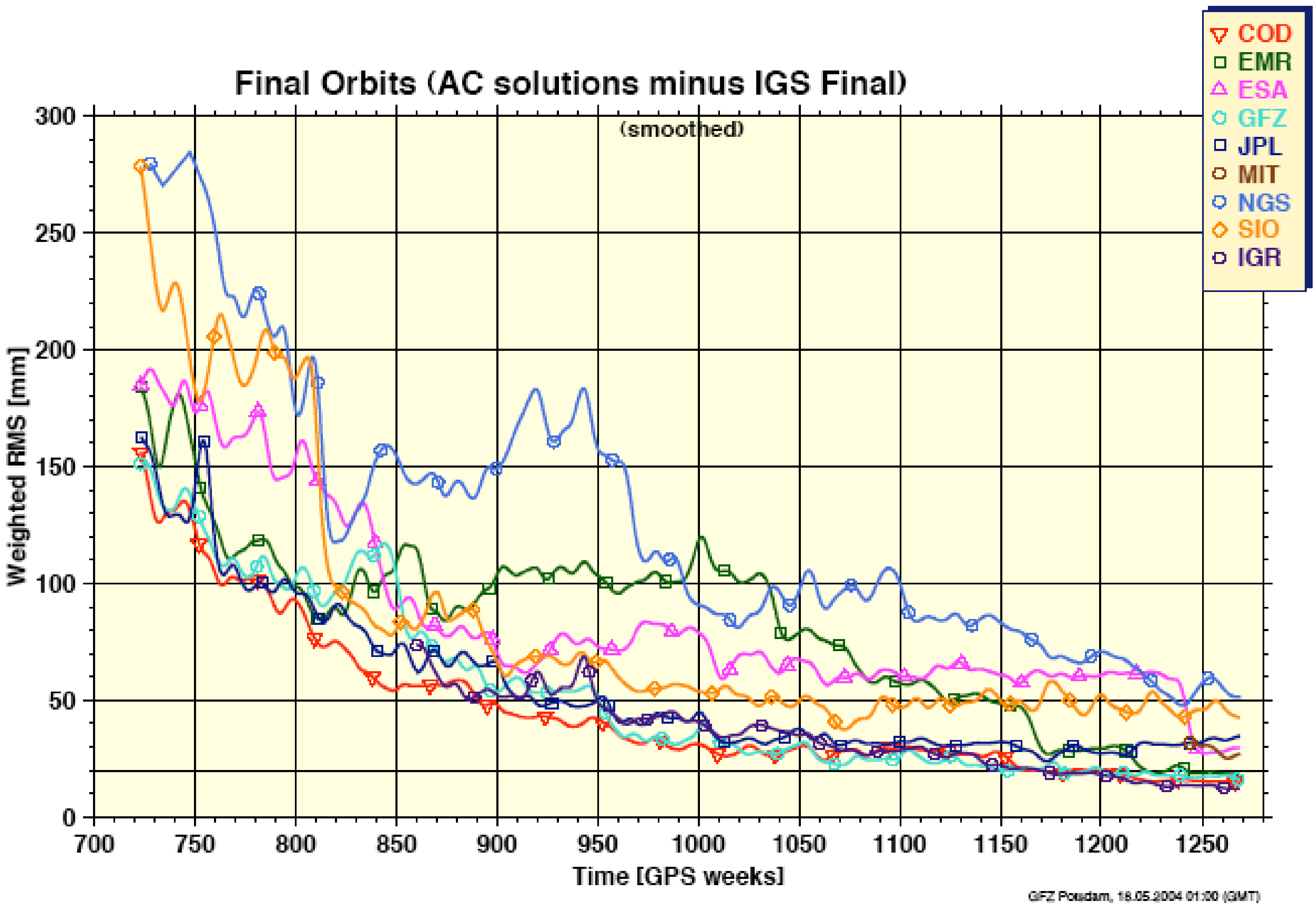
Effect is small and it’s change is generally negligible

Elimination of geometric effects

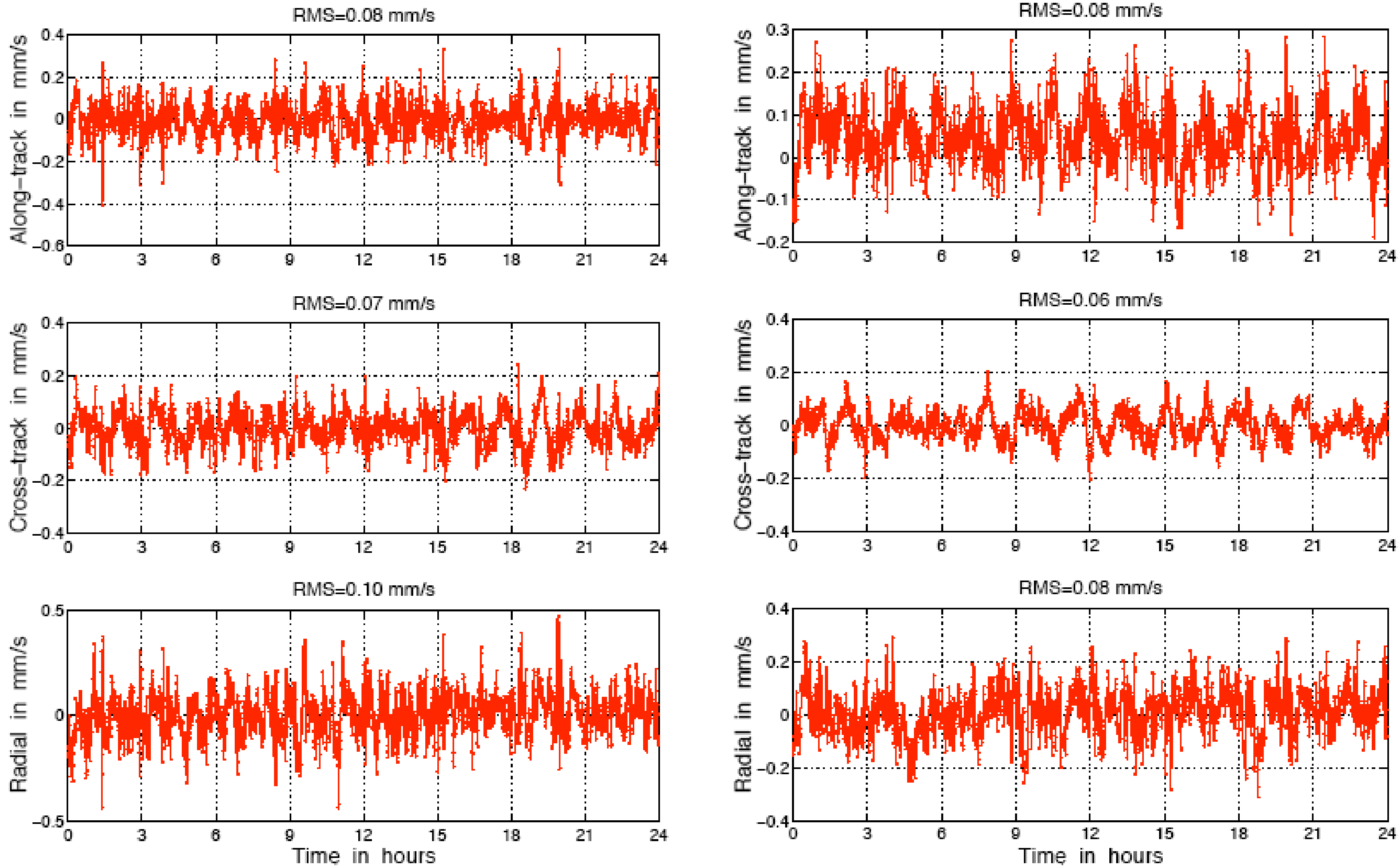
$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t^s_{sys} + \delta\rho_{trp} + \delta\rho_{ion}$$
$$+\delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

- To meet the 0.2 mm/sec requirement - precision orbit determination is required
- GPS orbits and LEO orbits must be determined
- Velocity error projected on the "LEO to occulting GPS vector" is critical

