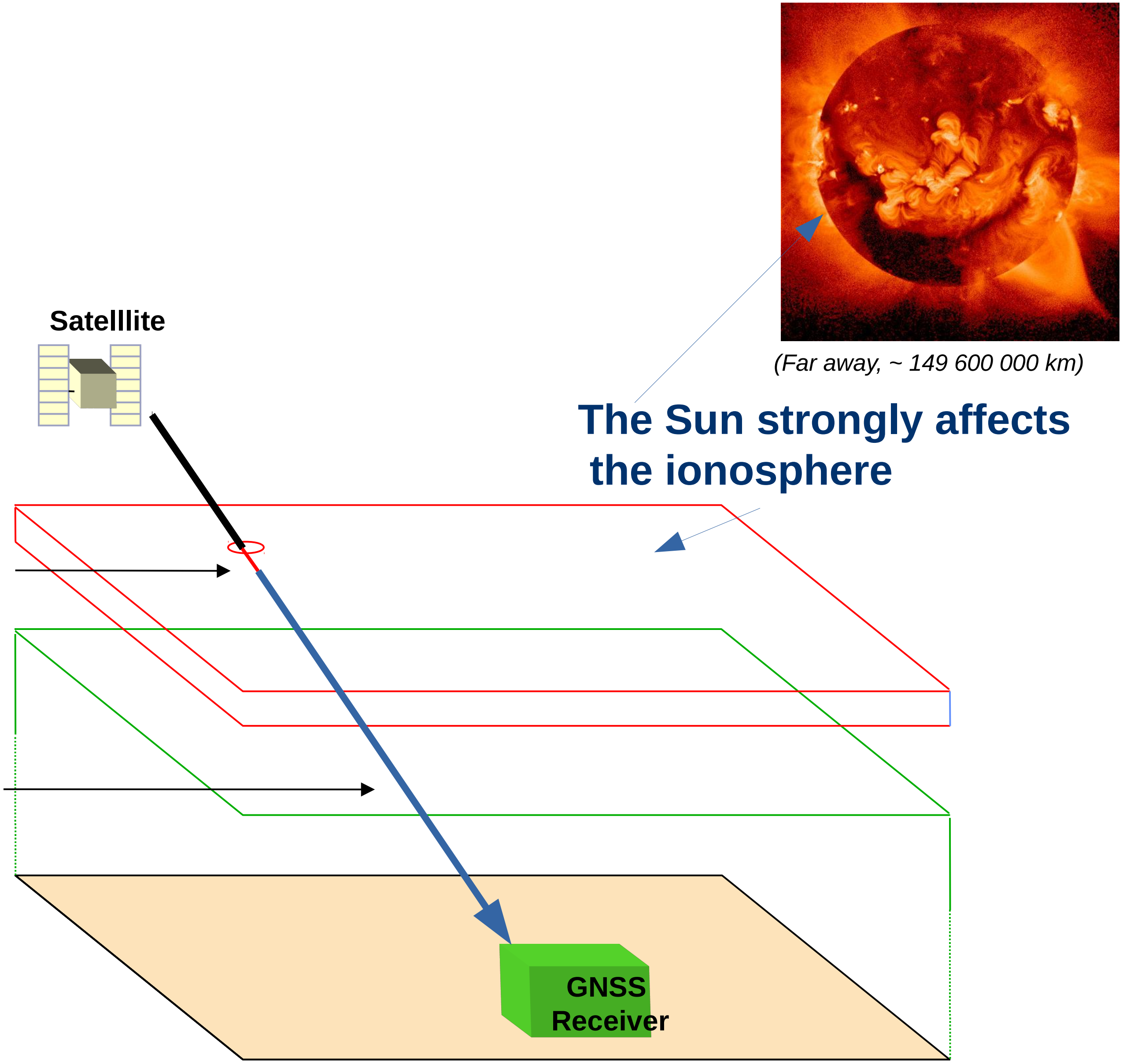
Kartverket

Ionosphere

Part 2 - Effects on GNSS

Knut Stanley Jacobsen

GNSS signals have to pass through the ionosphere



Satelllite

(GPS satellites orbit at ~ 20 000 km altitude)

(Far away, ~ 149 600 000 km)

The Sun strongly affects the ionosphere

<u>Ionosphere</u>

(Altitude: ~50 km to ~1000 km)

(Density normally peaks at ~ 350 km)

Troposphere

(Altitude: 0 km to 15 km)

GNSS Receiver

GNSS observation equations

Satellite “s”

Range

Speed of light

Ideally:

$$\rho_r^s = \sqrt{\left(\left(x^s - x_r\right)^2 + \left(y^s - y_r\right)^2 + \left(z^s - z_r\right)^2\right)} = c\,t$$

Travel time of
signal (measured)

Receiver “r”

GNSS observation equations

Satellite “s”

Range

Speed of light

Ideally:

$$\rho_r^s = \sqrt{\left((x^s - x_r)^2 + (y^s - y_r)^2 + (z^s - z_r)^2 \right)} = c\,t$$

Travel time of
signal (measured)

Receiver “r”

Accounting for various error sources:

$$P_{r,i}^s = \rho_r^s + \delta\rho_r^s + c(\delta t_r - \delta t^s) + T + \frac{1}{f_i^2} I + b_{P,i}^s + b_{r,P,i} + \epsilon_{P_i}$$

Pseudorange

$$L_{r,i}^s = \rho_r^s + \delta\rho_r^s + c(\delta t_r - \delta t^s) + T - \frac{1}{f_i^2} I + b_{L,i}^s + b_{r,L,i} - \lambda_i N_{r,i}^s + \epsilon_{L_i}$$

Phase

Frequency “i”

GNSS observation equations

Ideally:

Satellite “s”

Range

Speed of light

$$\rho_r^s = \sqrt{\left((x^s - x_r)^2 + (y^s - y_r)^2 + (z^s - z_r)^2\right)} = c\,t$$

Receiver “r”

Travel time of
signal (measured)

Accounting for various error sources:

Satellite
orbit error

Receiver
clock error

Satellite
clock error

Troposphere

Ionosphere

Satellite code bias

Receiver code bias

Remaining errors
(multipath, noise, etc)

$$P^s_{r,i} = \rho_r^s + \delta\rho_r^s + c\left(\delta t_r - \delta t^s\right) + T + \frac{1}{f_i^2} I + b^s_{P,i} + b_{r,P,i} + \epsilon_{P_i}$$

Pseudorange

$$L^s_{r,i} = \rho_r^s + \delta\rho_r^s + c\left(\delta t_r - \delta t^s\right) + T - \frac{1}{f_i^2} I + b^s_{L,i} + b_{r,L,i} - \lambda_i N^s_{r,i} + \epsilon_{L_i}$$

Phase

Frequency “i”

