University of Nottingham
UK | CHINA | MALAYSIA

Mitigation of Ionospheric Scintillation Effects for Precise GNSS Positioning

Dr Sreeja Vadakke Veettil

International School of Space Science

L'Aquila

19 September 2018

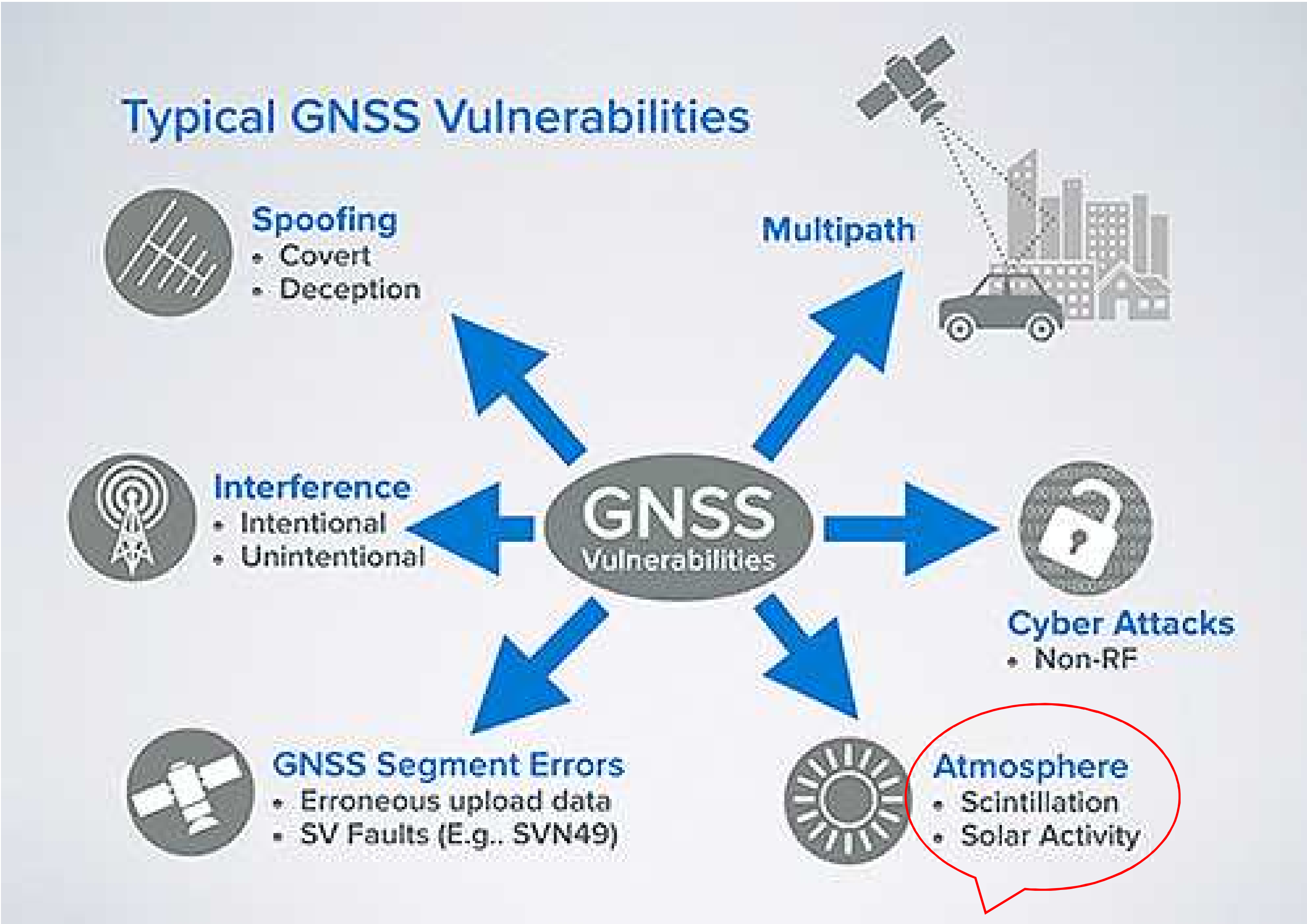
Sreeja.Veettil@nottingham.ac.uk

Global Navigation Satellite Systems (GNSS)

Satellite navigation systems that provide autonomous geo-spatial positioning with global coverage

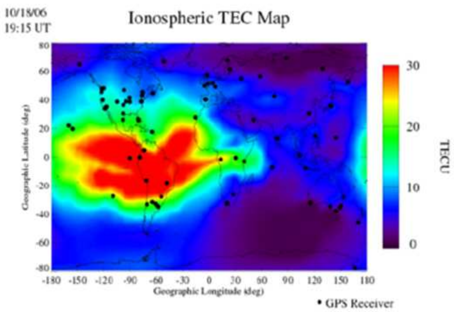
GNSS High Accuracy Applications

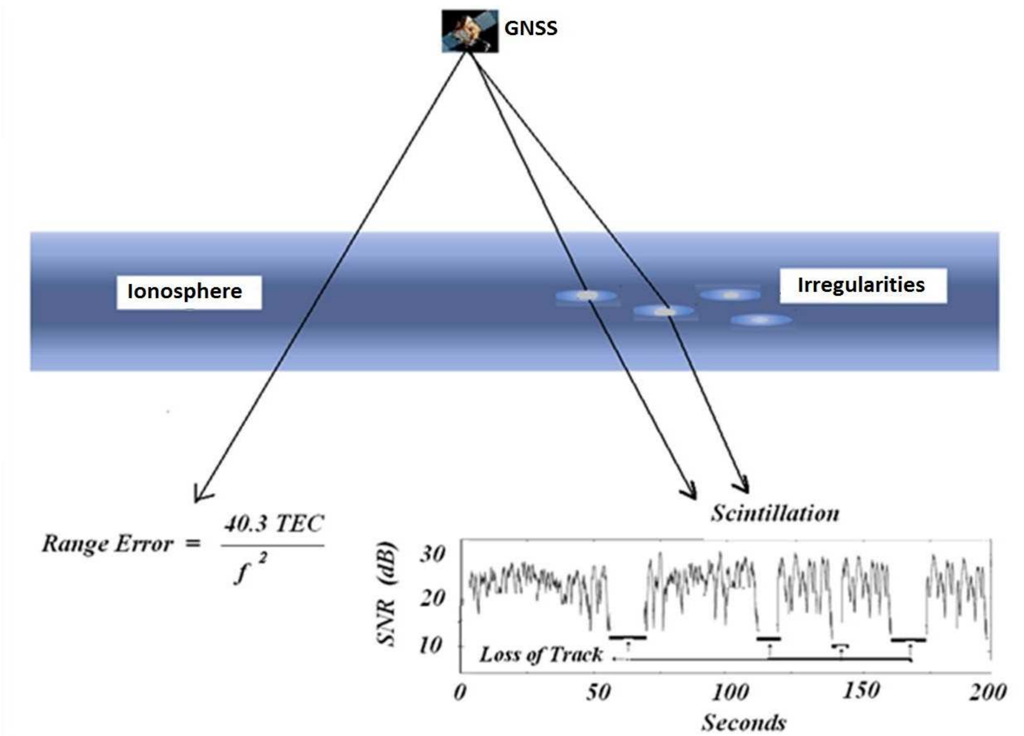
Fundamentals of GNSS threats

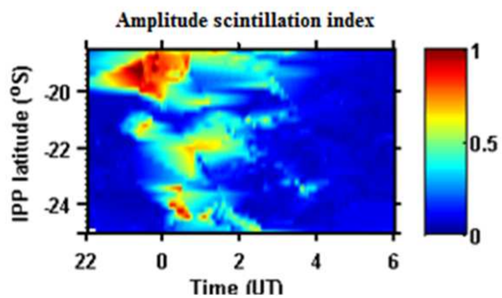


GNSS and the Ionosphere

- Earth's ionosphere: **Single largest error source** in GNSS positioning error budget
- Ionospheric effects on GNSS signals

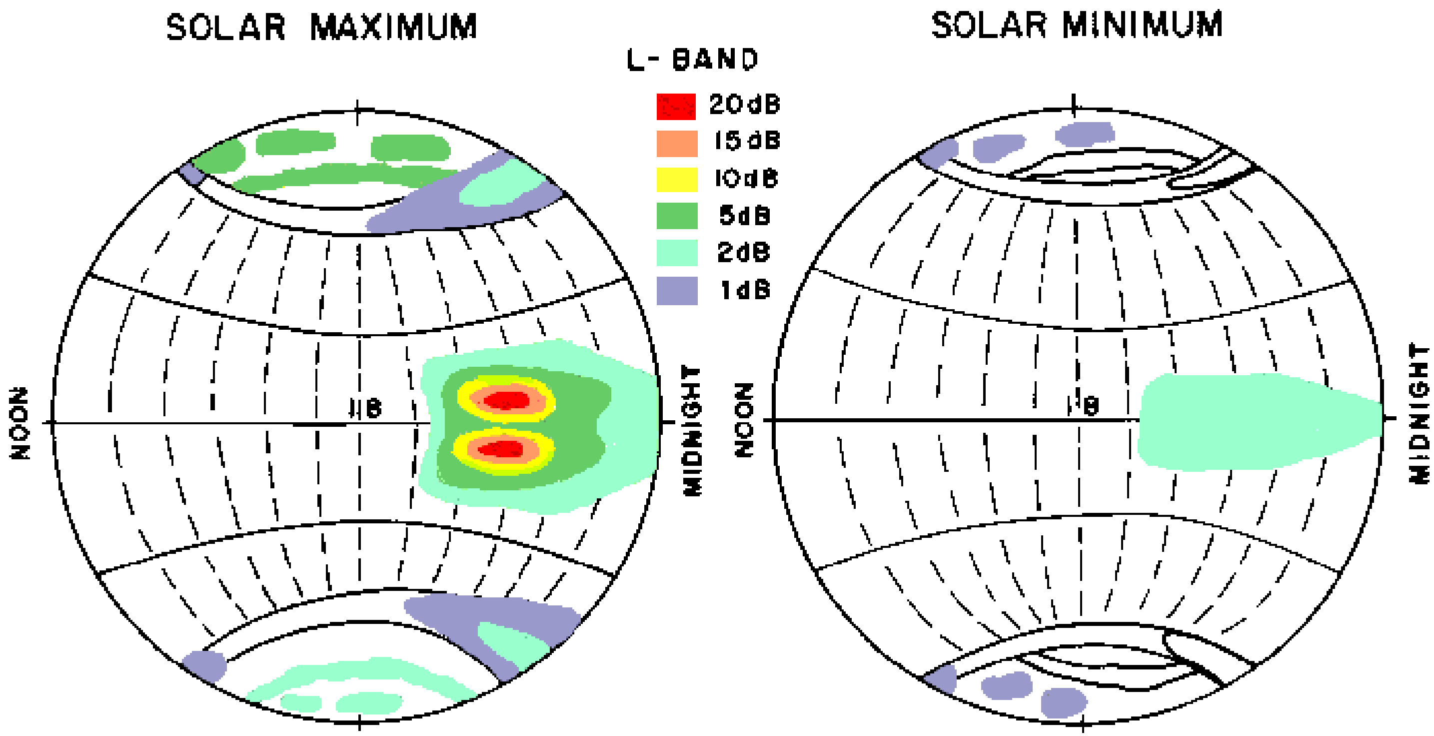






Ionospheric Scintillation Phenomenon

- Rapid fluctuations in the amplitude and phase of transionospheric radio signals



Basu, S. et al., J. Atmos. Terr. Phys, v.64, pp. 1745-1754,2002

How do we measure scintillation?