Quality of IGS Final Orbits



Comparison of CHAMP Velocities From Different Institutions



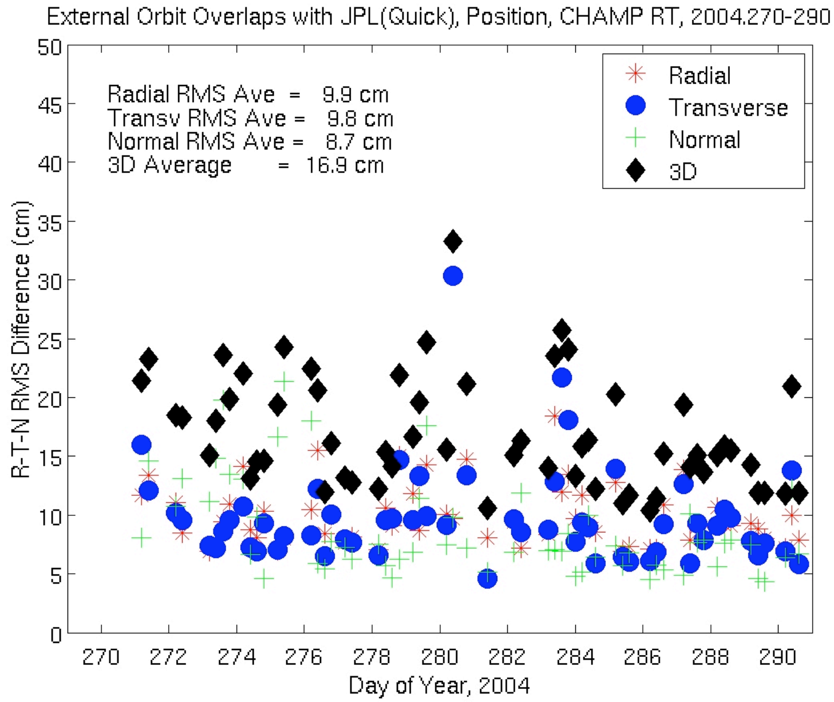
CSR–TUM Velocities

GFZ–TUM Velocities

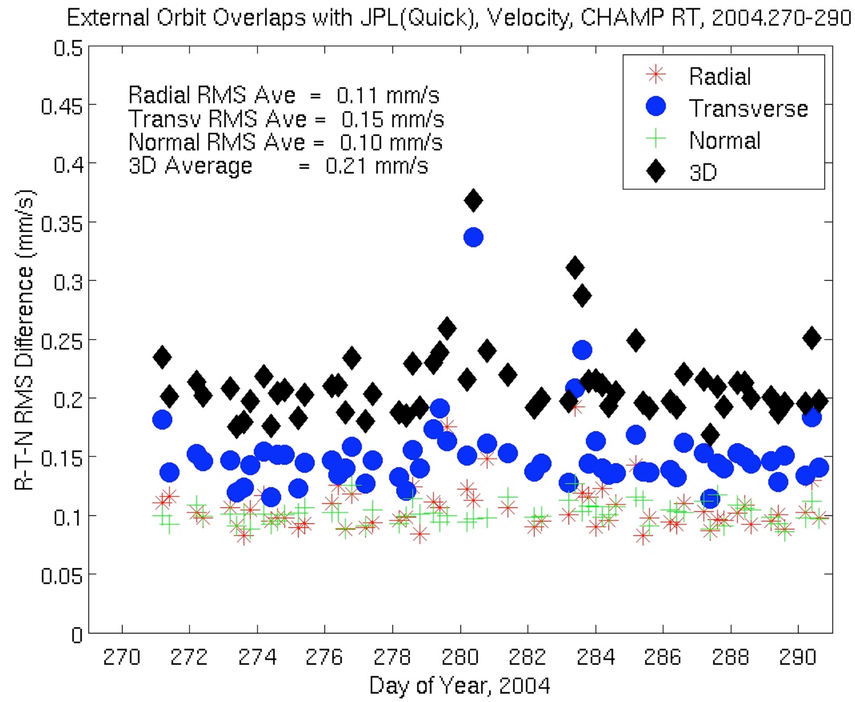
Near Real-Time CHAMP Orbit Overlap Results (vs. JPL) with Bernese v5.0