Frequency of
carrier wave

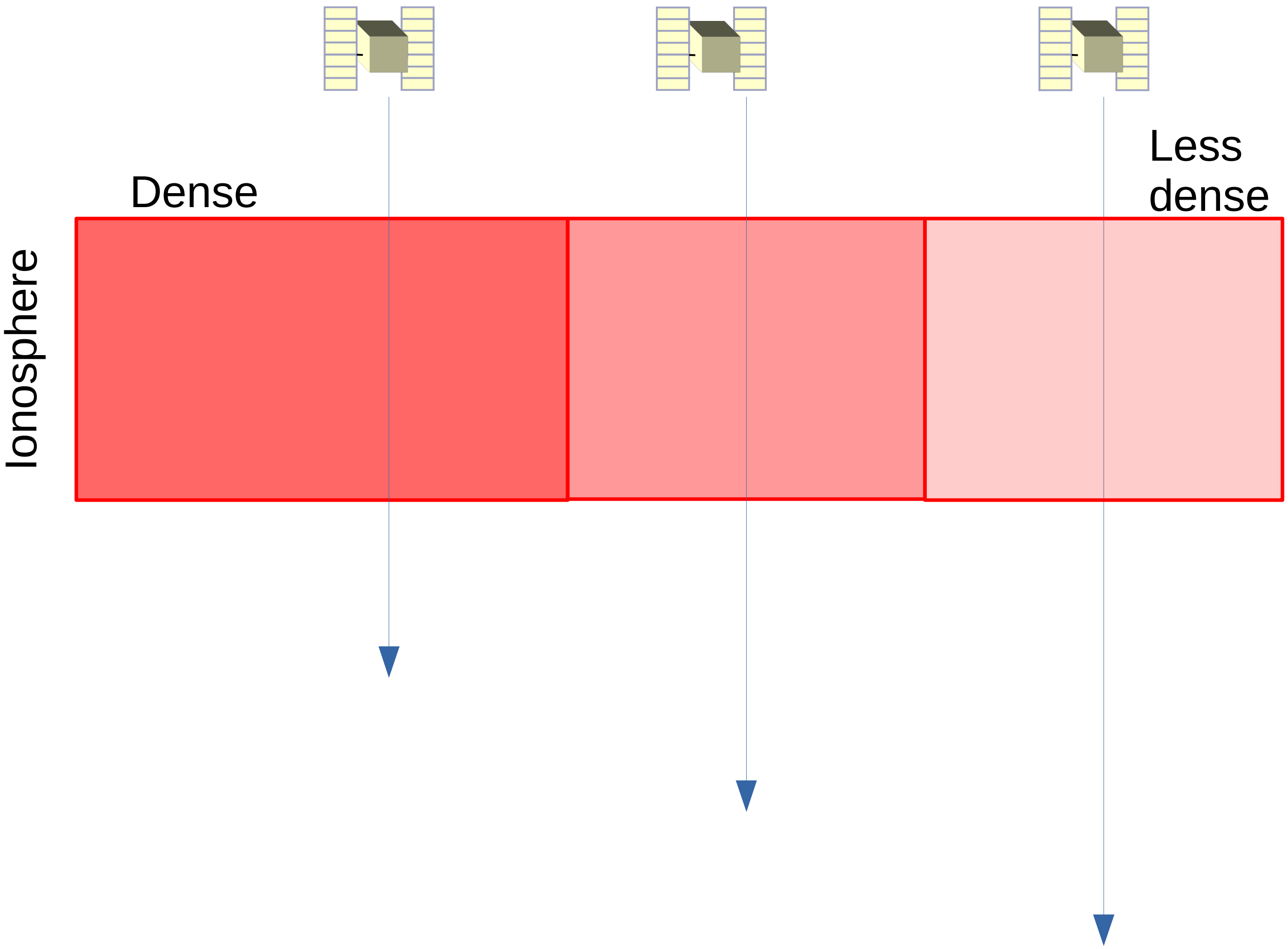
Satellite
phase
bias

Receiver
phase
bias

Wavelength of
carrier wave

Integer ambiguity

Signal delay



Electromagnetic waves are delayed when passing through a plasma.

The delay is proportional to the integrated density of the plasma along the signal path.

In addition, the signal phase is advanced.

Signal delay can be corrected to the first order by the use of dual frequency equipment

Scintillation

Fine structuring of the ionospheric plasma causes random changes to signal phase along the signal wavefront.

The resulting self-interference causes great problems for receivers.

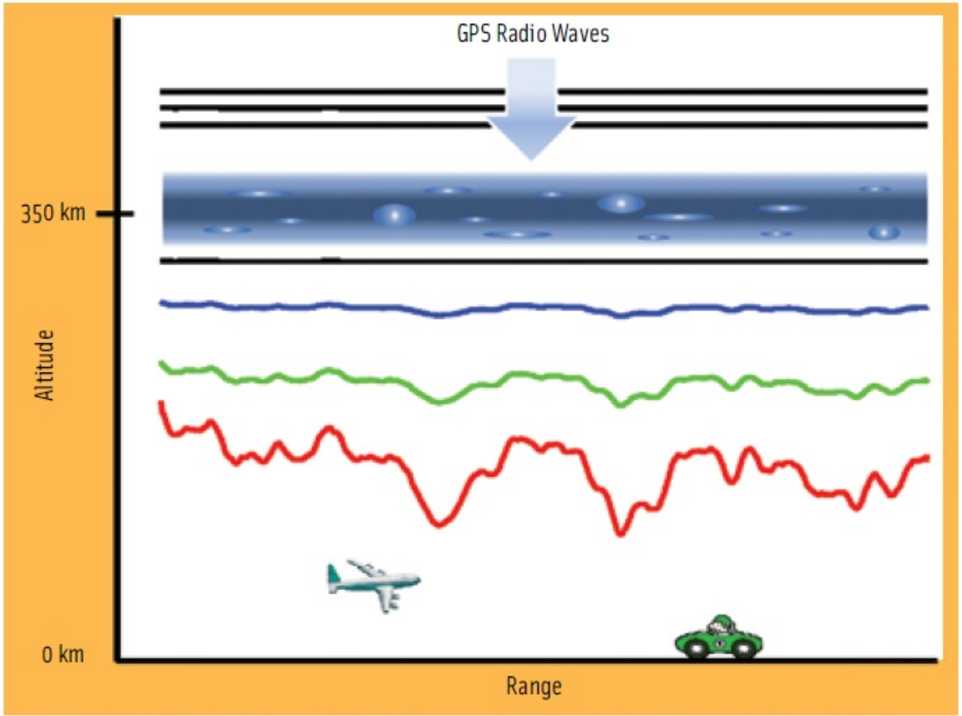


FIGURE 2 Radio wave propagation through a disturbed ionosphere. The horizontal curves represent signal amplitude. Irregularities in the ionosphere introduce phase shifts that become amplitude perturbations as the wave propagates below the ionosphere.

Example: Signal to noise ratios:

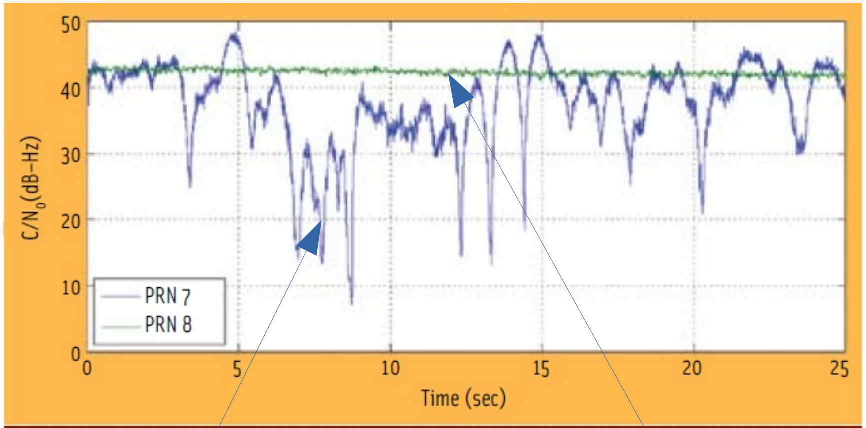


FIGURE 3 Two examples of GPS carrier-to-noise ratios for a non-scintillating satellite signal (PRN 7) and for a scintillating satellite signal (PRN 8).

