Research seminar on Sun-Earth connections

Space weather and GNSS

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Outline

1. What is satellite navigation
2. Space weather impact on satellite navigation
3. Mitigation of the space weather effects
4. Space weather monitoring with navigation satellites

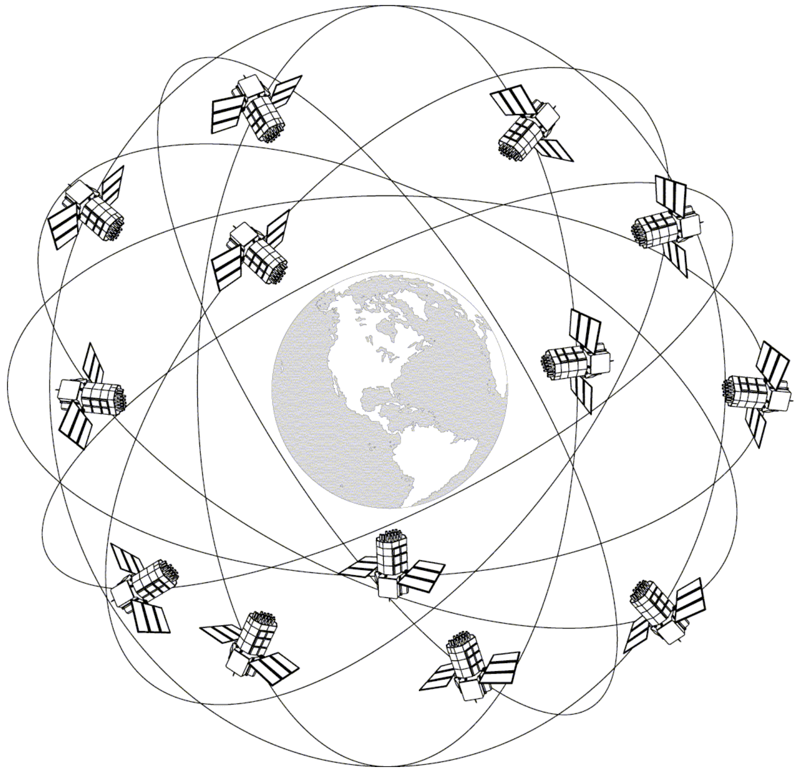
What is GNSS?

GNSS = Global Navigation Satellite System

- GNSS (Global Navigation Satellite System) is a generic name for all existing and future navigation satellite systems
- Currently the US developed GPS (Global Positioning System) is only fully operational satellite navigation system

  => most (≈ all) civilian users are using GPS
- Other navigation satellite systems exist or are under development:
  - Russian GLONASS (GLObal NAvigation Satellite System)
  - European Galileo system
- Also other "space" nations have at least considered developing their own navigation satellite systems (Japan, China, India)
- Something to think about: How many navigation satellite constellations do we need for one planet??

NAVSTAR GPS



Nominal constellation:

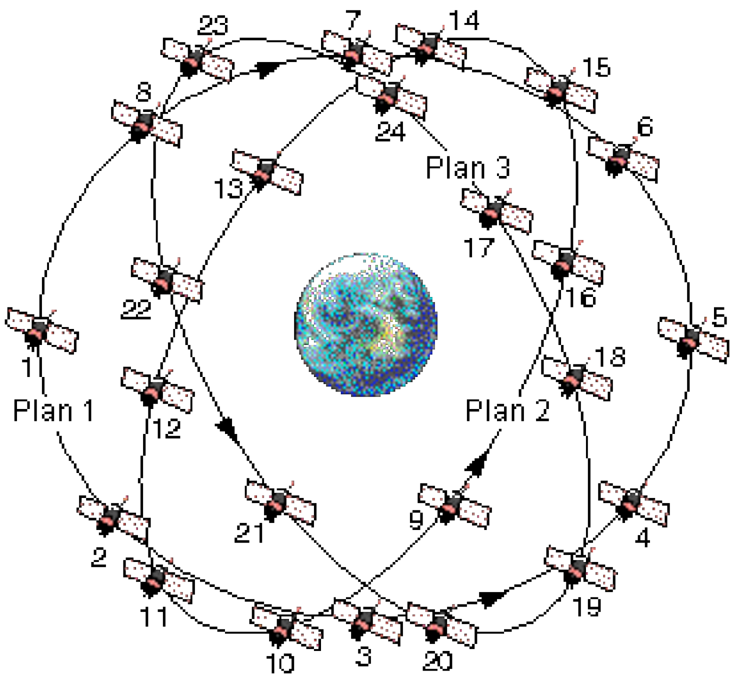
- 24 satellites
- 6 orbit planes at i = 55º
- Orbit height 20 200 km
- Orbit period 12 h

