INTER-SATELLITE-LINKS IN GNSS

(September 2012)

Prepared by Francisco Amarillo, ESA

DISCLAIMER

THIS PRESENTATION:

- CONTAINS HIGH LEVEL CONSIDERATIONS ON THE USE OF INTER-SATELLITE LINKS IN GNSS SYSTEMS.
- CONCLUSIONS ARE PRELIMINARY, AND MAY BE REVISED AT A LATER STAGE.
- REPORTS EXCLUSIVELY THE OPINION OF THE AUTHOR
- FOCUSES ON TECHNICAL AND ENGINEERING ASPECTS

INTER-SATELLITE-LINKS FROM GNSS SYSTEMS POV.

WHAT TYPE OF BENEFITS COULD BRING AT GNSS SYSTEM LEVEL.

NAVIGATION SYSTEMS EVOLUTION-1

ENHANCED FUNCTION	FREE-ERROR NAVIGATION DETERMINATION

DIRECTIONS

- **PERFORMANCE ENHANCEMENT** [User Driven]
- GROUND FACILITIES REDUCTION [System Driven]
- MAINTENANCE & OPERATION COST REDUCTION [System Driven]
- EXTENSION TO OTHER COMMUNITIES [User Driven]
- EXTENSION TO DIFFICULT ENVIRONMENTS [User Driven]

TODAY'S SYSTEMS:

ORBIT+CLOCK ERROR DETERMINATION

<< sub-meter (67%)

FUTURE SYSTEMS:

ORBIT+CLOCK ERROR DETERMINATION

<< sub-decimeter (67%)

ENABLING TECHNOLOGIES

- **INTER-SATELLITE RANGING**
- **NEW OD&TS ALGORITHMIC**
- **BEAM-FORMING FOR NSS**
- **LASER RANGING FOR NSS**

NAVIGATION SYSTEMS EVOLUTION-2

ENHANCED FUNCTION	FREE-ERROR NAVIGATION DISSEMINATION

DIRECTIONS

- **PERFORMANCE ENHANCEMENT [User Driven]**
- GROUND FACILITIES REDUCTION [System Driven]
- MAINTENANCE & OPERATION COST REDUCTION [System Driven]
- EXTENSION TO OTHER COMMUNITIES [User Driven]
- EXTENSION TO DIFFICULT ENVIRONMENTS [User Driven]

TODAY'S SYSTEMS:
ORBIT + CLOCK ERROR DISSEMINATION
< few hours (max)

FUTURE SYSTEMS:
ORBIT + CLOCK ERROR DISSEMINATION
< few minutes (max)

ENABLING TECHNOLOGIES

- **INTER-SATELLITE COMMUNICATIONS**

INTER-SATELLITE-LINKS FROM OBSERVABLES POV.

WHAT TYPE OF OBSERVATIONS CAN BE GENERATED.

OBSERVATIONS-1

TIME (s)	SATELLITE-TO-SATELLITE PAIRS [x, y] = [S/C number in transmission mode, S/C number in reception mode]											SLOTS
[000, 005]	[13, 15]	[12, 16]	[11, 17]	[10, 18]	[09, 19]		[05, 23]	[04, 24]	[03, 25]	[02, 26]	[01, 27]	01
[005, 010]	[15, 13]	[16, 12]	[17, 11]	[18, 10]	[19, 09]		[23, 05]	[24, 04]	[25, 03]	[26, 02]	[27, 01]	01
[010, 015]	[14, 15]	[13, 16]	[12, 17]	[11, 18]	[10, 19]		[06, 23]	[05, 24]	[04, 25]	[03, 26]	[02, 27]	02
[015, 020]	[15, 14]	[16, 13]	[17, 12]	[18, 11]	[19, 10]		[23, 06]	[24, 05]	[25, 04]	[26, 03]	[27, 02]	02
[020, 025]	[01, 02]	[27, 03]	[26, 04]	[25, 05]	[24, 06]		[20, 10]	[19, 11]	[18, 12]	[17, 13]	[16, 14]	03
[025, 030]	[02, 01]	[03, 27]	[04, 26]	[05, 25]	[06, 24]		[10, 20]	[11, 19]	[12, 18]	[13, 17]	[14, 16]	03
[030, 035]	[01, 03]	[27, 04]	[26, 05]	[25, 06]	[24, 07]		[20, 11]	[19, 12]	[18, 13]	[17, 14]	[16, 15]	04
[035, 040]	[03, 01]	[04, 27]	[05, 26]	[06, 25]	[07, 24]		[11, 20]	[12, 19]	[13, 18]	[14, 17]	[15, 16]	04
[040, 045]	[02, 03]	[01, 04]	[27, 05]	[26, 06]	[25, 07]		[21, 11]	[20, 12]	[19, 13]	[18, 14]	[17, 15]	05
[045, 050]	[03, 02]	[04, 01]	[05, 27]	[06, 26]	[07, 25]		[11, 21]	[12, 20]	[13, 19]	[14, 18]	[15, 17]	05
[050 055]	[02, 04]	[01, 05]	[27, 06]	[26, 07]	[25, 08]		[21, 12]	[20, 13]	[19, 14]	[18, 15]	[17, 16]	06
[055, 060]	[04, 02]	[05, 01]	[06, 27]	[07, 26]	[08, 25]		[12, 21]	[13, 20]	[14, 19]	[15, 18]	[16, 17]	06
[260, 265]	[13, 14]	[12, 15]	[11, 16]	[10, 17]	[09, 18]		[05, 22]	[04, 23]	[03, 24]	[02, 25]	[01, 26]	27
[265, 270]	[14, 13]	[15, 12]	[16, 11]	[17, 10]	[18, 09]		[22, 05]	[23, 04]	[24, 03]	[25, 02]	[26, 01]	27

Connectivity example

(satellite ID is different from PRN)

Source: ESA GSP Programme: GNSS+ & ADVISE

OBSERVATIONS-2

❑ Two sequential one-way code-phase observations

TX's local clock at TX time

$$p_a^b\left(t_{pb}+\Delta t_{p,b}+\Delta t_{\max}\right)=d_a^b\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)+C^b\left(t_{pb}+\Delta t_{\max}\right)-C_a\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)$$
$$+H_{TX}^b\left(t_{pb}+\Delta t_{\max}\right)-H_a^{RX}\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)+\varepsilon_a^b\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)$$

RX's local clock at RX time

•••

Propagation delay

TX's HW bias in TX mode

RX's HW bias in RX mode

❑ Two sequential doppler observations

$$D_a^b\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)=\left.\frac{\partial d_a^b\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)}{\partial t}\right|_{t_{pb}+\Delta t_{pb}+\Delta t_{\max}}+\left.\frac{\partial C^b\left(t_{pb}+\Delta t_{\max}\right)}{\partial t}\right|_{t_{pb}+\Delta t_{\max}}$$
$$-\left.\frac{\partial C_a\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)}{\partial t}\right|_{t_{pb}+\Delta t_{pb}+\Delta t_{\max}}+\delta_a^b\left(t_{pb}+\Delta t_{pb}+\Delta t_{\max}\right)$$

•••

❑ Two sequential carrier-phase observations. Today disregarded. Wavelength may be too small ≈ 1.3 cm.

Source: ESA GSP Programme: GNSS+ & ADVISE

OBSERVATIONS-3

– **Conceptual transformation of two code-phase observations, referred to a common epoch, to cross-links observables**

❑ Orbit observable

2nd order corrections

$$og_{ab}(t_p)=\frac{o_a^b(t_p)+o_b^a(t_p)}{2}+\delta g=$$

Geometry Information

$$+\frac{d_a^b(t_p)+d_b^a(t_p)}{2}$$

< 1 cm when clock is replaced by de-trended clock

$$+\frac{C^b(t_p-\Delta t_{pb})-C_b(t_p)}{2}+\frac{C^a(t_p-\Delta t_{pa})-C_a(t_p)}{2}$$

$$+\frac{H_{TX}^b(t_p)-H_b^{RX}(t_p)}{2}+\frac{H_{TX}^a(t_p)-H_a^{RX}(t_p)}{2}$$

cross-link bias

$$+\frac{\bar{\varepsilon}_a^b(t_p)+\bar{\varepsilon}_b^a(t_p)}{2}$$

Error reduction with respect to conventional observable

❑ Clock observable

$$oc_{ab}(t_p)=\frac{o_a^b(t_p)-o_b^a(t_p)}{2}=$$

< 1cm after correction based on the initial orbit knowledge, as only errors in the S/C velocity counts

$$+\frac{d_a^b(t_p)-d_b^a(t_p)}{2}$$

$$+\frac{C^b(t_p-\Delta t_{pb})+C_b(t_p)}{2}-\frac{C^a(t_p-\Delta t_{pa})+C_a(t_p)}{2}$$