Blue line:
Disturbed
signal
(scintillation)

Green line:
Undisturbed
signal

Disturbances are quantified by various indices

The amplitude scintillation index “S4” is the normalized standard deviation of the signal intensity

$$S4=\frac{\sqrt{\langle I^2\rangle-\langle I\rangle^2}}{\langle I\rangle^2}$$

The phase scintillation index “sigma phi” is the standard deviation of the detrended signal phase

$$\sigma_\varphi=\sqrt{\langle\varphi^2\rangle-\langle\varphi\rangle^2}$$

The Rate-Of-TEC-Index (ROTI) is also a measure of phase variation, but through a different equation

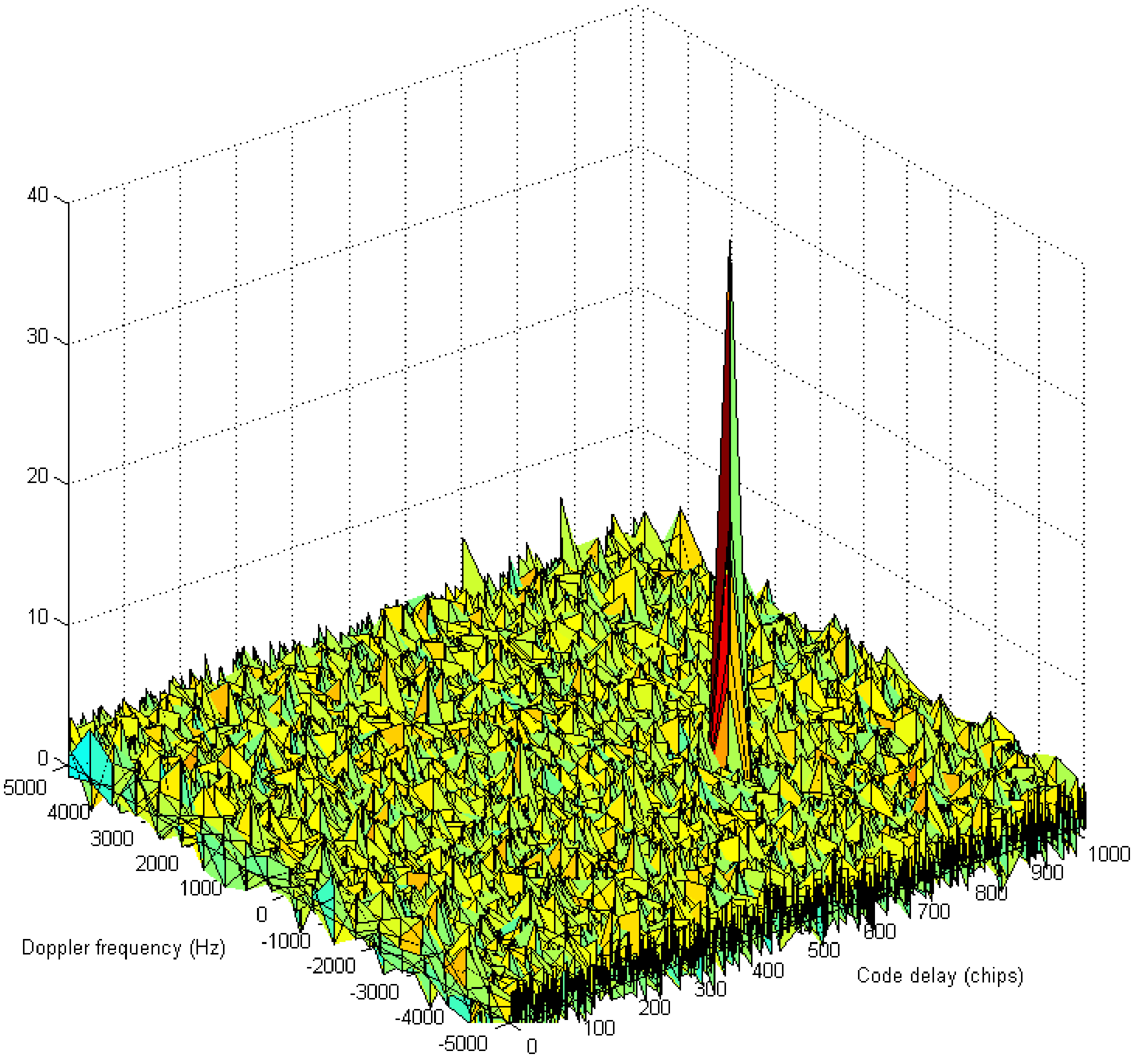
$$ROTI=\sqrt{\langle ROT^2\rangle-\langle ROT\rangle^2}$$

$$ROT(i)=\frac{L_{GF}(i)-L_{GF}(i-1)}{t(i)-t(i-1)}$$

$$L_{GF}(i)=\lambda_1 L_1(i)-\lambda_2 L_2(i)$$

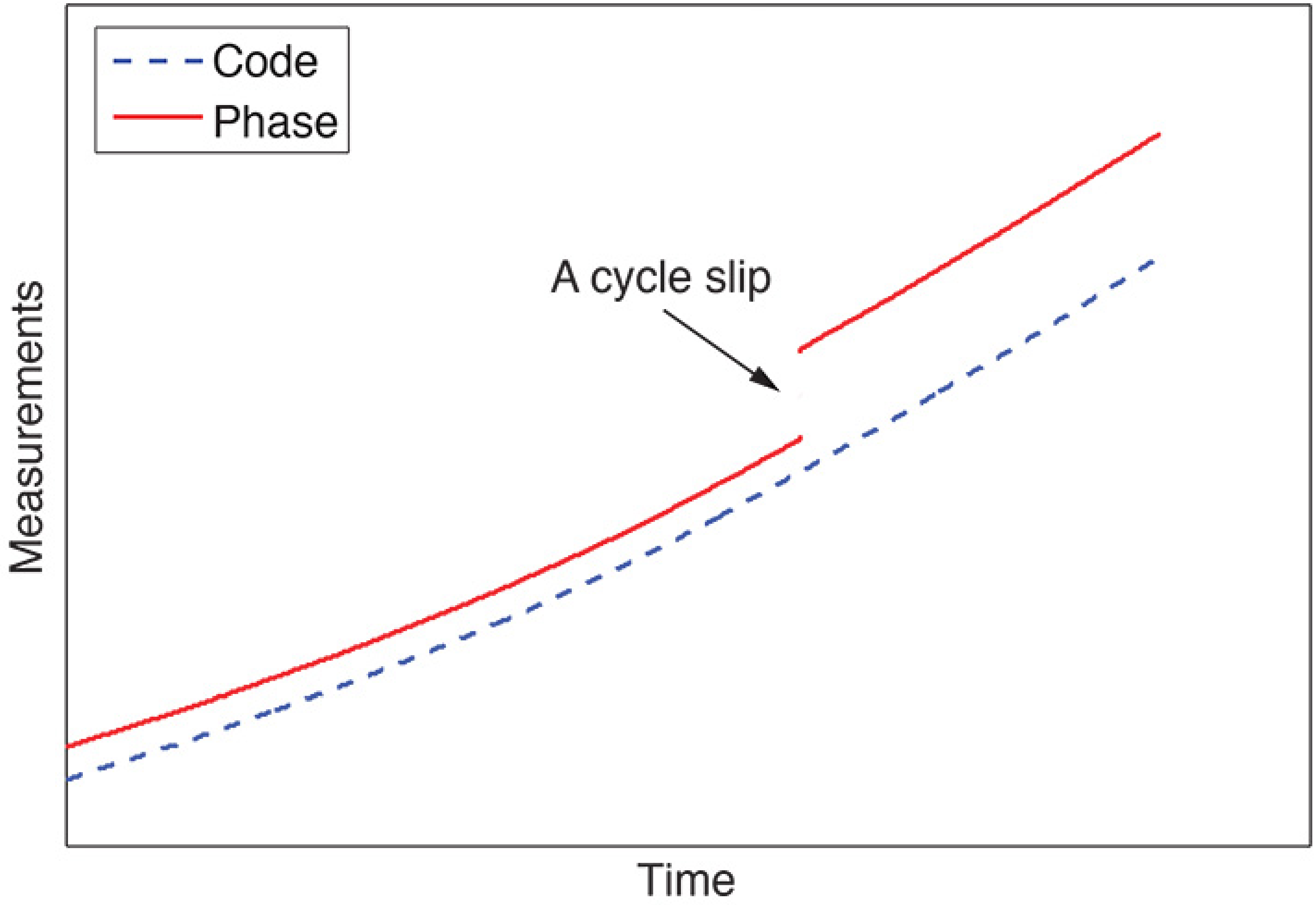
Effects on the receiver hardware

Amplitude and phase scintillations can cause the receiver to lose track of the signal.



