Effects of magnetic storms on GPS signals

Andreja Sušnik

Supervisor: doc.dr. Biagio Forte

Outline

1. Background
    - GPS system
    - Ionosphere
2. Ionospheric Scintillations
3. Experimental data
4. Conclusions

The GPS system

stands for "**G**lobal **P**ositioning **S**ystem",

is a U.S. space-based radio-navigation system that provides reliable positioning, navigation, and timing services to civil users on a continuous worldwide basis.

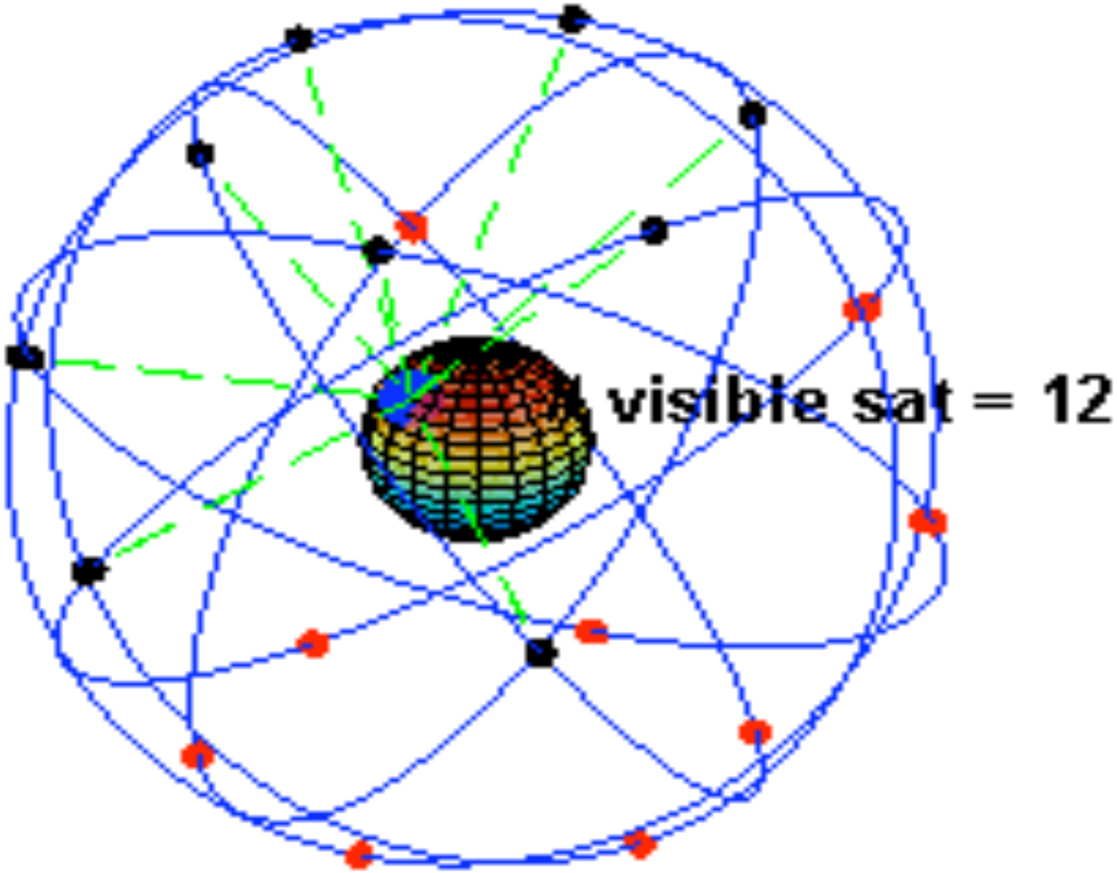
The GPS system consist of three segments:

- Space segment
- Control segment
- User segment

The GPS system

Space segment

- 24 to 36 satellites
- in six orbital planes
- at altitude 20,183 km



The GPS system

Control segment

The GPS system

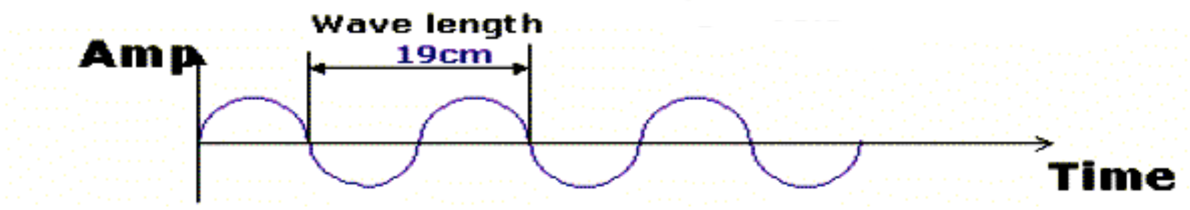
User segment

Applications:
- navigation
- geodesy
- timing
- surveying
- surveillance
- aviation
- agriculture
- cadastre

The GPS system

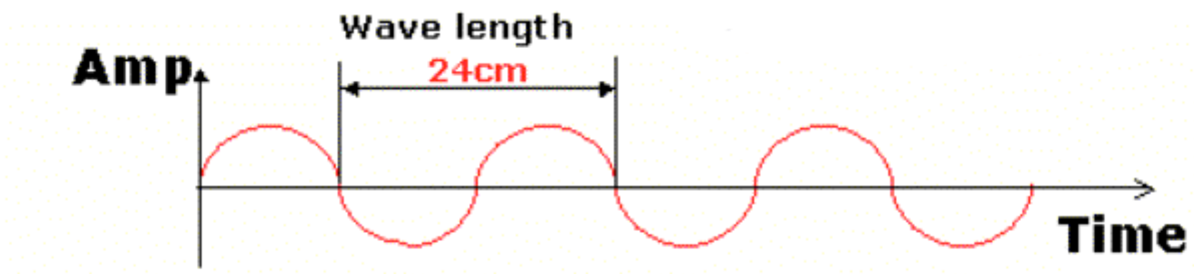
- each GPS satellite transmits continuously using two radio frequencies in the L-band:

L1 : 1.575 GHz



Signal structure:
- *Carrier*
- *Ranging code* (pseudo-random codes, PRN)
- *Navigation data*

L2 : 1.227 GHz



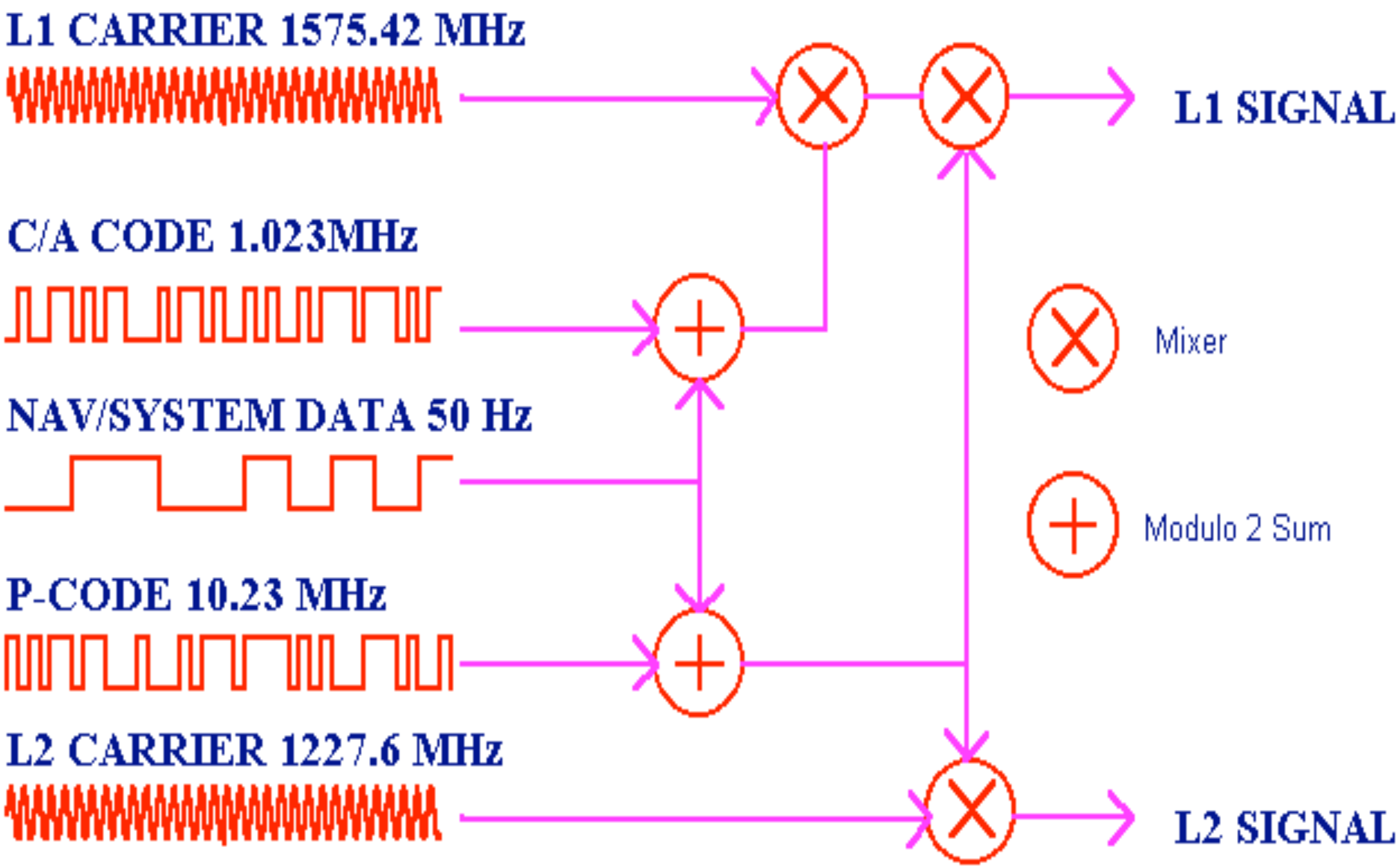
The GPS system

Signal Structure:

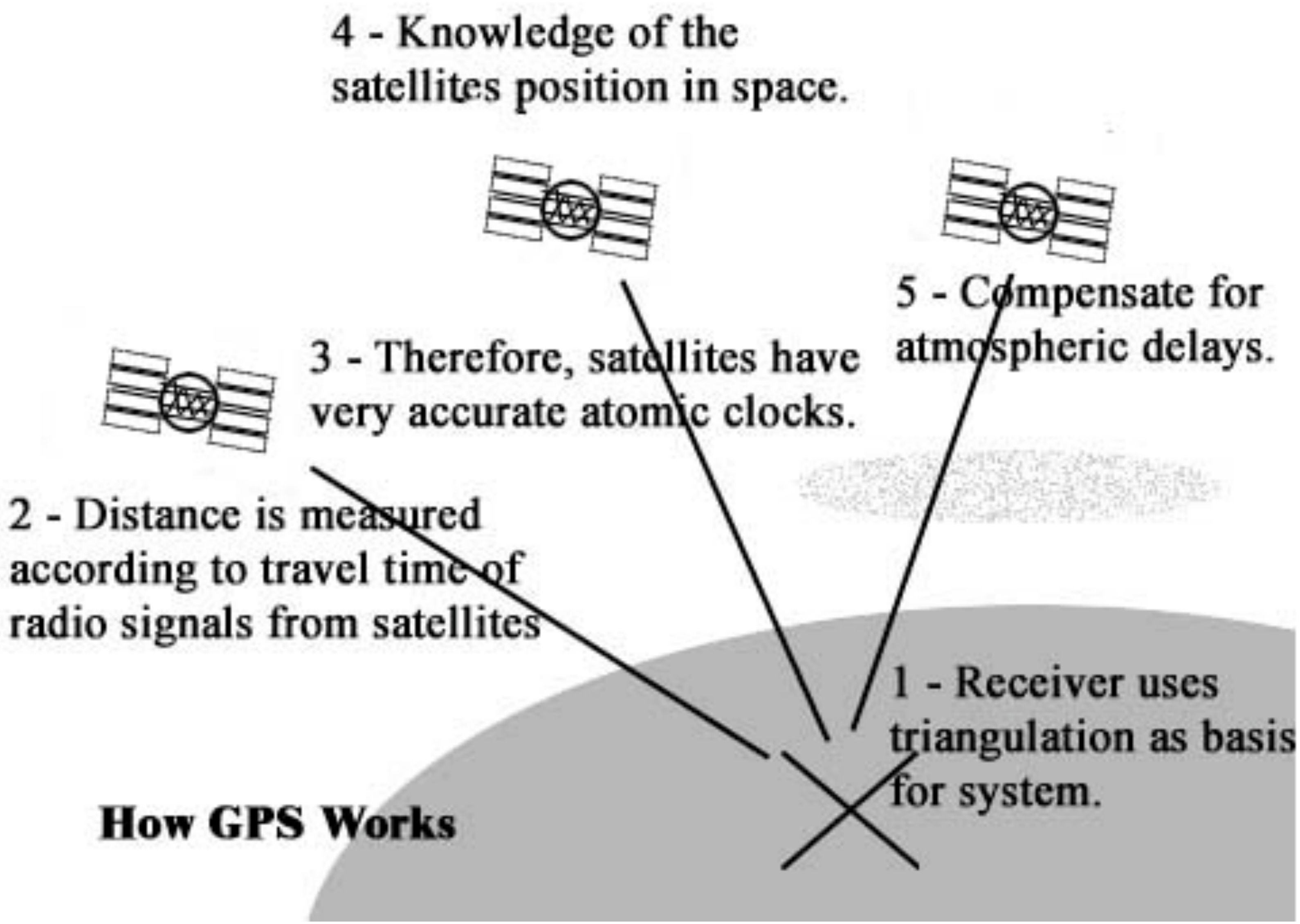
Carrier

Ranging code
(pseudo-random codes, PRN)

Navigation data

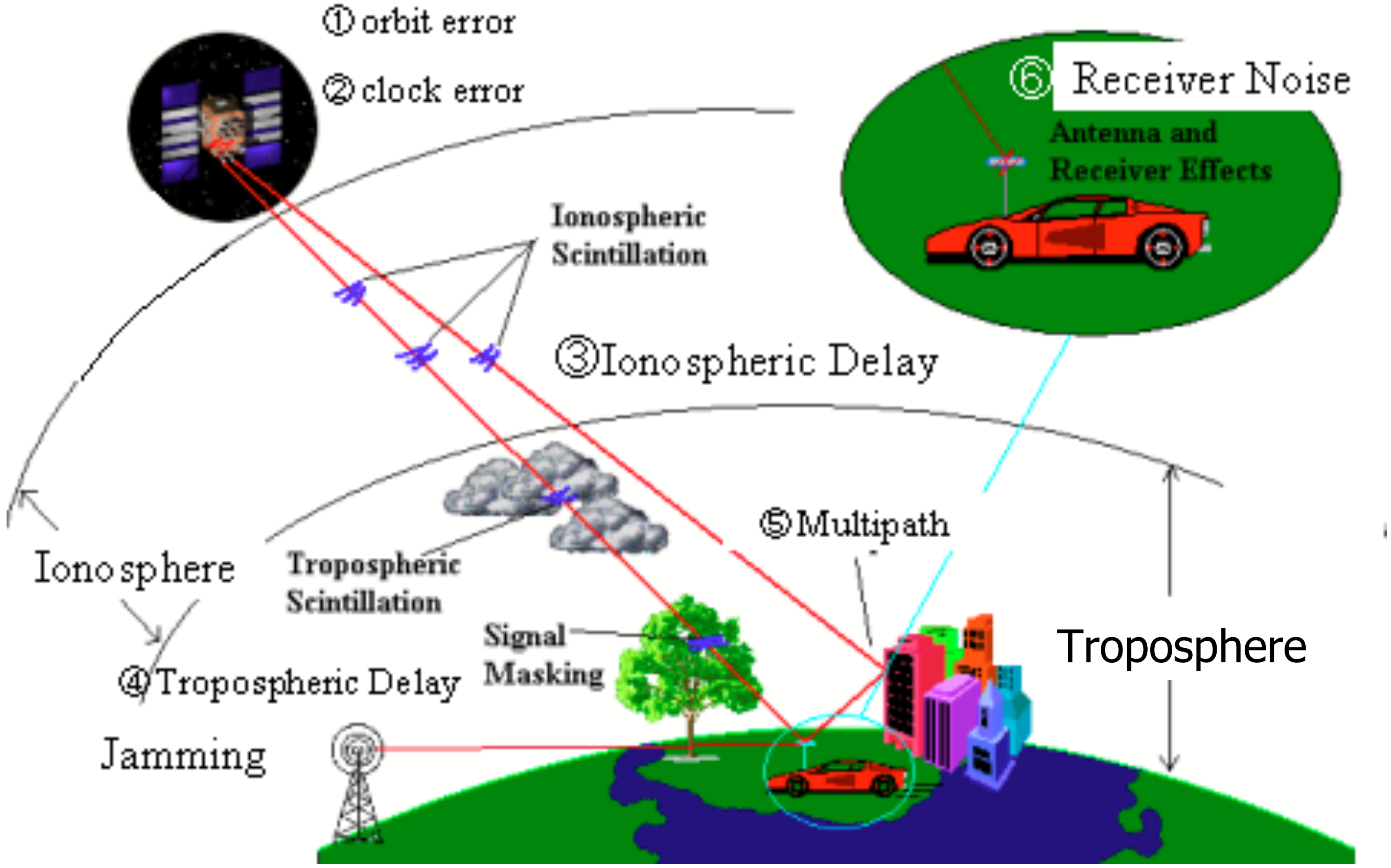


How does it work?



http://www.little-yeti.com/gpsmanual/chapter01.htm

Error Sources



http://www.soi.wide.ad.jp/

1 – orbit error = ± 2.5 meters
2 – clock error = ± 2 meters
3 – Ionospheric Delay = ± 5 meters
4 – Tropospheric Delay = ± 0.5 meters
5 – Multipath = ± 1 meters

Ionospheric Delay

- Group Delay
- Phase Advance
- Doppler Shift
- Faraday Rotation
- Ray-path bending

} Total electron content = TEC

- Random fluctuations,
  in both intensity and phase

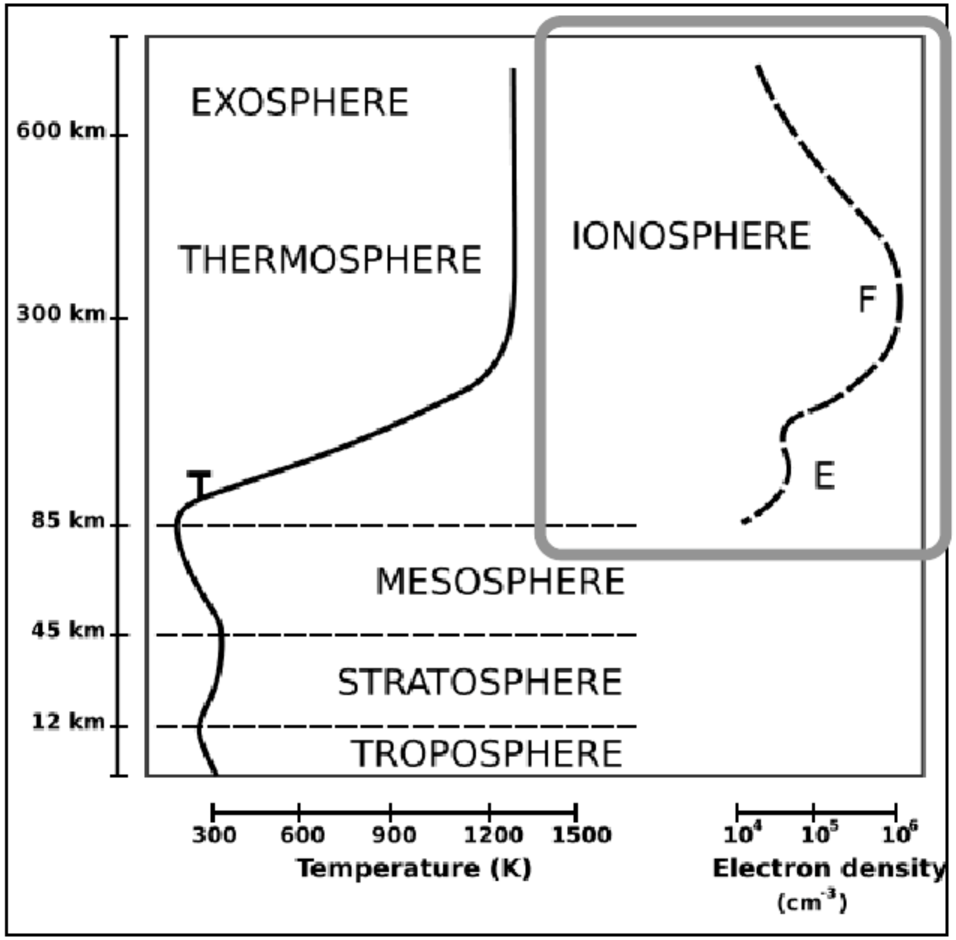
} Ionospheric scintillations

TEC units 1 TECU = 10^{16} electrons/m^2

Ionosphere

- it is the upper part of the Earth's atmosphere that is ionized by solar radiation