$$+\frac{H_{TX}^b(t_p)+H_b^{RX}(t_p)}{2}-\frac{H_{TX}^a(t_p)+H_a^{RX}(t_p)}{2}$$

$$+\frac{\bar{\varepsilon}_a^b(t_p)-\bar{\varepsilon}_b^a(t_p)}{2}$$

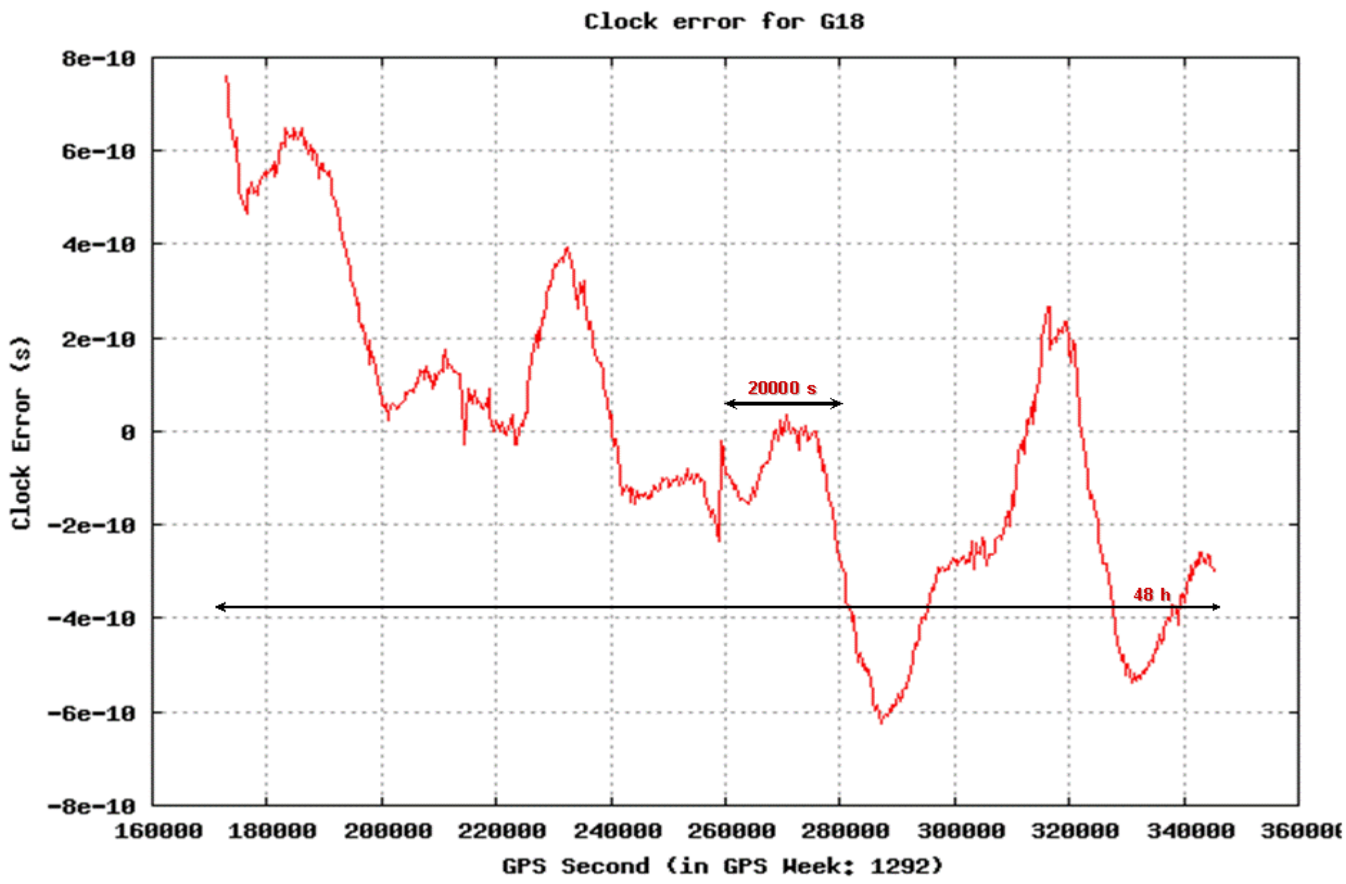
cross-link effective clock for S/C b

cross-link effective clock for S/C a

Source: ESA GSP Programme: GNSS+ & ADVISE

OBSERVATIONS-4

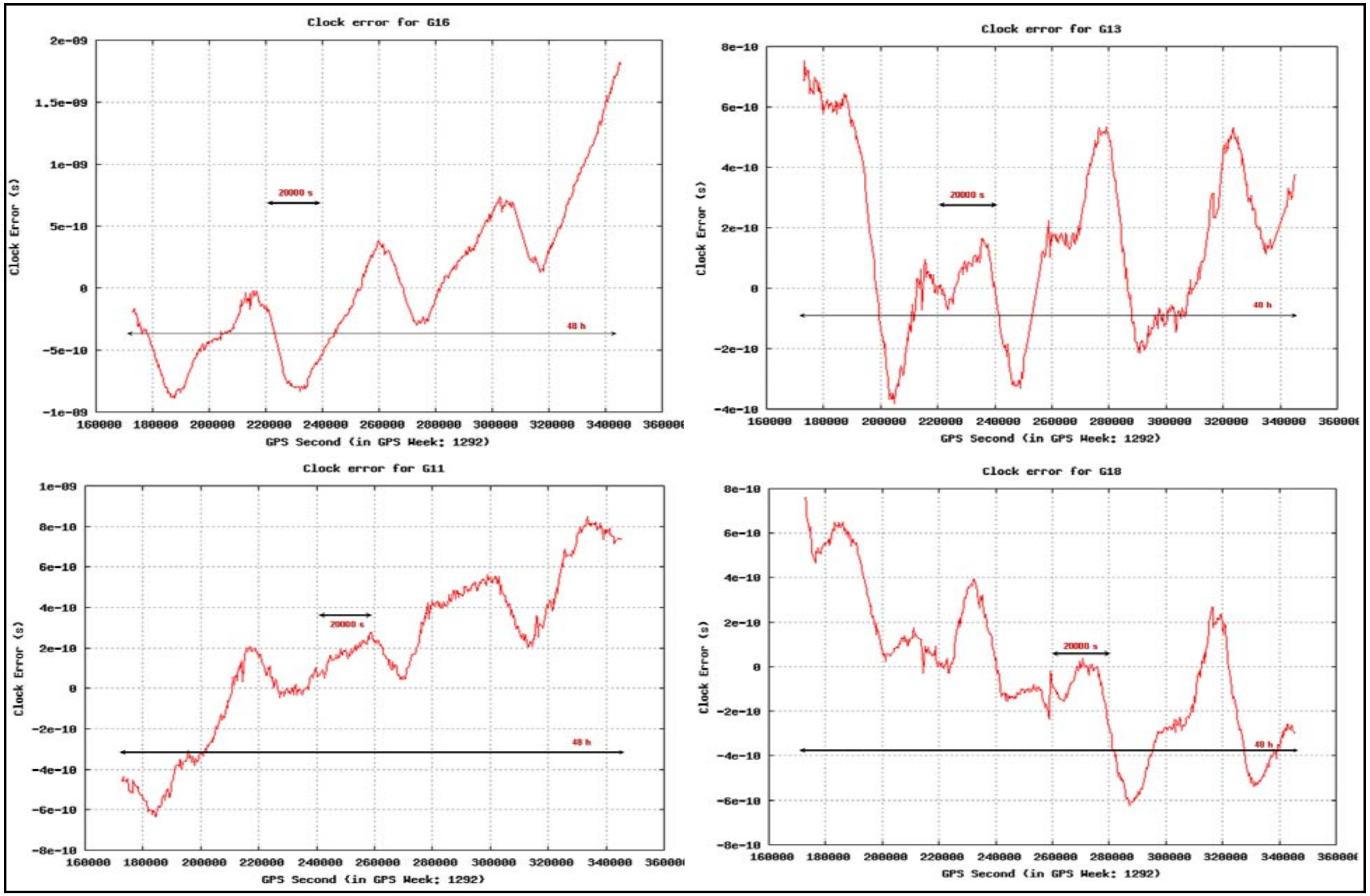
- Cross-link orbit observable. Example de-trended clock time series (RAFS)



Source: ESA GSP Programme: GNSS+ & ADVISE

OBSERVATIONS-5

- ❑ **Cross-link orbit observable. Example de-trended clock time series (RAFS)**



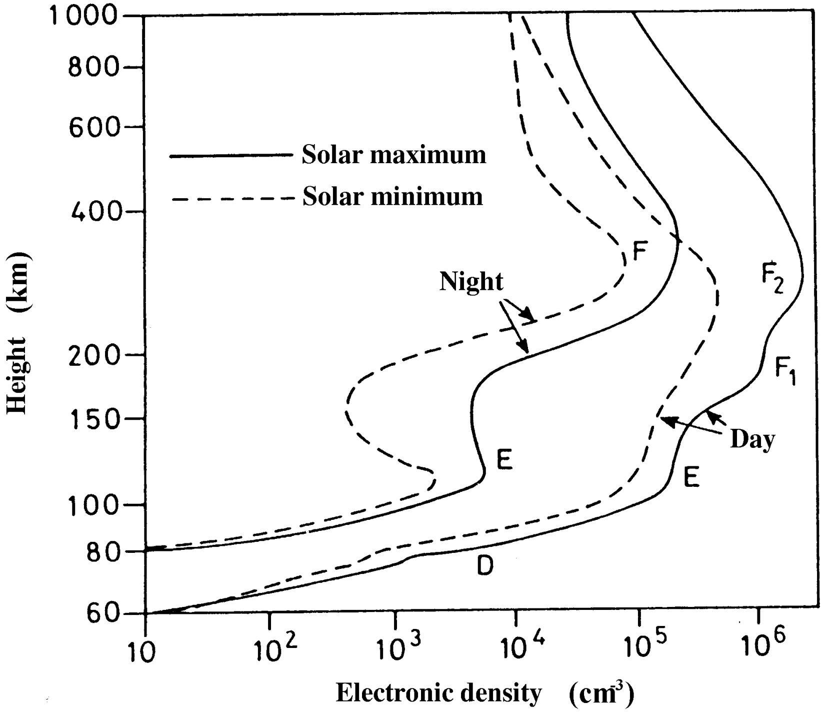
Source: ESA GSP Programme: GNSS+ & ADVISE

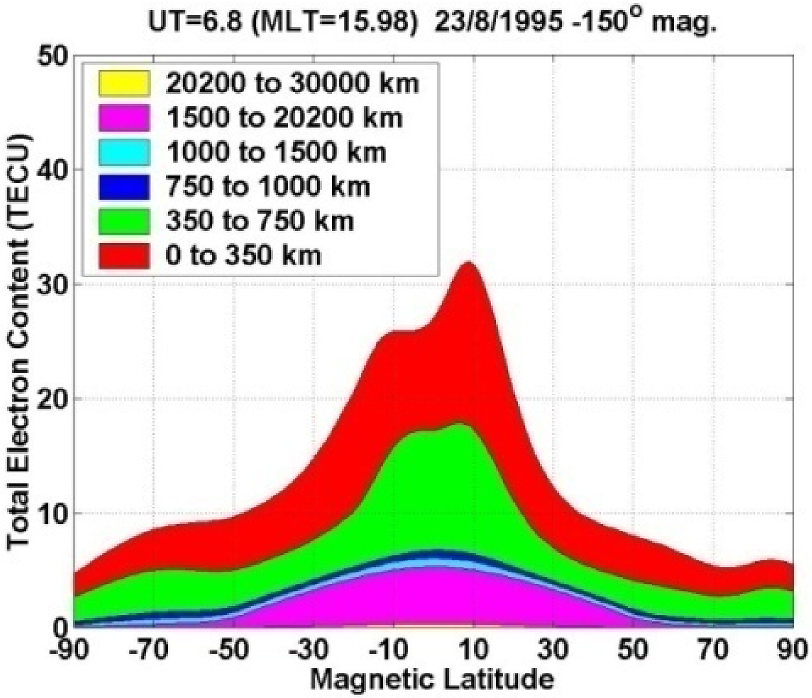
INTER-SATELLITE-LINKS FROM IONOSPHERE POV.

EFFECTS WHICH CAN BE EXPECTED

APPLICATIONS ON IONOSPHERIC SOUNDING.

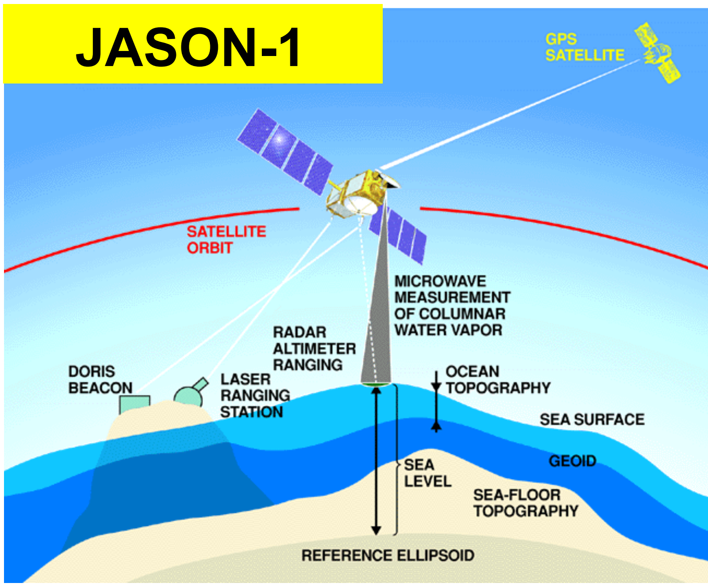
IONOSPHERE - 1





Antenna pointing range: Azimuth: [-180°, 180°]. Co-elevation: [00°, 70°]

IONOSPHERE - 2

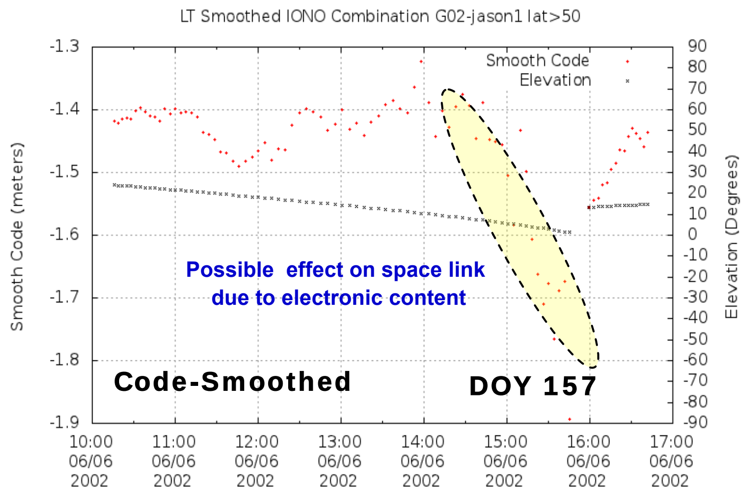


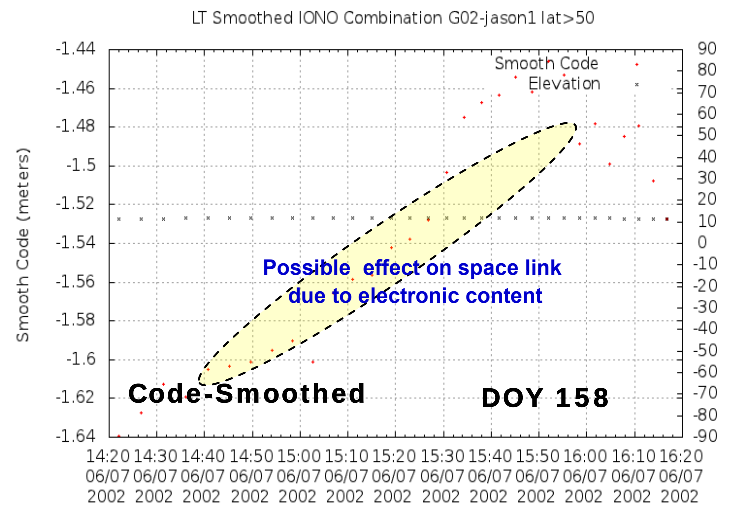
Altitude	1336 Kms	Season North Hemisphere	Spring and Summer
Solar Activity (F10.7)	Medium-High (~154,5)	Dates (Obs&Orb)	2002/06/06 - 2002/06/28
Geomagnetical Activity	Low	Source	Observations IGS Orbits GMV

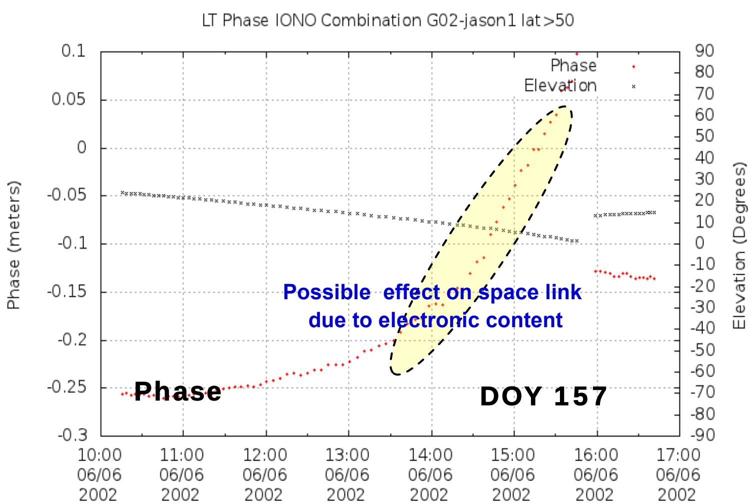
Source: GMV under ESA GSP Contract. 2012.