Effects on the receiver hardware

Phase scintillations that do not cause a complete tracking loss can cause a partial tracking loss resulting in a break in the phase time series. (a “cycle slip”)



Where do the effects enter the observation equation?

Signal delay

$$P^{s}_{r,i}=\rho^{s}_{r}+\delta\rho^{s}_{r}+c\left(\delta t_{r}-\delta t^{s}\right)+T\boxed{+\frac{1}{f_{i}^{2}}I}+b^{s}_{P,i}+b_{r,P,i}+\epsilon_{P_{i}}$$

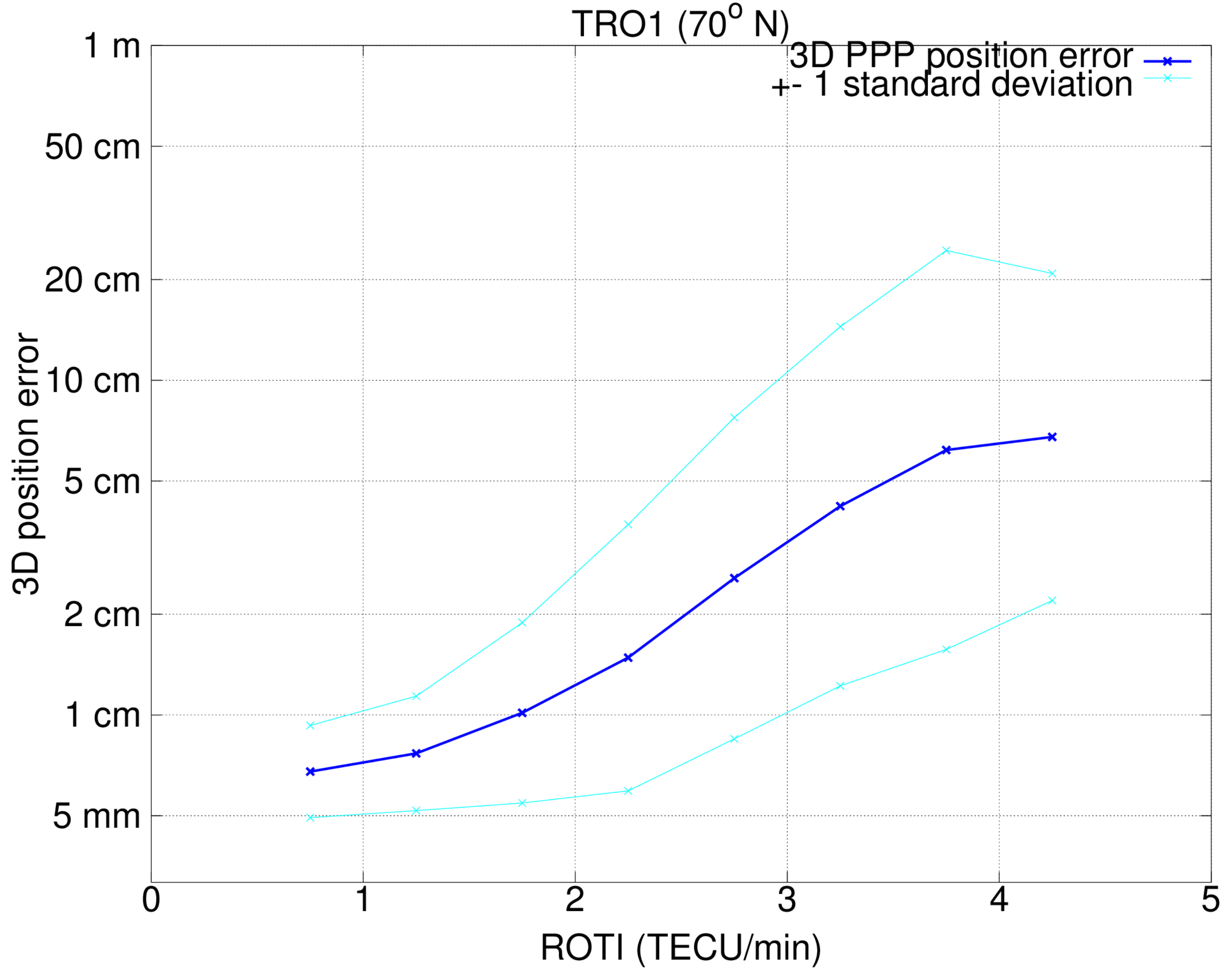
$$L^{s}_{r,i}=\rho^{s}_{r}+\delta\rho^{s}_{r}+c\left(\delta t_{r}-\delta t^{s}\right)+T\boxed{-\frac{1}{f_{i}^{2}}I}+b^{s}_{L,i}+b_{r,L,i}-\lambda_{i}N^{s}_{r,i}\boxed{+\epsilon_{L_{i}}}$$

Phase scintillation

Phase advance

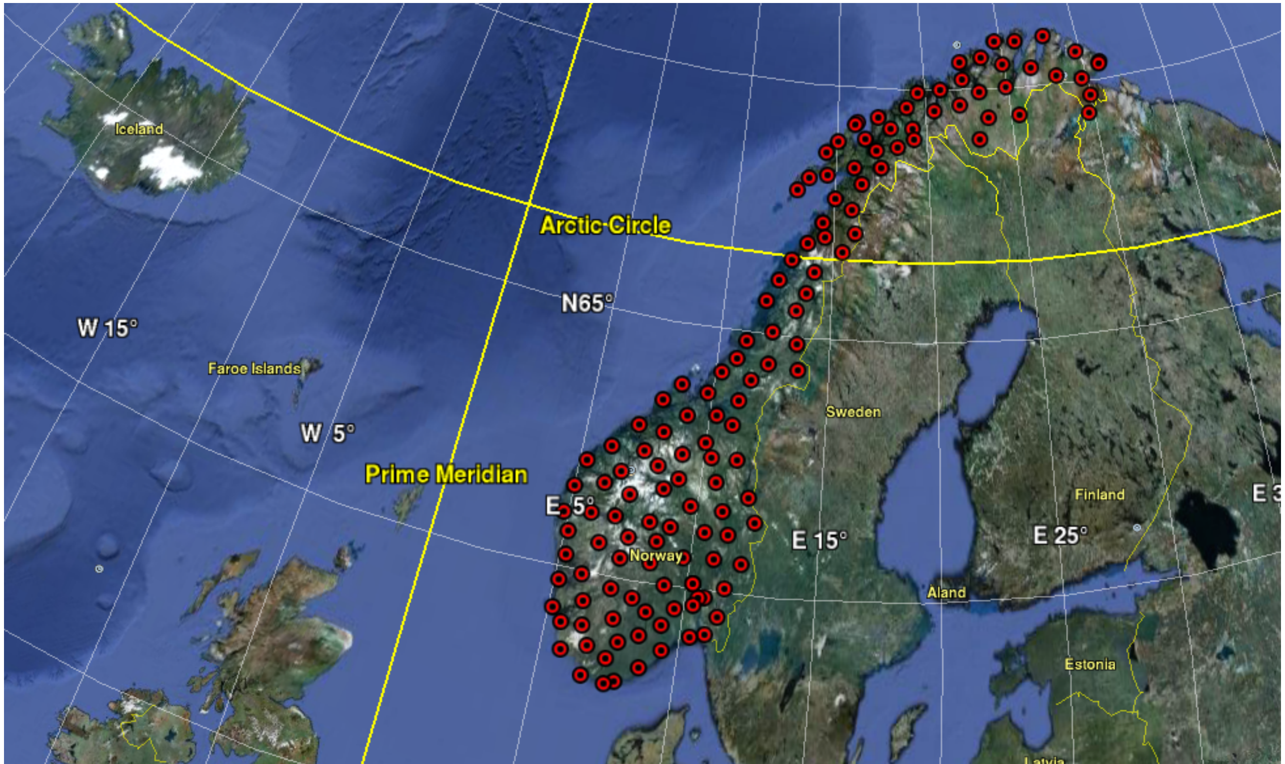
(Amplitude scintillation does not enter the observation equation)