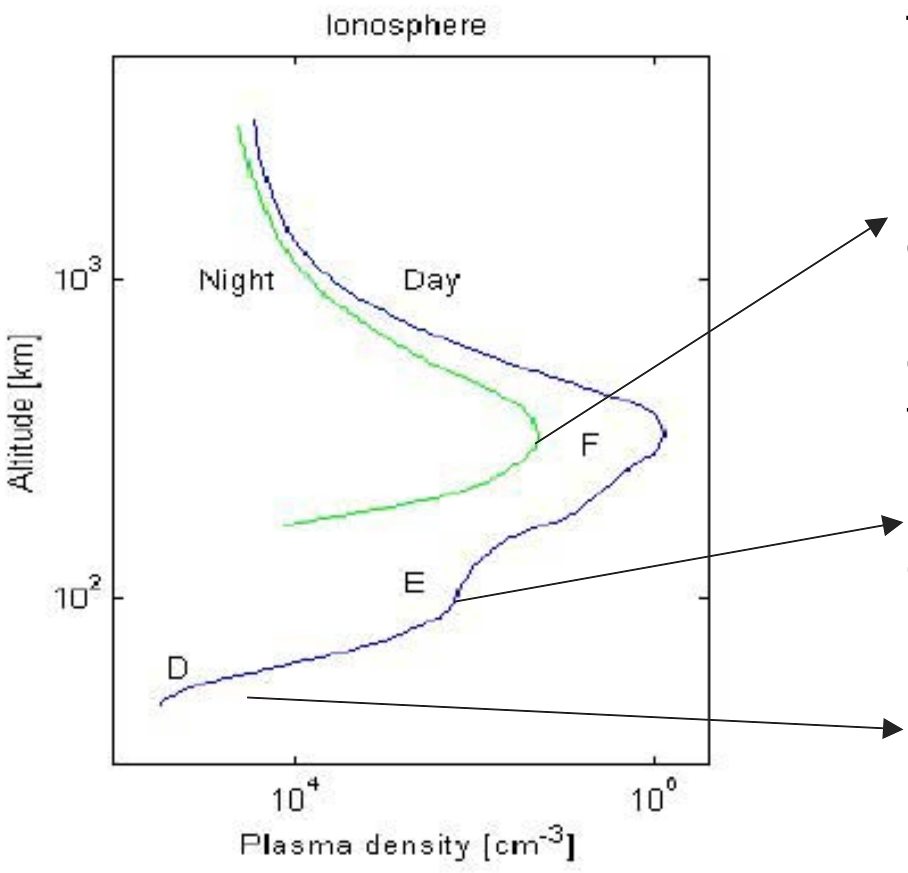
- it extends from about 75 to 1000 km and completely encircles the Earth



Public domain image from WikiMedia Commons

Vertical structure of the Earth atmosphere

Ionosphere



Ionospheric layers and the corresponding electron densities

The ionosphere is composed of three main layers: the D, E, and F regions:

- ***F-region*****:** 150-1000km contains a range of ions from NO^+ and O^+ at the bottom to H^+ and He^+ ions at the top. Electron density reaches an absolute maximum in this region,

- ***E-region*****:** 95-150km, contains mostly O_2^+ and NO_2^+ ions, with metallic long lived ions to a minor extent,

- ***D-region*****:** 75-95km up, relatively weak ionization due to its position at the bottom.

1. Background
   - GPS system
   - Ionosphere
1. Ionospheric Scintillations
2. Experimental data
3. Conclusions

Ionospheric Scintillations

- GPS signal traversing Earth's atmosphere suffers distortion of phase and amplitude.

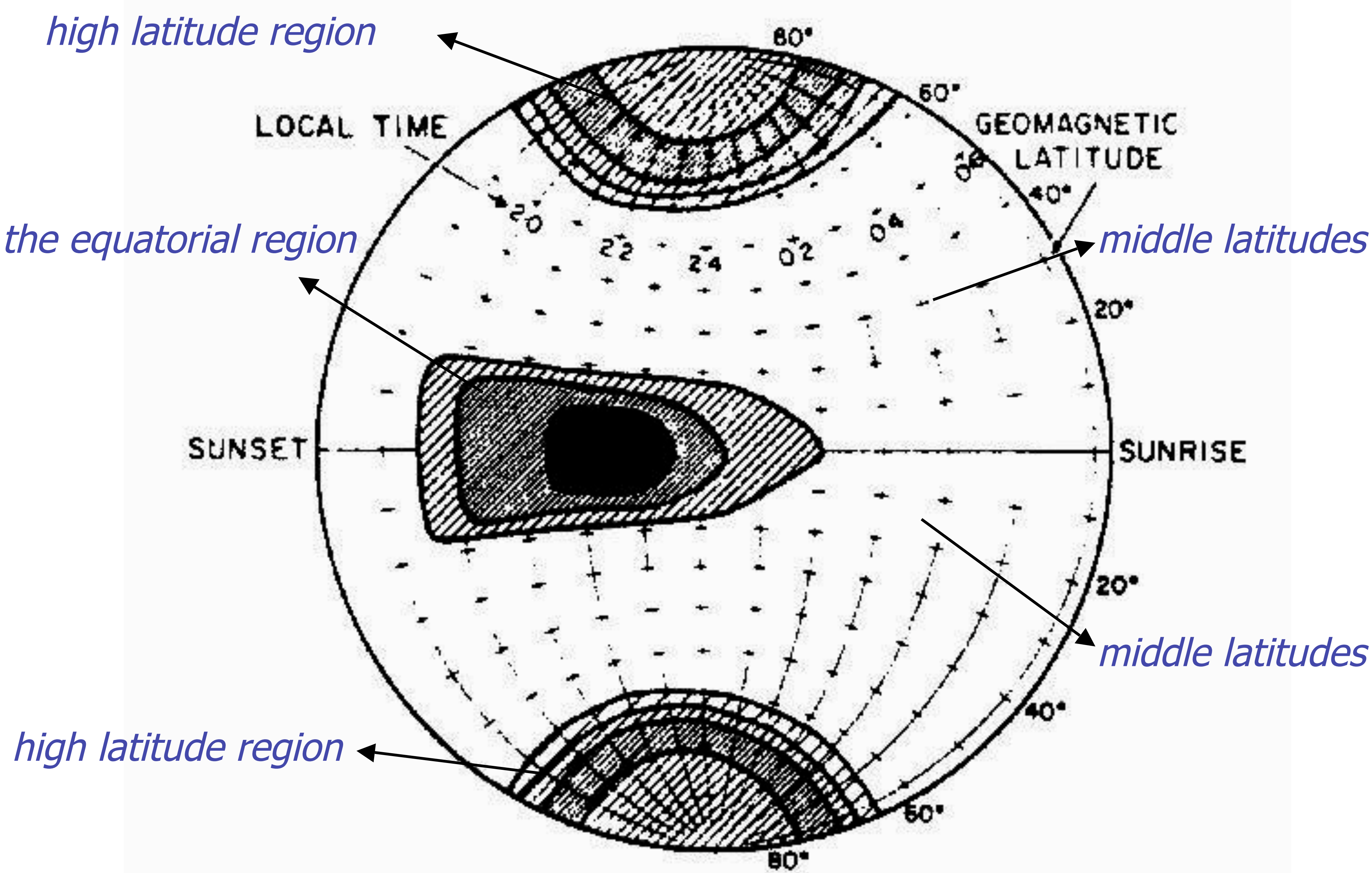
- When it traverses small-scale ionospheric plasma-density irregularities, fading, phase fluctuations, and angle of arrival variations are experienced at the receivers

↓

IONOSPHERIC SCINTILLATION

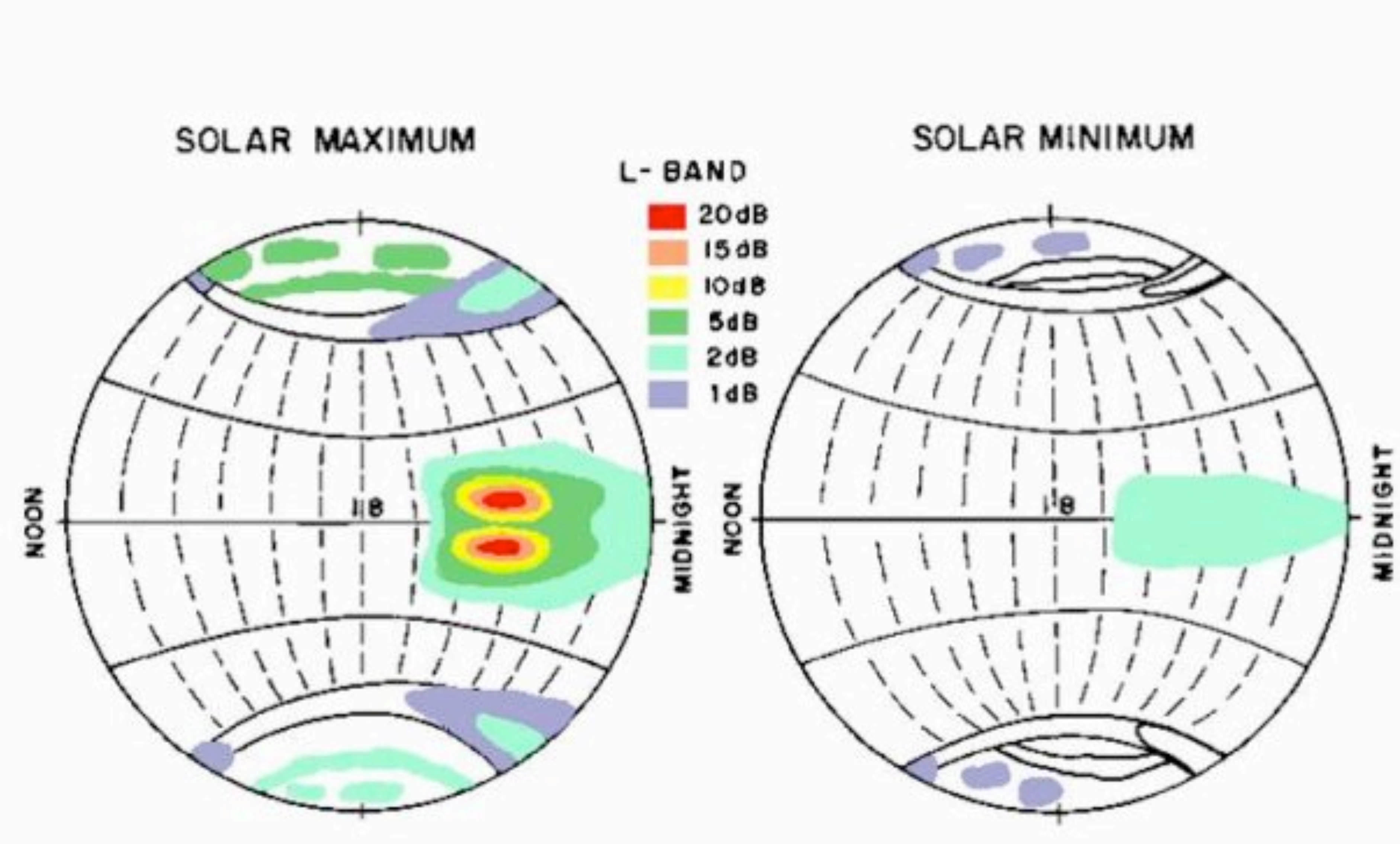
- varies widely with transmission frequency, magnetic and solar activity, season, and latitude

Ionospheric Scintillations (1)



Global depth of scintillation fading (proportional to density of crosshatching), during low and moderate solar activity (Aarons and Basu, 85)