Arcs for every CHAMP data dump

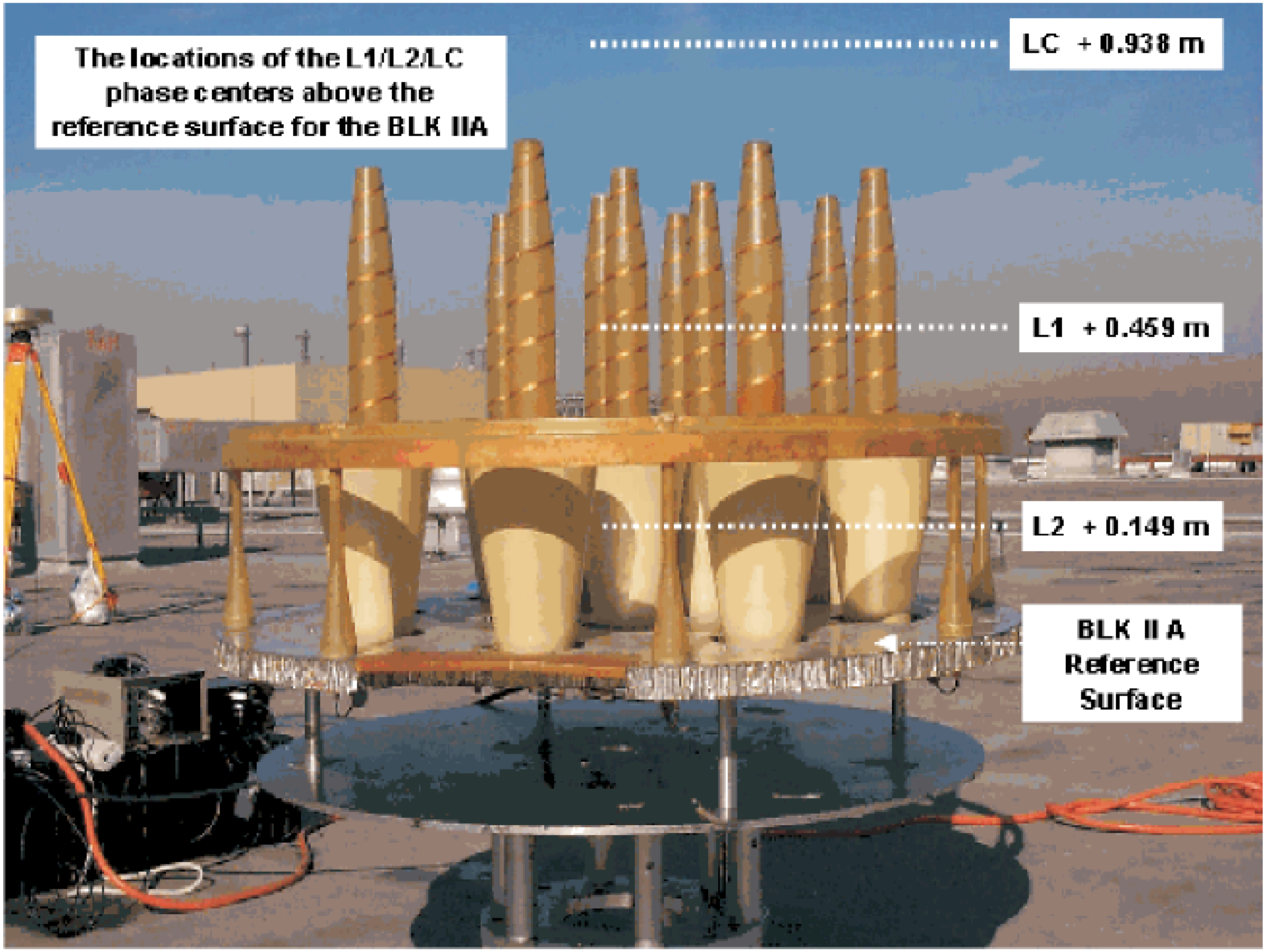
Position



Velocity



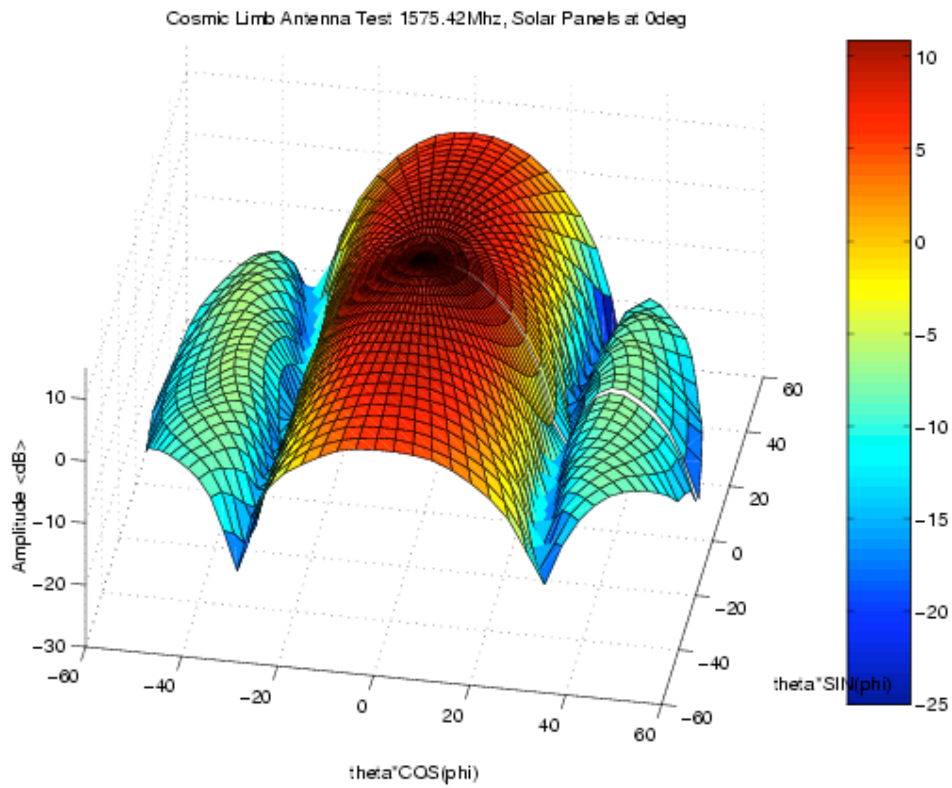
GPS Satellite Antenna Offsets



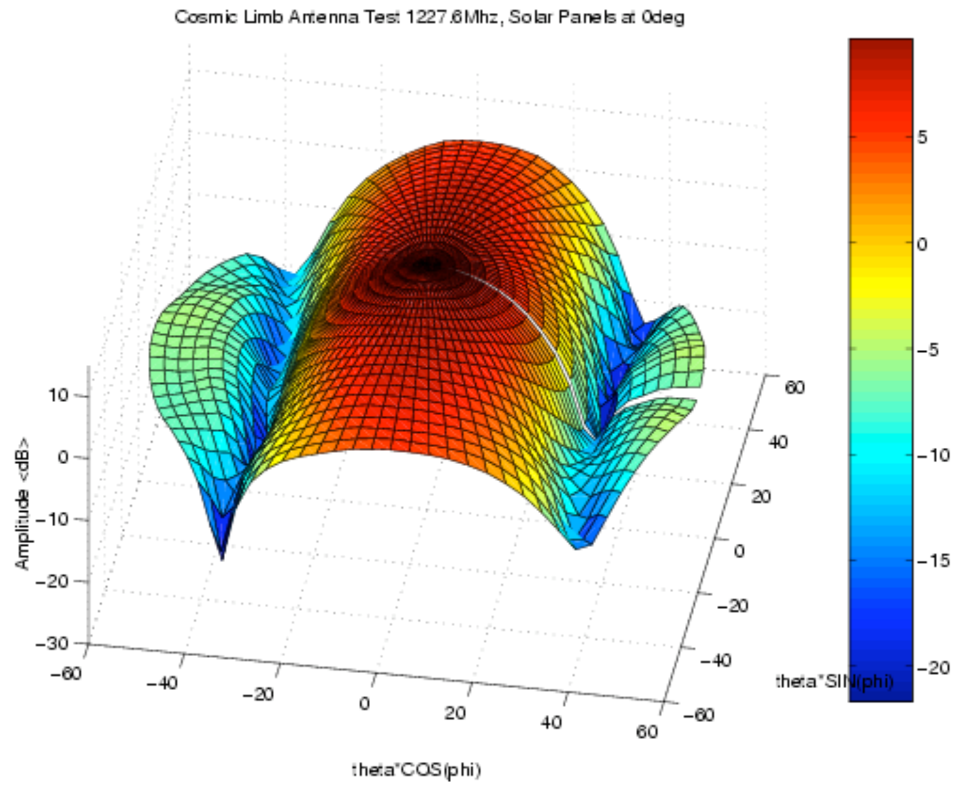
(Gerry Mader, NGS)

COSMIC GPS Limb Antenna Gain
SAD=0deg

L1

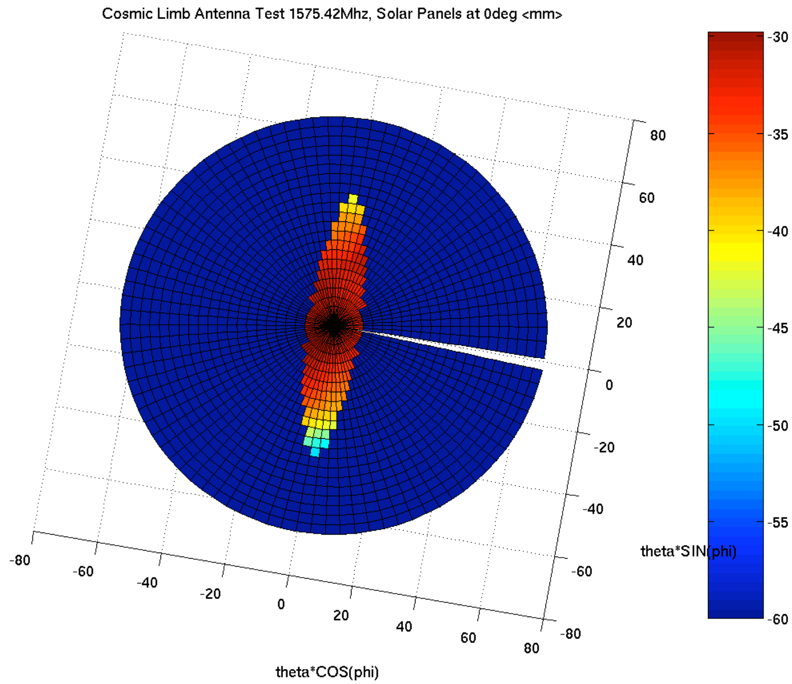


L2

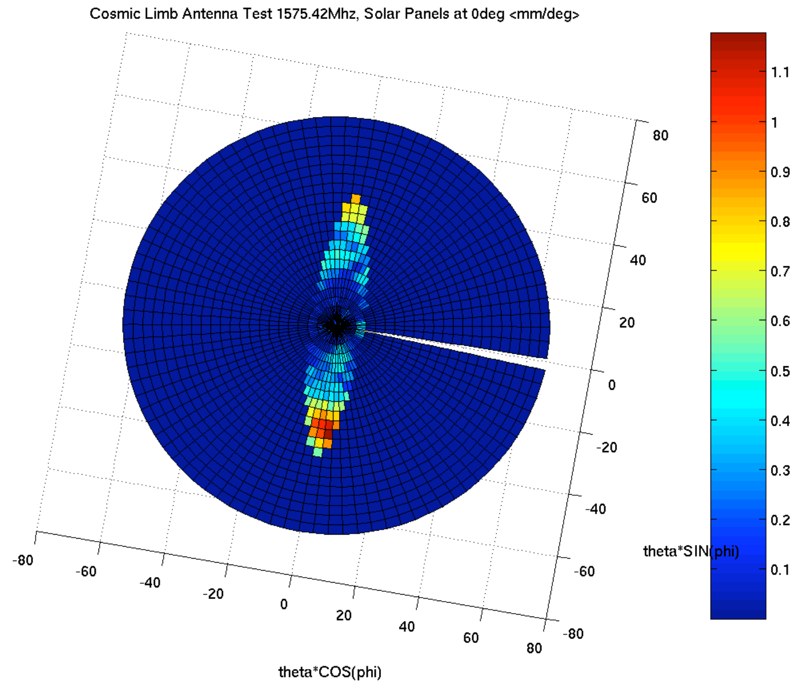


COSMIC GPS Limb Antenna
L3 Phase (FOV=7 X 40)
Solar panel orientation(0)

L3 Phase (mm)



Gradient Magnitude(mm/deg)



Elimination of ionospheric effects

$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta\rho_{trp} + \delta\rho_{ion}$$
$$+\delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