- **Amplitude Scintillation index S4**:

Standard deviation of the received signal power normalized to the average signal power

$$S_4 = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle}$$

where I is the received intensity and <.> denotes ensemble average (over 60s of high rate data)

- **Phase scintillation index σ_φ**:

Standard deviation of the phase measurements

$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle}$$

where φ is the carrier phase measurement

GNSS Scintillation monitoring receivers

- High rate data sampling (50Hz)
- High quality oscillator
- Record amplitude and phase scintillation indices

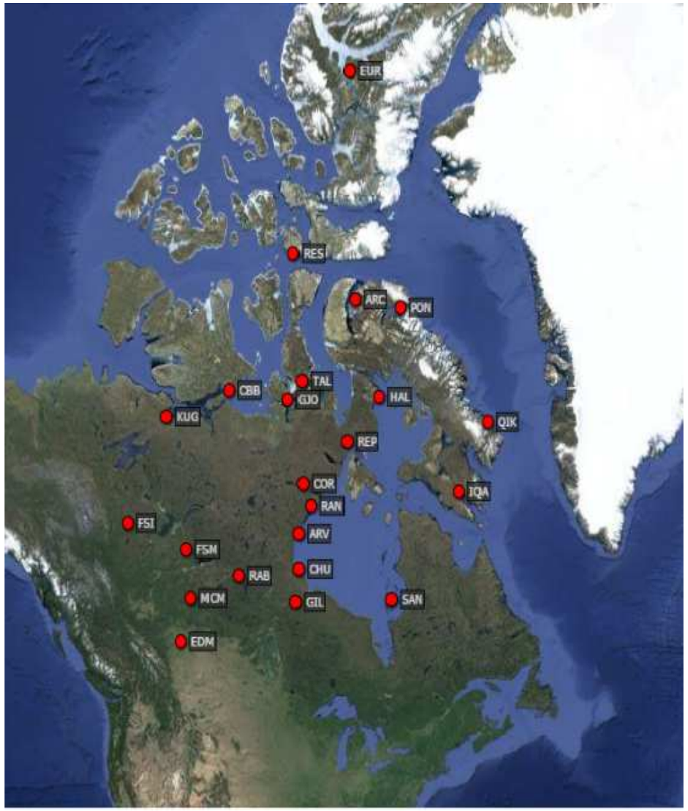
The pioneer NovAtel GSV4004 receiver (late 1990's)

- GPS only
- Now replaced by the NovAtel GPStation-6TM

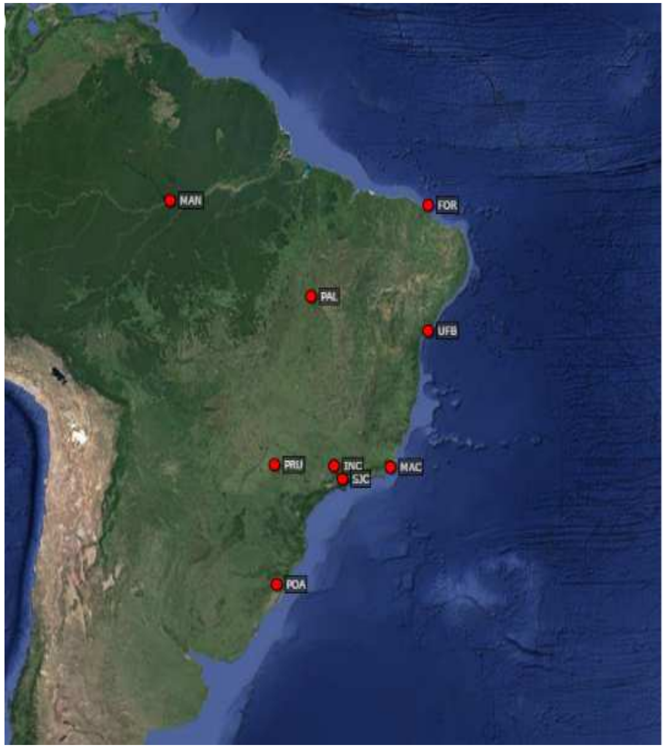
- Multi-constellation multi-frequency
- Now replaced by the PolaRx5S

Scintillation monitoring networks

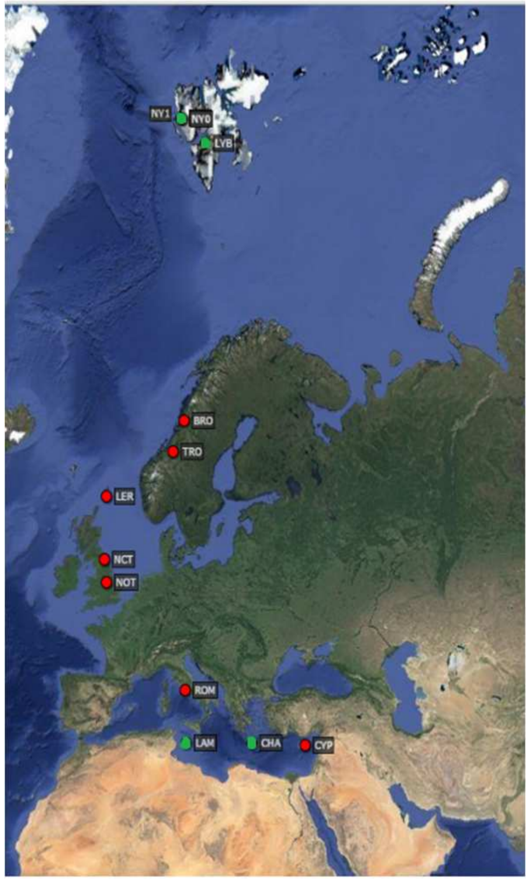
Canada
(CHAIN)



Brazil
(CIGALA/CALIBRA)



Europe



University of Nottingham
UK | CHINA | MALAYSIA

Scintillation effects on GNSS receivers (1)

- Significantly degrade GNSS receiver tracking performance
- Code and phase tracking loop performances can be degraded

Scintillating signals enter GNSS Rx tracking loop

Amplitude scintillation → signal-to-noise ratio decreases below the receiver threshold → signal loss and cycle slips

Phase scintillation → rapid phase shifts → exceed the loop bandwidth → loss of phase lock

GNSS position errors

Scintillation effects on GNSS receivers (2)

- Variance of the error at Delay Locked Loop / Phase Locked Loop output (tracking jitter) - good measure of scintillation effect on the receiver signal tracking
- Scintillation sensitive tracking error models: Conker et al. [2003] / Moraes et al. (2014)

$$\sigma^2_{\phi_\varepsilon} = \sigma^2_{\phi_S} + \sigma^2_{\phi_T} + \sigma^2_{\phi_{osc}}$$

Effect of scintillation

Effect of thermal noise

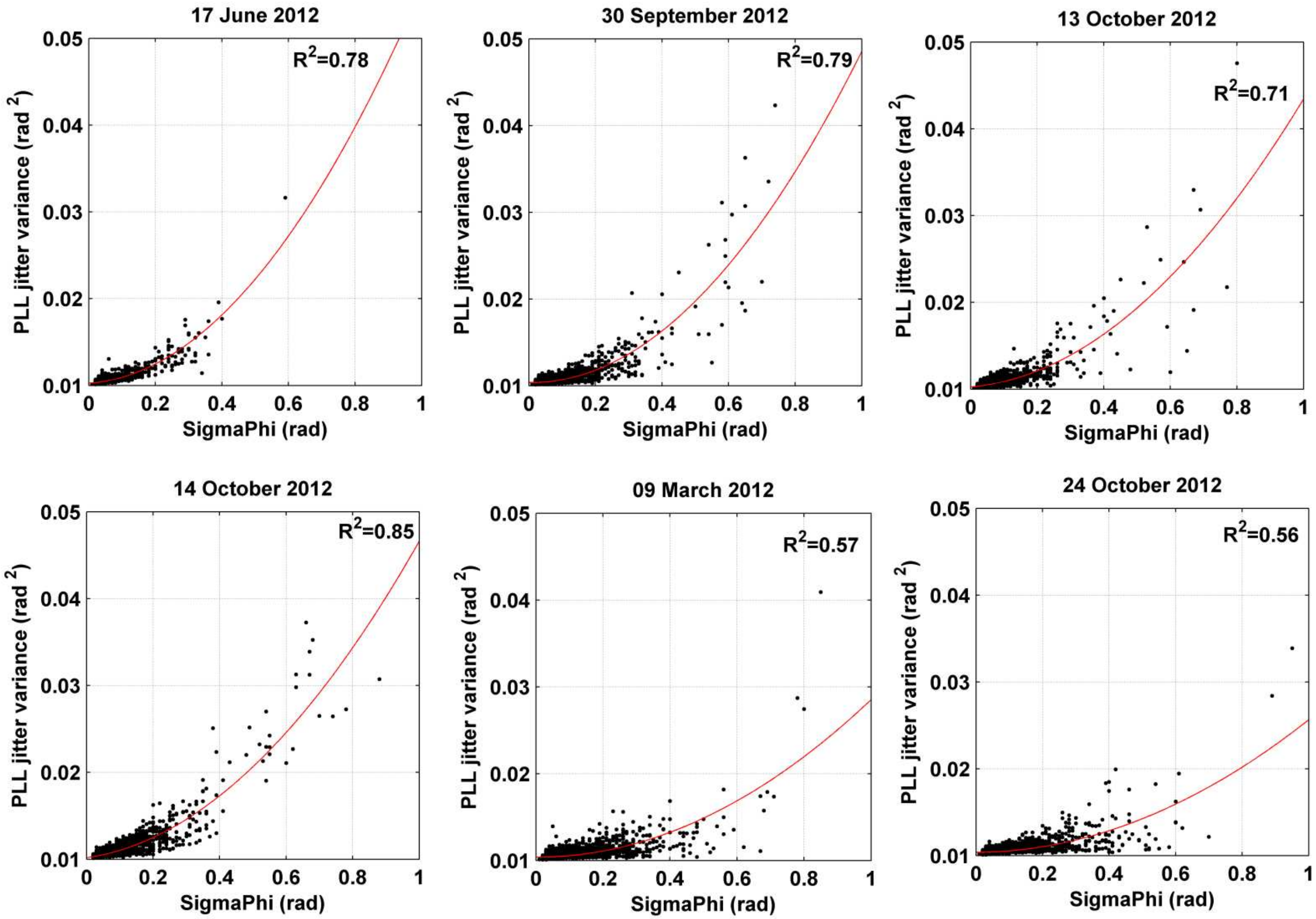
Effect of oscillator noise

$$\sigma^2_{\phi_S} = \frac{\pi T}{k f_n^{p-1} \sin \frac{[2k+1-p]\pi}{2k}}$$

$$\sigma^2_{\phi_T} = \frac{B_n}{(c/n_0)_{L1C/A}(1-S4^2_{L1})} \cdot \left(1 + \frac{1}{2\eta (c/n_0)_{L1C/A}(1-2S4^2_{L1})}\right)$$

Conker et al., Radio Sci., doi: 10.1029/2000RS002604,2003
Moraes et al., Radio Science, v9(1), 2014