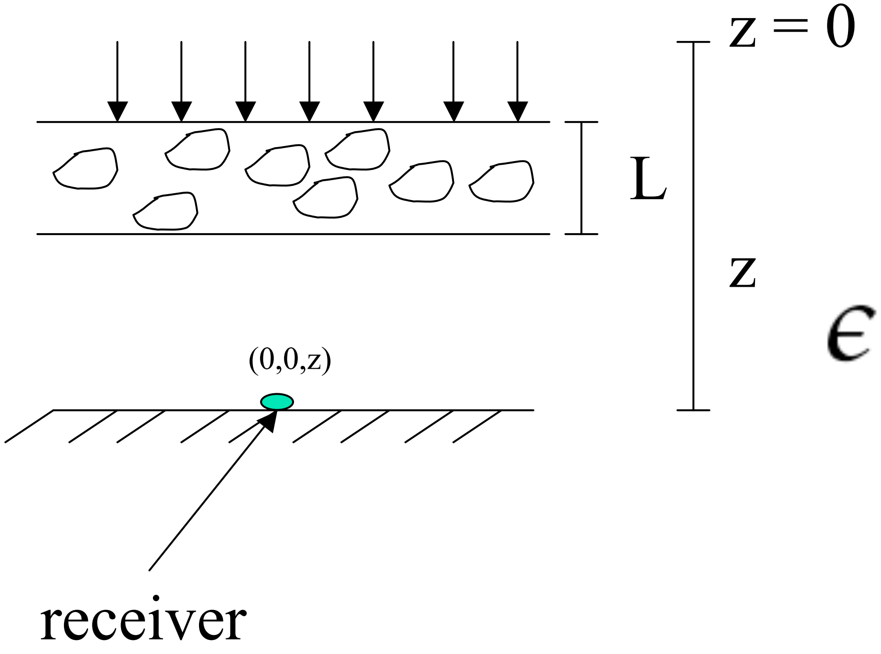
Ionospheric Scintillations (2)



Pattern of ionospheric scintillation during solar maximum and solar minimum (Basu et al., 1988).

Ionospheric Scintillations (2)

- scintillation of the GPS signals is a consequence of the existence of spatial electron-density fluctuations within the ionosphere



L = irregularity slab

$$\epsilon = \langle \epsilon \rangle [1 + \epsilon_1(\vec{r}, t)]$$

$$\langle \epsilon \rangle = (1 - f_{p0}^2 / f^2)\epsilon_0$$

$$\epsilon_1(\vec{r}, t) = \frac{(f_{p0}/f)^2 [\Delta N(\vec{r}, t)/N_0]}{1 - (f_{p0}/f)^2}$$

Ionospheric Scintillations (3)

- as the wave propagates through the irregularity slab, only the phase is affected by the random fluctuations in refractive index

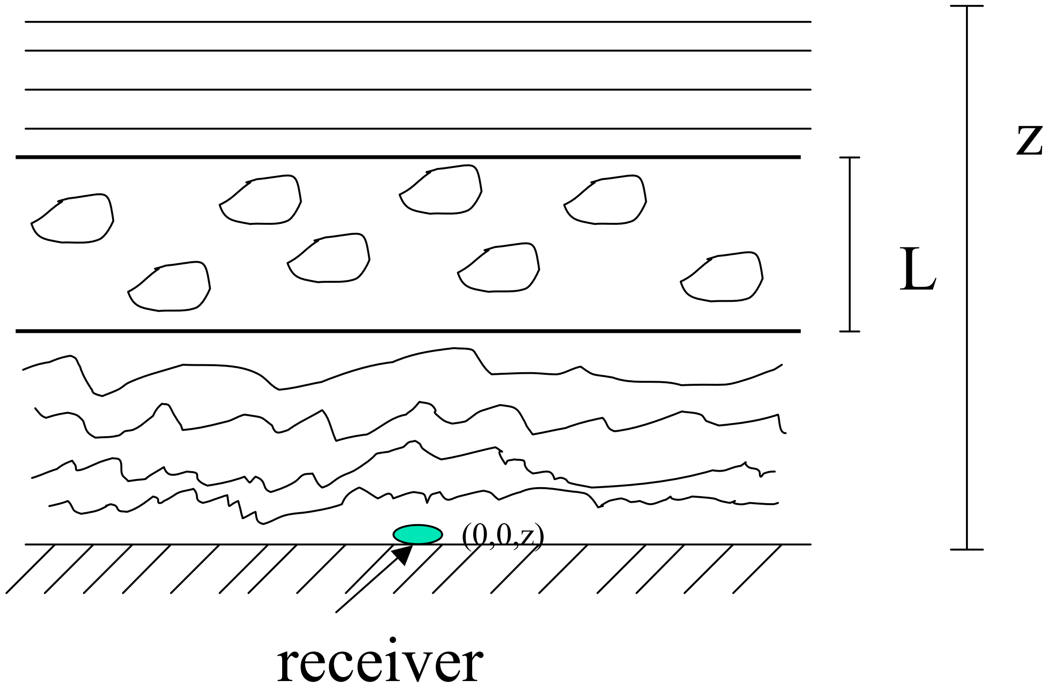
$$\Delta\varphi = -2\pi r_e \, \Delta N_T / k_0^{\,2}$$

$k_0 = 2\pi/\lambda$ = is the free-space wavenumber, in the layer with irregularities.

$\Delta\varphi$ = is the variation of the optical path length within the layer with irregularities.

Ionospheric Scintillations (4)

- as the wave propagates toward the receiver, further phase mixing occurs, changing the modulation of the wave



$$d_F = \sqrt{\lambda(z - L/2)}$$

Ionospheric Scintillations (5)

Assumption:

- the temporal variations of the irregularities are much slower than the wave period
- the characteristic size of irregularities is much greater than the wavelength

↓

PHASE SCREEN

in which the irregular layer is replaced by a screen, changing only the wave's phase.

Ionospheric Scintillations (6)

Scintillation activity

- typically is measured by means of several indices:

- S_4 index

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

$\langle \cdot \rangle$ = indicates ensemble averages

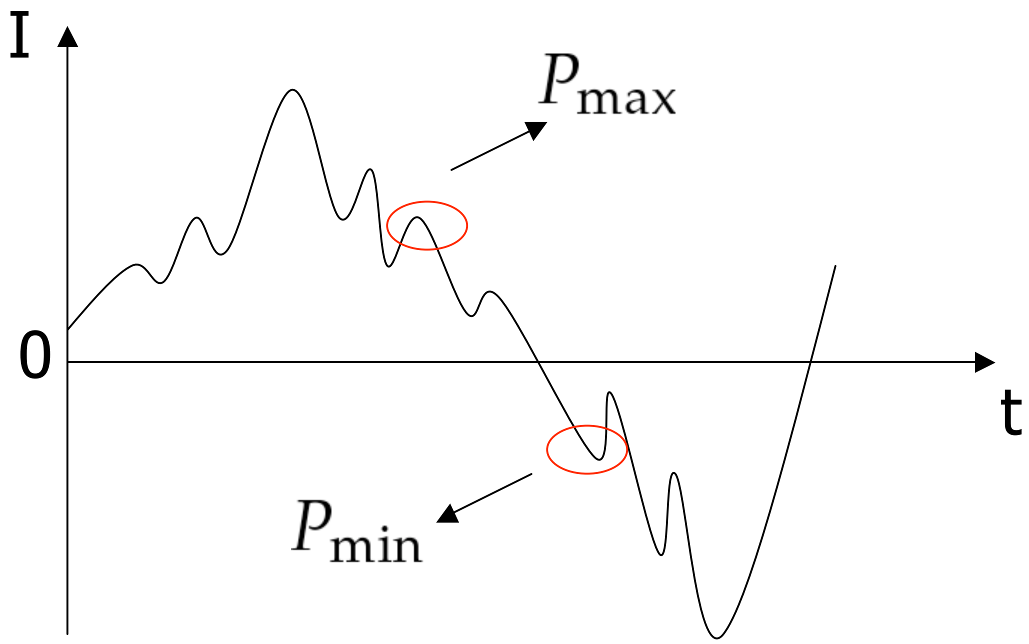
I = received intensity

- σ_ϕ the phase scintillation index

Ionospheric Scintillations (7)

- SI index

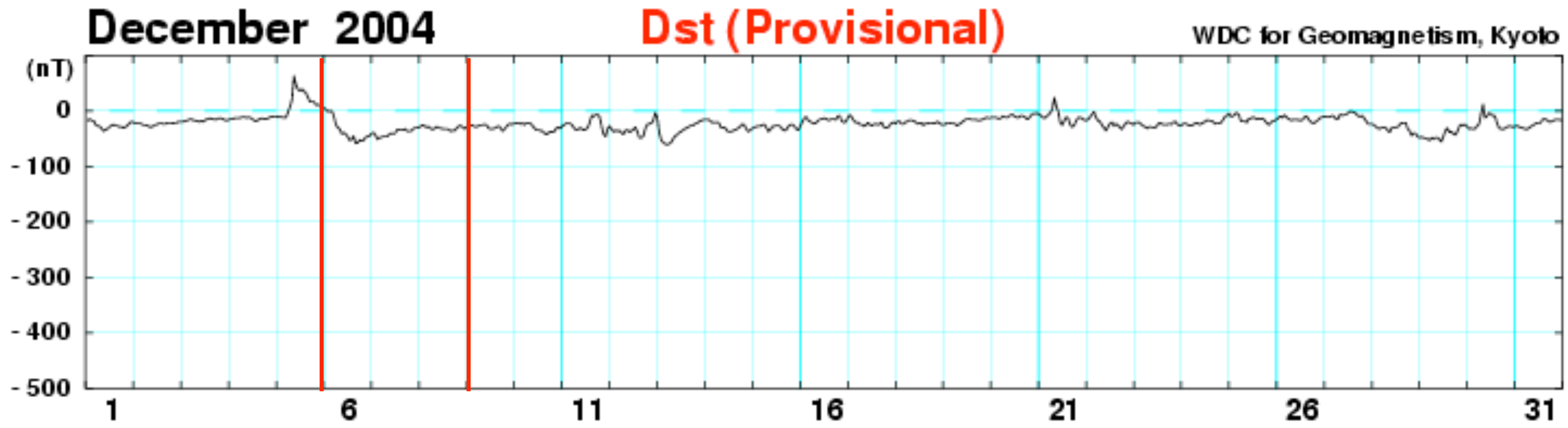
$$SI = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}}$$