- To meet the 0.2 mm/sec requirement - dual frequency receivers are required
- Ionospheric effect on phase can reach 100 meters and can change rapidly
- Ionosphere needs to be calibrated on all links (on 4 links for double difference)
- Different ionospheric corrections are applied on occulting and reference links
- Ionospheric error remains the limiting error source for stratospheric temperatures

Ionosphere-Free Linear Combination L_c

The coefficients of the ionosphere-free LC are:

$$\kappa_{1,c} = \frac{f_1^2}{f_1^2 - f_2^2}, \quad \kappa_{2,c} = -\frac{f_2^2}{f_1^2 - f_2^2}$$

and we get:

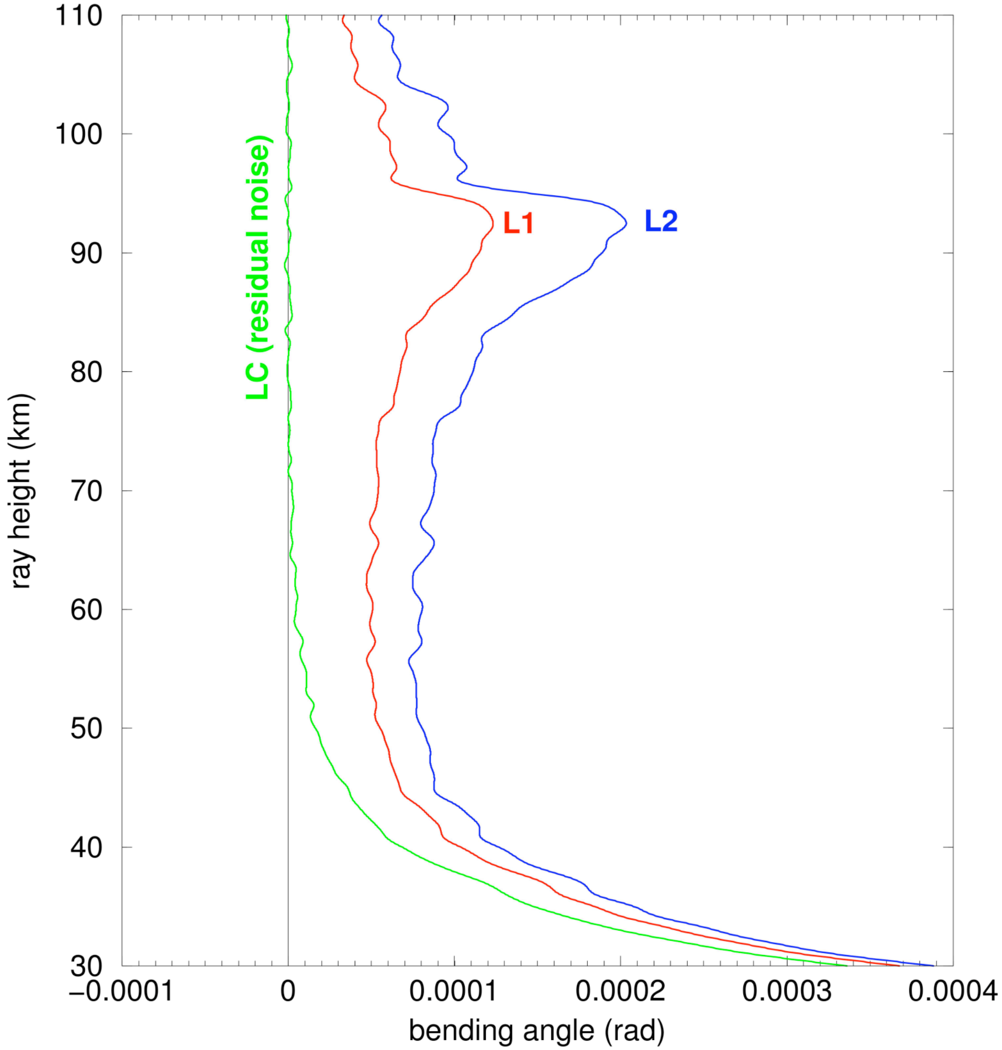
$$\begin{aligned}
L_c &= \kappa_{1,c} L_1 + \kappa_{2,c} L_2 \\
&= \kappa_{1,c}(\rho' + I_1 + \lambda_1 N_1) + \kappa_{2,c}(\rho' + \frac{f_1^2}{f_2^2} I_1 + \lambda_2 N_2) \\
&= \rho' + (\kappa_{1,c}\lambda_1 N_1 + \kappa_{2,c}\lambda_2 N_2) \\
P_c &= \kappa_{1,c} P_1 + \kappa_{2,c} P_2 \\
&= \rho'
\end{aligned}$$

Ionospheric calibration on the reference link

M. Rothacher

Ionospheric calibration on the occulting link

Is performed by linear combination of L1 and L2 bending angles at the same impact parameter (by accounting for the separation of ray tangent points).



$$\alpha(a) = \frac{f_1^2\alpha_1(a) - f_2^2\alpha_2(a)}{f_1^2 - f_2^2}$$

α bending angle

a impact parameter

Effect of the small-scale ionospheric irregularities with scales comparable to ray separation is not eliminated by the linear combination, thus resulting in the residual noise on the ionospheric-free bending angle.

Elimination of multipath effects

$$
\begin{aligned}
L_r^s \;=\; & \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta\rho_{trp} + \delta\rho_{ion} \\
& + \delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon
\end{aligned}
$$

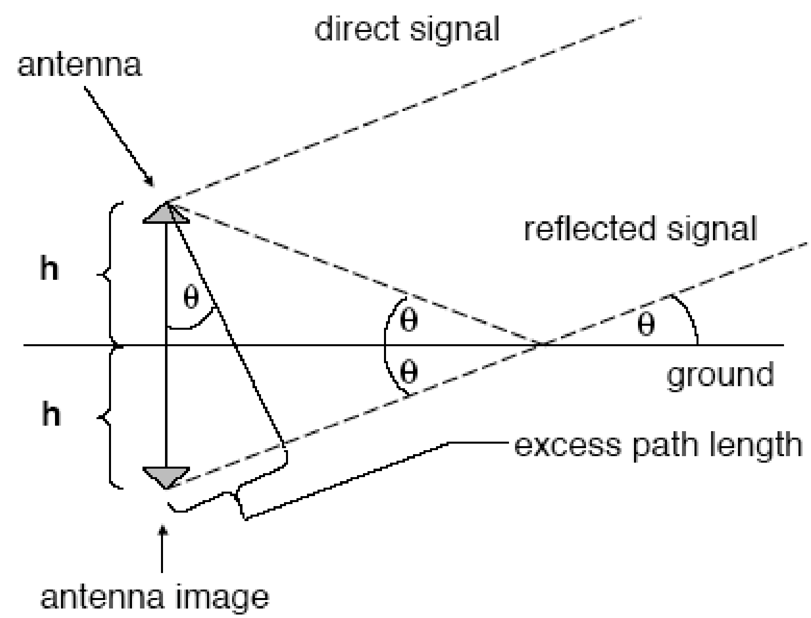
•To meet the 0.2 mm/sec requirement - precision orbit determination is required

• Multipath effect on phase can reach 5 cm

• Multipath is depends on direction of incoming signal,

Multipath Effects

- The antenna receives (apart form the direct signal) **reflections** of the signal from **objects in the vicinity**.
- **Superposition** of direct and indirect signal.
- Systematic deviations in code up to **50 m**, in phase up to **5 cm**.
- Variations with periods of **5-30 min**.