Status

- Currently 4 reserve satellites in orbit
  => 28 satellites in constellation
- Fully operational since
  17 July1995
- GPS modernizations to has been
  started on 25 September 2005
  => second frequency for civilian users

  => improved positioning accuracy

GLONASS



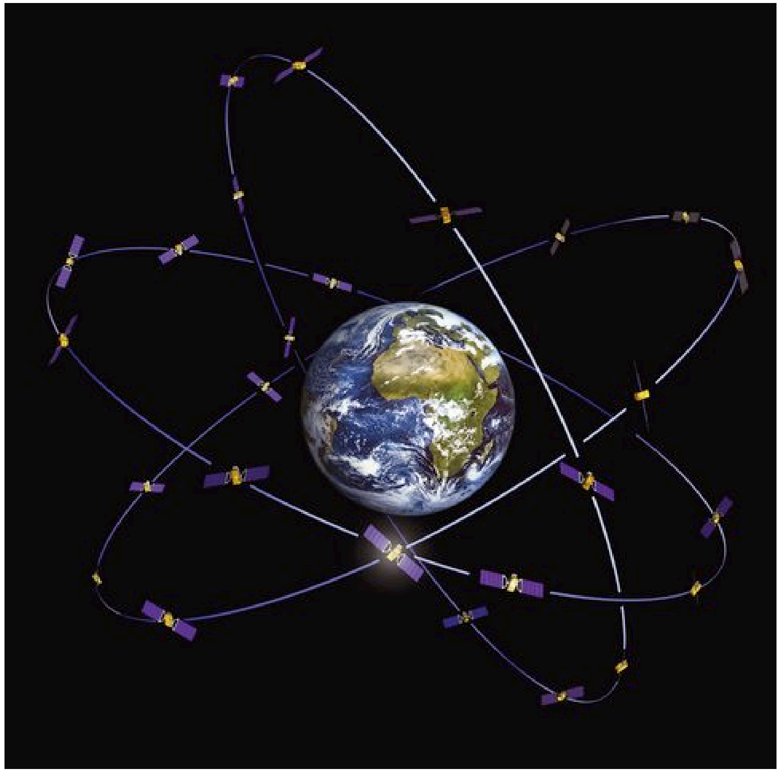
Nominal constellation:

- 24 satellites (21 + 3)
- 3 orbit planes at i = 64.8º
- Orbit height 19 100 km
- Orbit period 11 h 15 min

Status

- Currently 12 operating satellites + 2 waiting to be commissioned
- Development plans:
  - 18 operational satellites by 2008
  - Fully operational system by 2010

Galileo



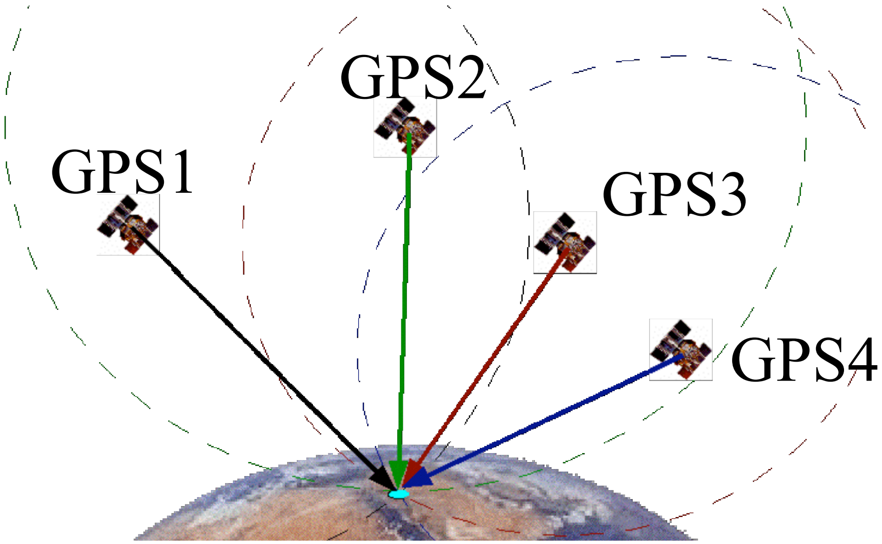
Nominal constellation:

- 30 satellites (27 +3)
- 3 orbit planes at i = 56º
- Orbit height 23 222 km
- Orbit period ≈ 14 h

Status

- First test satellite GIOVE A launched on 28 December 2005
- Second test satellite GIOVE B to be launched in 2006
- Operational constellation to be deployed starting 2008
- Fully operational status by 2010?