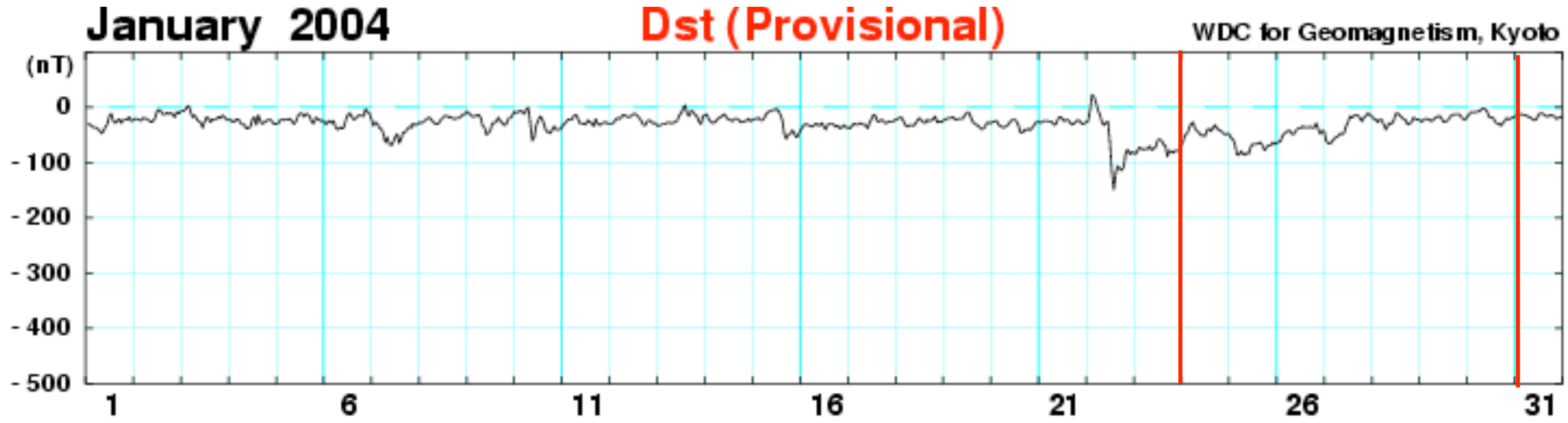


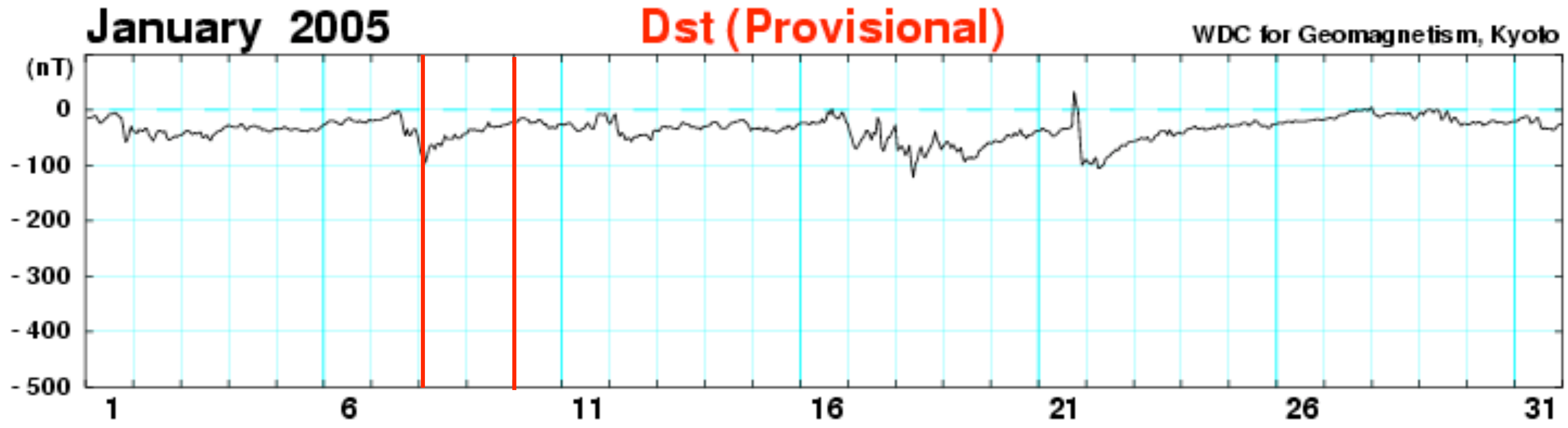
1. Background
   - GPS system
   - Ionosphere
2. Ionospheric Scintillations
3. Experimental data
4. Conclusions

Experimental data (1)

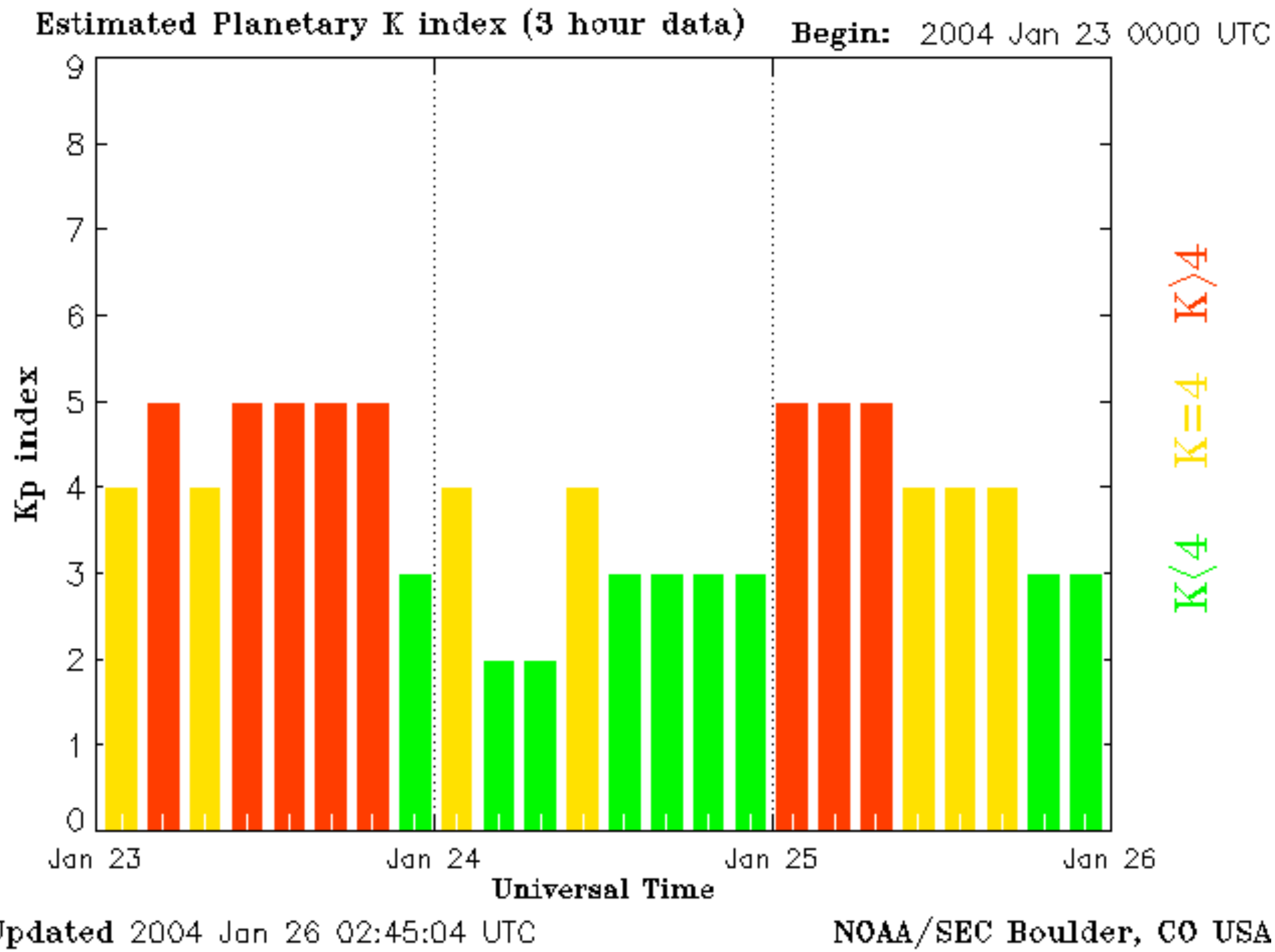
- GPS scintillation monitor at the Dirigibile Italia Station (Ny Alesund, Svalbard)
- the monitor is dual frequency GPS receiver able to record 50 Hz raw data (intensity and phase)
- three magnetic storm events are considered, including quiet days prior the storm, main storm phases and recovery phases:
  - from 6.12.2004 to 8.12.2004
  - from 23.1.2004 to 30.1.2004
  - from 8.1.2005 to 9.1.2005


December 2004
Dst (Provisional)
WDC for Geomagnetism, Kyoto
(nT)
0
-100
-200
-300
-400
-500
1
6
11
16
21
26
31

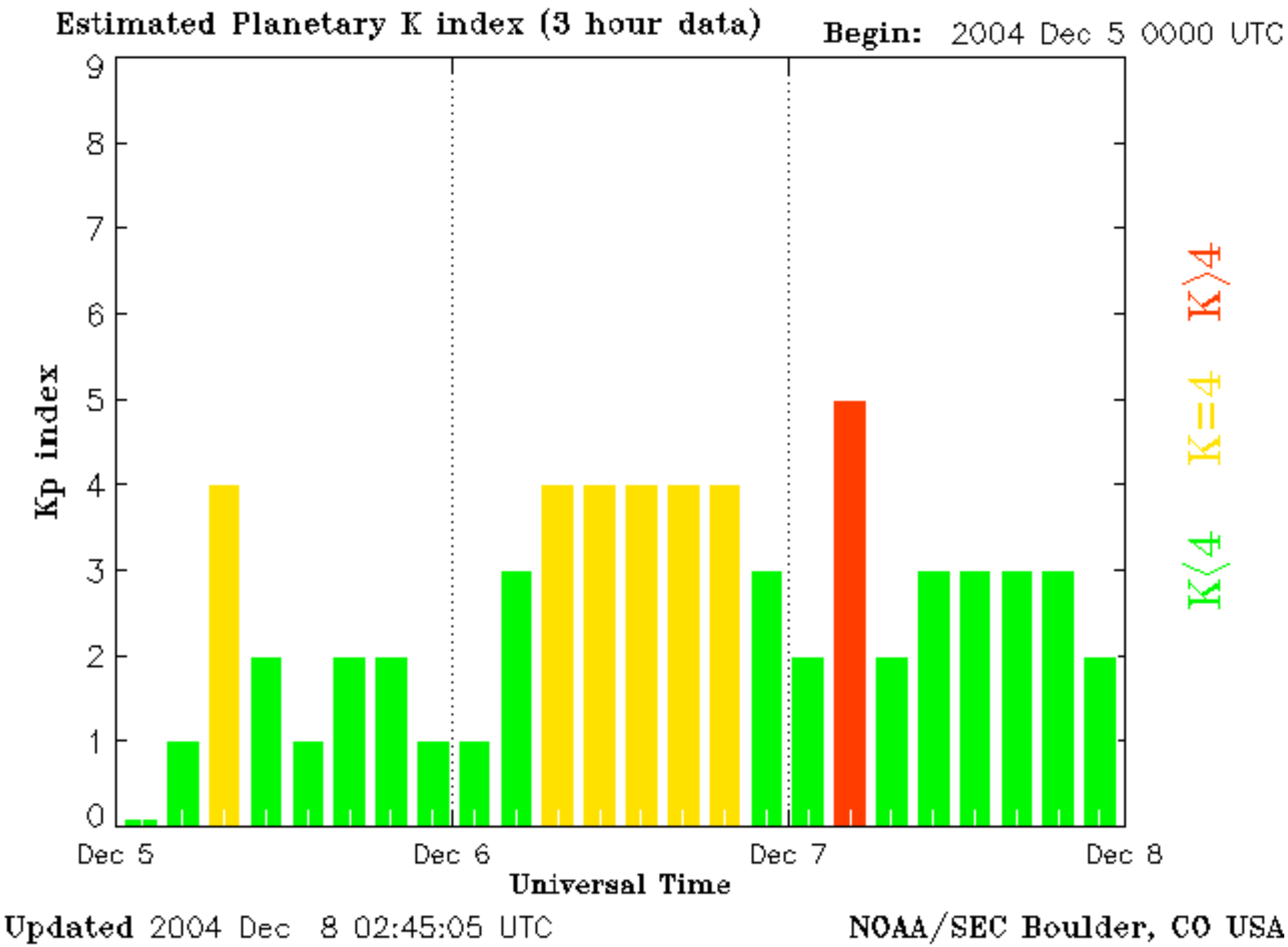

January 2004
Dst (Provisional)
WDC for Geomagnetism, Kyoto
(nT)
0
-100
-200
-300
-400
-500
1
6
11
16
21
26
31