Scintillation and Receiver Tracking



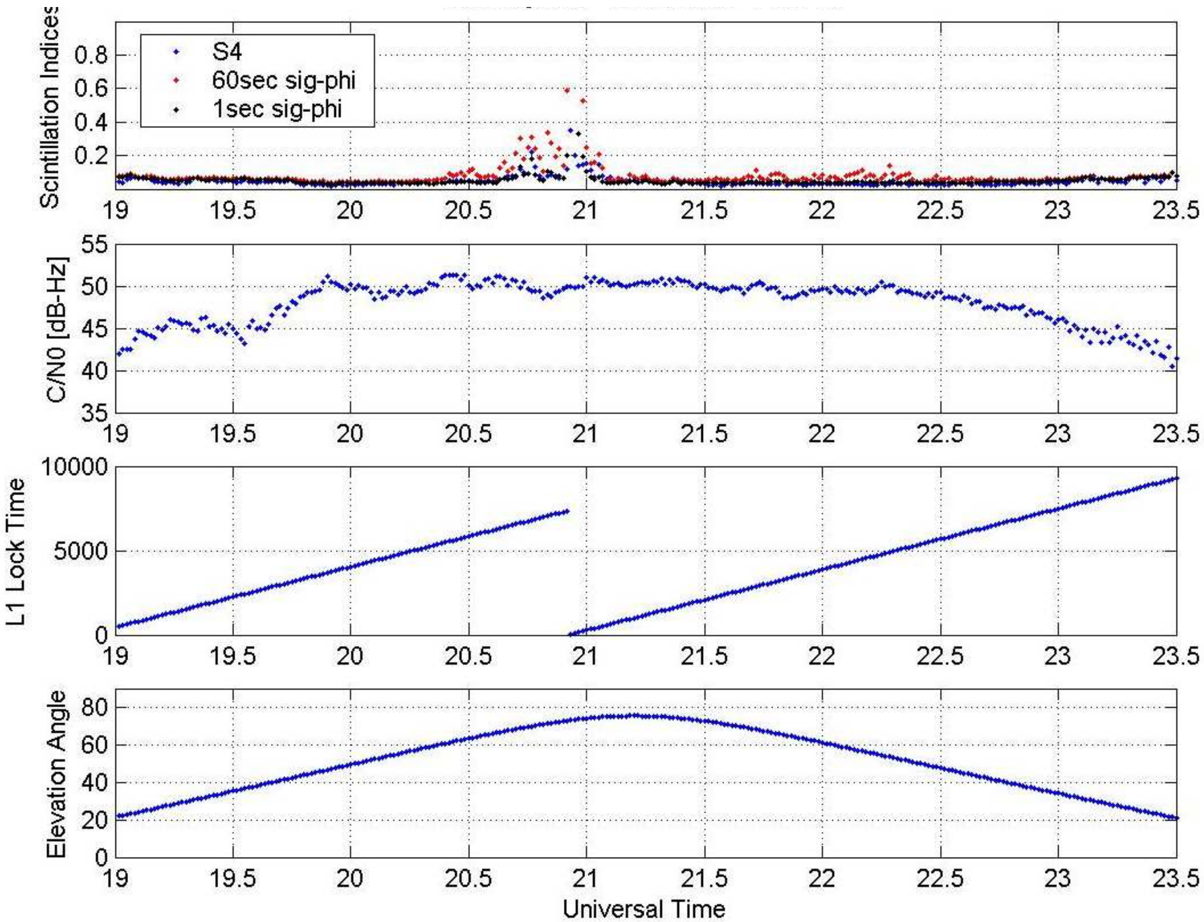
Aquino and Sreeja, Space weather, doi:10.1002/swe.20047,2013;

Scintillation x Positioning Errors

- Loss of lock on satellite – weaker geometry, large positioning errors, even outages
- Measurement quality degradation (large residuals)
- Positioning accuracy degradation (‘wrong’ coordinates)

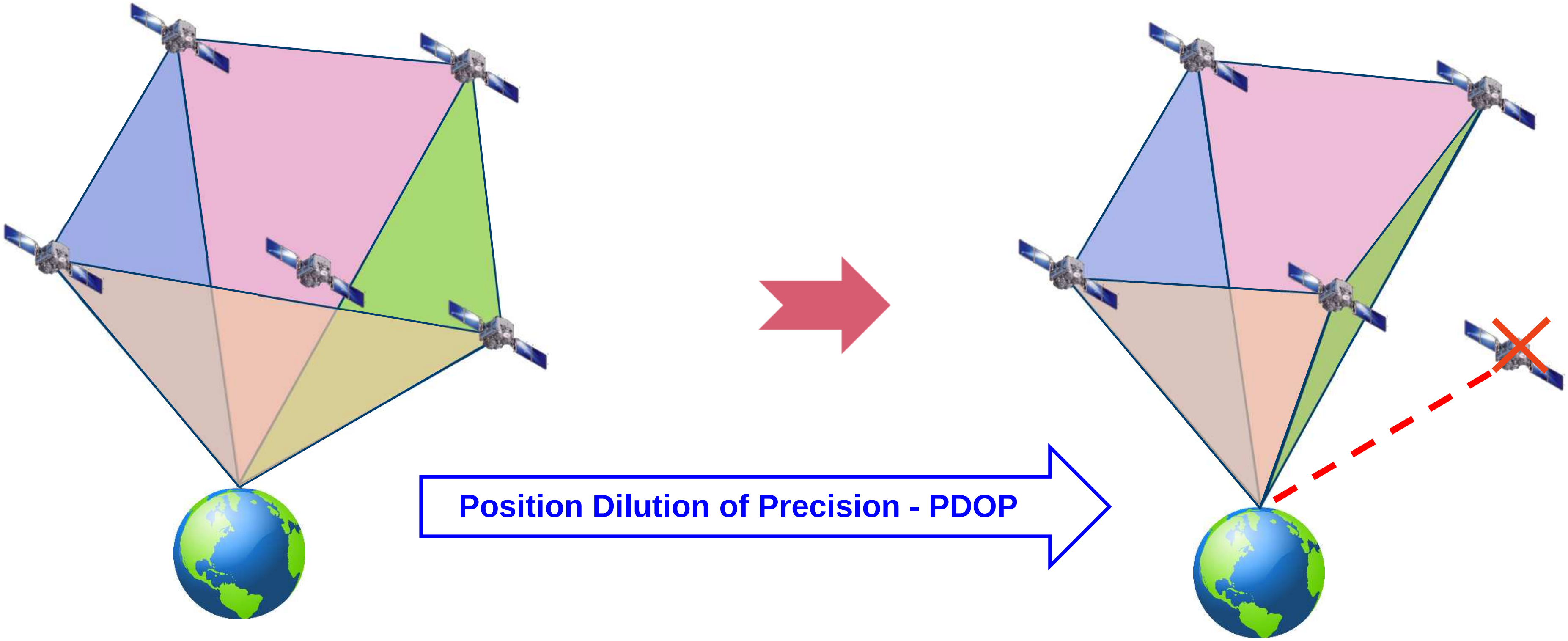
Loss of Lock correlated with scintillation

Bronnoysund (~65° N) – GSV4004 Scintillation Monitor



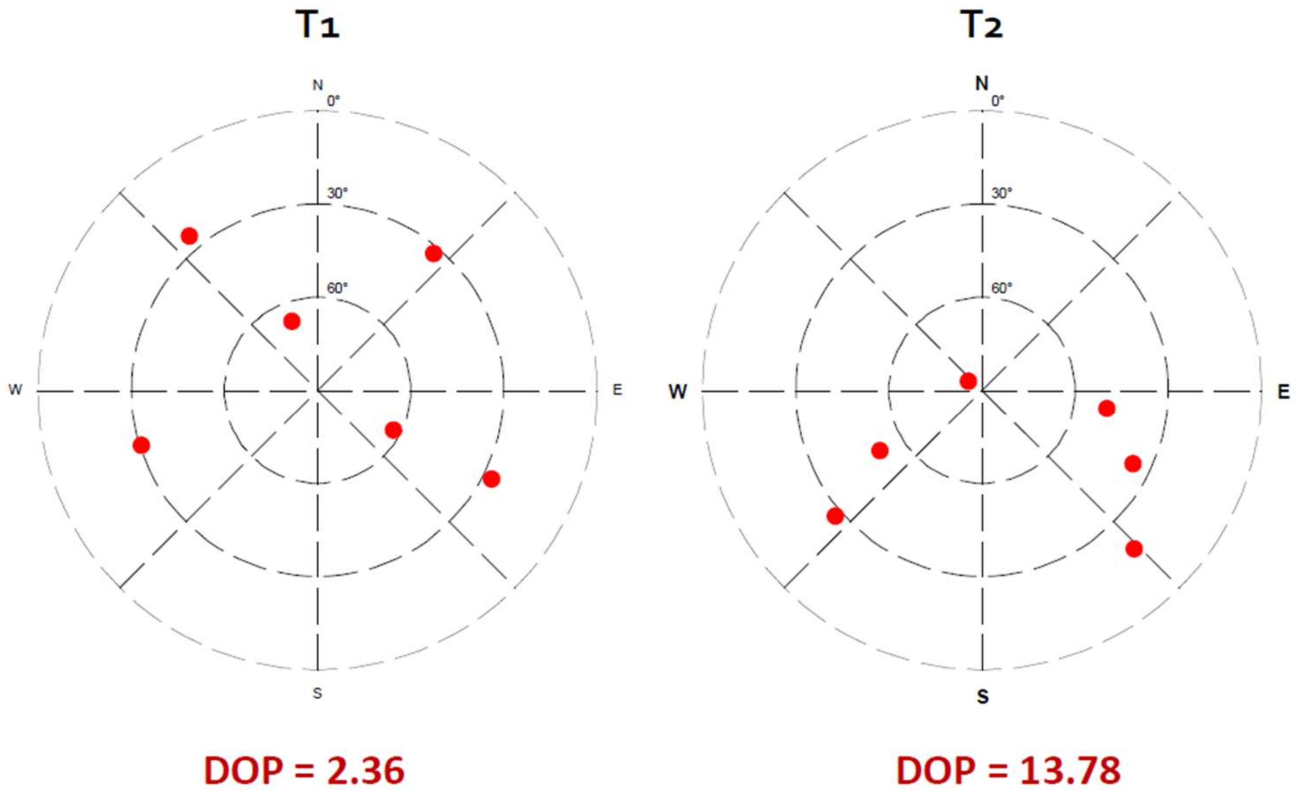
Impact of scintillation on positioning (1)

Loss of lock on satellite >> weaker geometry >> even outages



Impact of scintillation on positioning (1a)

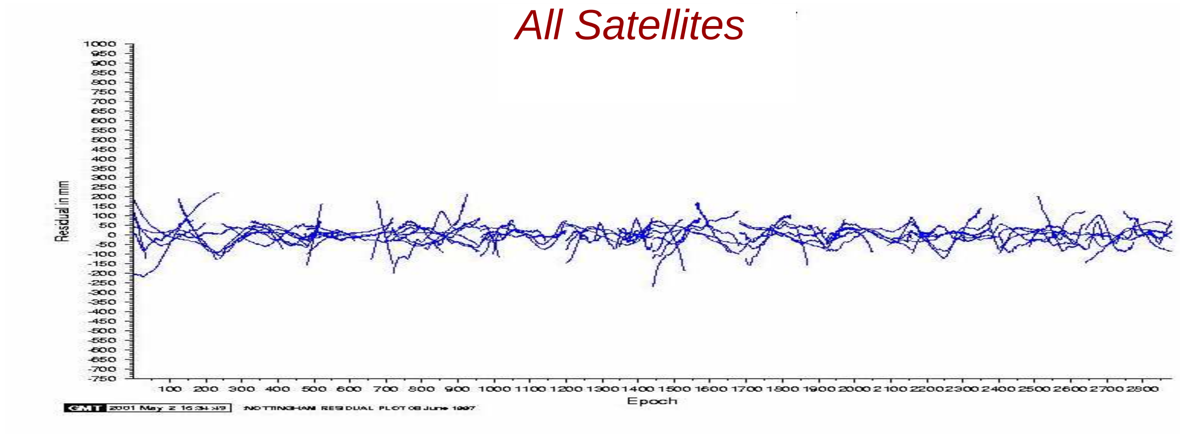
High DOP values vary not only with the number of satellites being tracked



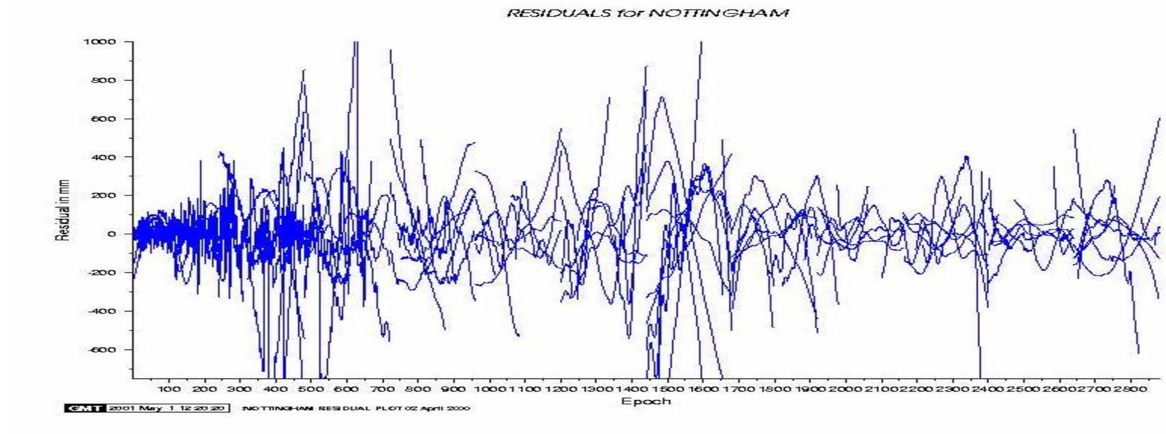
Courtesy of M Lonchay

Impact of scintillation on positioning (2)