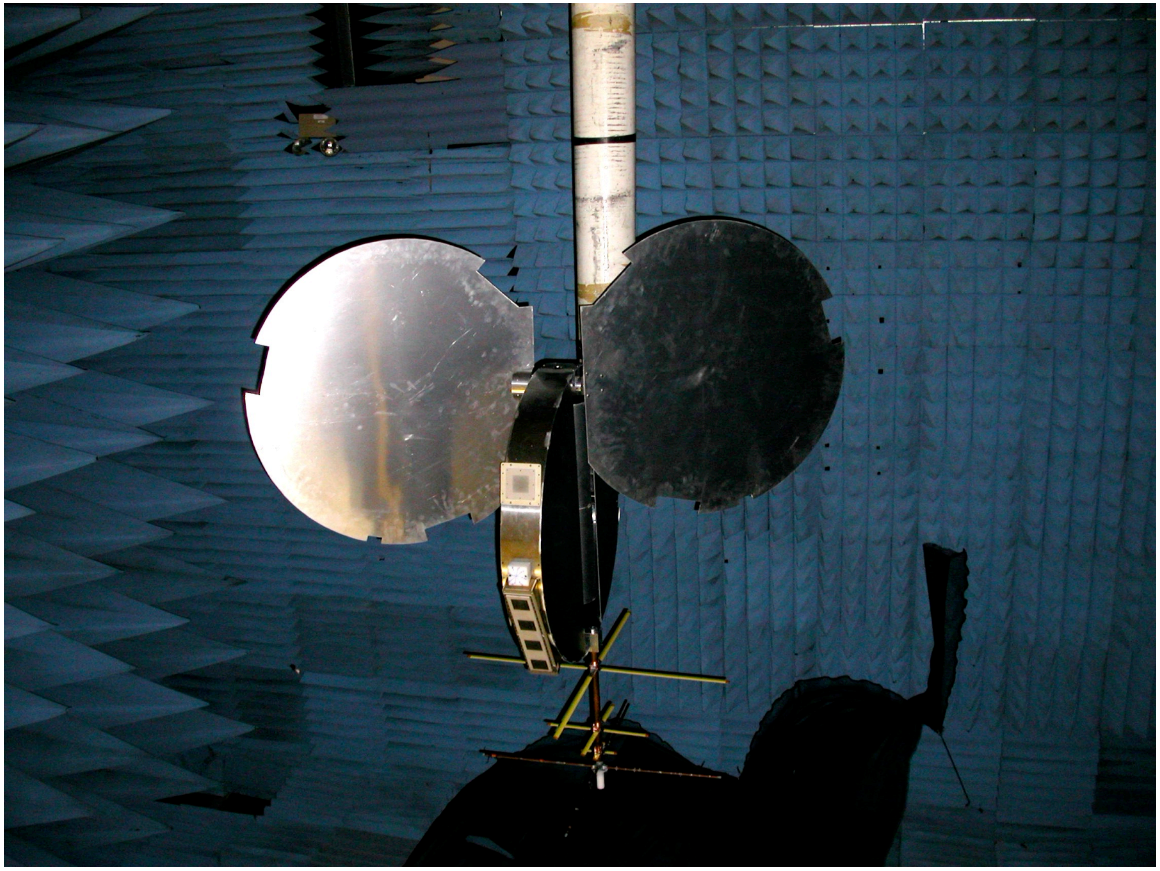
- Most critical at **low elevation**, with **short** observations times.
- **Package of measures**: Antenna design (choke ring, ground plane, . . .); selection of site (free horizon, . . .); longer observation sessions (averaging of effects).

M. Rothacher

Outdoor GPS Antenna Test at UCAR

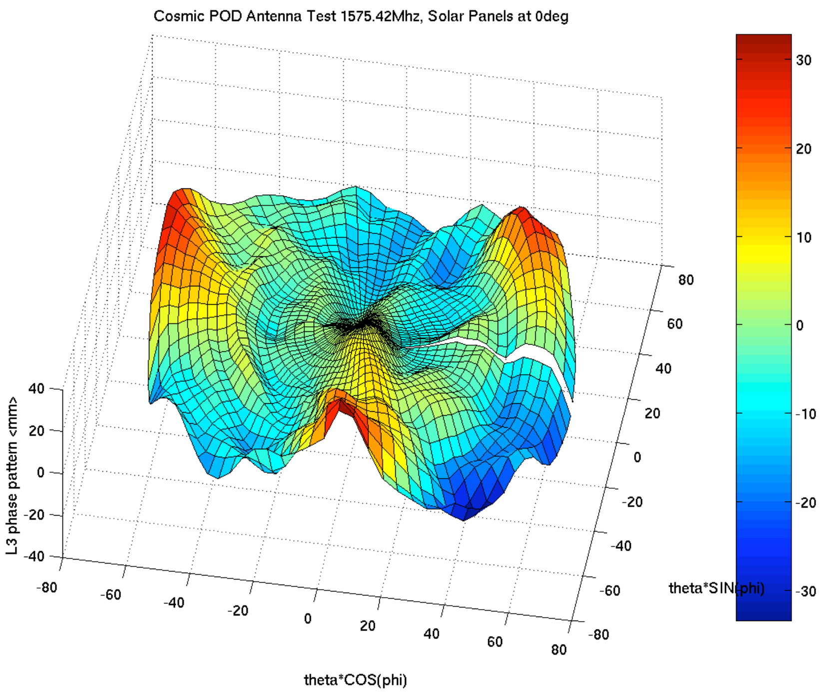
Formosat3 / COSMIC Satellite model during antenna tests with “solar panel” in 0 deg. orientation

COSMIC GPS Antenna Test at Ball Aerospace

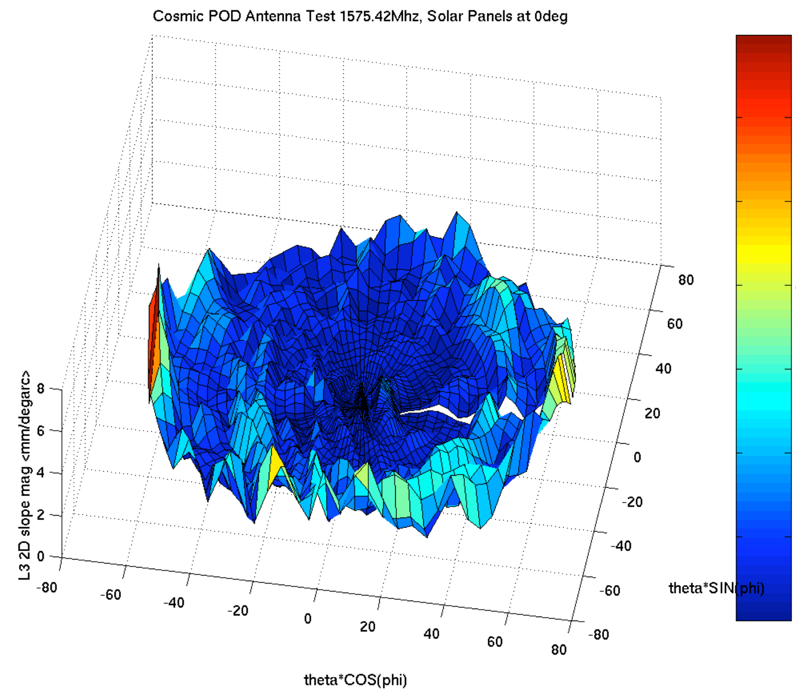


COSMIC GPS POD Antenna
L3 Phase (FOV=60)
SAD(0)

L3 Phase (mm)



Gradient Magnitude(mm/deg)



Elimination of relativistic effects

$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta \rho_{trp} + \delta \rho_{ion} + \delta \rho_{rel} + \delta \rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

- Needs to be modeled for POD
- Effect can reach ~ 10 m

Relativistic Corrections (1)

The satellite clocks (as well as the station clocks) are affected by **special** (relative velocity of the satellite) and **general relativistic effects** (gravity field of the Earth).

Special relativity: moving clocks are **slower** than clocks at rest.

General relativity: due to the **weaker gravity field** at the altitude of the GPS satellites the satellite clocks are **faster** by about **40 μs/d** than clocks on the Earth's surface.

Resulting **frequency difference** $\Delta f = f - f_0$ between satellite and receiver:

$$\frac{\Delta f}{f_0} = \frac{f - f_0}{f_0} = \frac{1}{2}\frac{v^2}{c^2} + \frac{\Delta U}{c^2}$$

f_0	Frequency received by the receiver
f	Frequency emitted by the satellite
v	Velocity of the satellite (about 4 km/s)
ΔU	Difference in gravity potential between satellite and receiver

M. Rothacher

Relativistic Corrections (2)

Assuming a circular orbit and a spherical Earth (with mass M_E) we get approximately:

$$\frac{\Delta f}{f_0} = \frac{1}{2}\frac{v^2}{c^2} + \frac{GM_E}{c^2}\left(\frac{1}{|\boldsymbol{r}^s|} - \frac{1}{|\boldsymbol{r}_r|}\right) \approx -4.464 \cdot 10^{-10}$$

The frequency of the satellite clock is **shifted** at the ground by $\Delta f = 4.464 \cdot 10^{-10} \cdot f_0 = 4.57 \cdot 10^{-3}$ Hz to a value of **10.22999999543 MHz**, so that the receiver will receive the nominal frequency of 10.23 MHz despite the relativistic effects mentioned above.