January 2005
Dst (Provisional)
WDC for Geomagnetism, Kyoto
(nT)
0
-100
-200
-300
-400
-500
1
6
11
16
21
26
31

Kp index for the day 2004-01-25



Kp index for the day 2004-12-7



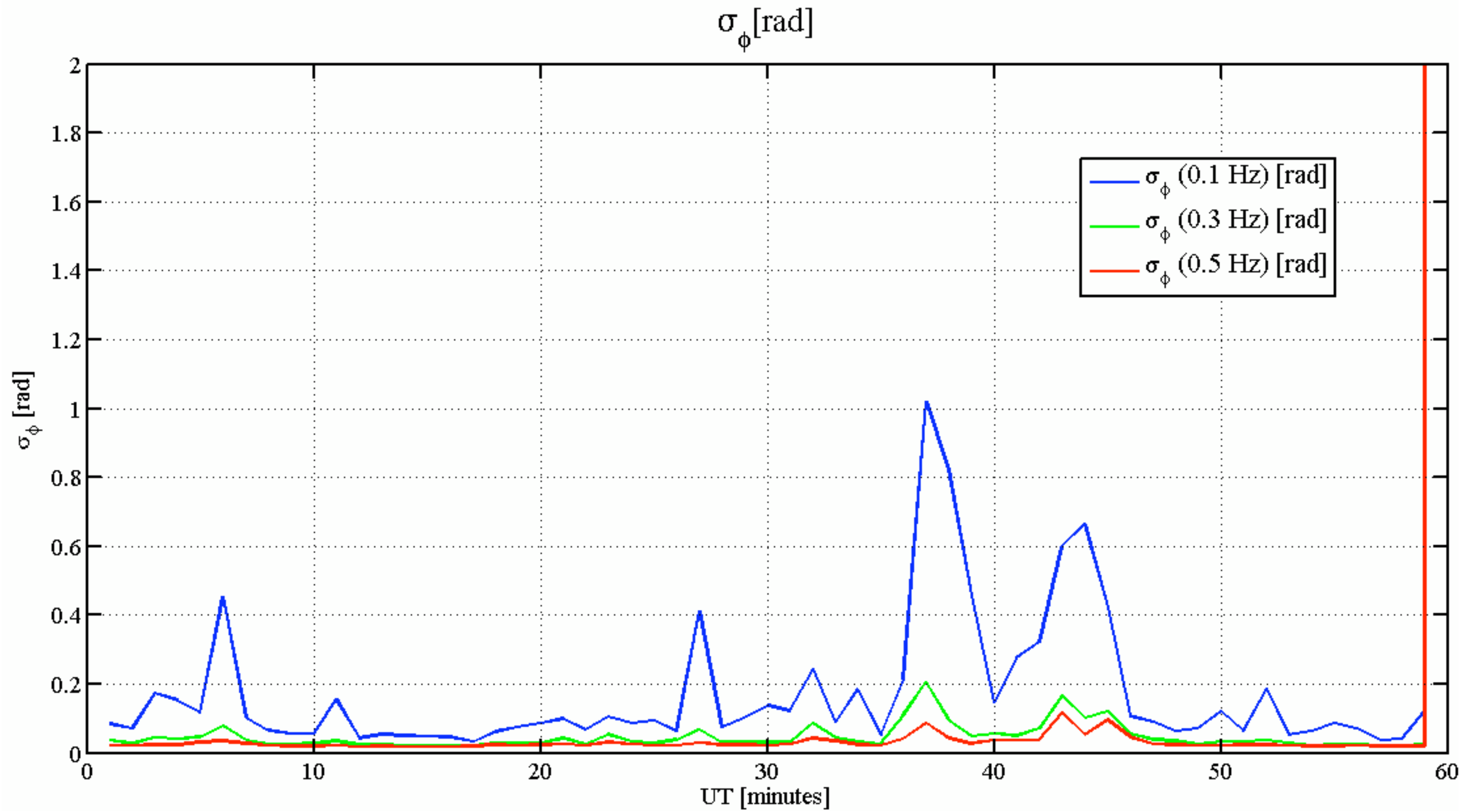
Experimental data (2)

- raw signal intensity and phase are detrended with a 6th order Butterworth high-pass filter, in order to remove undesired effects from the signals dynamics.

- three different values of the filter low frequency cutoff have been used:
  - 0.1 Hz blue
  - 0.3 Hz green
  - 0.5 Hz red