Measurement quality degradation >> large residuals



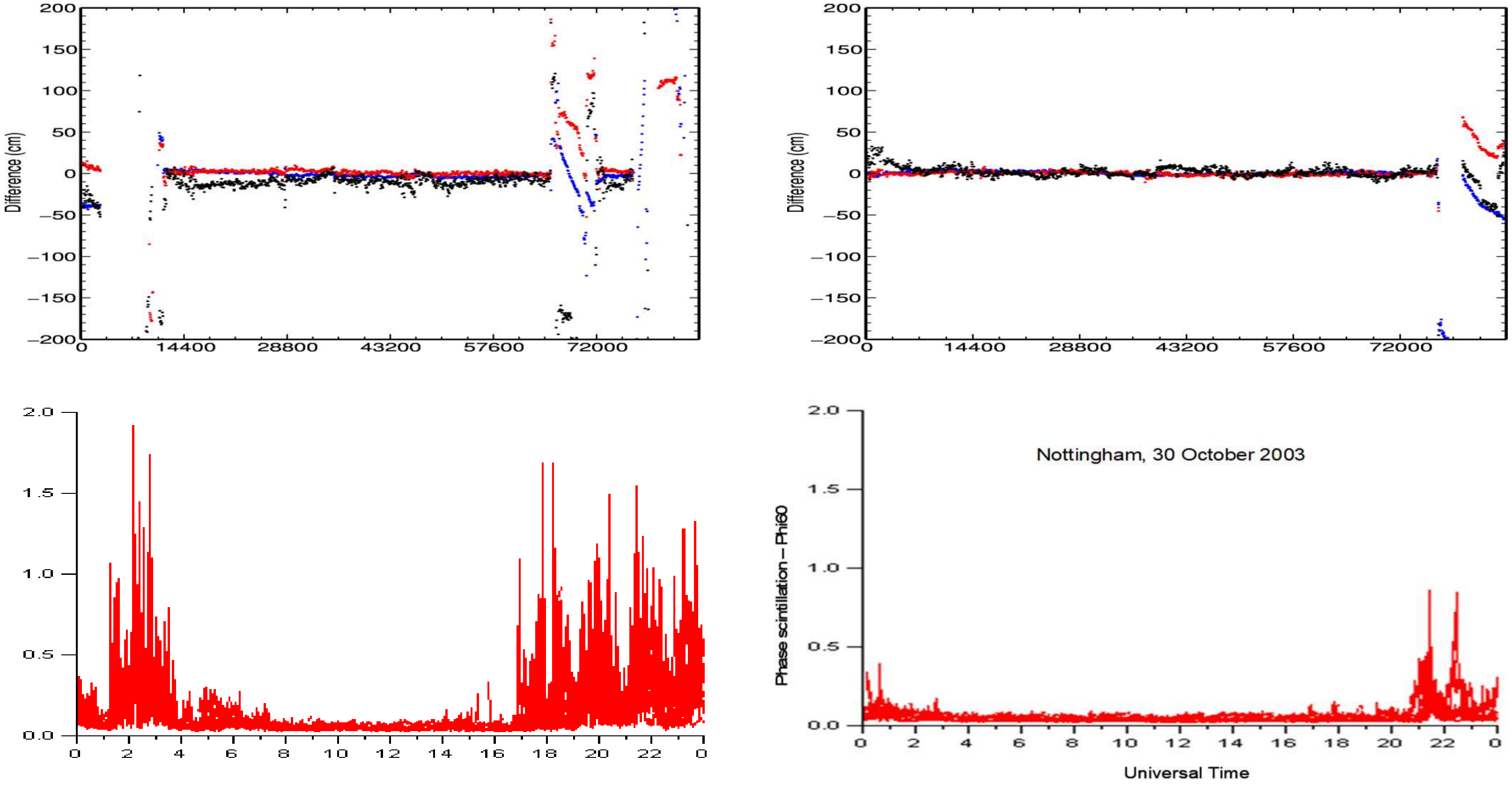
08 Jun 1997
Low of the Solar Cycle



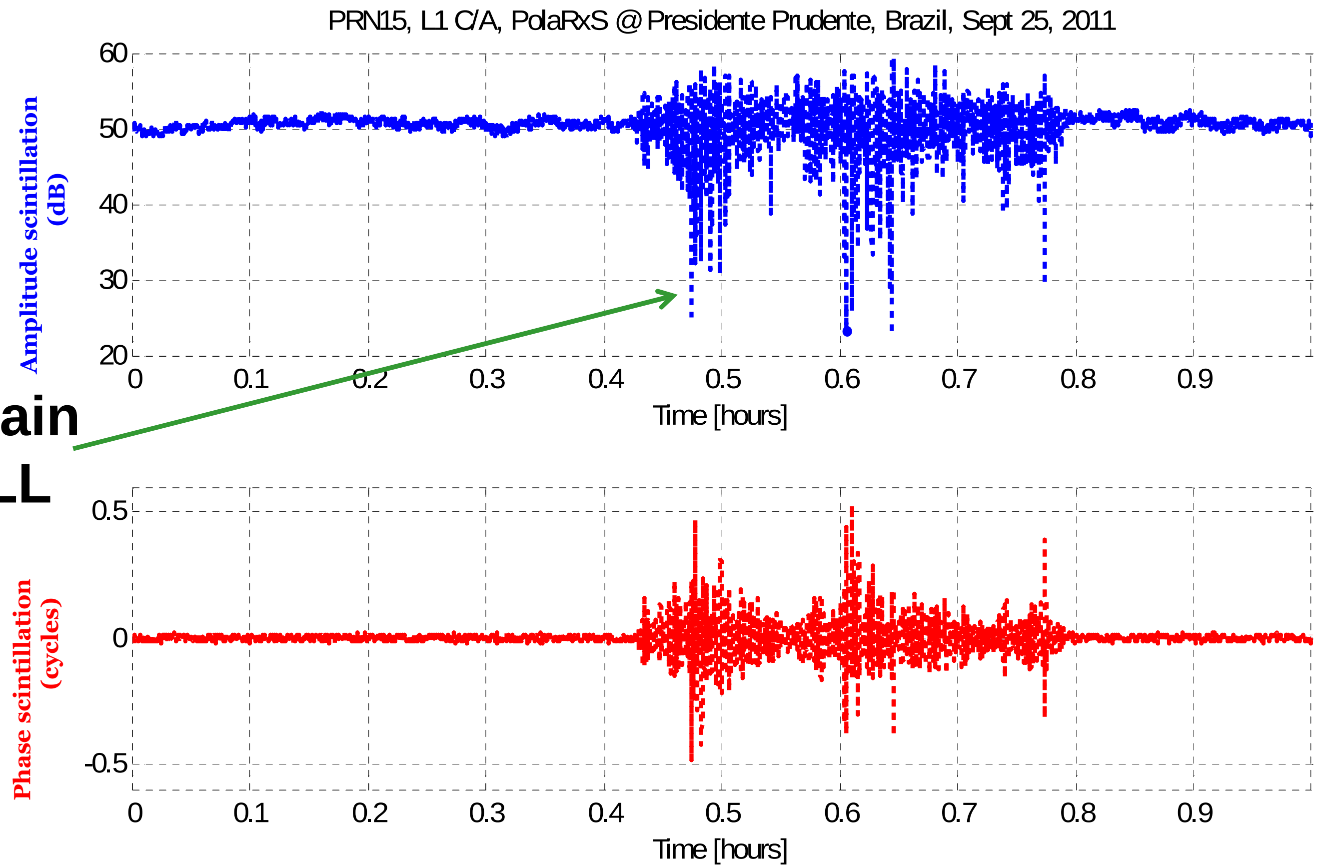
02 Apr 2001
Peak of the Solar Cycle
(major Geomagnetic Storm)

Impact of scintillation on positioning (3)

Positioning accuracy degradation >> ‘wrong’ coordinates



Impact on Tracking



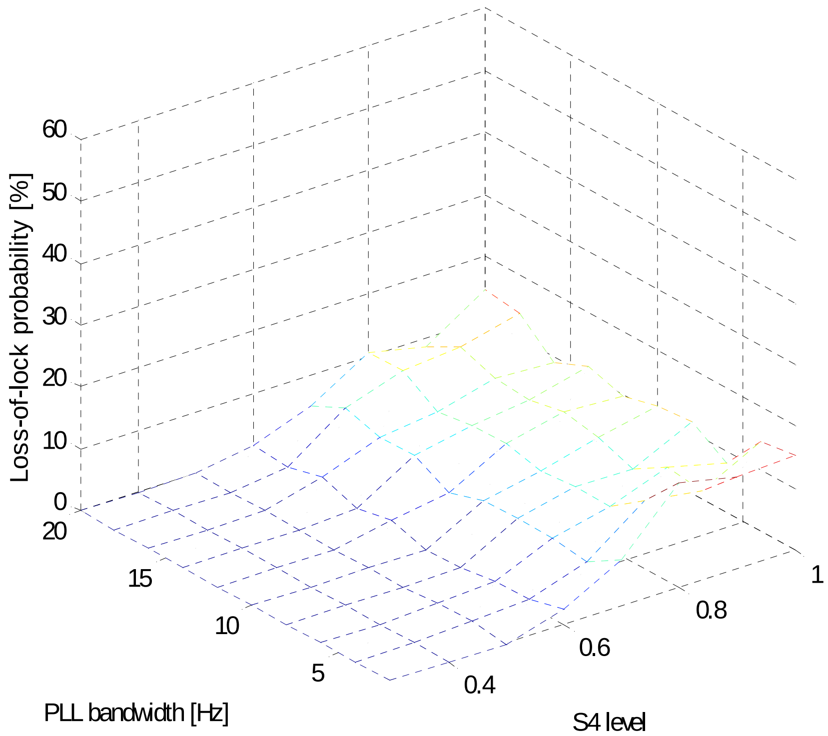
Deep fade is the main problem for the PLL

Courtesy of B Bougard

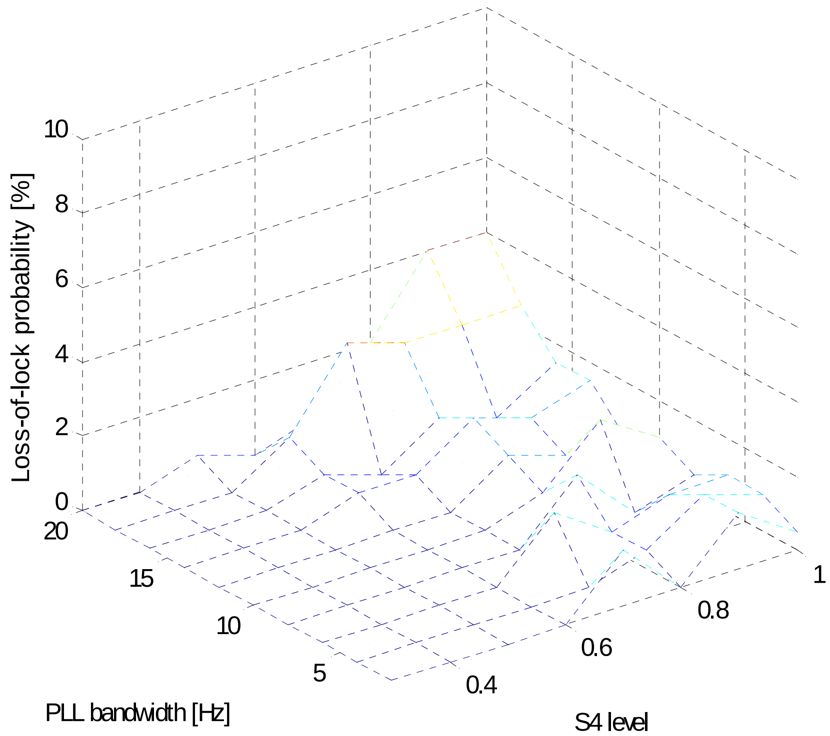
Tracking level mitigation

Simulated scintillation (Cornell model - Spirent)