Effects on the position solution



Effects on RTK positioning network

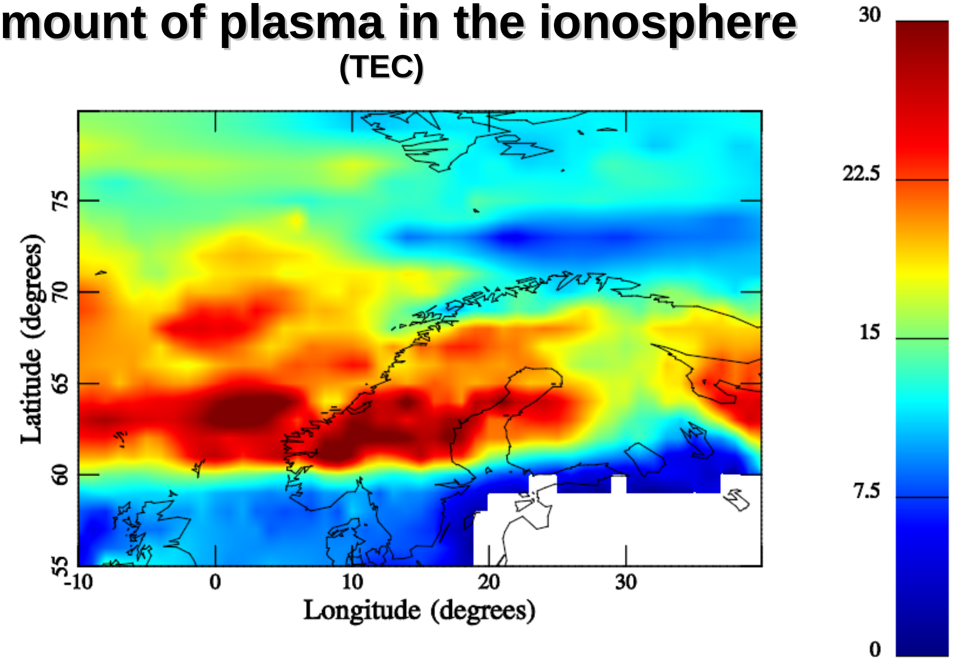
SATREF
cpos



2011-10-24 22:05 UT

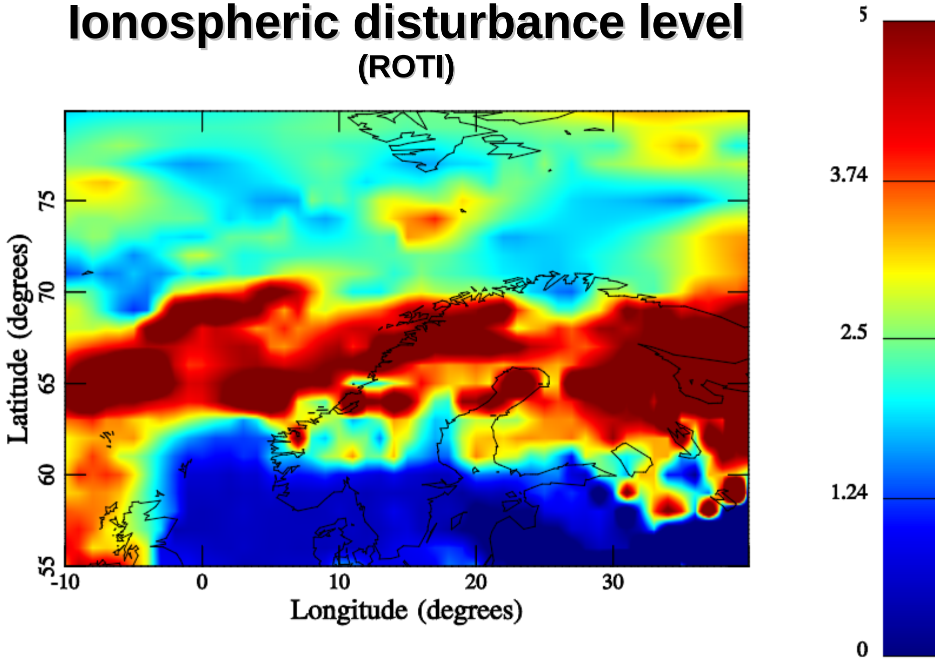
Amount of plasma in the ionosphere

(TEC)



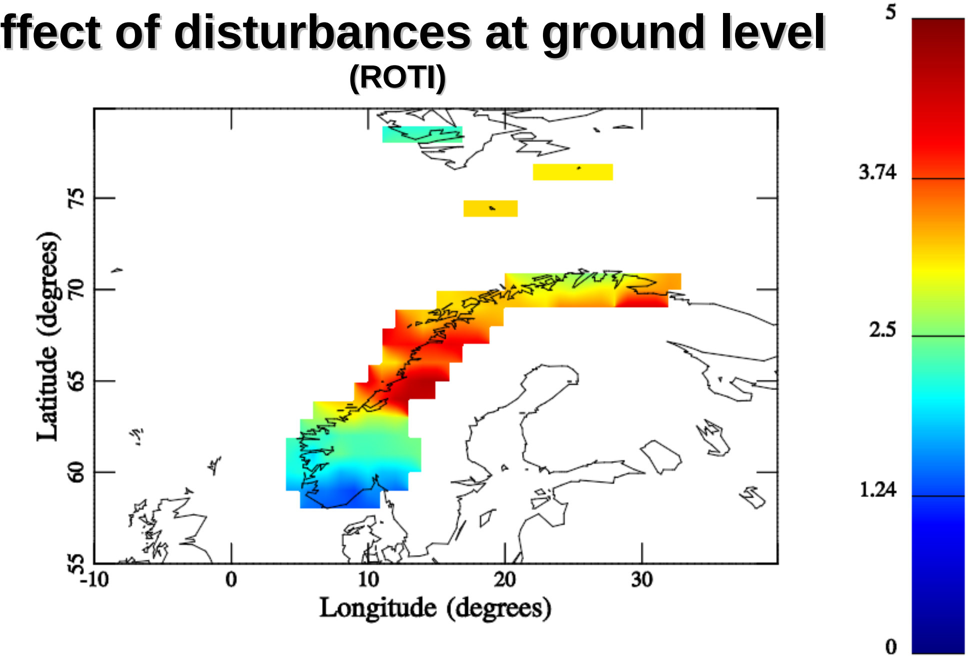
Ionospheric disturbance level

(ROTI)