This frequency shift only corrects for a **constant** clock rate. Because the GPS orbits are not exactly circular, the satellite clock also shows **periodic variations**:

$$\delta\rho_{rel,1} = \frac{2}{c}\sqrt{GM_E\, a}\; e \sin E = \frac{2 \cdot \boldsymbol{r}^s \cdot \dot{\boldsymbol{r}}^s}{c^2}$$

with e the numerical eccentricity, a the semi-major axis and E the eccentric anomaly of the satellite orbit. This distance correction $\delta\rho_{rel,1}$ may amount to more than **10 m**.

M. Rothacher

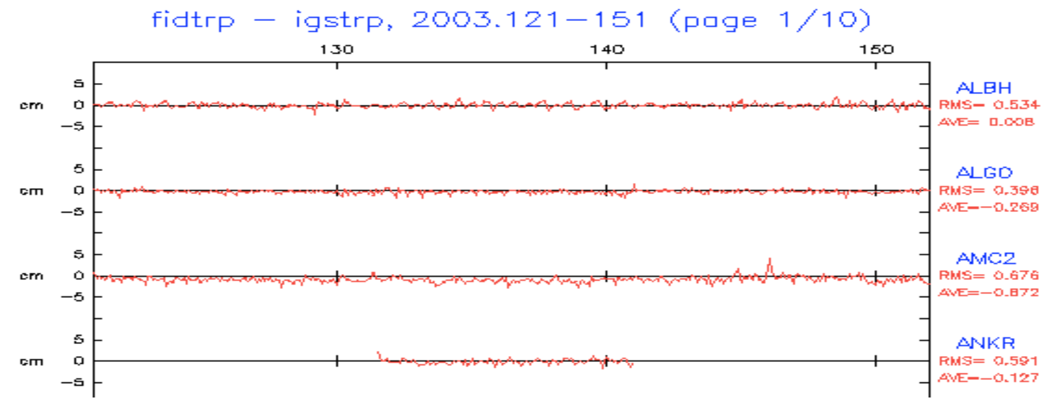
Elimination of tropospheric effects

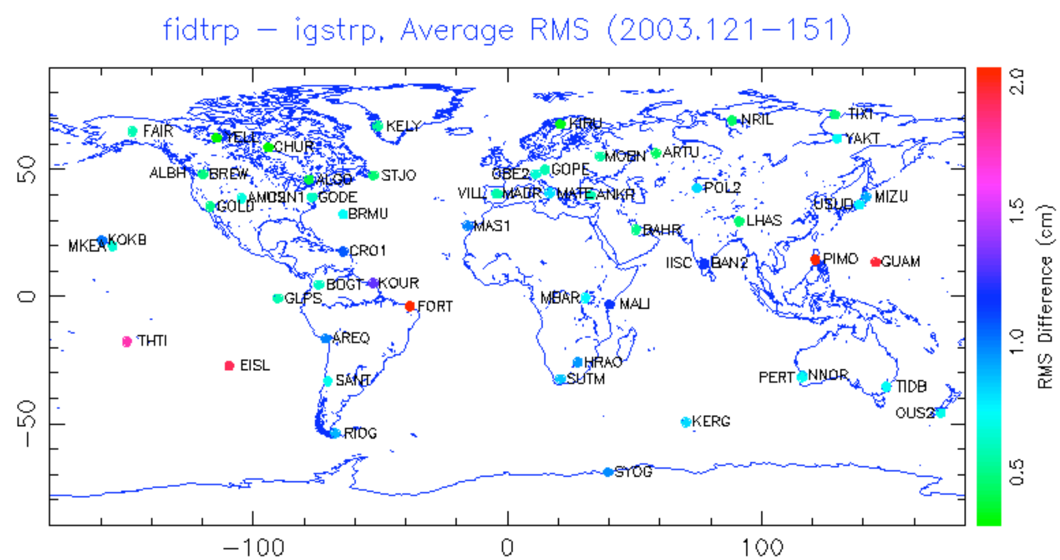
$$L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta\rho_{trp} + \delta\rho_{ion} + \delta\rho_{rel} + \delta\rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon$$

- Tropospheric effect on reference links to fiducial site need to be corrected
- Effect is small less than ~30 cm and will not change rapidly
- Effect needs to be modeled for clock estimation and effect on LEO POD

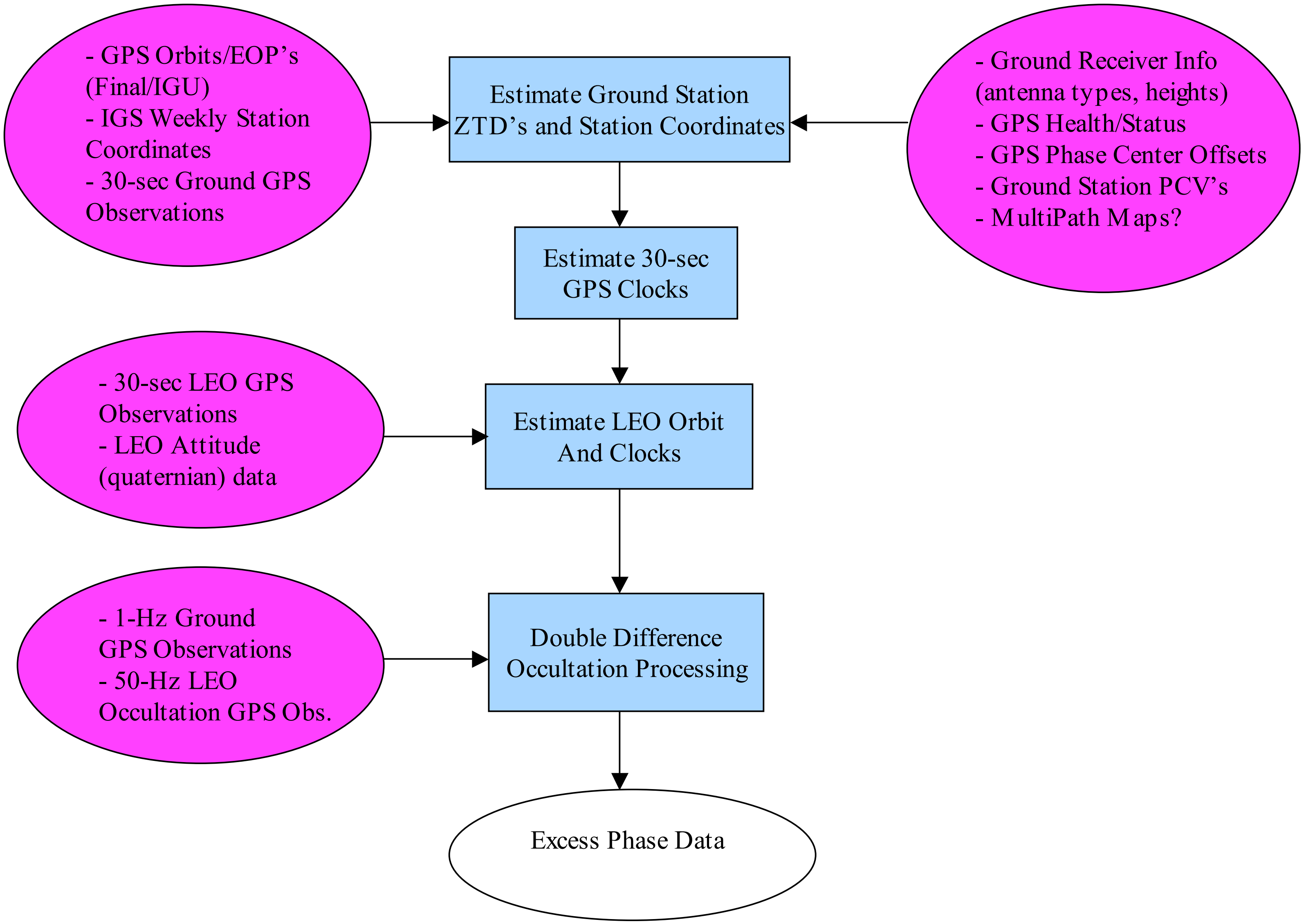
Global Fiducial network processing has been implemented

- Comparisons of CDAAC post-processed zenith delays with IGS final values
- CDAAC software in place to automatically fetch files, populate database with comparison values and display reports, including global summary maps.
- Most sites show monthly average RMS differences with IGS of < 1cm with little bias