Standard lock detector



Optimised lock detector



L1 data bearing signals – GPS & Glonass

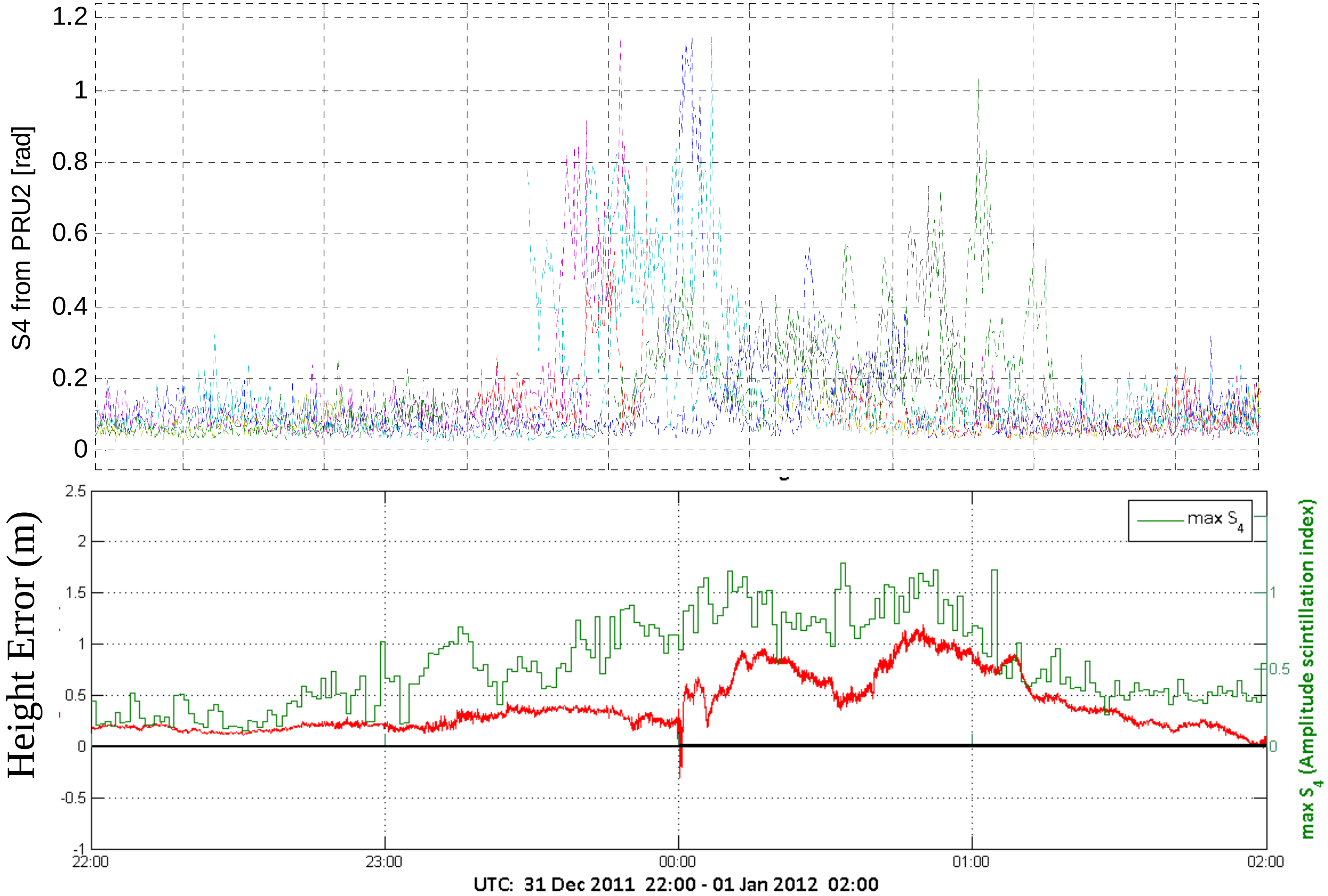
cigala

Implemented in Septentrio receivers

Septentrio

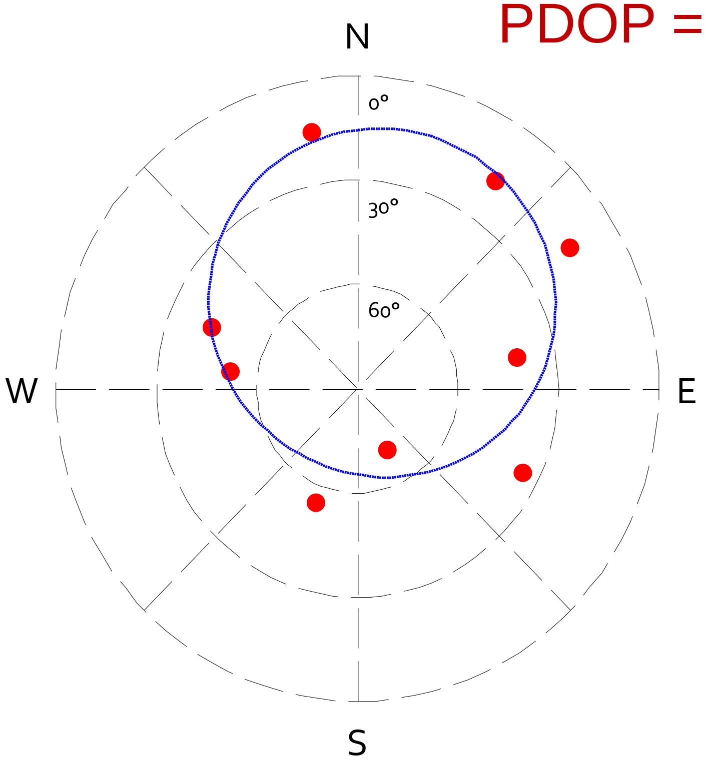
Courtesy of B Bougard

However problem is transferred to PVT!

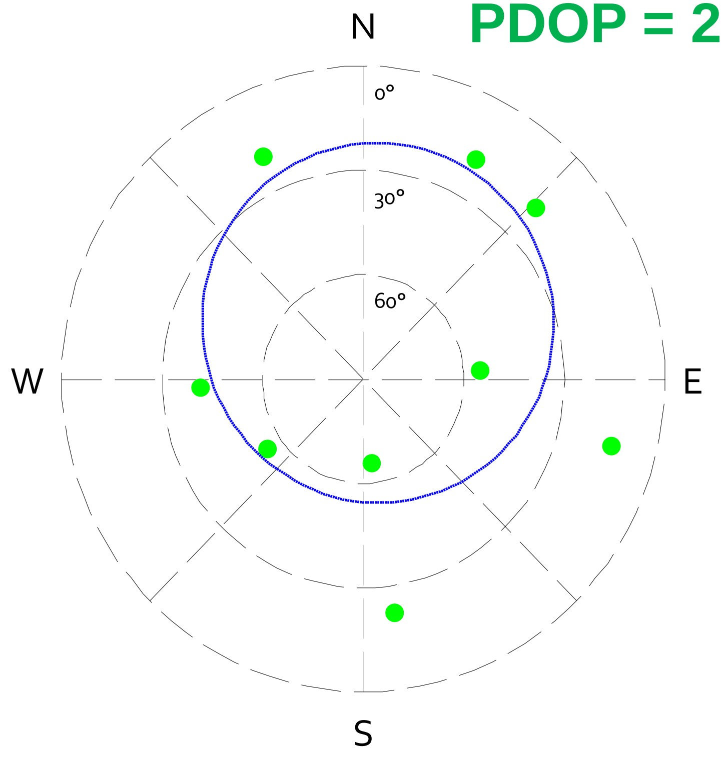


Dilution of Precision (DOP)