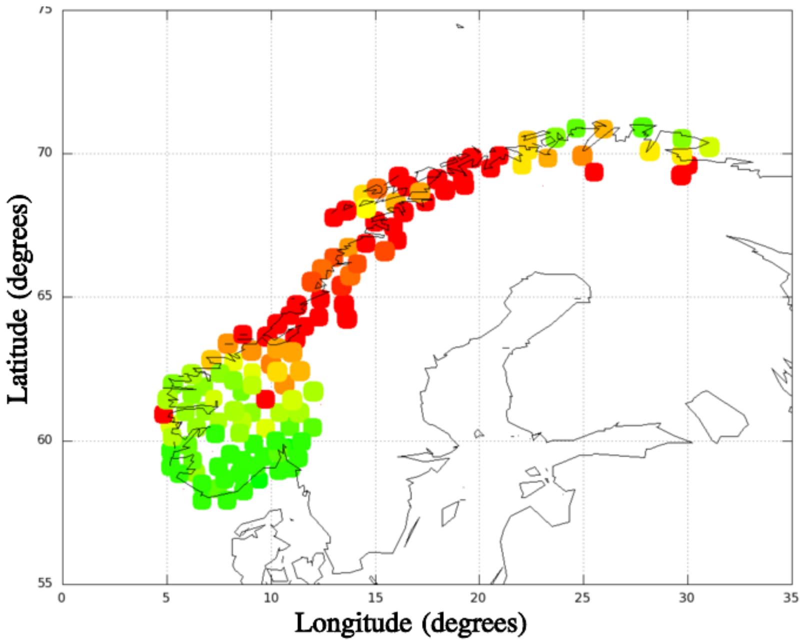


Effect of disturbances at ground level

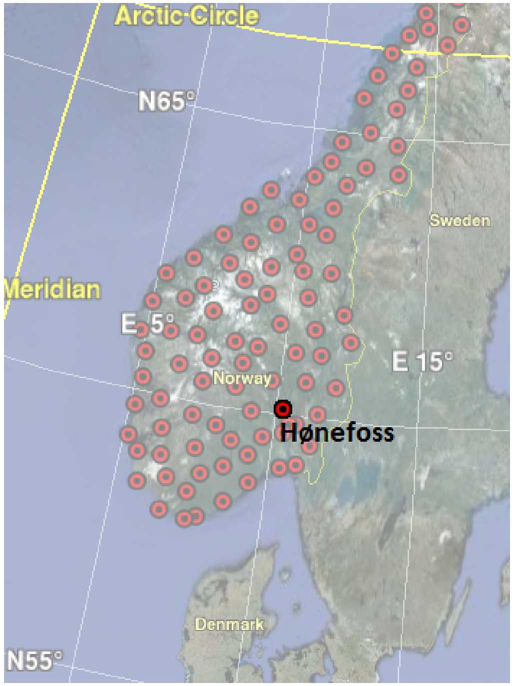
(ROTI)