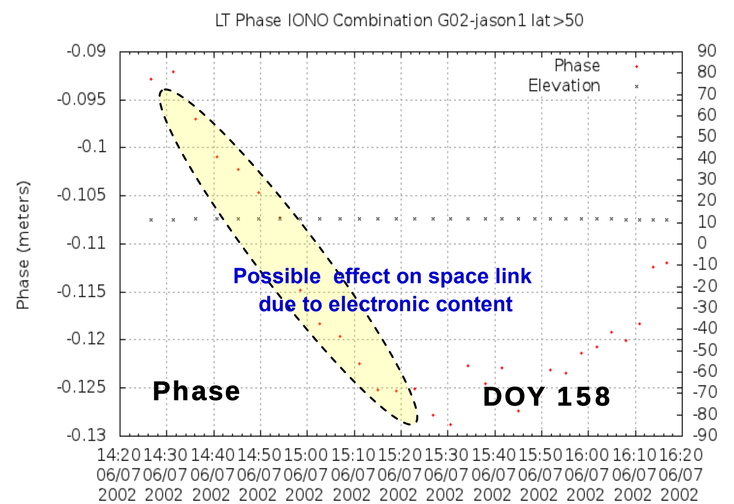
IONOSPHERE - 3

|High geomagnetic latitude|





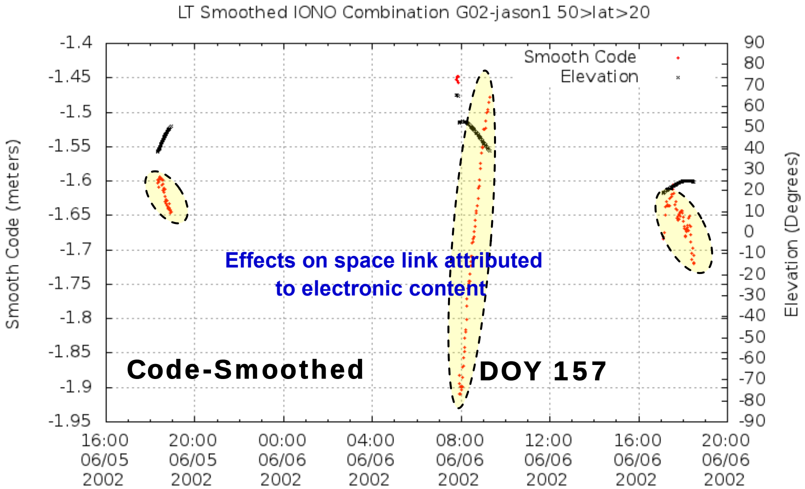


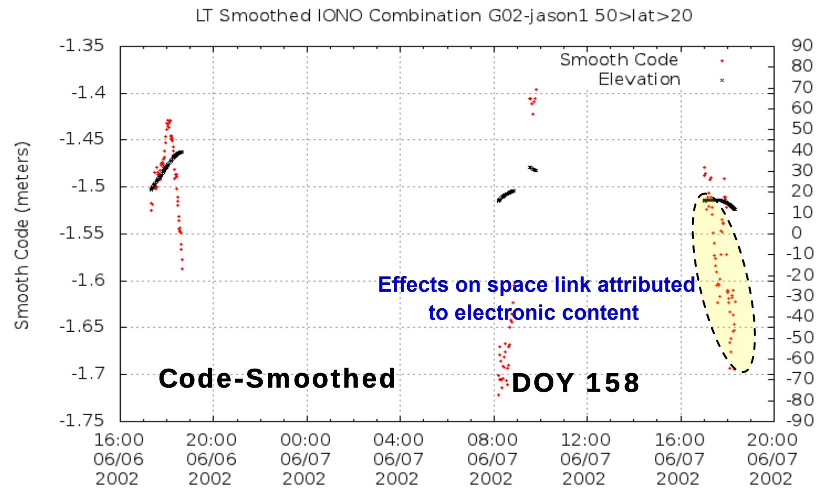


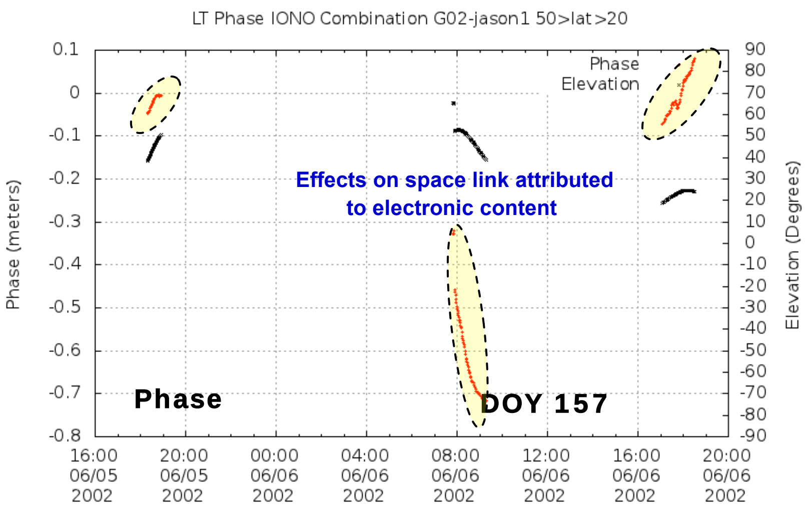
Source: GMV under ESA GSP Contract. 2012.

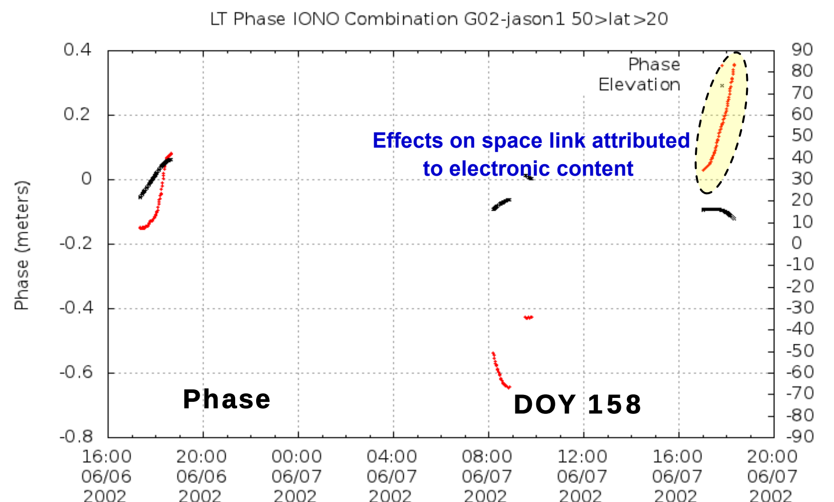
IONOSPHERE - 4

|Low geomagnetic latitude|



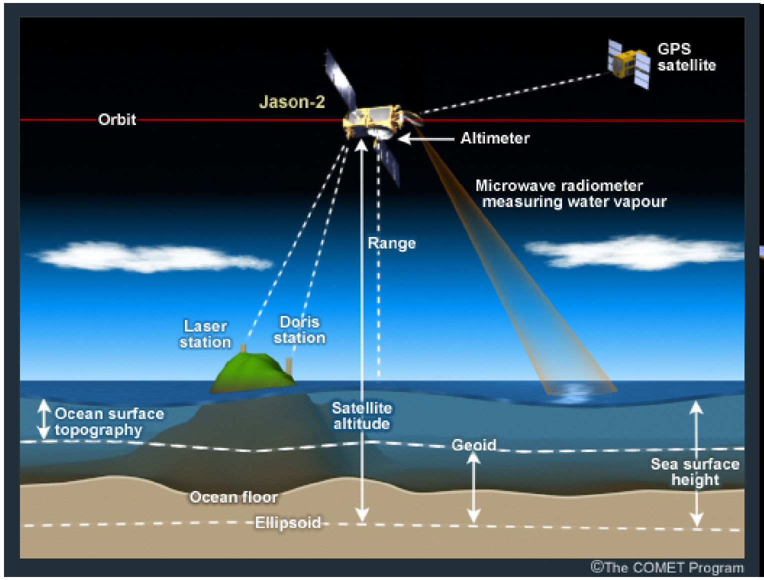






Source: GMV under ESA GSP Contract. 2012.

IONOSPHERE - 5

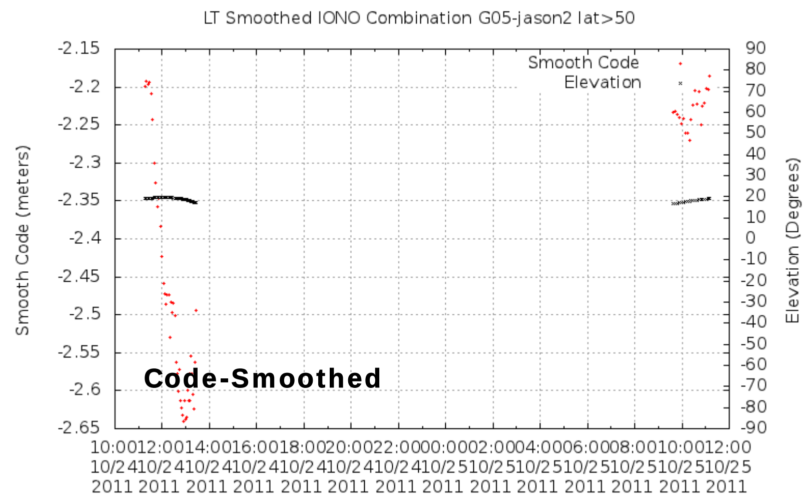


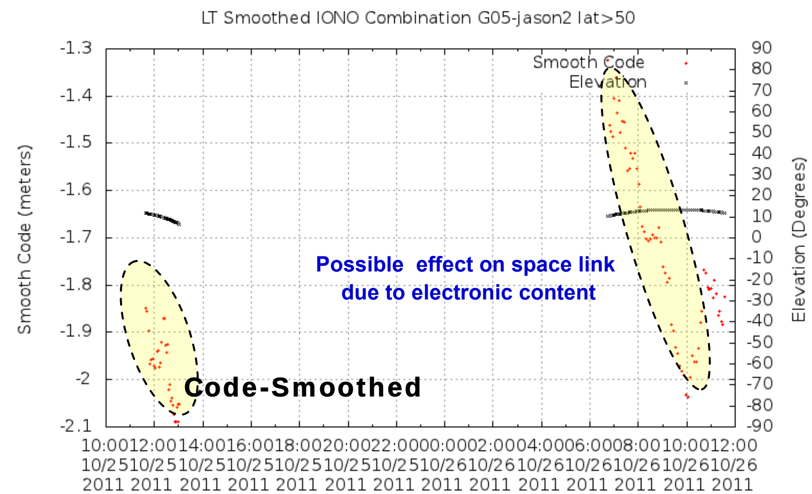
Altitude	1336 Kms	Season North Hemisphere	Summer and Autumn
Solar Activity (F10.7)	Low (~65,6)	Dates (Obs&Orb)	2008/07/14 - 2009/01/03
Geomagnetical Activity	Low	Source	Observations IGS Orbits GMV

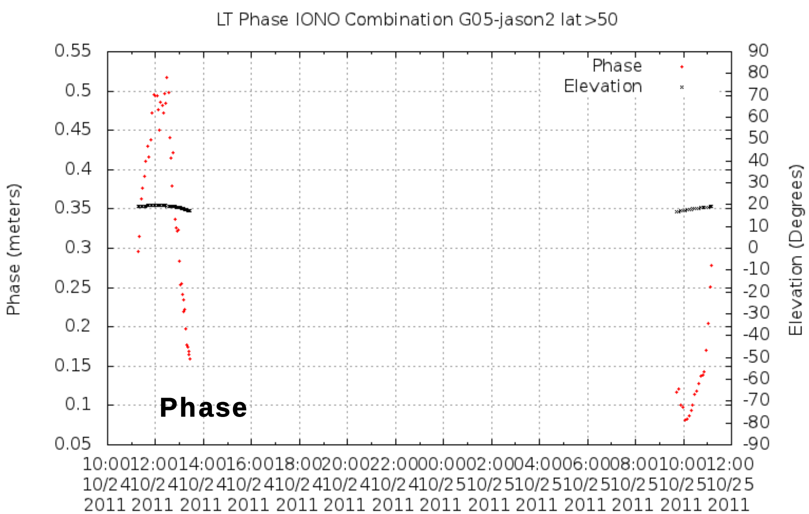
Source: GMV under ESA GSP Contract. 2012.