PDOP = 10.79



PDOP = 2.58

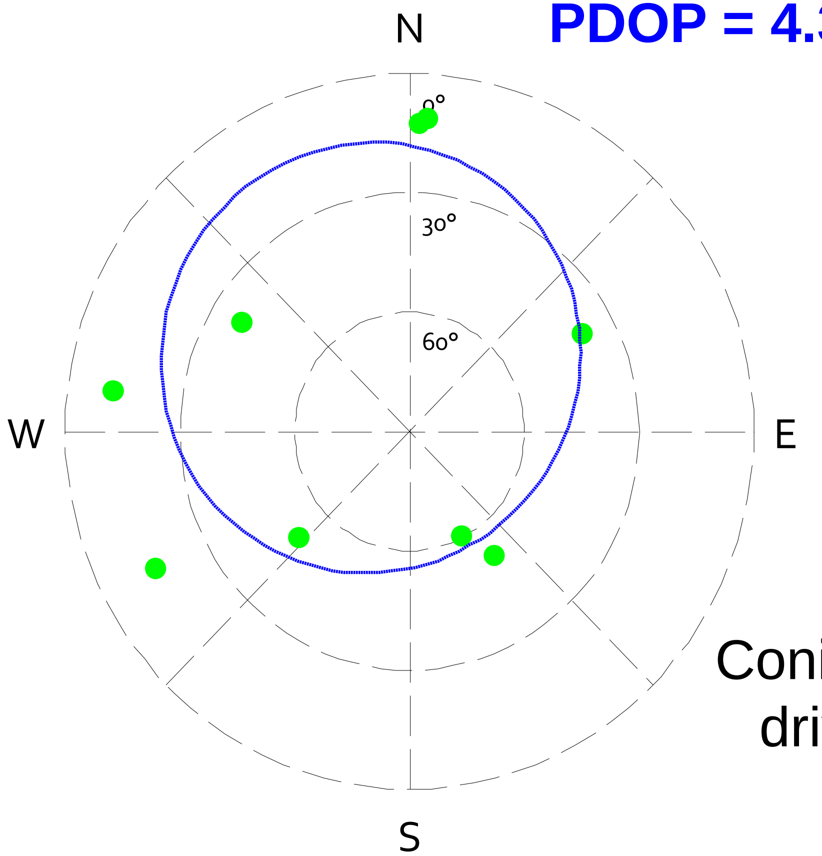


Courtesy of M Lonchay

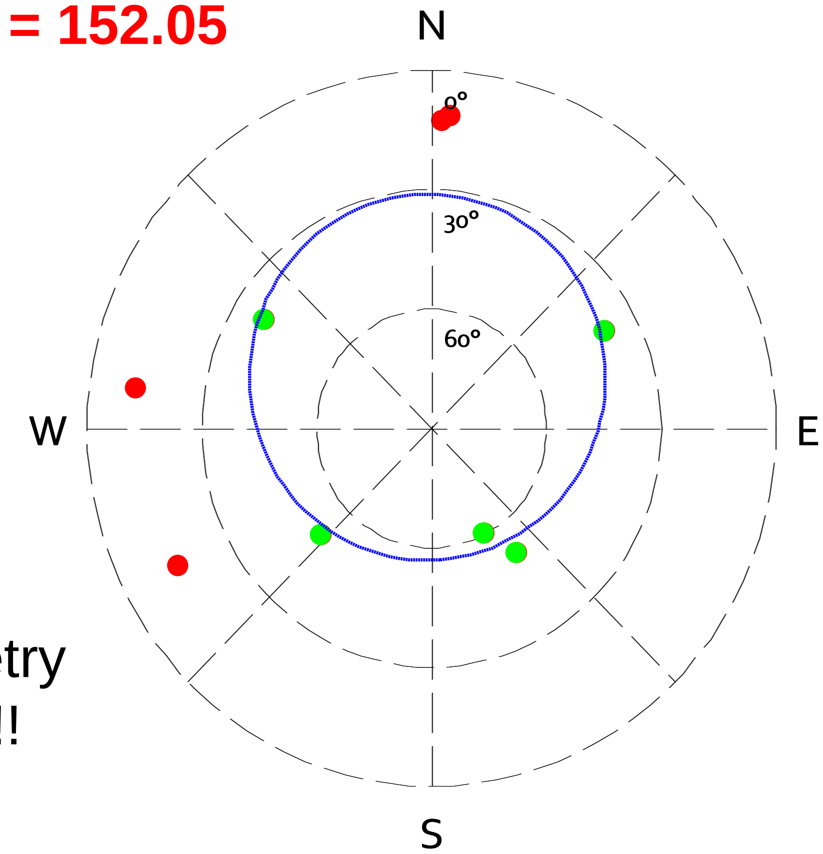
Université de Liège

Effect of Satellite geometry

PDOP = 4.39



PDOP = 152.05

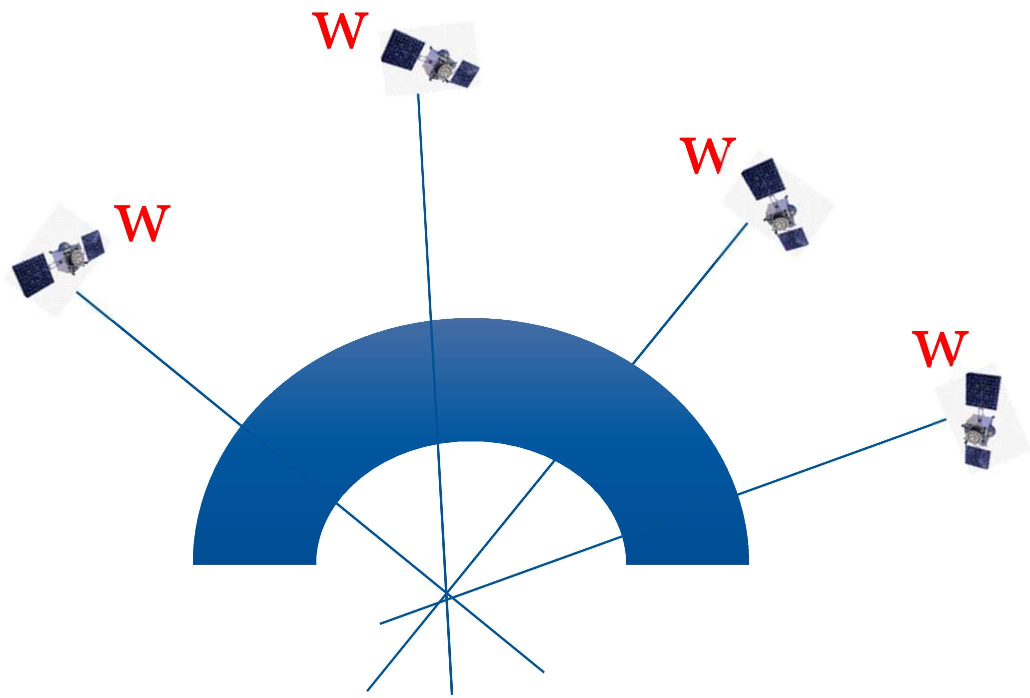


Conical satellite geometry
drives DOP to infinity!!

Courtesy of M Lonchay

Université de Liège

Least Squares stochastic model



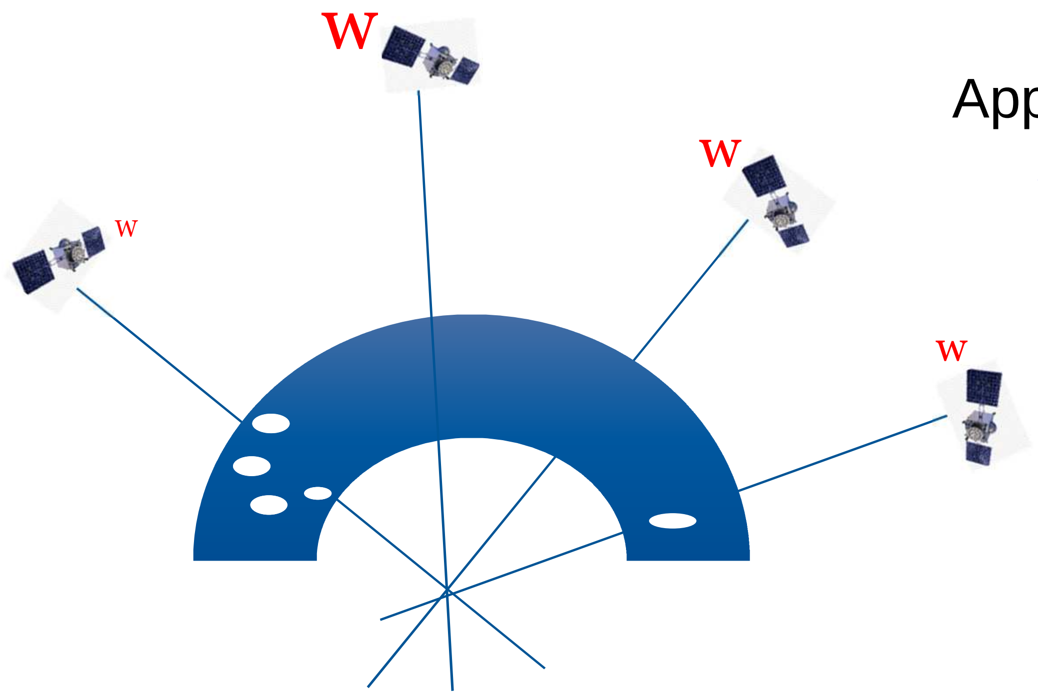
Usually

same constant weight for all satellite

$$\hat{x} = (A^t W A)^{-1} (A^t W b)$$

$$W = c \times I$$

Improve the LSQ stochastic model!



Better

Apply different weights to individual satellites

While maintaining the same geometry!

$$\hat{x} = (A^t W A)^{-1} (A^t W b)$$

$$W \neq c \times I$$

GNSS Positioning Solution

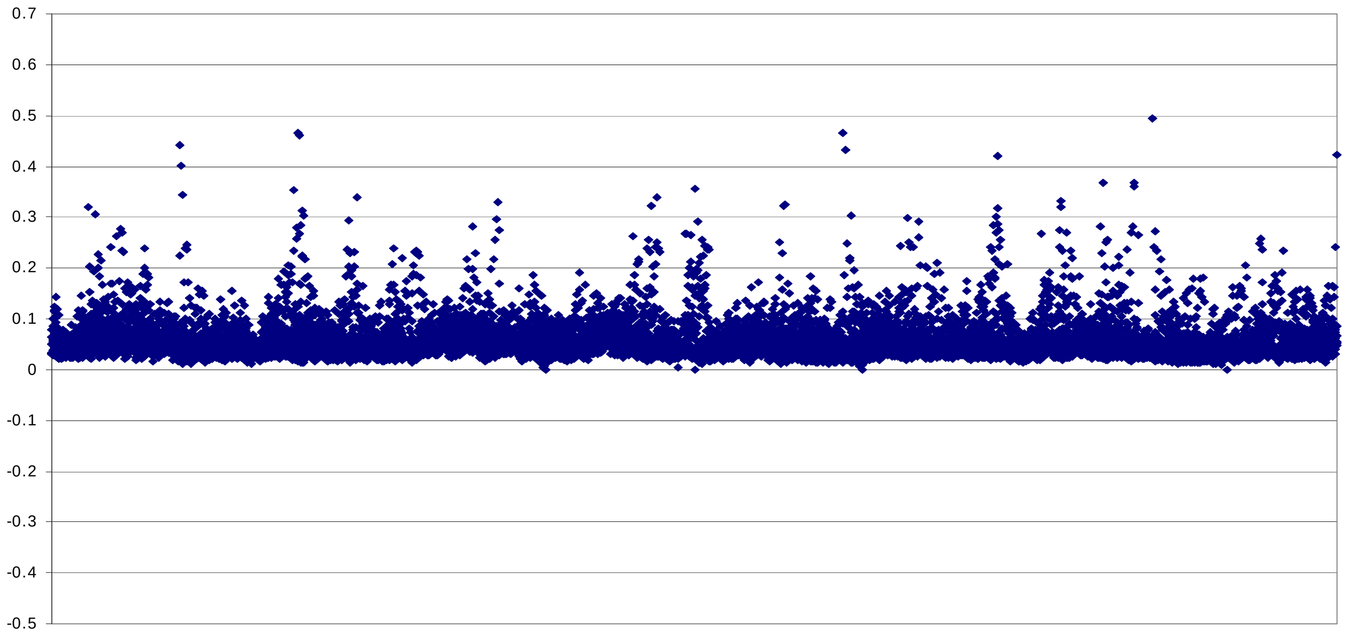
- Different weighting approaches:
  - Satellite elevation angle
  - Carrier to noise ratio (CN0)
  - Receiver tracking error variances (Aquino et al. 2009)
    - Inverse of the tracking error variances estimated per epoch per satellite
    - Use scintillation indices and high rate (50 Hz) data