CDAAC GPS Processing Overview



CDAAC Excess Phase File Description

- Netcdf Filename: atmPhs_CHAM.2002.213.03.51.G28_0001.0003_nc
- Netcdf Header information: Date/time, mission, leoID, dumpID, occPRN, refPRN, fiducial name, s/w version info, …
- Netcdf Data:
  - Time: precise observation time of received signal (GPS seconds)
  - SNR's: C/A L1 SNR, P L1 SNR, P L2 SNR (0.1 Volts/volt)
  - LEO position/velocity: of antenna phase center at signal receive time in Earth Centered Inertial (ECI) True-of-Date (TOD) reference frame (km,km/s)
  - GPS position/velocity: of antenna phase center at signal transmit time in ECI TOD reference frame (km,km/s)
  - L1, L2, LC(ionosphere-free) excess phase data (m)
  - Receiver Open-Loop Phase model (m)
  - Double-differenced Open-Loop Phase model (m)
  - Receiver Open-Loop range model (m)
  - Receiver Open-Loop phase in excess to vacuum, with data message bits present (m)

C Rocken “Ground based GPS Meteorology” NCAR GPS Meteorology Colloquium, June 20 - July 2, 2004, Boulder, CO

GPS Modernization

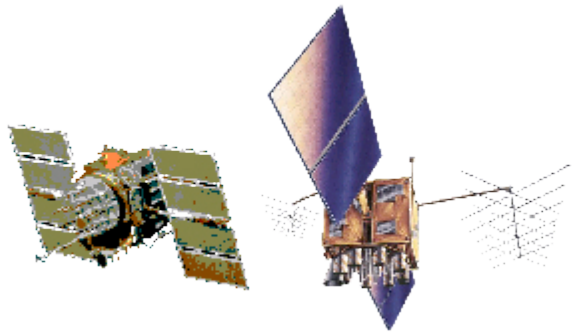
Figure 1. GPS Block-IIR Satellite Today

Presently there are 30 active GPS satellites transmitting:

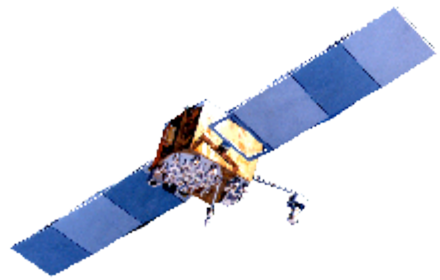
Carrier	Frequency	Code
L1	1575.42 MHz	C/A and P/Y
L2	1227.6 MHz	P/Y

Modernization

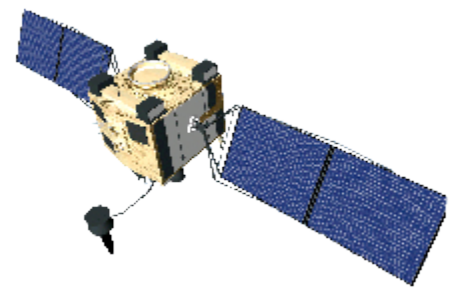
Block IIA/IIR



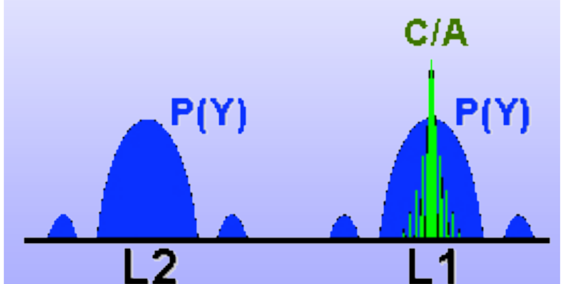
Block IIR-M, IIF



Block III



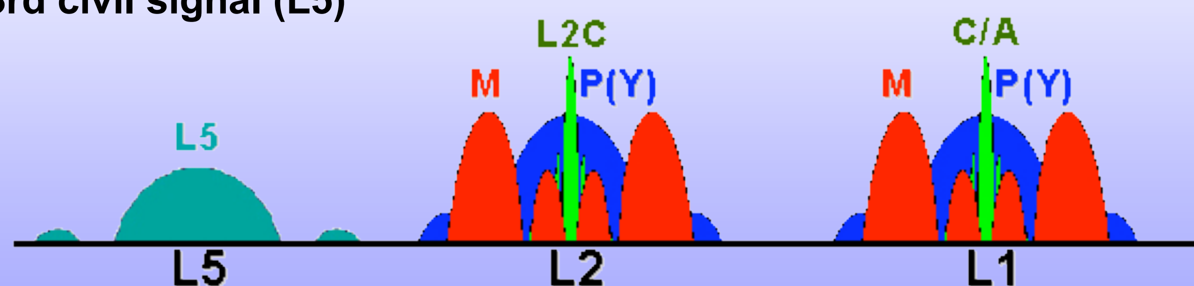
<u>IIA / IIR</u>: Basic GPS
- C/A civil signal (L1C/A)
- Std Service, 16-24m SEP
- Precise Service, 16m SEP
  - L1 & L2 P(Y) nav



<u>IIR-M</u>: IIA/IIR capabilities &
- 2nd civil signal (L2C)
- New military code
- Flex A/J power (+7dB)

<u>IIF</u>: IIR-M capability plus
- 3rd civil signal (L5)

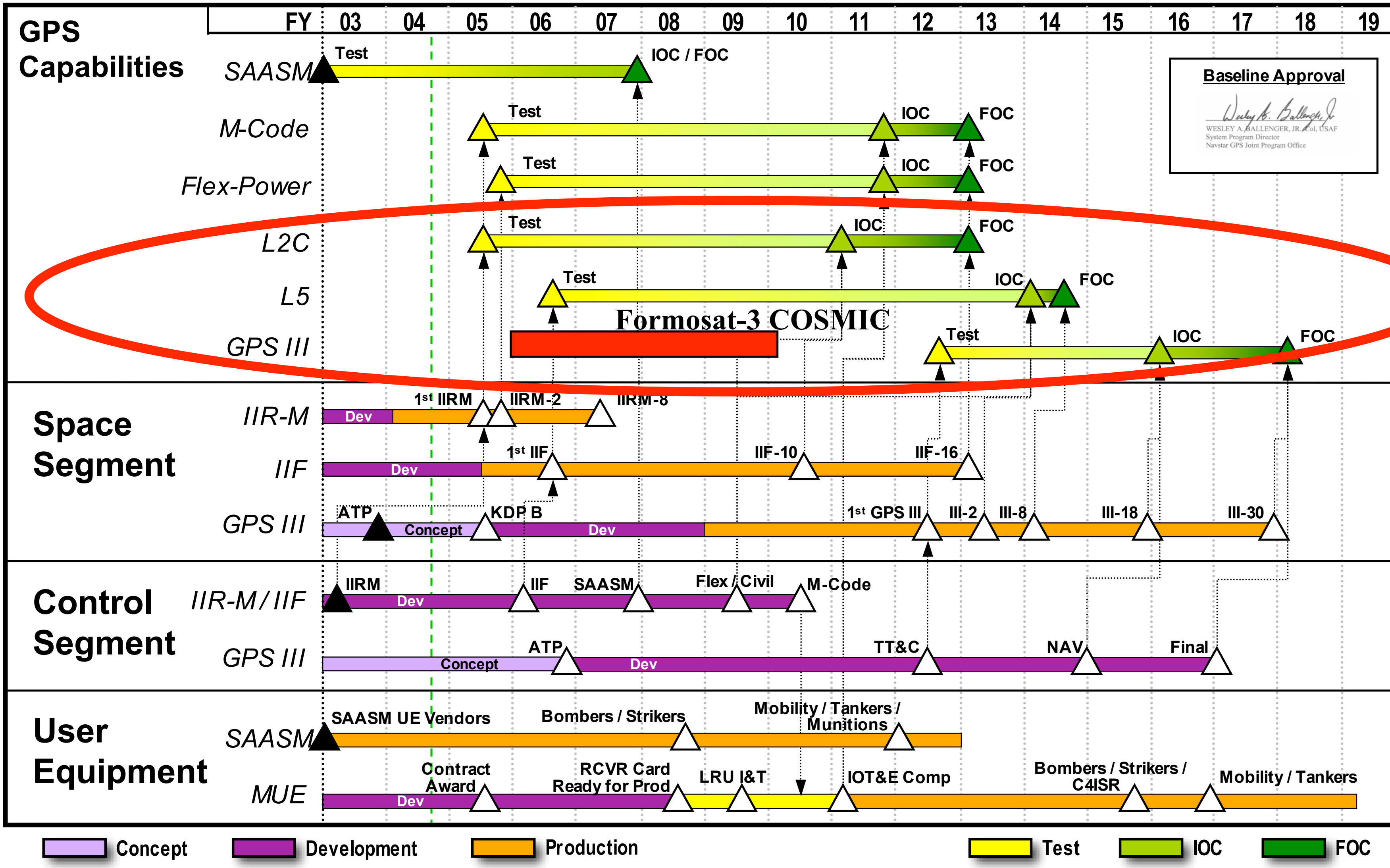
<u>III</u>: IIF capabilities &
- Improved civil signal (L1C)
- Increased accuracy (4.8-1.2m)
- Navigation surety
  - Increased A/J power (+20 dB)