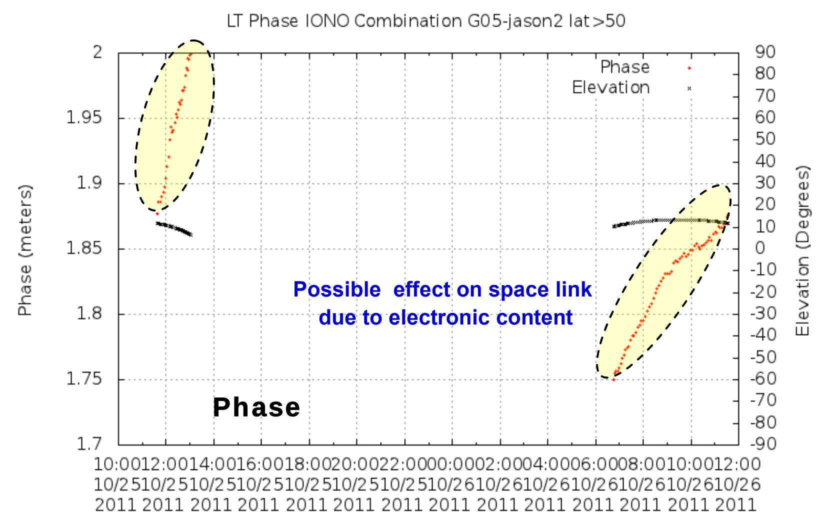
IONOSPHERE - 6

|High geomagnetic latitude|





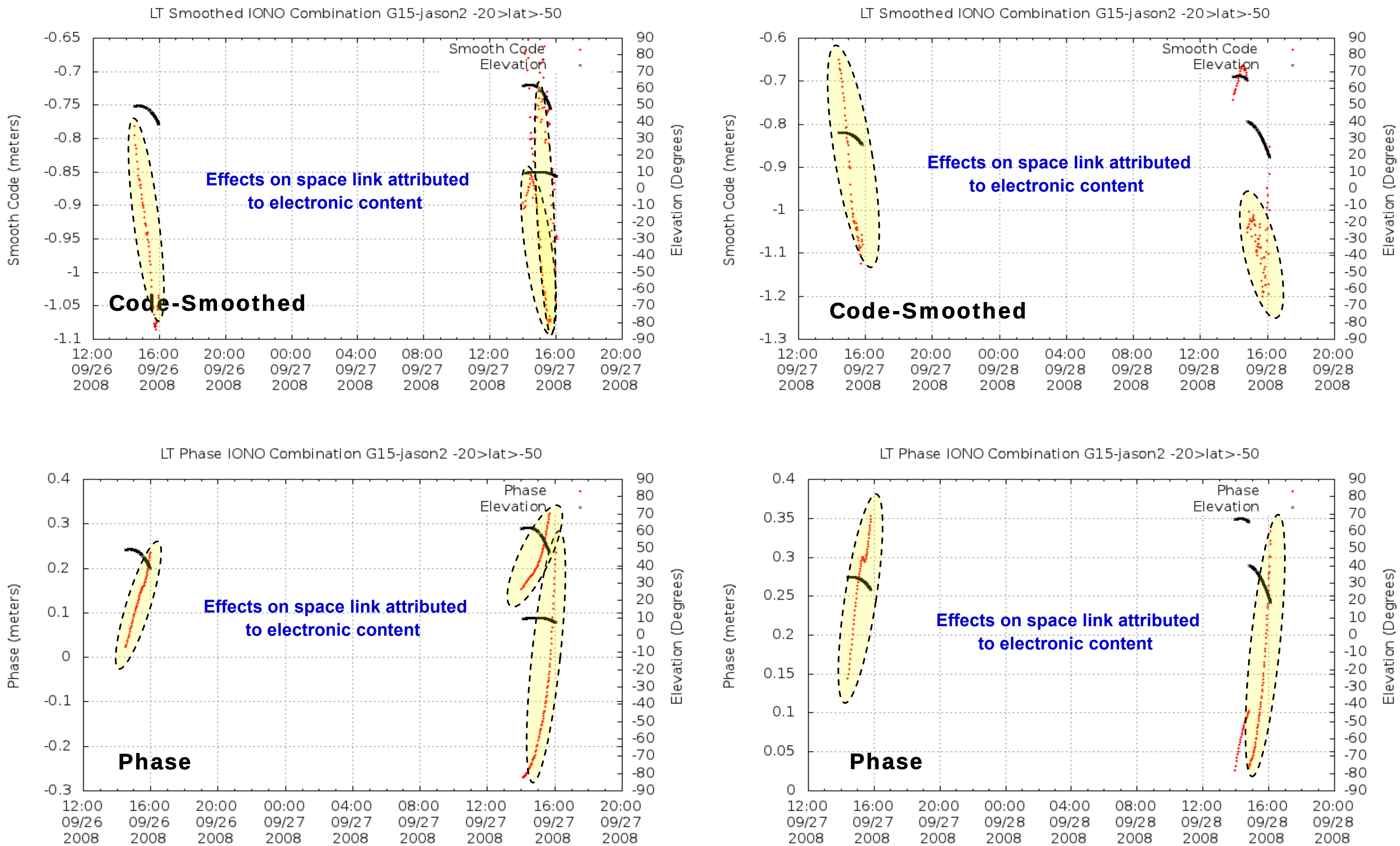




Source: GMV under ESA GSP Contract. 2012.

IONOSPHERE - 7

|Low geomagnetic latitude|



Source: GMV under ESA GSP Contract. 2012.

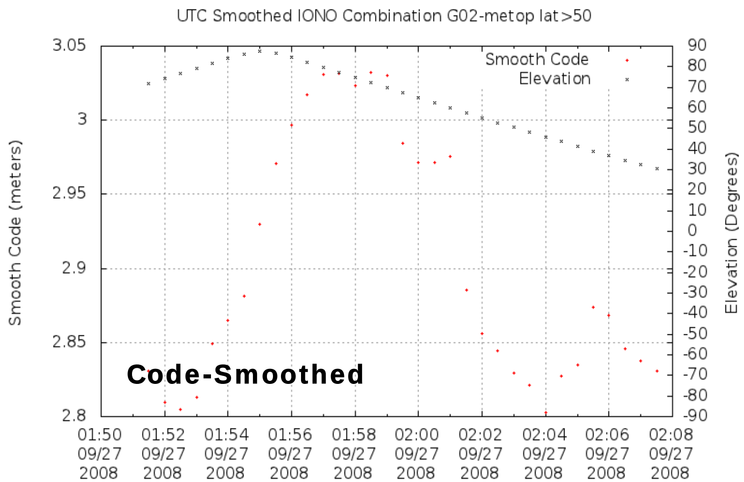
IONOSPHERE - 8

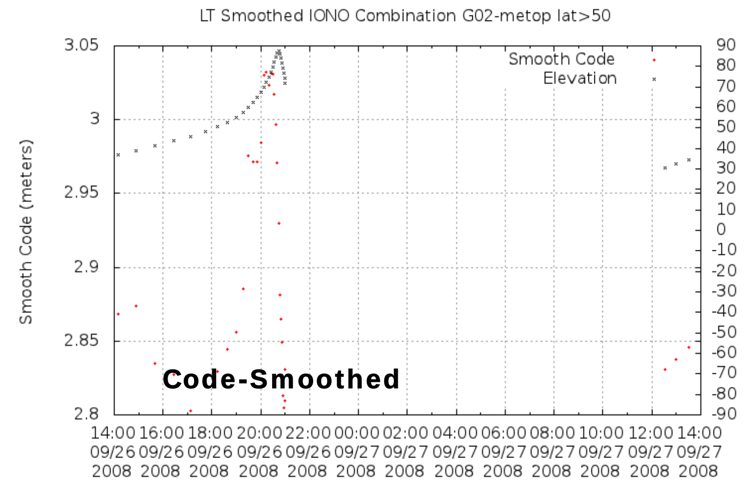
Altitude	817 Kms	Season North Hemisphere	Summer and Autumn
Solar Activity (F10.7)	Low (~64,6)	Dates (Obs&Orb)	2008/07/16-2008/09/29
Geomagnetical Activity	Low	Source	Observations IGS Orbits GMV

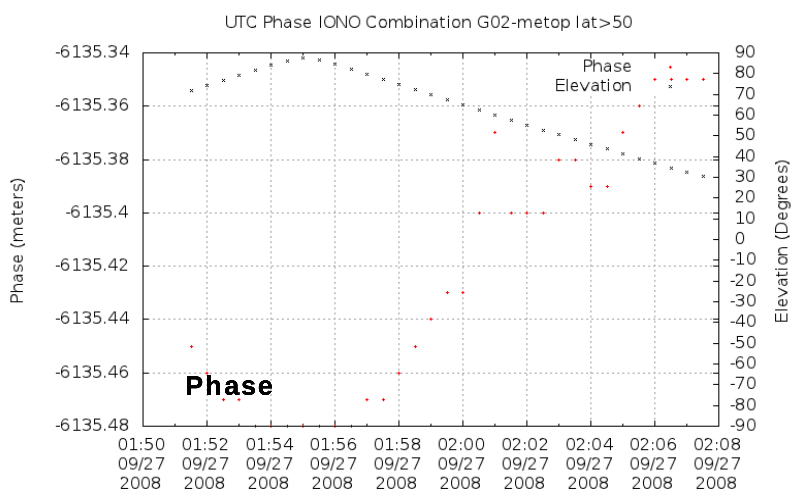
Source: GMV under ESA GSP Contract. 2012.