Aquino et al., J. Geod., v.83, pp. 953-966,2009

Ionospheric conditions

Ny Alesund (79ºN) - 30 October 2004; Kp reached 6

data courtesy of INGV Rome

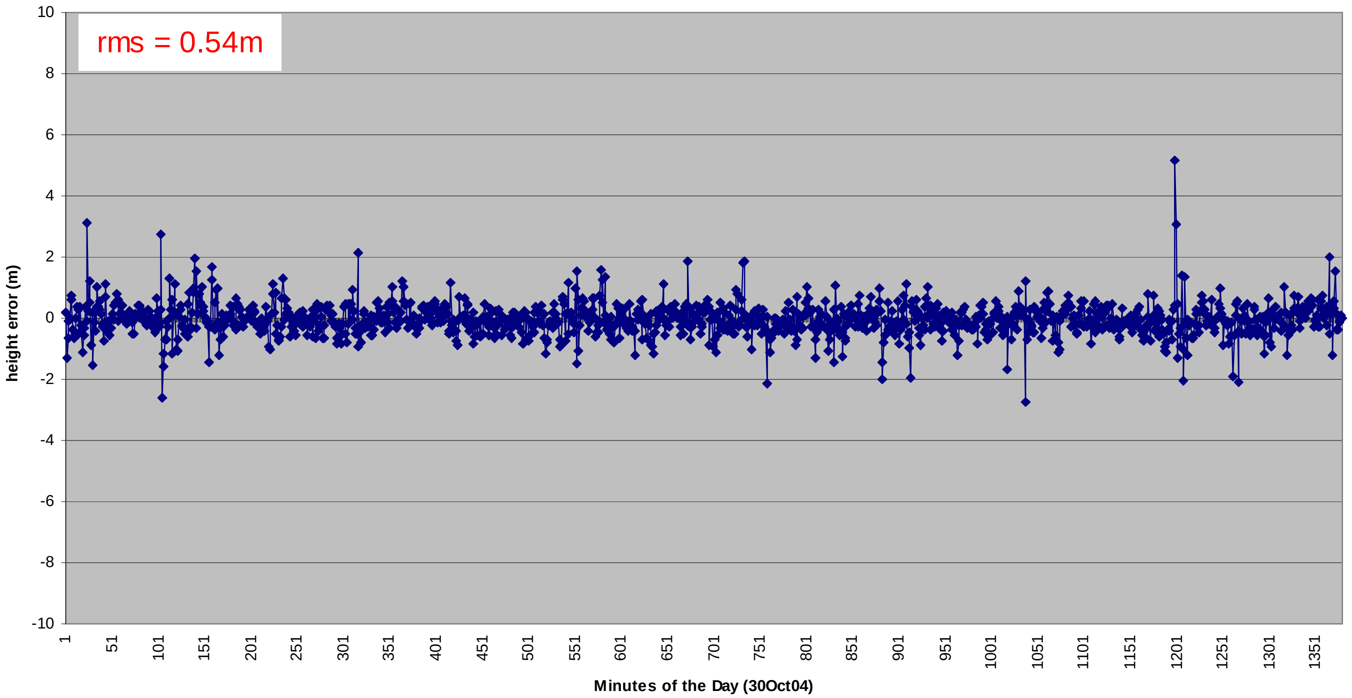


Aquino et al., J. Geod., v.83, pp. 953-966,2009

Non-Mitigated Solution

1km baseline Ny Alesund (79ºN) - 30 October 2004; Kp reached 6

data courtesy of INGV Rome

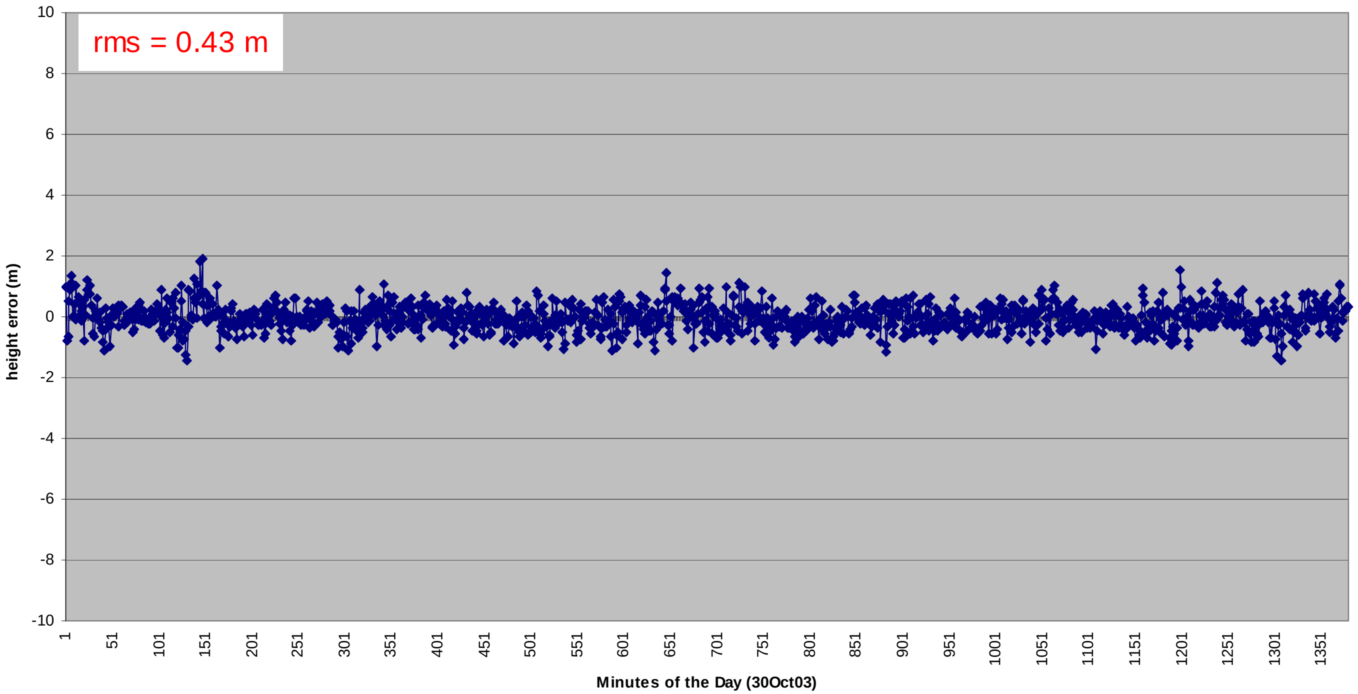


Aquino et al., J. Geod., v.83, pp. 953-966,2009

Mitigated Solution

1km baseline Ny Alesund (79ºN) - 30 October 2004; Kp reached 6

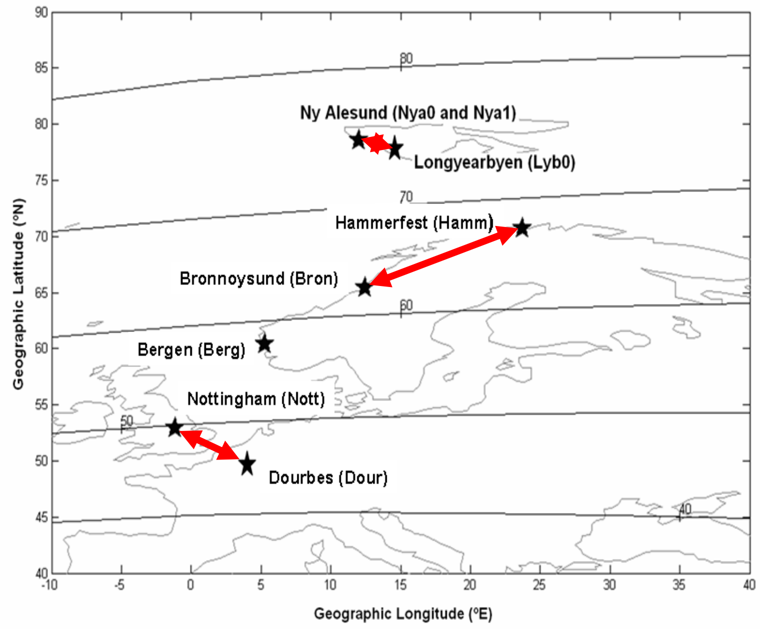
data courtesy of INGV Rome



Aquino et al., J. Geod., v.83, pp. 953-966,2009

Varying Baseline Solutions

Baseline Length	Average latitude	Maximum Kp	RMS w/o mitigation	RMS with mitigation	Height error improvement
1km	~79ºN	6	0.54m	0.43m	21%
125km	~78ºN	5	1.44m	0.90m	38%
511km	~52ºN	6	1.52m	1.26m	17%
752km	~68ºN	5	6.43m	5.32m	17%