Slide courtesy Col Mark Crews SMS/GPE

GPS Enterprise Perspective Schedule

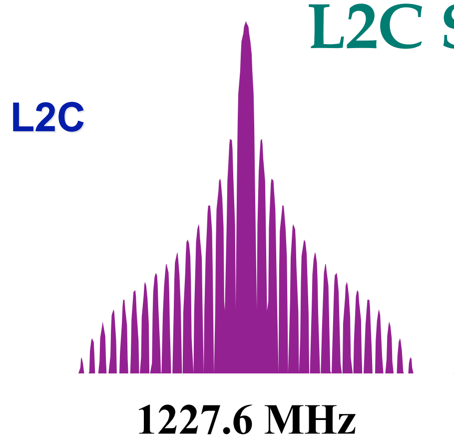
FY05 PB Baseline



JPO Approved Baseline Based on FY05 PB
Updated as of: 23 Aug 04 SMR

Slide based on Col Mark Crews SMS/GPE

L2C Second Civil Signal



Begins with IIR-M sats
First launch: May 2005
24 Satellites: 2012

- **Benefits of L2C**
  - » **Improves PNT for ~ 50,000 current scientific/commercial dual frequency users**
  - » **Extends safety-of-life, single-frequency E-911 applications**
  - » **Provides better protection (24 dB) than C/A against code cross correlation and continuous wave (CW) interference**
  - » **Improved data structure for enhanced data demodulation (5 dB better than C/A)**

Slide courtesy Col Mark Crews SMS/GPE

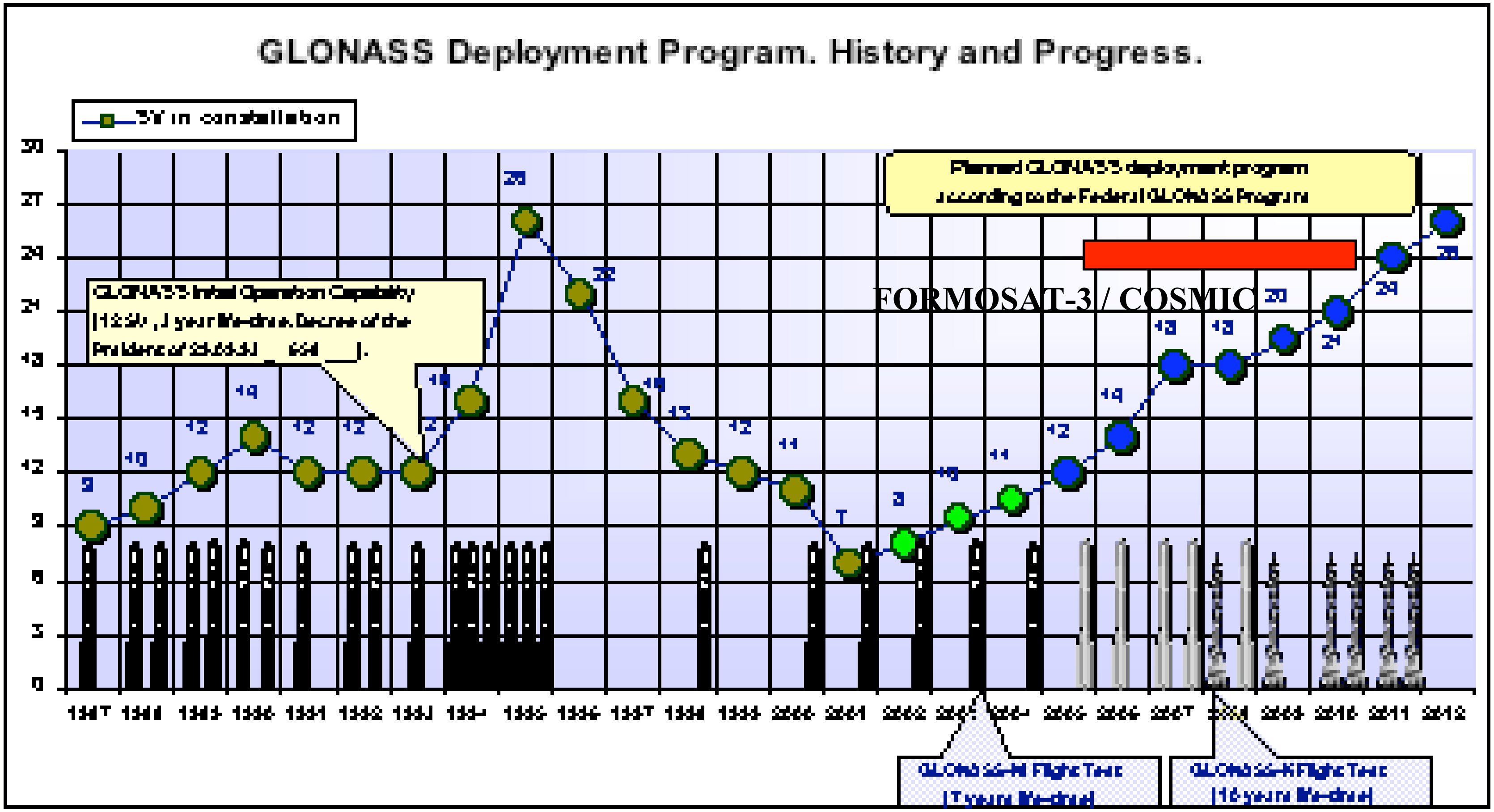
L5 Third Civil Signal

Begins with IIF sats
First launch: 2007
24 Satellites: 2014

- **Improves signal structure for enhanced performance**
  - » Higher power (-154.9 dBW)
  - » Wider bandwidth (24 MHz)
  - » Longer spreading codes in the navigation message
- **Aeronautical Radionavigation Services band**
  - » Co-primary allocation at WRC-2000 (1164-1215MHz)
- **L5 signal definition in IS-GPS-705**

Slide courtesy Col Mark Crews SMS/GPE

Glonass Constellation History and Perspective



GLONASS deployment milestones:

- » 18 satellites in constellation – 2007
- » 24 satellites in constellation – 2010-2011

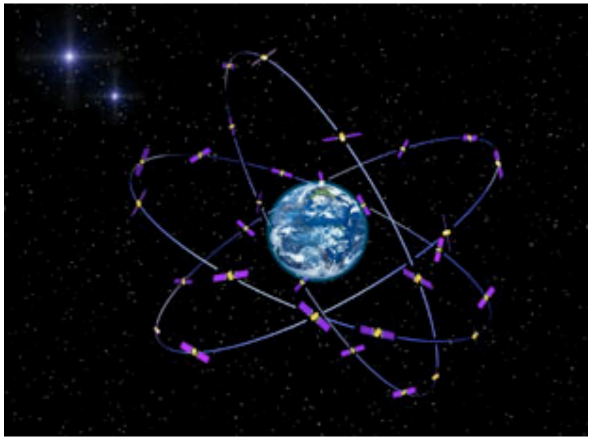
14 satellites in constellation

S. Revnivykh

GALILEO

Space Segment

- 30 Satellites (27 operational/3 in-orbit spares)
- Altitude: ~23,000 km from the earth's surface
- 3 orbital planes (9+1 satellites for each plane), 56° inclination
- Satellite design life ~ 12 years
- Satellite mass: 680 kg
- Satellite dimension: 2.7 x 1.2 x 1.1 m^3
- Satellite power: 1600 w (end of life)
- Continuous signal transmission on 3 frequencies for ranging purpose (having 2+ frequencies allows for compensation of ionospheric signal delay)
- Regular ground contact to update navigational data (every 100 min.)
- Integrity data is updated every second via the satellite constellation



- Initial launch end of 2005
- Additional satellites launched after 2008