Principles of satellite navigation

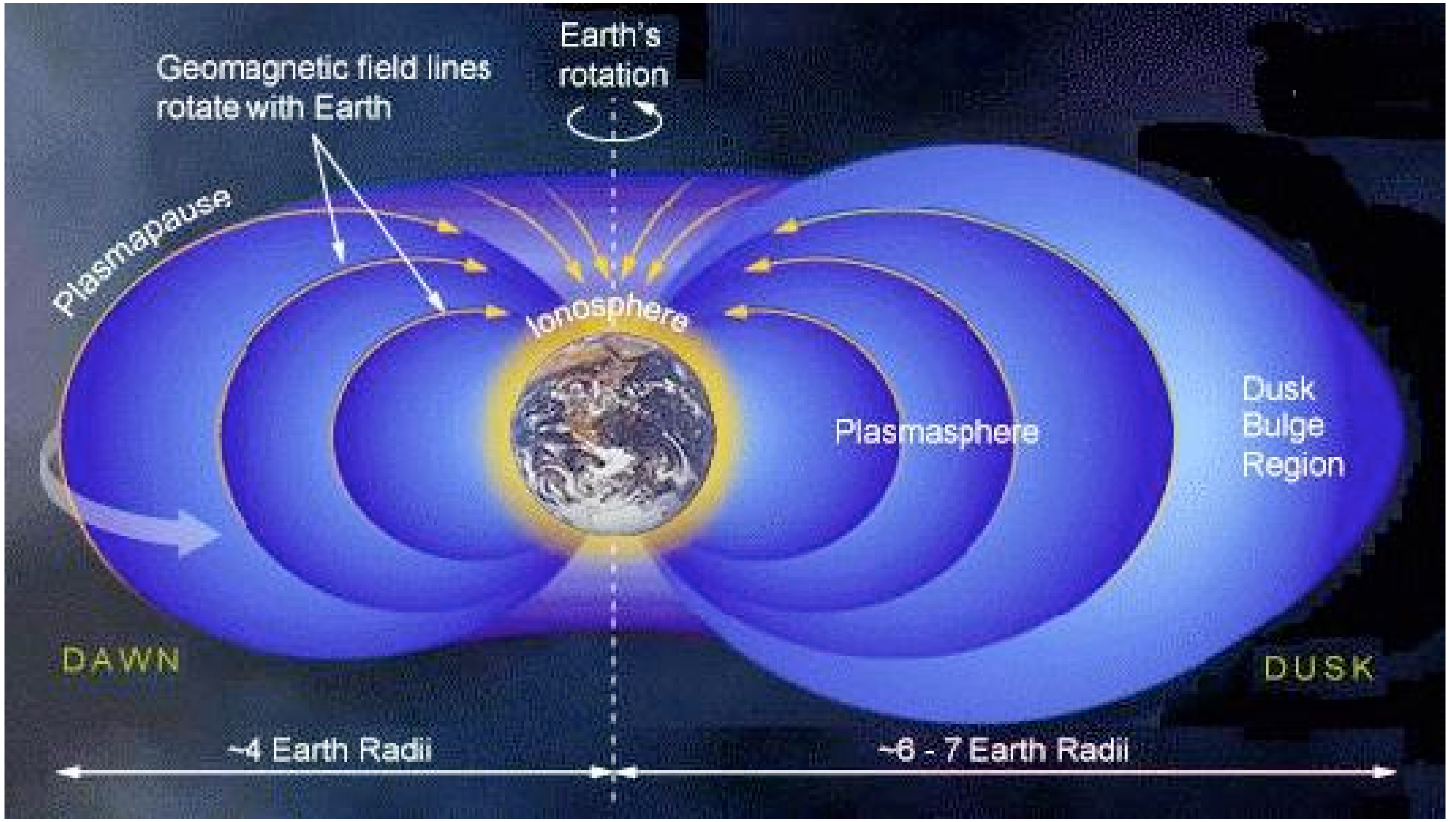


$$\rho_1 = \sqrt{(x_1 - x_{rx})^2 + (y_1 - y_{rx})^2 + (z_1 - z_{rx})^2} + ct_{rx}$$
$$\rho_2 = \sqrt{(x_2 - x_{rx})^2 + (y_2 - y_{rx})^2 + (z_2 - z_{rx})^2} + ct_{rx}$$
$$\rho_3 = \sqrt{(x_3 - x_{rx})^2 + (y_3 - y_{rx})^2 + (z_3 - z_{rx})^2} + ct_{rx}$$
$$\rho_4 = \sqrt{(x_4 - x_{rx})^2 + (y_4 - y_{rx})^2 + (z_4 - z_{rx})^2} + ct_{rx}$$