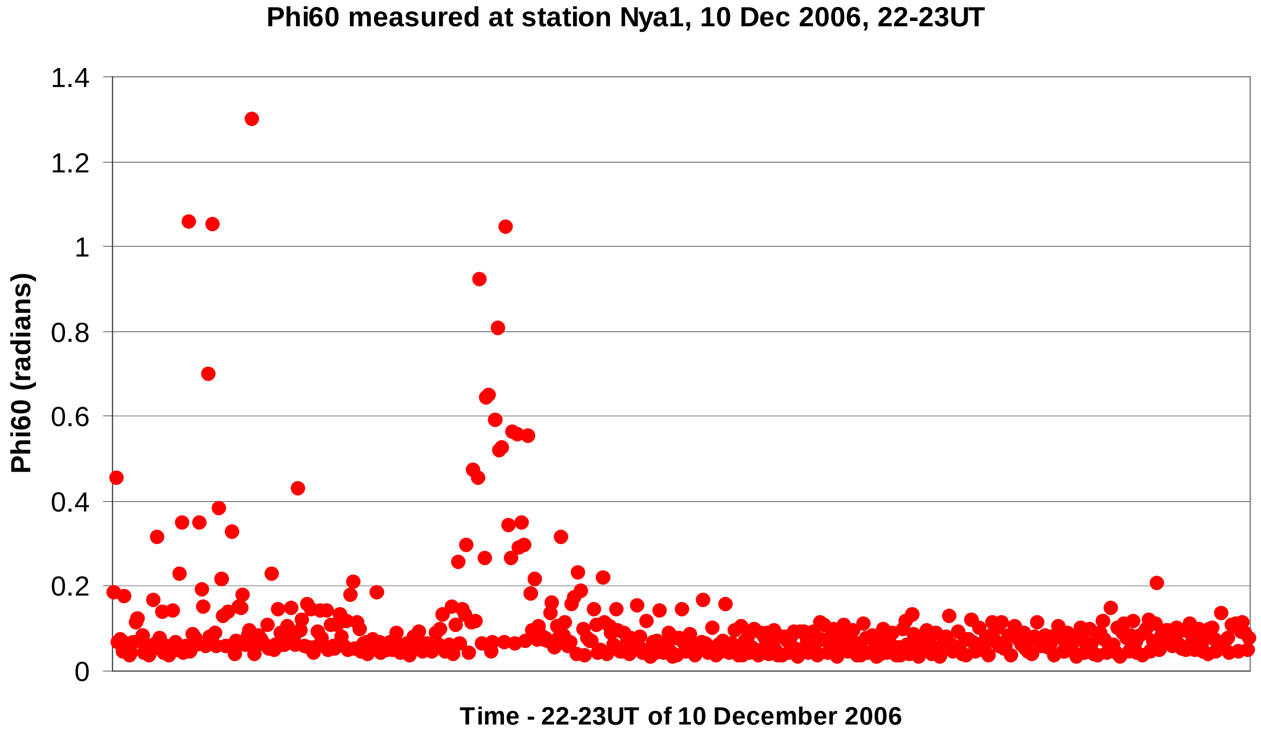


Aquino et al., J. Geod., v.83, pp. 953-966,2009

University of Nottingham
UK | CHINA | MALAYSIA

Ionospheric conditions

125km baseline Ny Alesund/Longyearbean (~78ºN) – *data courtesy of INGV Rome*

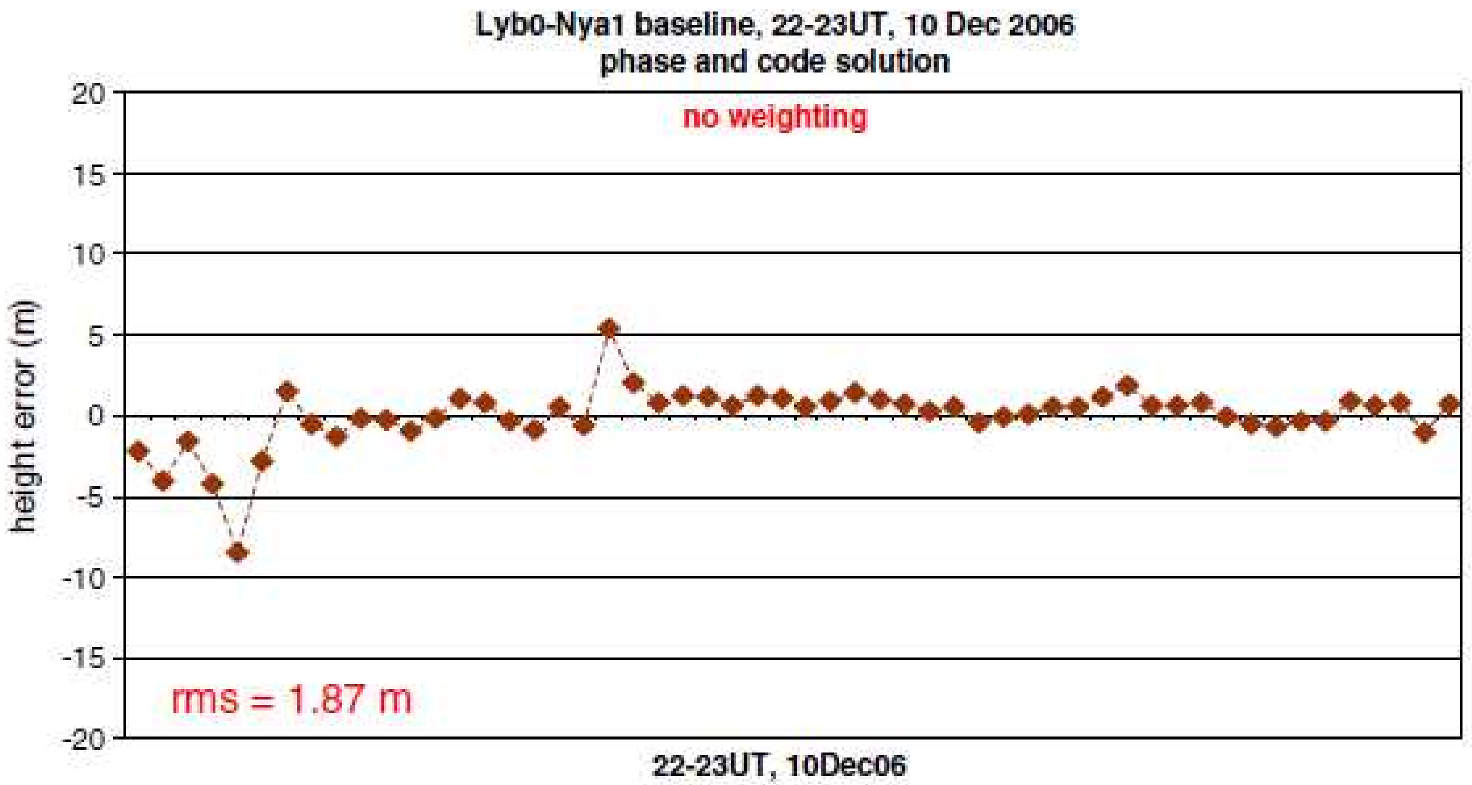


Aquino et al., J. Geod., v.83, pp. 953-966,2009

University of Nottingham
UK | CHINA | MALAYSIA

Non-Mitigated Solution

125km baseline Ny Alesund/Longyearbean (~78ºN) – *data courtesy of INGV Rome*

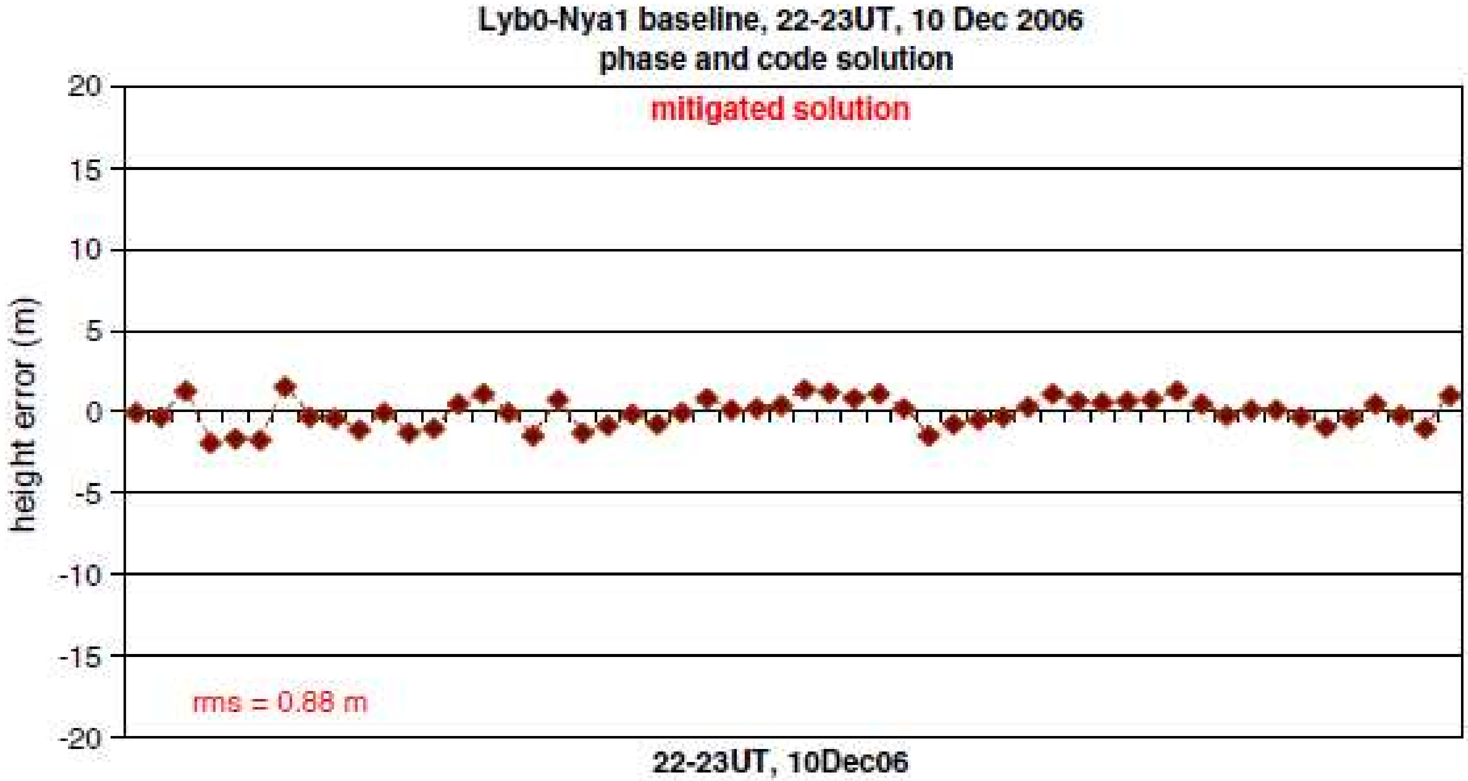


Aquino et al., J. Geod., v.83, pp. 953-966,2009

University of Nottingham
UK | CHINA | MALAYSIA

Mitigated Solution

125km baseline Ny Alesund/Longyearbean (~78ºN) – *data courtesy of INGV Rome*



Aquino et al., J. Geod., v.83, pp. 953-966,2009

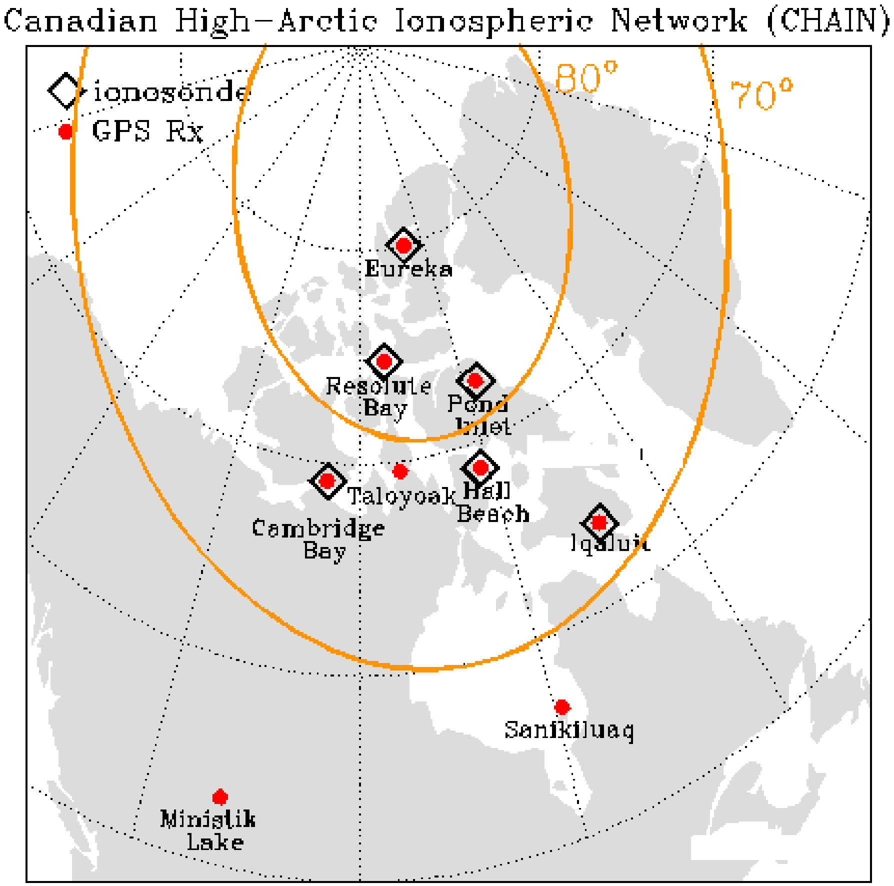
University of Nottingham
UK | CHINA | MALAYSIA

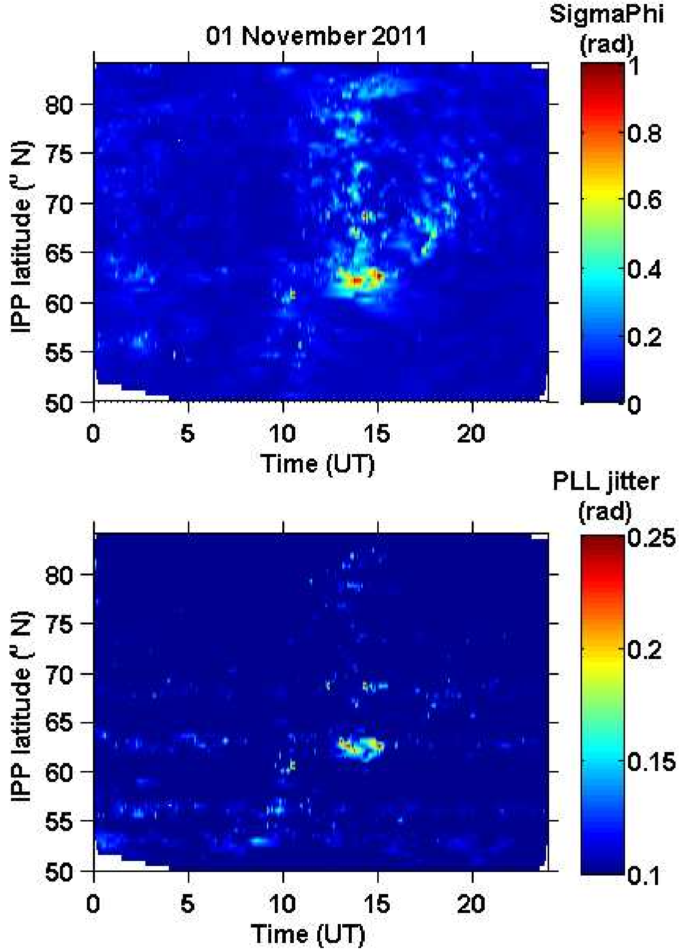
Mitigation Tool: Tracking Jitter variance maps

- Contour maps of verticalised tracking jitter to give **overall tracking conditions**
- Maps can **assist users** in **estimating line of sight tracking conditions** for different PLL configurations and signals
- Possible use to **mitigate GNSS positioning errors**
- Maps can be constructed over an area => users can estimate their slant jitter using a mapping function

Sreeja et al., Space Weather, doi:10.1029/2011SW000707,2011

Tracking Jitter variance maps





Prikryl et al., Annals of Geophysics, doi:10.4401/ag-6219,2013

University of Nottingham
UK | CHINA | MALAYSIA

Summary

- Growing reliance on GNSS for high accuracy positioning
- **Ionospheric scintillation:** serious problem for GNSS high accuracy positioning
- Effects range from **degradation of accuracy to outages**
- Scintillation leads to **degradation** in the GNSS **receiver signal tracking performance**
- Possible to **improve signal tracking**
  - **Bad data** may remain and **propagate into PVT solution**
- **Technique to mitigate** scintillation effects on positioning
  - **An advanced stochastic model** improves the positioning performance

University of Nottingham
UK | CHINA | MALAYSIA

Further reading

Aquino M, Monico JFG, Dodson AH, Marques H, De Franceschi G, Alfonsi L, Romano V, Andreotti M (2009) Improving the GNSS positioning stochastic model in the presence of ionospheric scintillation. J. Geod., 83: 953–966, doi:10.1007/s00190-009-0313-6

Aquino M, Sreeja V (2013) Correlation of scintillation occurrence with interplanetary magnetic field reversals and impact on Global Navigation Satellite System receiver tracking performance. Space Weather 11(5):219-224. doi:10.1002/swe.20047

Basu S, Groves KM, Basu Su, Sultan PJ (2002) Specification and forecasting of scintillations in communication/navigation links: current status and future plans. J Atmos Solar-Terr Phys 64(16):1745–1754. doi:https://doi.org/10.1016/S1364-6826(02)00124-4

Conker RS, El Arini MB, Hegarty CJ, Hsiao T (2003) Modeling the effects of ionospheric scintillation on GPS/SBAS availability. Radio Sci. 38(1). doi:10.1029/2000RS002604.

Moraes AO, Costa E, de Paula ER, Perrella WJ, Monico JFG (2014) Extended ionospheric amplitude scintillation model for GPS receivers. Radio Sci 49(5):315-333. doi:10.1002/2013RS005307

Prikryl, P., Sreeja, V., Aquino, M. and Jayachandran, P. T. (2013), Probabilistic forecasting of ionospheric scintillation and GNSS receiver signal tracking performance at high latitudes, Annals of Geophysics, 56, 2, R0222; doi:10.4401/ag-6219.

Sreeja V, Aquino M, Elmas ZG (2011b) Impact of ionospheric scintillation on GNSS receiver tracking performance over Latin America: Introducing the concept of tracking jitter variance maps. Space Weather 9(10):S10002. doi:10.1029/2011SW000707