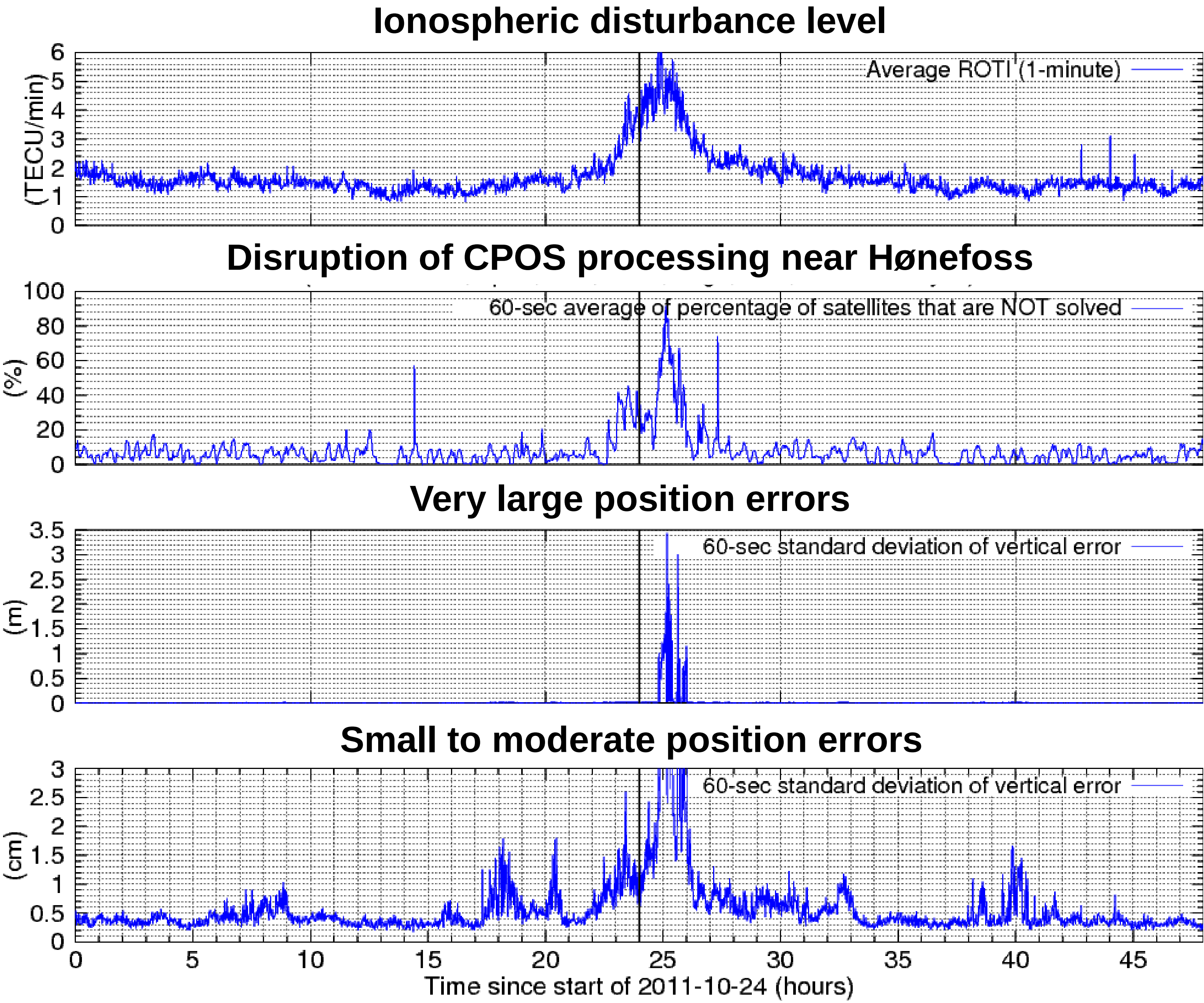


CPOS Processing Status



GNSS monitor measures user experience





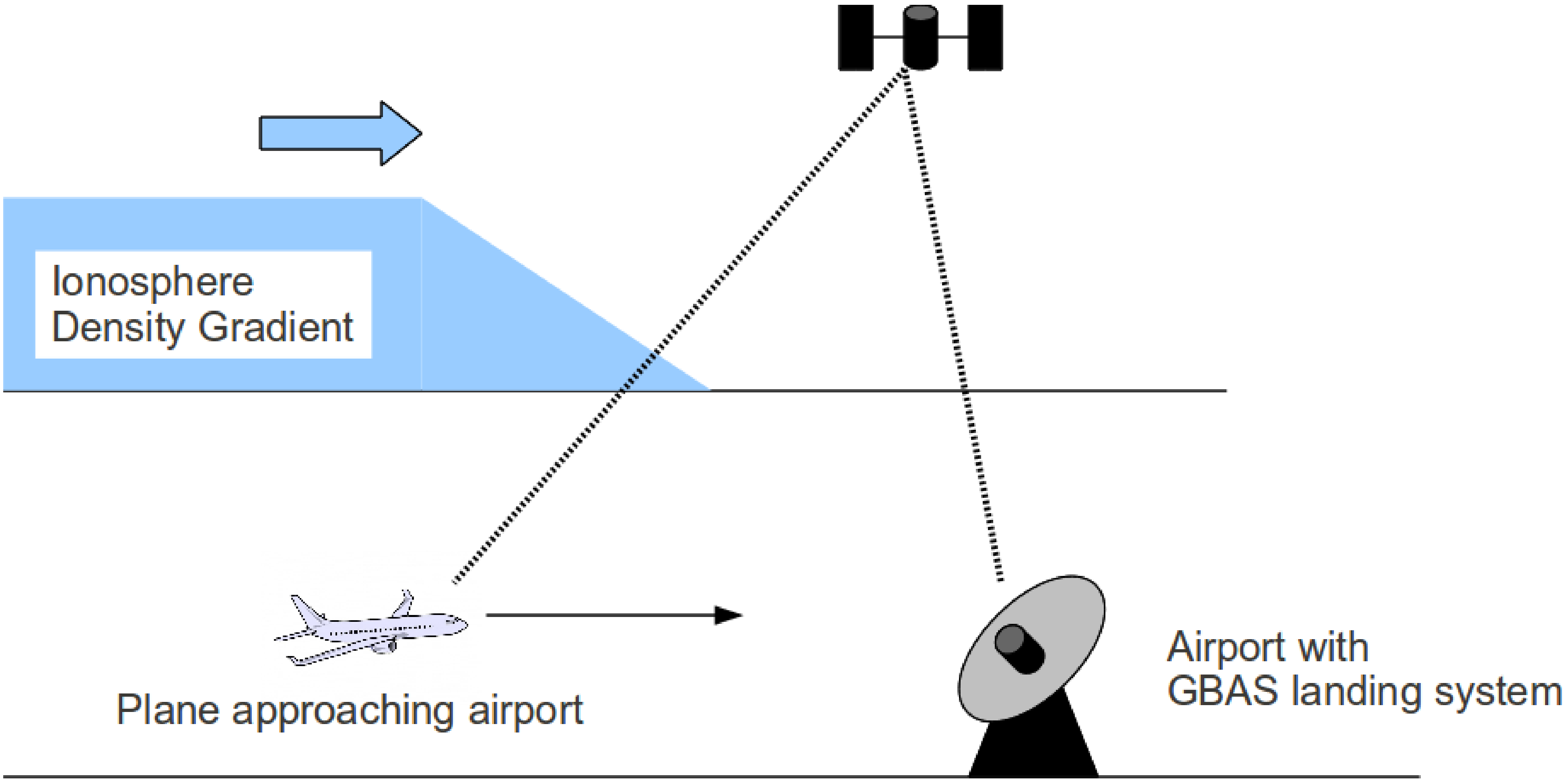
Ionospheric disturbance level

Disruption of CPOS processing near Hønefoss

Very large position errors

Small to moderate position errors

Ionospheric gradients may threaten GNSS support systems



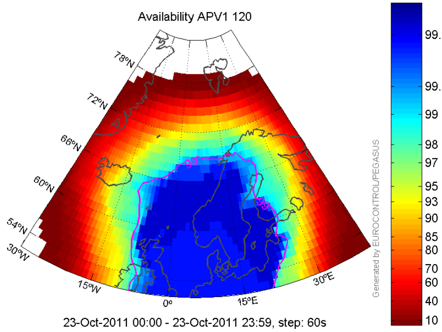
Effects on EGNOS

23 October	24 October	25 October	26 October

Geomagnetic storm

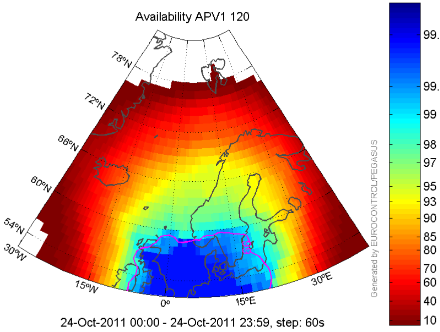
EGNOS (APV-1 Availability) in Scandinavia

Availability APV1 120



23-Oct-2011 00:00 - 23-Oct-2011 23:59, step: 60s

Availability APV1 120



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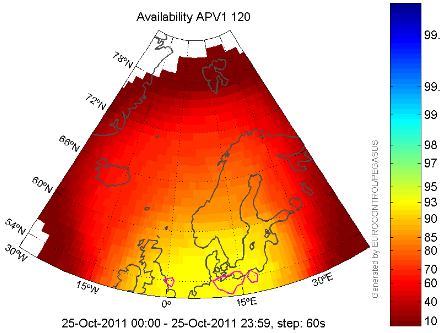
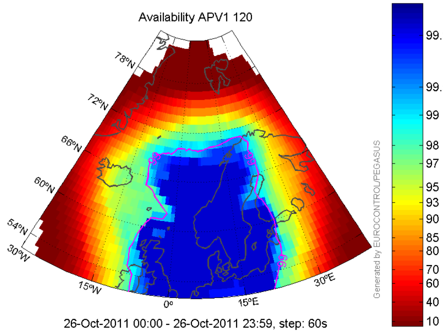
Availability APV1 120



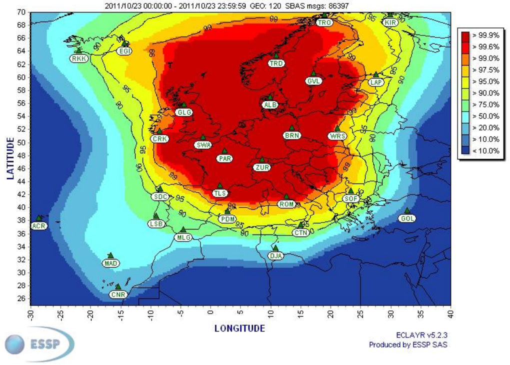
25-Oct-2011 00:00 - 25-Oct-2011 23:59, step: 60s

Availability APV1 120



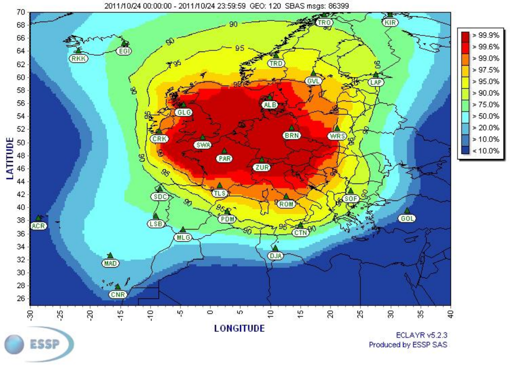
26-Oct-2011 00:00 - 26-Oct-2011 23:59, step: 60s

EGNOS (APV-1 Availability) in Europe



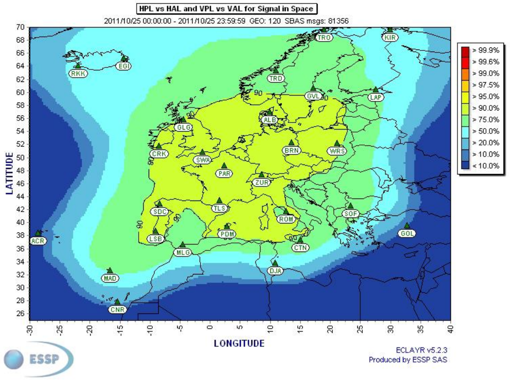
HPL vs HAL and VPL vs VAL for Signal in Space