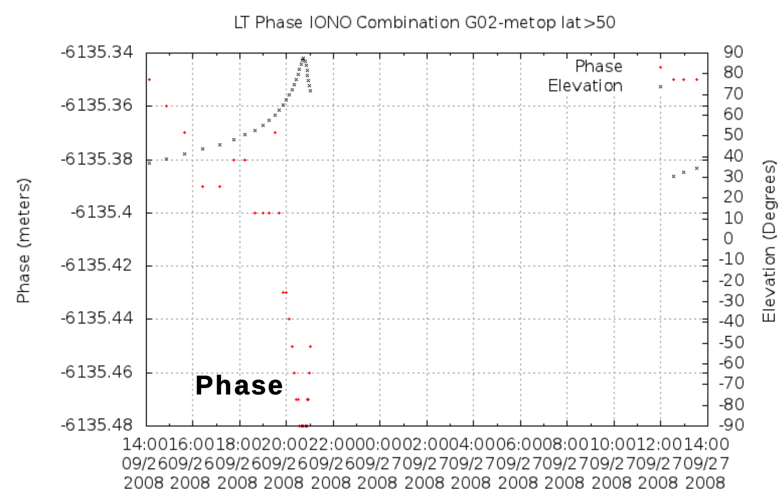
IONOSPHERE - 9

|High geomagnetic latitude|





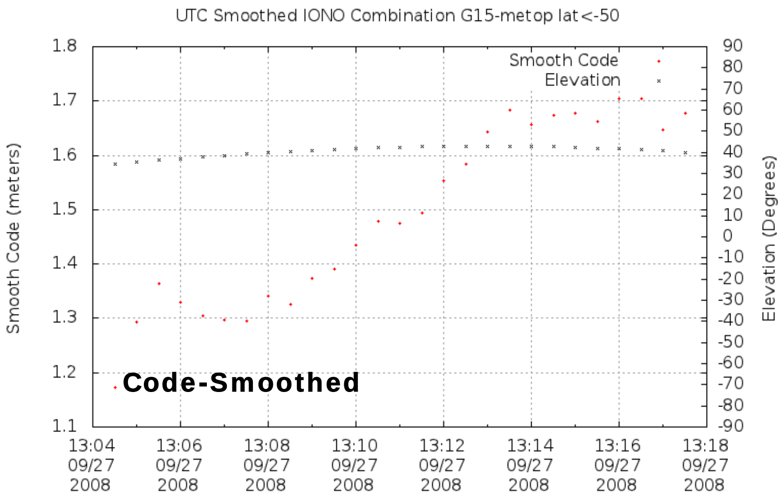


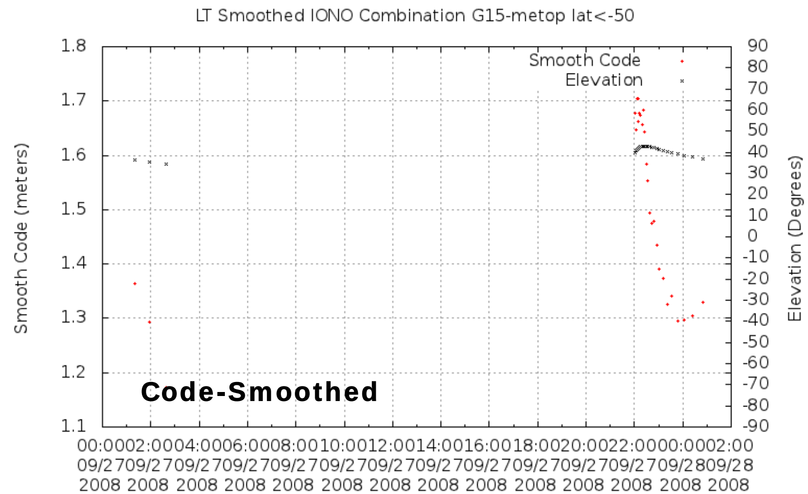


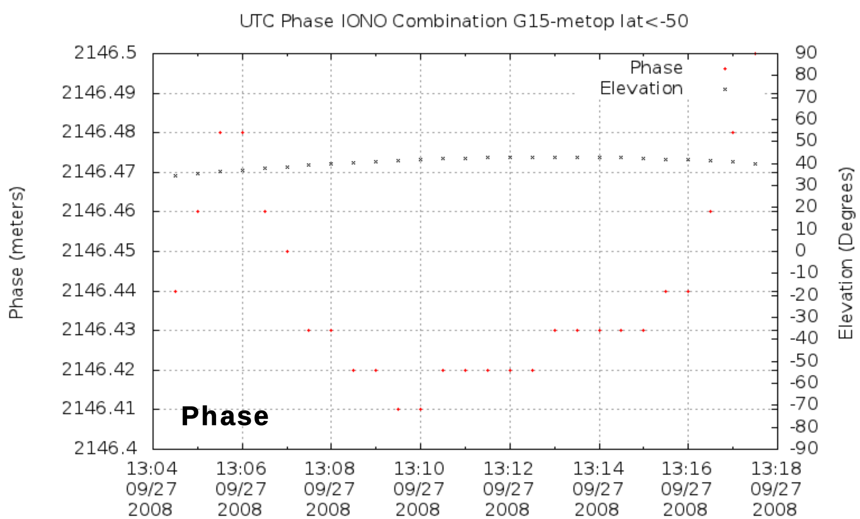
Source: GMV under ESA GSP Contract. 2012.

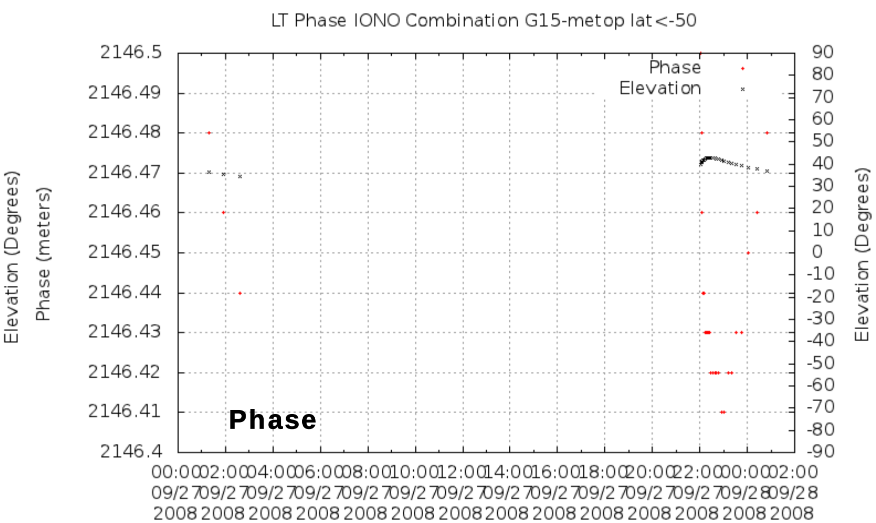
IONOSPHERE - 10

|Low geomagnetic latitude|









Source: GMV under ESA GSP Contract. 2012.

IONOSPHERE - 11

- Upper layers of the ionosphere can introduce relevant biases in the space to space links
  - Relevance increases as LoS distance to Earth decreases
  - Relevance increases with solar activity
  - Relevance increases with geomagnetic activity
- Biases diminish rapidly as frequency increases. Dependency with the inverse of the square of the frequency. 10 m error in L-band implies:
  - 1000 cm in L-band   01575.42 MHz
  - 0100 cm in C-band   05020.00 MHz
  - 0012 cm in Ku-band   14350.00 MHz
  - 0003 cm in K-band   23000.00 MHz
  - 0000 cm in V-band   60000.00 MHz

CONNECTION CRS-TRS

WHY RANGING & TIME-TRANSFER TO GROUND SEGMENT IS STILL REQUIRED

CONNECTION CRS-TRS-1

- ISL metrology time series provides accurate information on the:
  - Relative position between S/Cs
  - Relative synchronization error between S/Cs on-board clocks
- ISL metrology time series doesn’t provide accurate information on the:
  - S/Cs position and velocity in the Terrestrial Reference System
  - S/Cs synchronization error relative to TAI
- ISL-based OD&TS provides accurate information on the:
  - S/C position and velocity in the Inertial Reference System
  - S/C synchronization error relative to a constellation clock ensemble
- However a GNSS Navigation Systems intend to provide accurate:
  - S/Cs position and velocity in the Terrestrial Reference System
  - S/Cs synchronization error relative to TAI

CONNECTION CRS-TRS-2

- **Celestial Reference System (CRS) and Terrestrial Reference System (TRS) differ due to:**

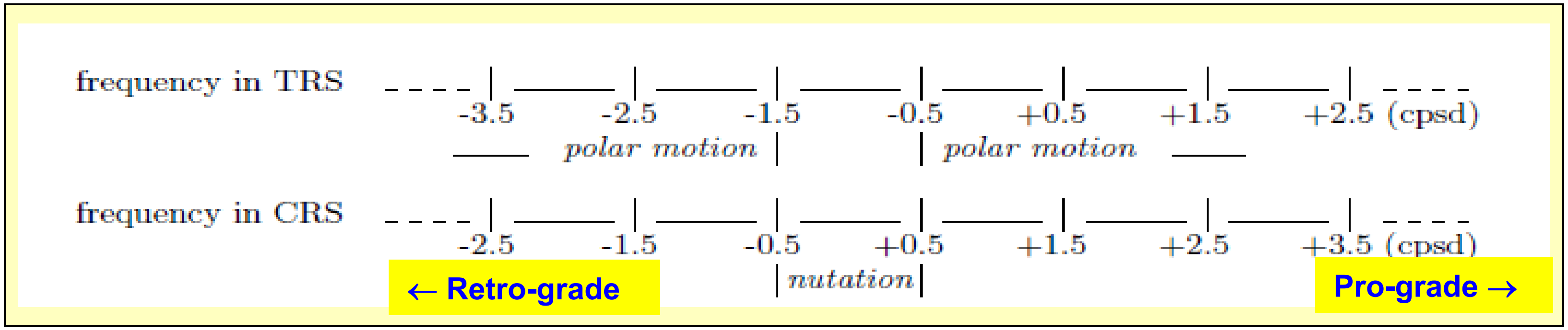
  - **Earth's Pole precession**
  - **Earth's Pole nutation**
  - **Earth's rotation**
  - **Celestial Pole movement**

  Accurately modelled by IERS

  - Irregularities of Earth's Pole position over Earth's crust → Polar Motion
  - Irregularities on the Earth's rotation → Length of Day variations

Permanent monitoring/estimation required to enable highly accurate OD&TS

CONNECTION CRS-TRS-3



POLE DYNAMIC

FREQUENCY < 0.5 cpsd

PRECESSION & NUTATION

FREQUENCY ~1 cpsd

EARTH's ROTATION

FREQUENCY > 0.5 cpsd (Excluding rotation)

POLAR MOTION

Source: IERS Conventions TN32. 2003.

CONNECTION CRS-TRS-4

CRS → *TRS*

Inertial reference system
defined by Astronomical convention

Earth-fixed reference system
defined by Galileo Geodetic Reference

$GCRS \longrightarrow ITRS \longrightarrow GTRS$

Geocentric Celestial Reference System

International Terrestrial Reference System

Galileo Terrestrial Reference System

$$[CRS] = Q(t) \cdot R(t) \cdot W(t)\ [TRS]$$

Polar motion

Rotation of Earth Rotation Angle ~ GST(t)

Transforms J2000 to Celestial Intermediate Pole CIP(t)

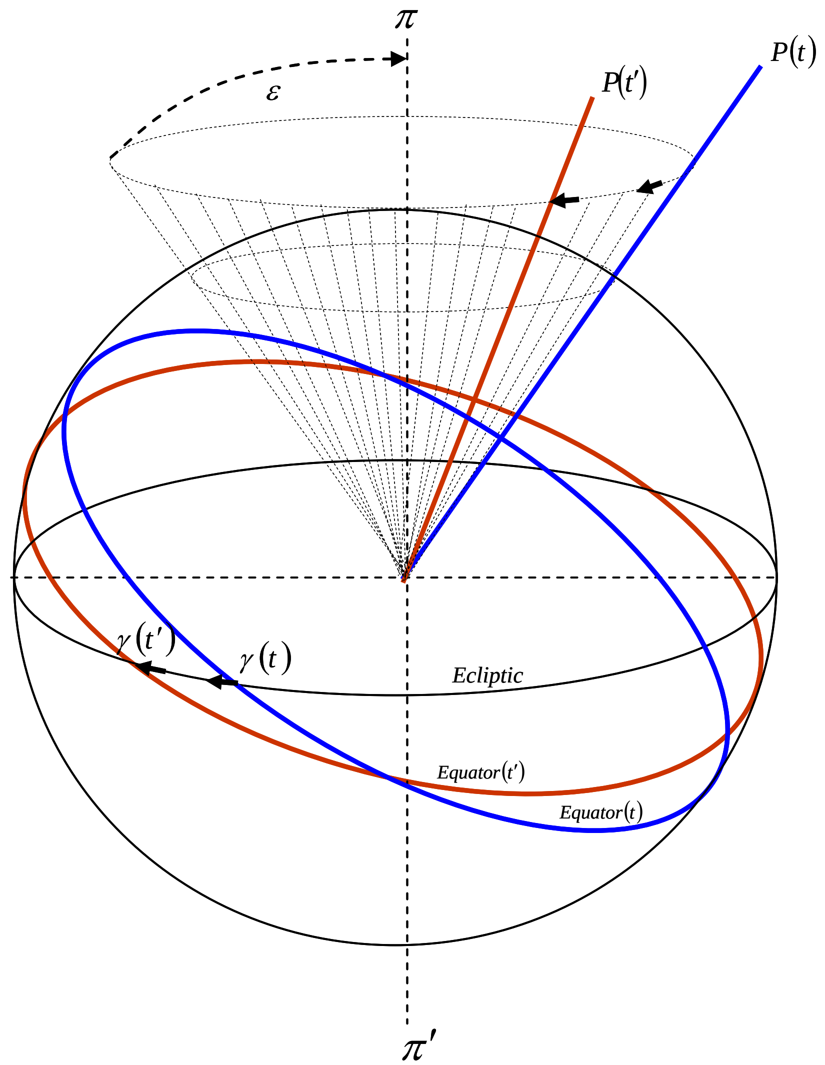
Source: IERS Conventions TN32. 2003

CONNECTION CRS-TRS-5

EARTH'S POLE PRECESSION

- Earth's Pole rotation around the Celestial Pole.
- Aries regression
- Lunar component: ~34'' per year
- Solar component: ~ 16'' per year
- Lunisolar component: ~ 50'' per year
- 1'' is equivalent to 30 m over Earth
- Period ~ 26000 years
- Other terms due to planetary precession components

Precession accurately modelled in IERS conventions.