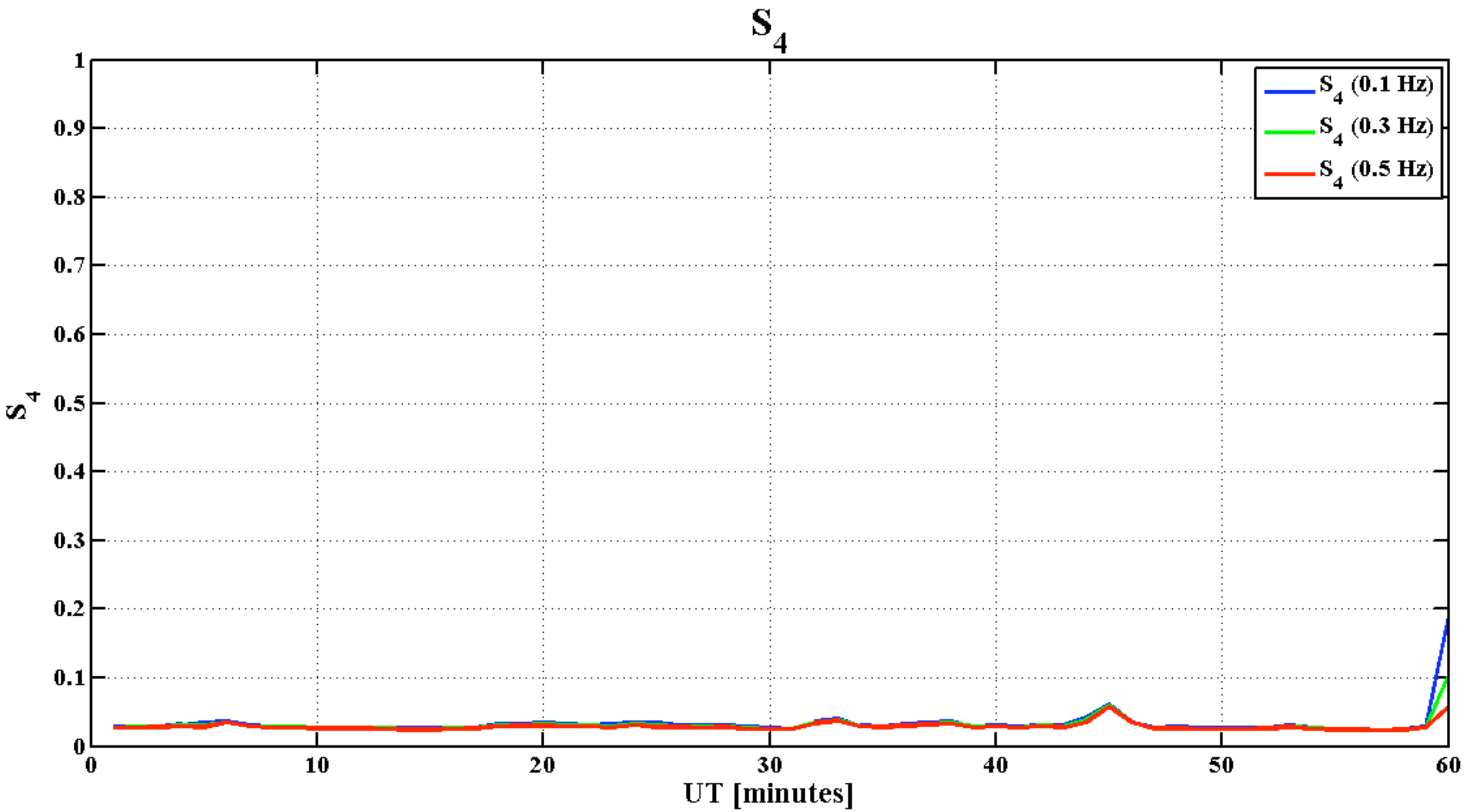
Results

0400-0500 UT on the day 2004-01-25, PRN 28



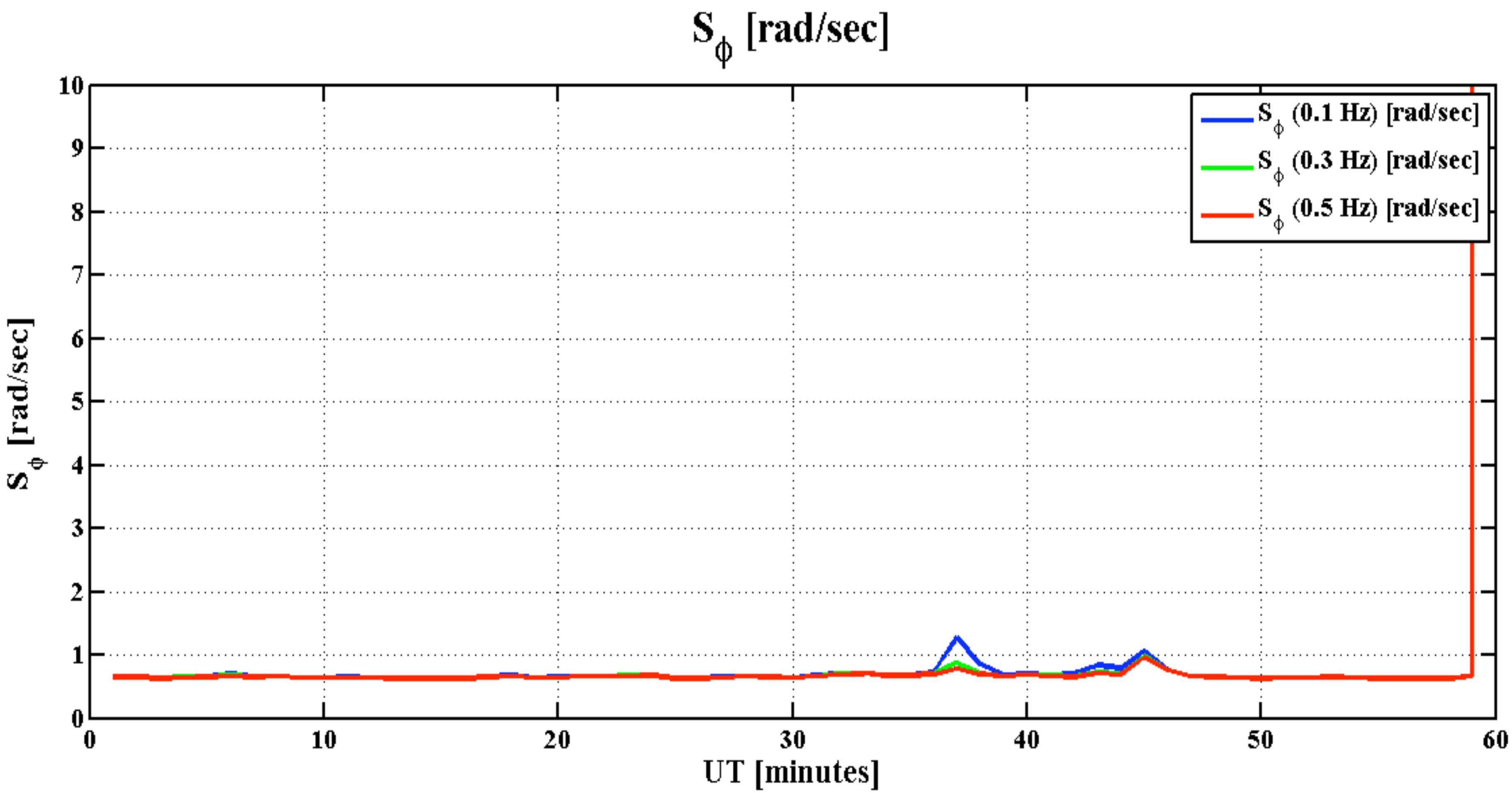
Results

0400-0500 UT on the day 2004-01-25, PRN 28



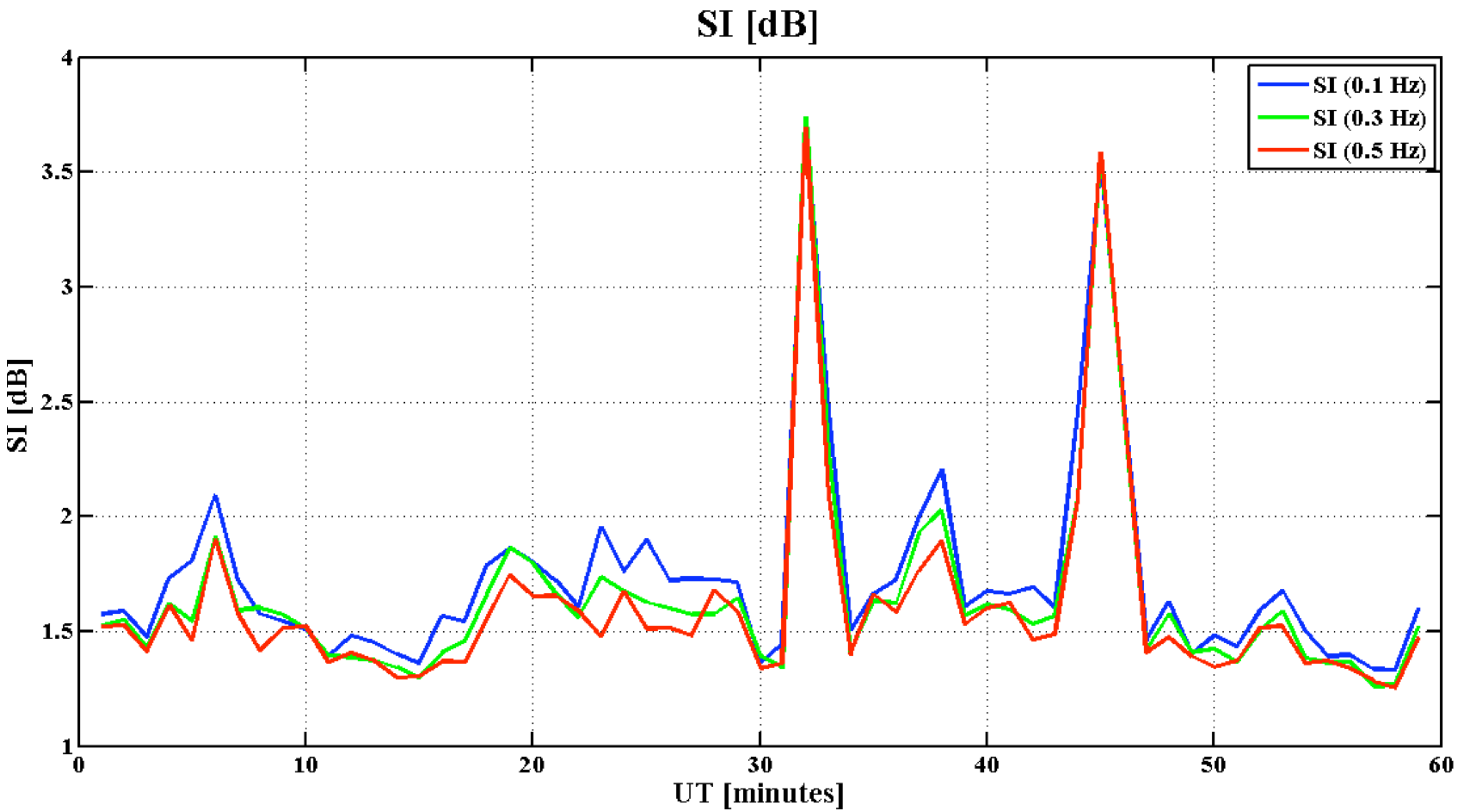
Results

0400-0500 UT on the day 2004-01-25 ,PRN 28



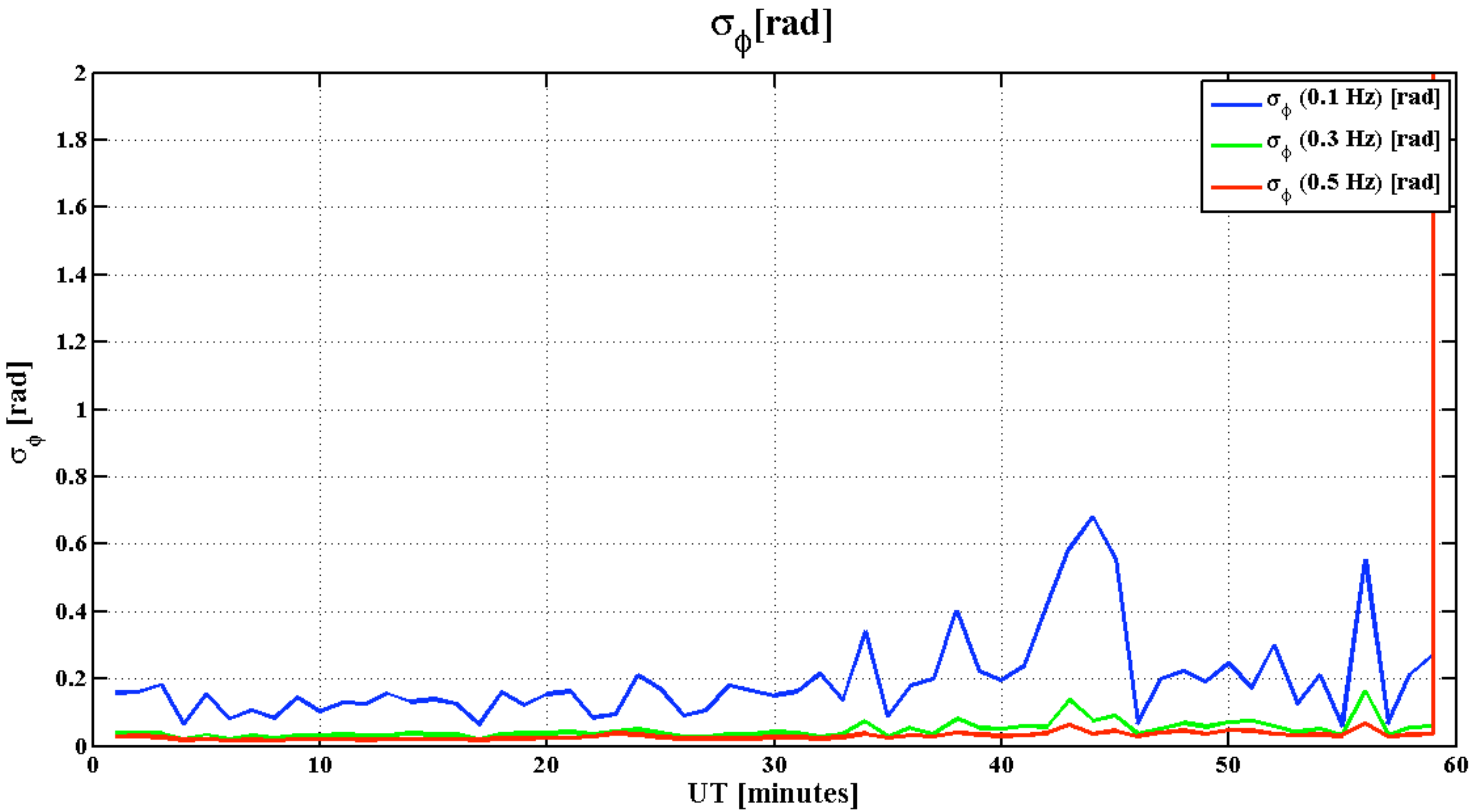
Results

0400-0500 UT on the day 2004-01-25, PRN 28



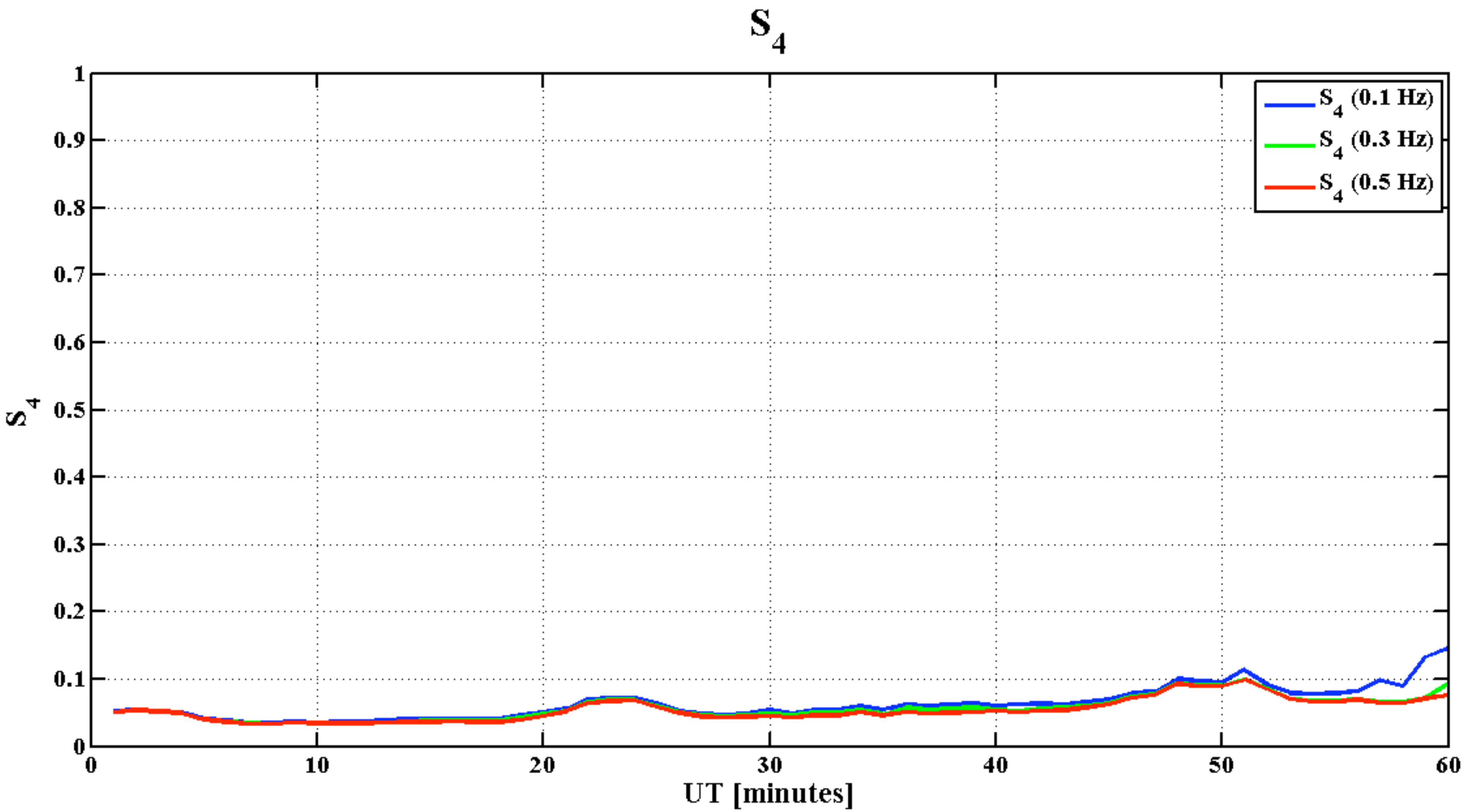
Results

1800-1900 UT on the day 2004-12-7 ,PRN 3



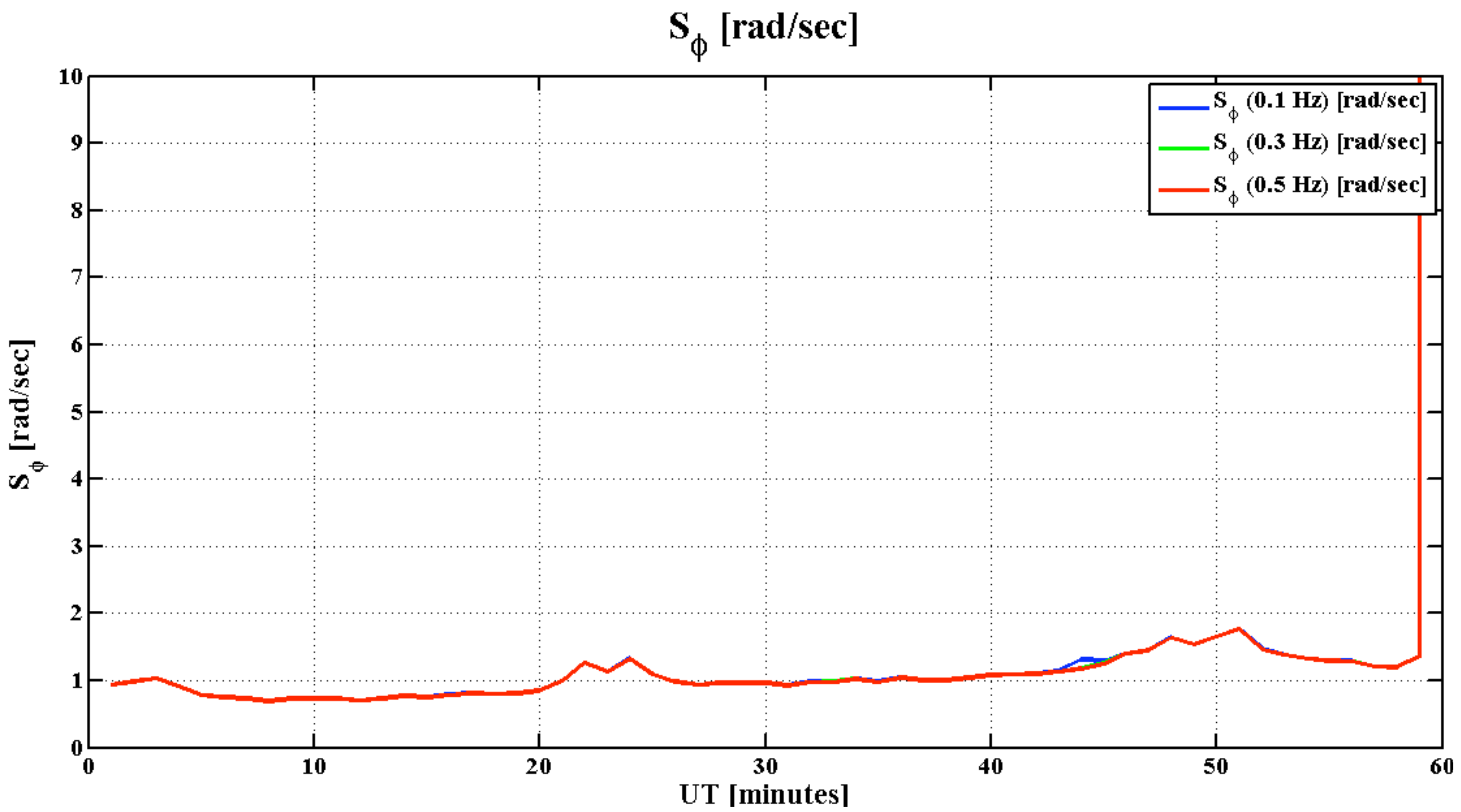
Results

1800-1900 UT on the day 2004-12-7 ,PRN 3



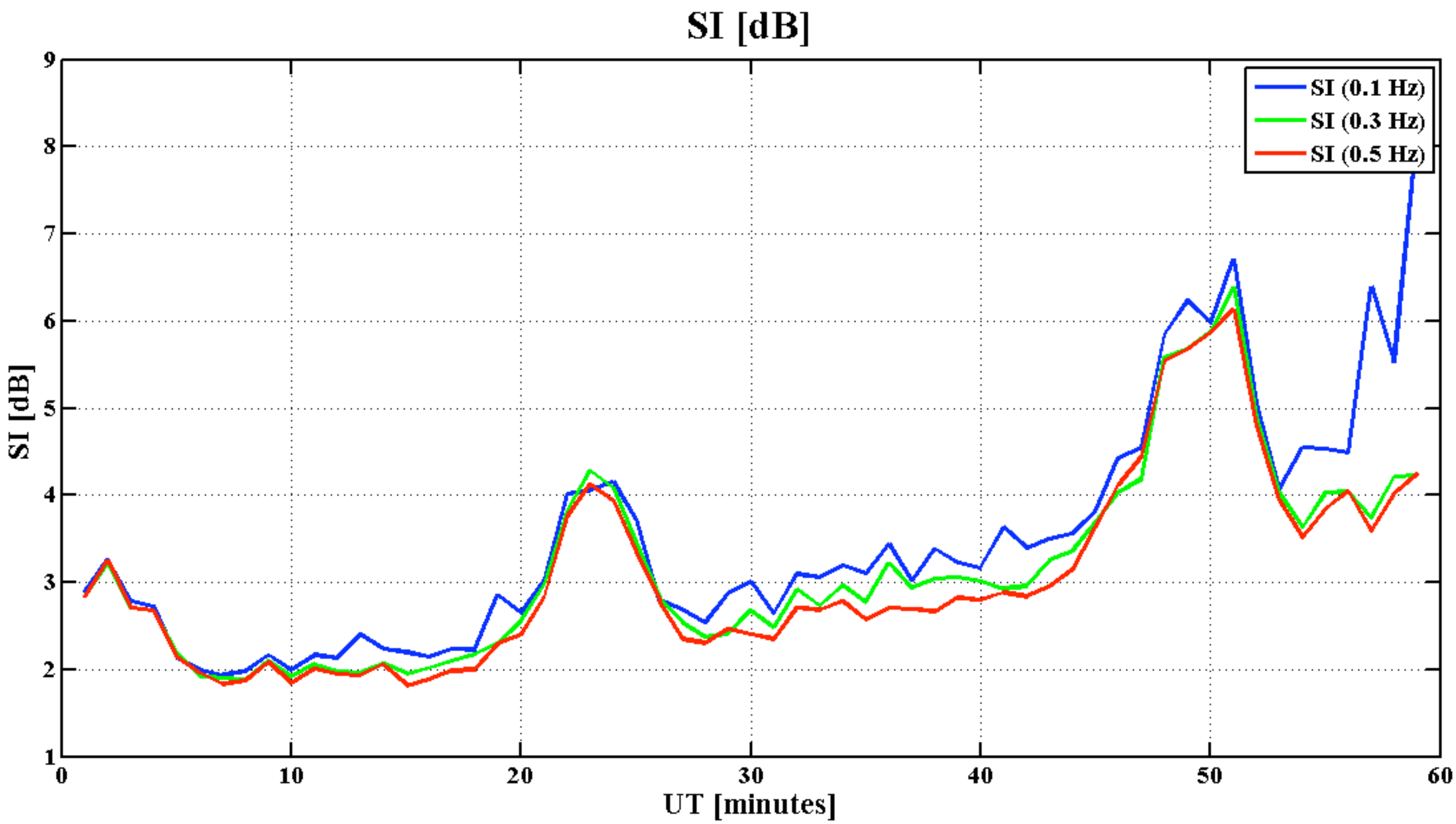
Results

1800-1900 UT on the day 2004-12-7 ,PRN 3



Results

1800-1900 UT on the day 2004-12-7 ,PRN 3



Conclusions

- an erroneous data detrending can be responsible for misleading data interpretation
- the new indices so far suggested show a better description of the events analyzed in terms of the measured scintillation activity
- more analyses will be done in the future on datasets from the African and Brazilian low latitudes sectors
- more experimental data at middle latitudes during solar maximum will be recorded at the UNG atmospheric observatory (Otlica)
- more experimental information at middle latitudes will be carried out by a TEC polarimeter to be implemented at the Otlica observatory later this year.

Thank you!