2011/10/23 00:00:00 - 2011/10/23 23:59:59 GEO: 120 SBAS msgs: 86397



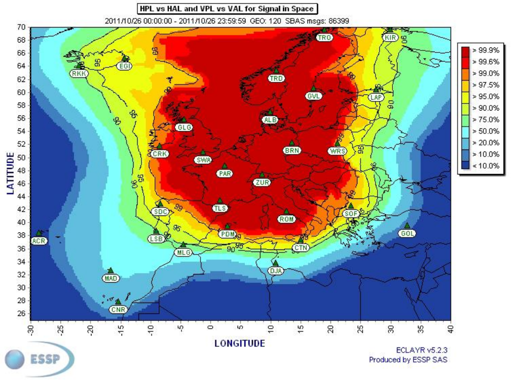
HPL vs HAL and VPL vs VAL for Signal in Space

2011/10/24 00:00:00 - 2011/10/24 23:59:59 GEO: 120 SBAS msgs: 86399



HPL vs HAL and VPL vs VAL for Signal in Space

2011/10/25 00:00:00 - 2011/10/25 23:59:59 GEO: 120 SBAS msgs: 81356



HPL vs HAL and VPL vs VAL for Signal in Space

2011/10/26 00:00:00 - 2011/10/26 23:59:59 GEO: 120 SBAS msgs: 86399

Mitigation - Delay

Signal delay (and phase advance) can be mitigated by:

- Forming a combination of measurements on two frequencies in such a way that the ionospheric component is eliminated

$$P_{r,i}^{s}=\rho_r^s+\delta\rho_r^s+c\left(\delta t_r-\delta t^s\right)+T+\frac{1}{f_i^2}I+b_{P,i}^{s}+b_{r,P,i}+\epsilon_{P_i}$$

$$L_{r,i}^{s}=\rho_r^s+\delta\rho_r^s+c\left(\delta t_r-\delta t^s\right)+T-\frac{1}{f_i^2}I+b_{L,i}^{s}+b_{r,L,i}-\lambda_i N_{r,i}^{s}+\epsilon_{L_i}$$

$$P_{IF}=\frac{f_1^2P_1-f_2^2P_2}{f_1^2-f_2^2}=\rho_r^s+\delta\rho_r^s+c\left(\delta t_r-\delta t^s\right)+T+\frac{f_1^2\left(b_{P,1}^{s}+b_{r,P,1}\right)-f_2^2\left(b_{P,2}^{s}+b_{r,P,2}\right)}{f_1^2-f_2^2}+\frac{f_1^2\epsilon_{P_1}-f_2^2\epsilon_{P_2}}{f_1^2-f_2^2}$$

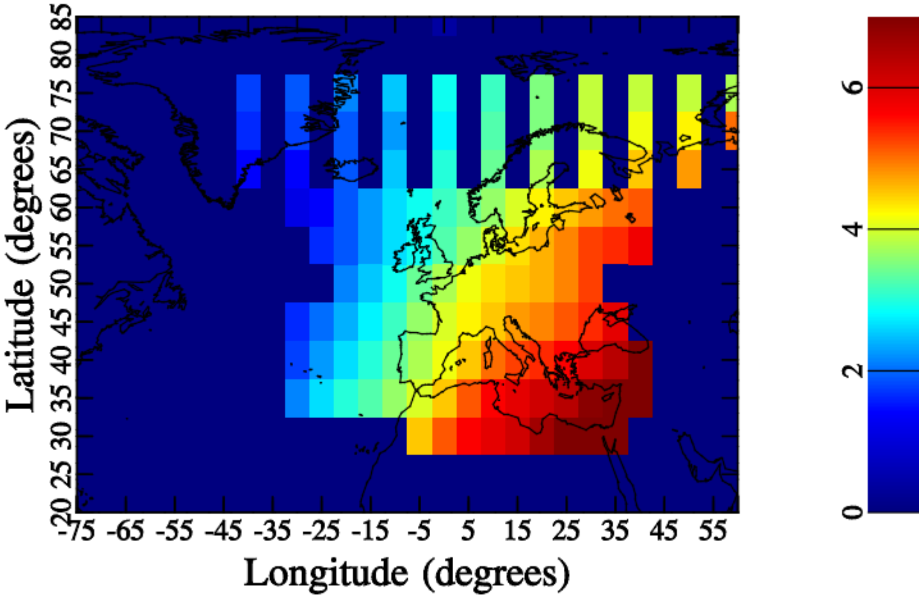
$$L_{IF}=\frac{f_1^2L_1-f_2^2L_2}{f_1^2-f_2^2}=\rho_r^s+\delta\rho_r^s+c\left(\delta t_r-\delta t^s\right)+T+\frac{f_1^2\left(b_{L,1}^{s}+b_{r,L,1}-\lambda_1N_{r,1}^{s}\right)-f_2^2\left(b_{L,2}^{s}+b_{r,L,2}-\lambda_2N_{r,2}^{s}\right)}{f_1^2-f_2^2}+\frac{f_1^2\epsilon_{L_2}-f_2^2\epsilon_{L_2}}{f_1^2-f_2^2}$$

Mitigation - Delay

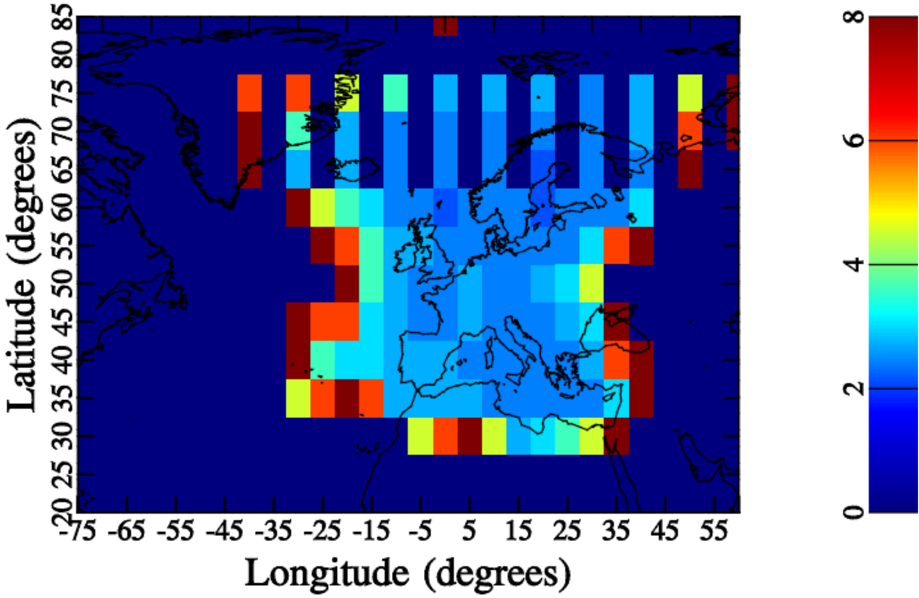
Signal delay (and phase advance) can be mitigated by:

- Receiving information about the ionospheric component from an external source. e.g:
  - Static empirical model
  - Empirical model with measured input variables
  - Measured ionosphere state from a receiver network

Total Electron Content [Meter]
2014-02-25 08:45 UTC



Grid Ionospheric Vertical Error [Meter]
2014-02-25 08:45 UTC



Mitigation - Scintillation

Scintillation is harder to mitigate, and has to be dealt with before the observables (pseudo-range and phase) are formed.

This means that the receiver hardware (and/or software, in the case of a software receiver) has to be built to be robust against scintillation.

Unfortunately, making the hardware robust against scintillation will generally require a decrease in performance in some other fashion.

Example: Normal receivers can handle phase scintillation better by increasing the bandwidth of the phase tracking loop, but this increases the noise in the resulting phase observable.

Question time!