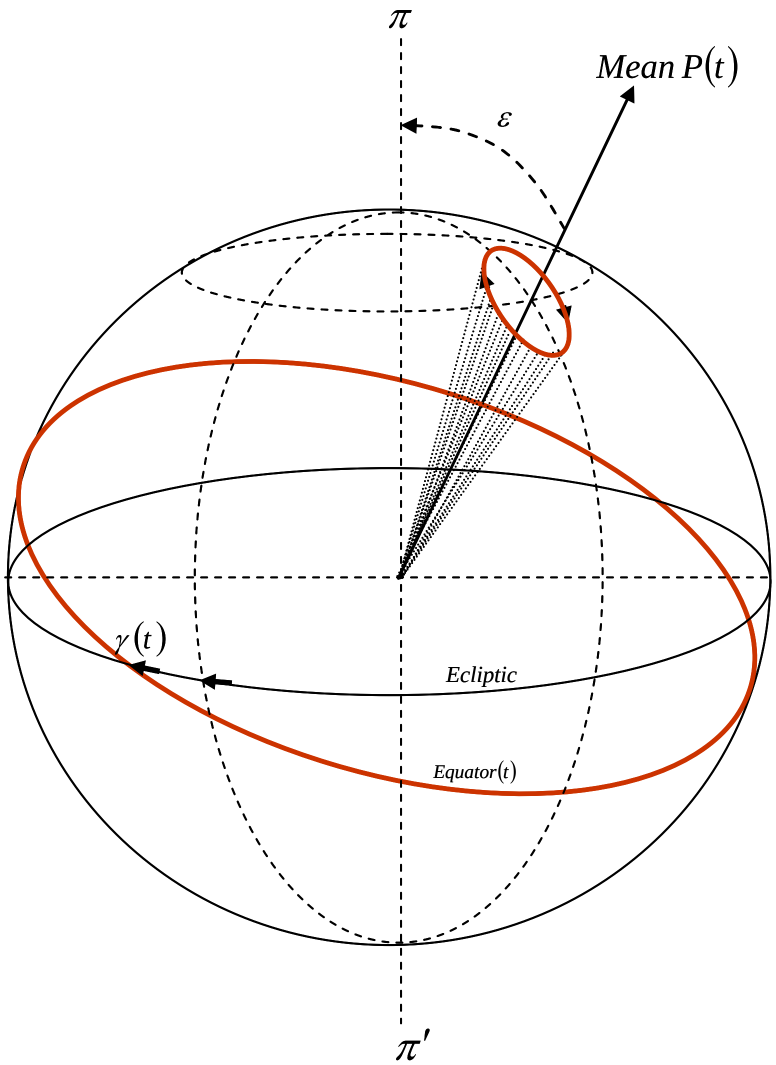


CONNECTION CRS-TRS-6

EARTH'S POLE NUTATION

- Earth's Pole (True Pole) rotation around an Earth's Pole corrected from precession (Mean Pole)
- Main term corresponds to an ellipse centred around Mean Pole with:
  - Semi major axis oriented towards л with magnitude ~ 9.2"
  - Semi minor axis oriented parallel to the ecliptic with magnitude ~ 6.6"
- Period ~ 18(2/3) years
- Many other terms with different periods and amplitudes

Nutation accurately modelled in IERS conventions.



CONNECTION CRS-TRS-7

$$[CRS] \longrightarrow Q^{-1}(t)[CRS]$$

Inertial reference system defined by Astronomical convention

Intermediate reference frame at epoch (t)

$$Q(t) \approx \{f_{ij}(X, Y)\}_{3\,x\,3} \qquad [1 \le i \le 3,\ 1 \le j \le 3]$$

$$\left(X, \quad Y, \quad Z = \sqrt{1 - X^2 + Y^2}\right)$$

$$\begin{aligned} X = \; & -0.01661699'' + 2004.19174288''t - 0.42721905''t^2 \\ & -0.19862054''t^3 - 0.00004605''t^4 + 0.00000598''t^5 \\ & +\textstyle\sum_i [(a_{s,0})_i \sin(\text{ARGUMENT}) + (a_{c,0})_i \cos(\text{ARGUMENT})] \\ & +\textstyle\sum_i [(a_{s,1})_i t \sin(\text{ARGUMENT}) + (a_{c,1})_i t \cos(\text{ARGUMENT})] \\ & +\textstyle\sum_i [(a_{s,2})_i t^2 \sin(\text{ARGUMENT}) + (a_{c,2})_i t^2 \cos(\text{ARGUMENT})] \\ & + \cdots, \end{aligned}$$

$$Y = \cdots$$

- CIP unit vector CRS coordinates at epoch (t)
- 't' is TT elapsed from 2000 January 1, 12h, in centuries
- 'ARGUMENT' is function of moon, sun and planetary arguments

Source: IERS Conventions TN32. 2003

CONNECTION CRS-TRS-8

$$[CIP] \longrightarrow R(t)^{-1}[CIP]$$

Intermediate reference frame at epoch (t)

Terrestrial reference frame not corrected from polar motion

$$R(t) = R_z(-ERA)$$

$$\theta(T_u) = 2\pi(0.7790572732640 + 1.00273781191135448 T_u)$$

$$T_u = (\text{Julian UT1 date} - 2451545.0)$$

$$UT1 = [UT1 - UTC] + [UTC - GST] + GST$$

(Note: GST = Galileo System Time, no Greenwich Sidereal Time)

- ERA is Earth Rotation Angle (θ)
- T_u refers UT1 to J200 Julian Date
- A priori model (IERS) for diurnal & sub-diurnal UT1-UTC fluctuations
- UT1-UTC mean daily value from pseudo-real time observation.

Source: IERS Conventions TN32. 2003

IRREGULARITIES OF POLE POSITION OVER EARTH'S CRUST (I).

- Polar Motion (Xp, Yp)
- Component with period ~ 435 days (CW)
- Component with period ~ 365 days
- Drift component, mostly ~ in direction 80th meridian
- Peak excursions of up to 20 m
- Partly predictable (from IERS)

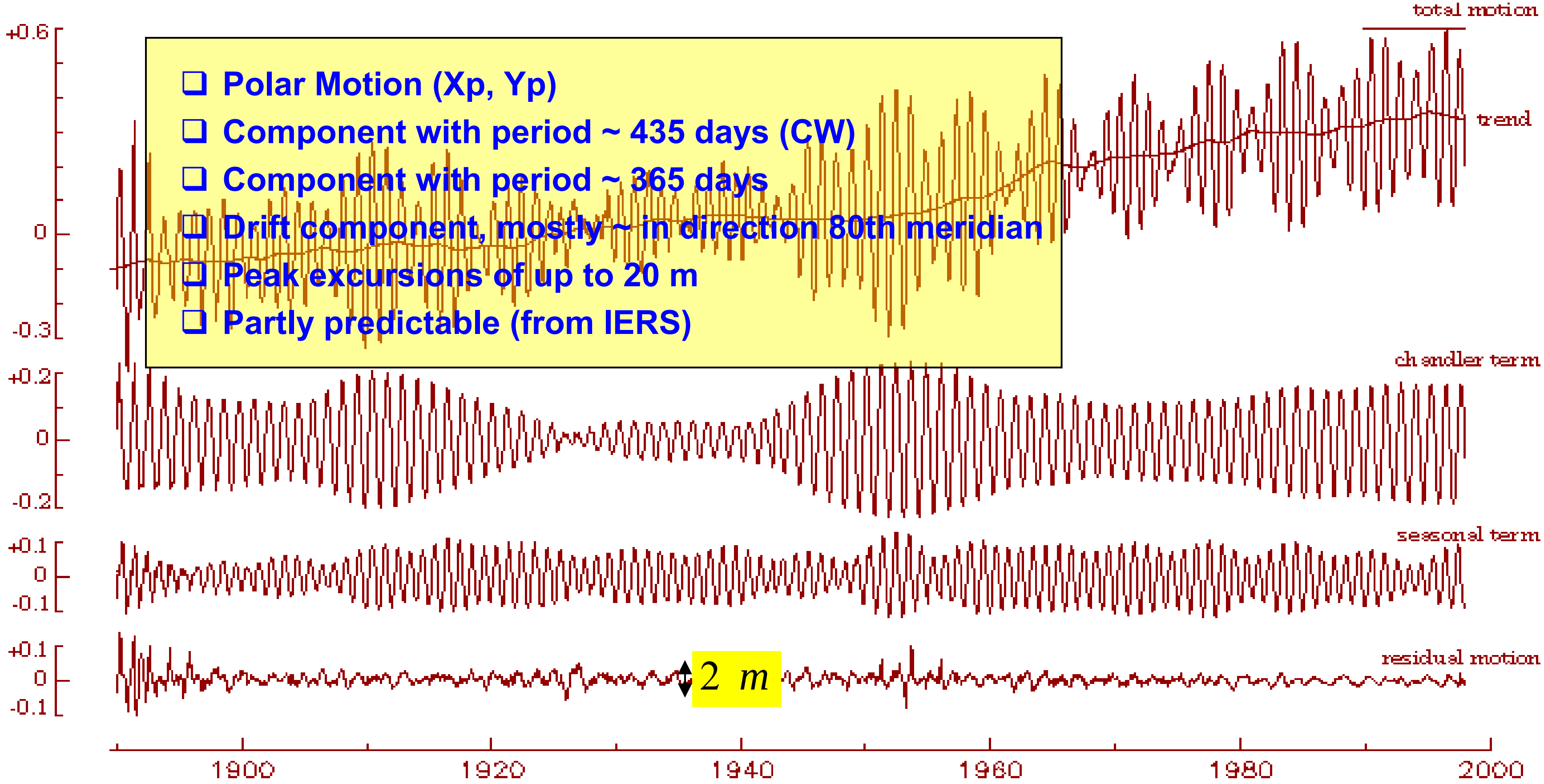


Figure II-3. Y - coordinate of the pole Unit: 1".

Source: IERS

CONNECTION CRS-TRS-10

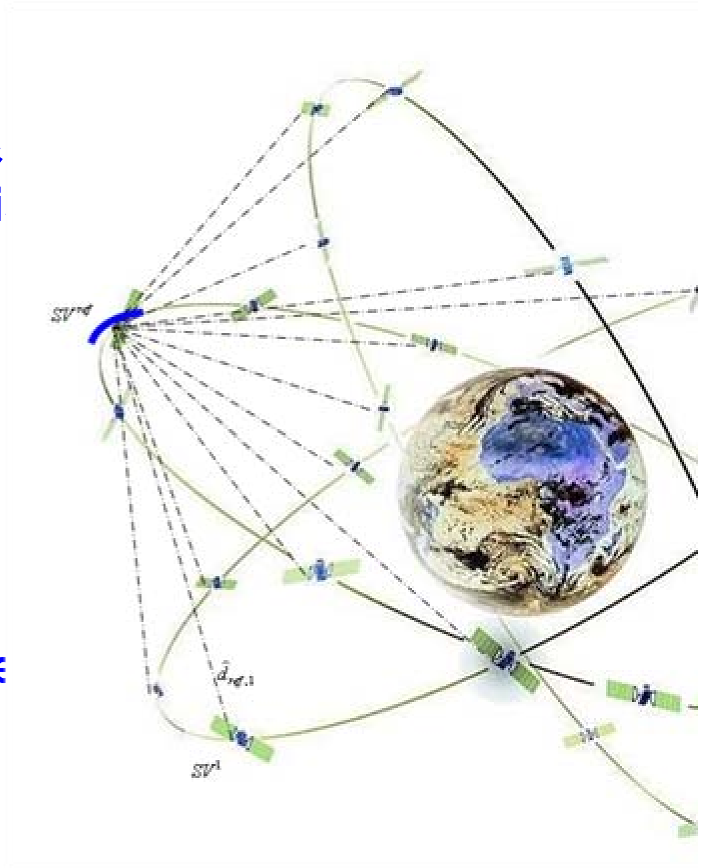
- Ranging observations needed to measure the short terms non modelled irregularities of the Earth Orientation Parameters (EOP).
- Conventional equipment most likely would be sufficient.
- Some techniques may improve the quality of the ranging observations.

CONSIDERATIONS ON ISL PAYLOAD.

PAYLOAD- 1

GENERAL CONSIDERATIONS

- Minimize inter-satellite communication & ranging PL complexity & technological ri
- Maximize inter-satellite ranging payload performance
- Maximize inter-satellite ranging payload reliability
- Minimize development cost and schedul



PAYLOAD- 2

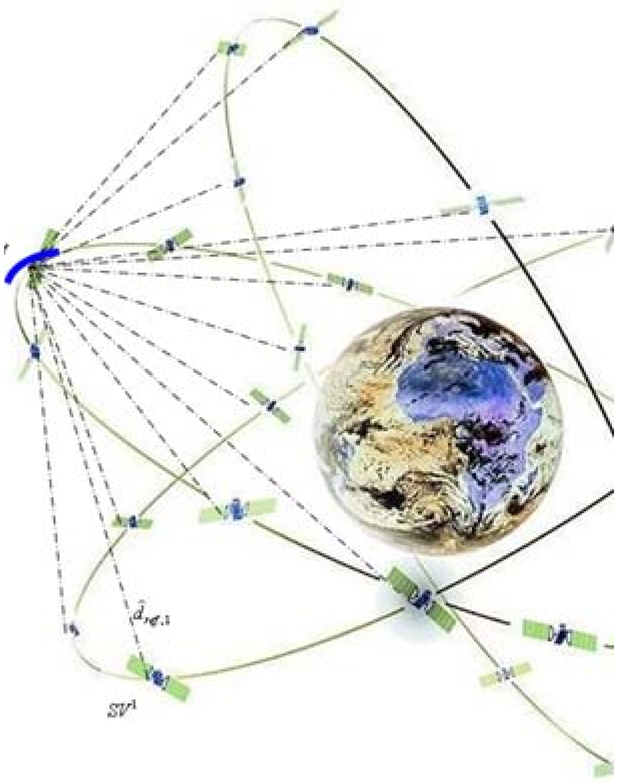
Minimize the inter-satellite communication & ranging payload complexity and technological risk

- ❑ Minimizing the number of frequencies required for the inter-satellite communication and ranging signal, in order to

  - Simplify the associated antenna sub-system (radiating elements and feeding networks of the radiating elements matched to one single band)

  - Simplify the associated transceiver radio-frequency front-ends (single-narrowband RF pass-band filters, single local oscillator & single intermediate frequency, single-band IF filters)

  - Minimize the presence of frequency dependent biases in the inter-satellite range observations



Source: ESA GSP Programme: GNSS+ & ADVISE

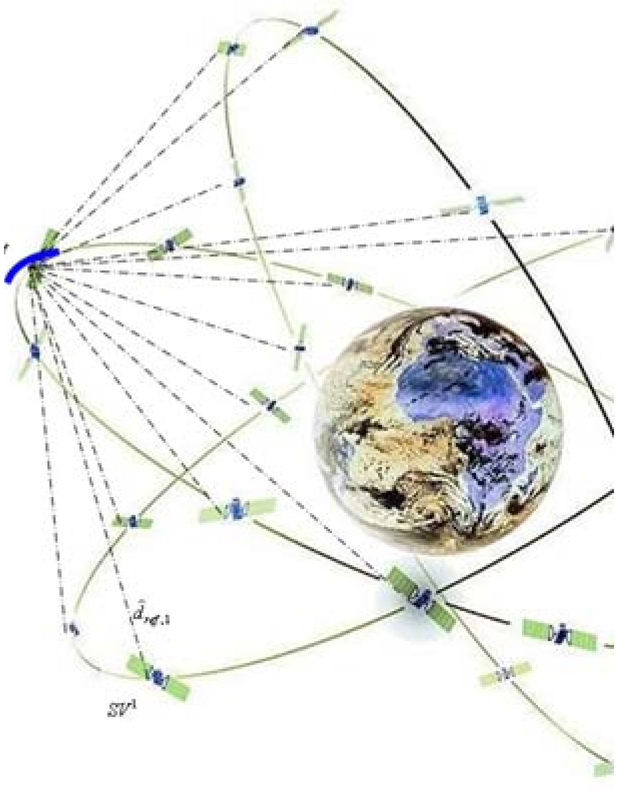
PAYLOAD- 3

(…) cont.

- Minimize the overall bandwidth required for the ISL signal to ease its acceptability at ITU level.

❑ Defining a single-point to single-point inter-satellite connectivity scheme, with connections established sequentially in order to:

- Reduce drastically the payload power consumption
- Enable the re-use of frequencies for transmission and reception
- Define a spacecraft-independent inter-satellite communication & ranging signal (besides spreading codes which are still satellite specific)

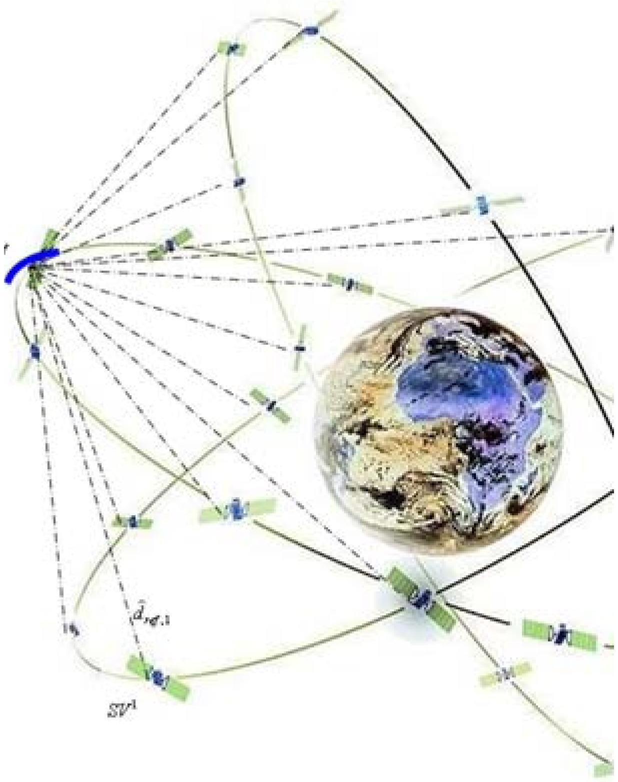


Source: ESA GSP Programme: GNSS+ & ADVISE

PAYLOAD- 4

(…) cont.

- ❑ Defining a non continuous tracking scheme with hot re-acquisition, which benefits from the availability on-board of the ephemeris and clock data associated to every spacecraft, with tracking slot duration long enough to neglect transitory effects, without constraining the duration of the overall TDMA cycle.
- ❑ Integrating physically the inter-satellite communication signal & inter-satellite ranging signal
- ❑ Defining a connectivity scheme which does not require of an antenna pattern for the ISL payload neither in transmission mode nor in reception mode, with an unnecessarily large directivity

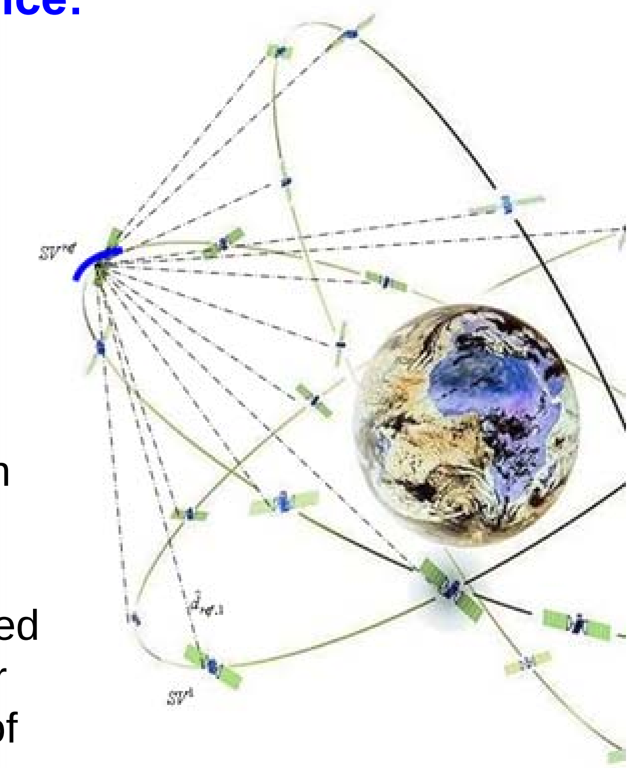


Source: ESA GSP Programme: GNSS+ & ADVISE

PAYLOAD- 5

Maximize inter-satellite ranging payload performance:

- Defining an antenna pattern, both in TX and RX mode, highly directive to minimize the necessary power, and to compensate the large free-space propagation losses between satellites.
- Ensuring that inter-satellite range observables are not ambiguous and competitive when compared against the conventional satellite-to-ground range observations, given the superior geometrical strength of the first.
- Ensuring that inter-satellite range observables are gathered bi-directionally. For what respects to ranging/time-transfer capabilities this approach enables an implicit separation of the geometrical information from the synchronization information already in the observables domain



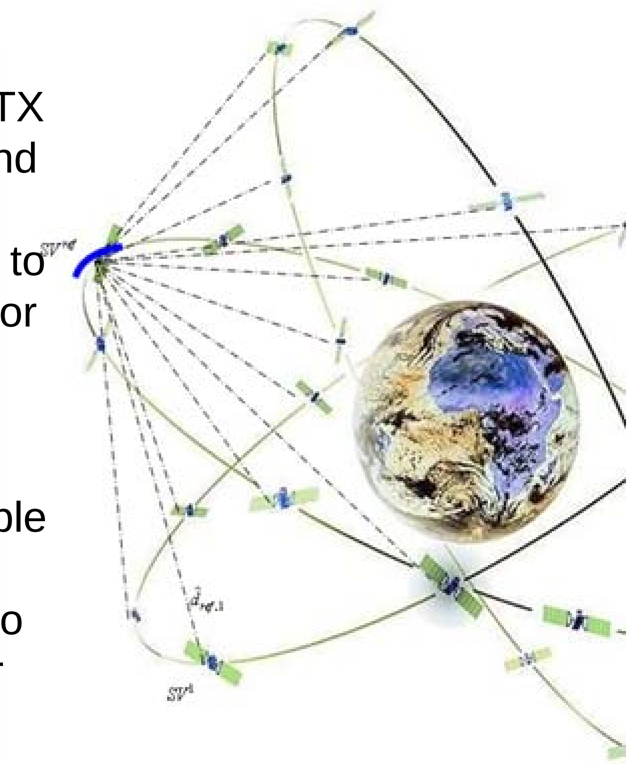
Source: ESA GSP Programme: GNSS+ & ADVISE

PAYLOAD- 6

(…) cont.

- ❑ Ensuring that, within a TDMA cycle, each ISL payload in TX mode is listened by different ISL payloads in RX mode, and each ISL payload in RX mode listens to different ISL payloads (either ISL v0/1) in TX mode. For what respects to ranging/time-transfer capabilities this enables the implicit or explicit cancellation within the orbit estimation process of the observables mean hardware biases.

- ❑ Defining an antenna pattern in TX and RX mode compatible with an accurate on-ground off-line calibration (regularly performed all along payload operational life) transparent to the end Global Navigation Satellite Systems (GNSS) user and to the spacecraft.



Source: ESA GSP Programme: GNSS+ & ADVISE

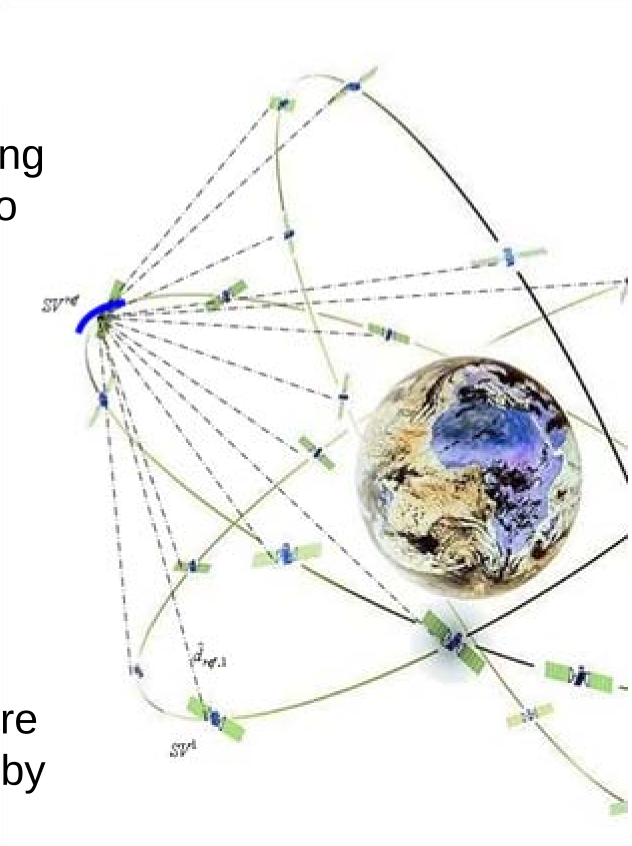
PAYLOAD- 7

(…) cont.

- Accommodating the inter-satellite communication & ranging antenna sub-system in a spacecraft facet perpendicular to the nadir axis, with visibility neither on the other facets of the spacecraft, nor on the solar panels, to minimize reflective & diffuse multipath.

- Defining an antenna pattern, in reception mode, highly directive to minimize the ranging errors induced by reflective and diffuse multipath.

- Specifying an inter-satellite communication and ranging antenna pattern ideally azimuth independent, and therefore invariant to the spacecraft yaw steering rotation imposed by the spacecraft attitude law.

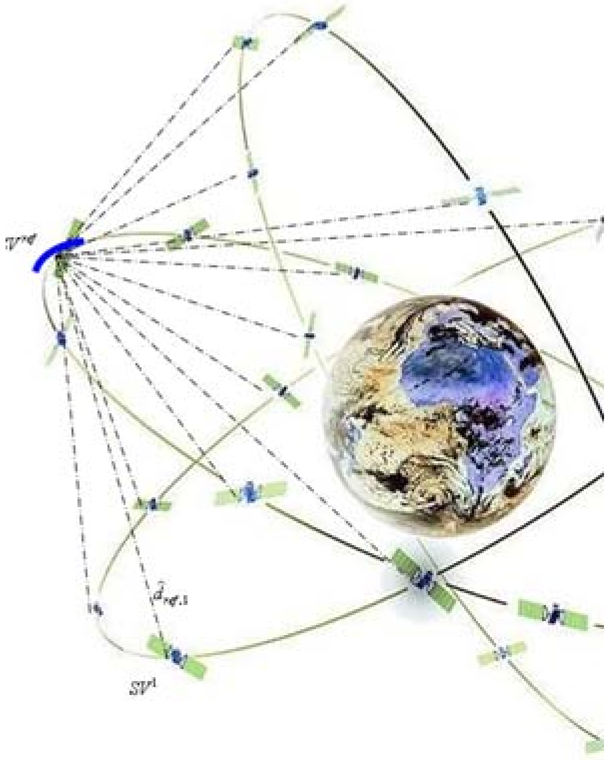


PAYLOAD- 8

Maximize inter-satellite ranging payload reliability:

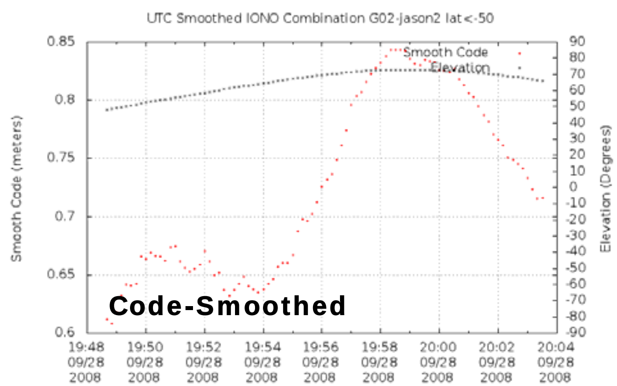
- A design based on known and extensively proven technologies (e.g. waveguides, antenna concepts for which relevant space-qualified heritage exists)

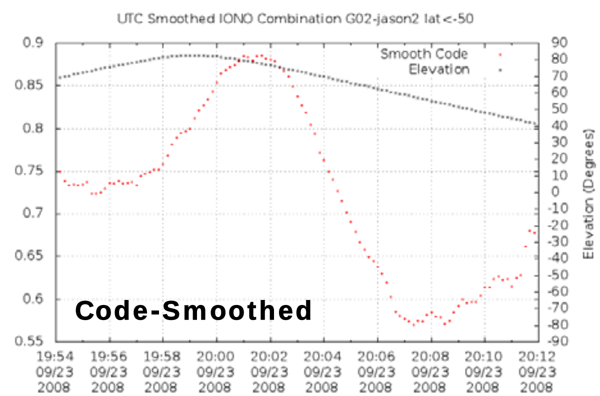
- Avoiding technologies, such as optical links, for which reliability figure is still too low to be considered for its use in an operational system.

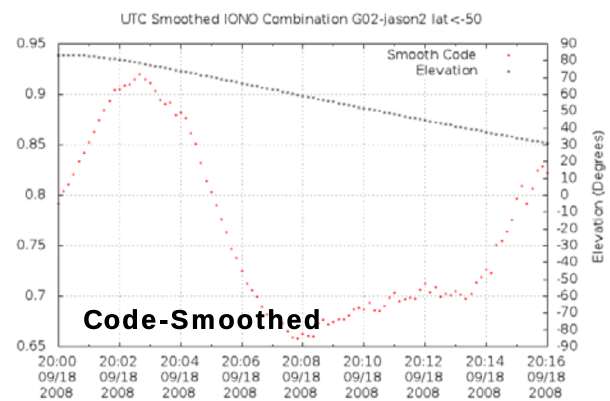


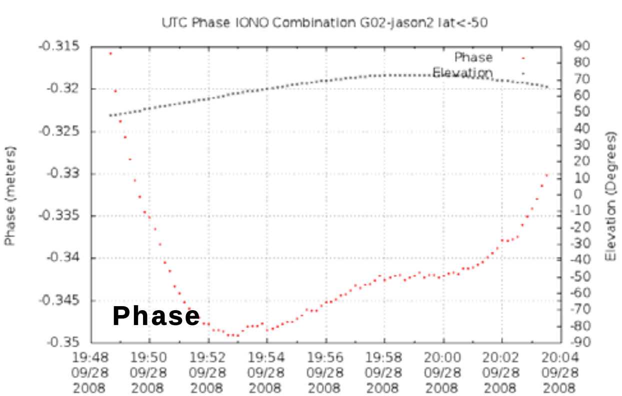
Source: ESA GSP Programme: GNSS+ & ADVISE

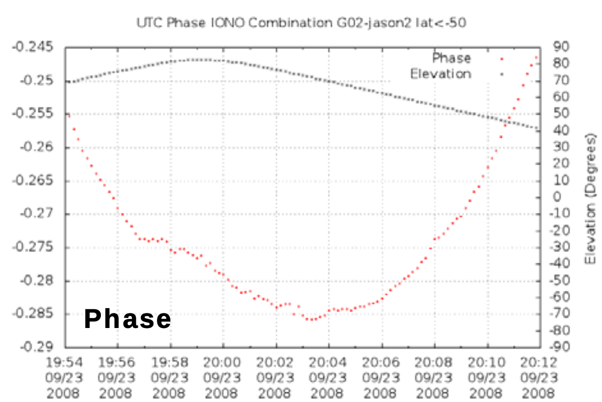
Hardware biases

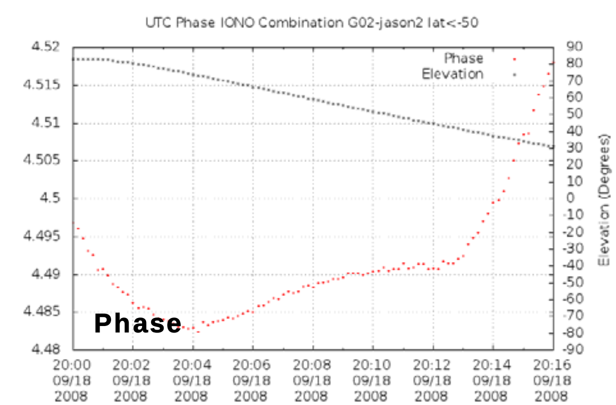








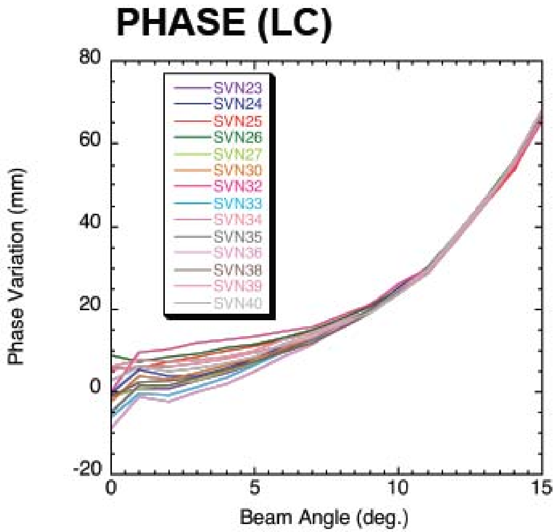


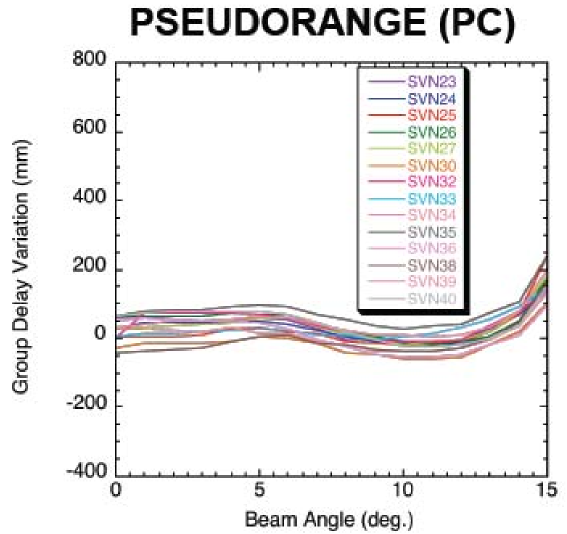


Source: GMV under ESA GSP Contract. 2012

PAYLOAD- 10

GPS BLOCK IIA TX ANTENNA



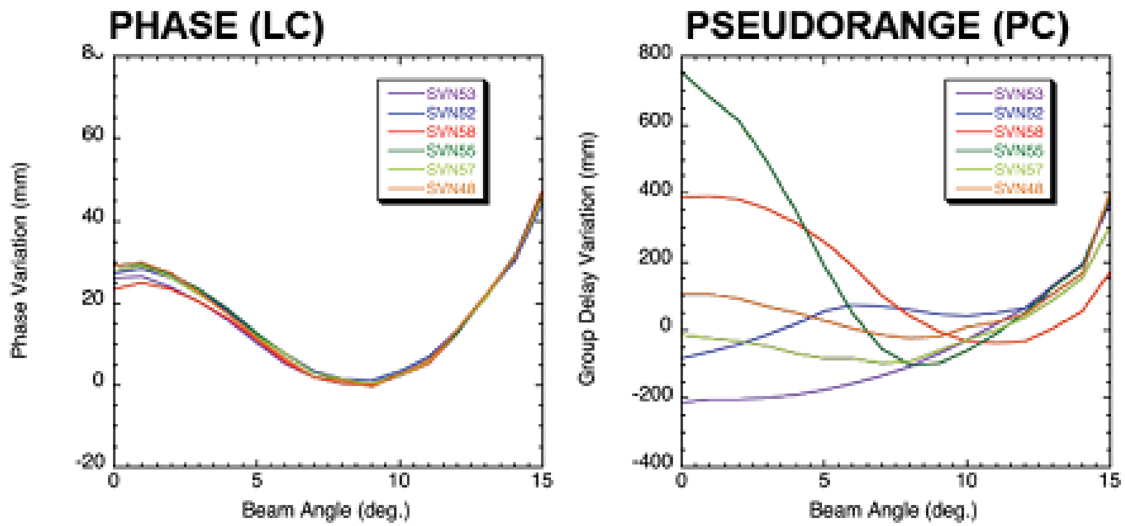


- **Sub-decimeter ranging necessitates to pay attention to all transmission and reception chains including transmission and reception antennas.**

Source: NASA – JPL. 2010.

PAYLOAD- 11

GPS BLOCK IIR TX ANTENNA



- Sub-decimeter ranging necessitates to pay attention to all transmission and reception chains including transmission and reception antennas.

Source: NASA – JPL. 2010.

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