- Three simultaneous range measurements give a position solution at two points
- Four range measurements give always a single, unique solution
- The nonlinear equations can be solved for the unknowns
  - Closed form solutions
  - Iteration based on linearization of the equations
  - Kalman filter

Why do we discuss satellite navigation on this course?

Space weather and satellite navigation



- GNSS orbit heights are about 3,5 Earth radii

  => the navigation signals transmitted by the GNSS satellites must pass through the plasmasphere and the ionosphere

Space weather disturbs satellite navigation

- Satellite navigation is one of the few applications where storms in the magnetosphere can bee detected in everyday life
- Ionosphere error (if not corrected somehow) is the largest error source in satellite navigation
- 30 m error in the position may not sound very serious, but for a landing aircraft or even for a boat near the coast of Finland it may become critical
- Commercial GNSS applications require accurate and reliable navigation

  => understanding the space weather becomes more important as the use of satellite navigation becomes more common

  => applications requiring extreme accuracy and reliability (e.g. navigation aid for impaired people) are under development

Wave propagation in the ionosphere (1/3)

- Maxwell's equations for plain waves in homogenous medium

$$\mathbf{k}\cdot\mathbf{E_0} = i\frac{\rho}{\varepsilon_0}$$

$$\mathbf{k}\cdot\mathbf{H_0} = 0$$

$$\mathbf{k}\times\mathbf{E_0} = \omega\mu_0\mathbf{H_0}$$

$$\mathbf{k}\times\mathbf{H_0} = (i\sigma - \varepsilon_0\omega)\mathbf{E_0},$$

- where **k** is the wave vector indicating the direction of the wave propagation.
- The wave equation can be derived from the last two terms as

$$\mathbf{k}\times(\mathbf{k}\times\mathbf{E_0}) + \frac{\omega^2}{c^2}\left(1 - \frac{i\sigma}{\omega\varepsilon_0}\right)\mathbf{E_0} = 0$$

Wave propagation in the ionosphere (2/3)

- The dispersion relation for the ionosphere can be derived by assuming that the electron motion is dominated by the electric field (e^{i_t})
- The motion of the electron can then be described by

$$m_e \frac{d\mathbf{v}}{dt} = i\omega m_e \mathbf{v} = q_e \mathbf{E}$$

- Because $\_\boldsymbol{E} = \boldsymbol{J} = q_e \boldsymbol{v} N$, the conductivity of the ionosphere can now be solved as

$$\sigma = \frac{-iq_e^2 N}{\omega m_e} = -i\varepsilon_0 \frac{\omega_e^2}{\omega}$$

- where $\_{}_e$ is the electron plasma frequency

$$\omega_e = \sqrt{\frac{q_e^2 N}{\varepsilon_0 m_e}}$$

Wave propagation in the ionosphere (3/3)

- The wave equation can be written by using the equation for the conductivity as

$$(\mathbf{k} \cdot \mathbf{E_0})\mathbf{k} - k^2\mathbf{E_0} + \frac{\omega^2}{c^2}\left(1 - \frac{\omega_e^2}{\omega^2}\right)\mathbf{E_0} = 0$$

- Because we know that $\mathbf{k} \perp \mathbf{E} \perp \mathbf{H}$ the dispersion relation for ionosphere is

$$k^2 = \frac{\omega^2}{c^2}\left(1 - \frac{\omega_e^2}{\omega^2}\right) = \frac{\omega^2}{c^2} n^2.$$

- The phase velocity of the propagating signal is then

$$v_p = \frac{\omega}{k} = \frac{c}{n}$$

- The group velocity for the wave comes from the dispersion relation

$$v_g = c\sqrt{1 - \frac{\omega_e^2}{\omega^2}} = cn$$

Phase and group velocity

- Ionosphere is dispersive => the signal propagation depends on the signal frequecy
- The phase velocity exceeds the speed of light

  => ionosphere causes phase advance for a GNSS carrier wave
- The group velocity is smaller that the speed of light

  => ionosphere delays any code modulated on a GNSS carrier wave
- The GNSS range estimation is based on the assumption that $v_p = v_g = c$

  => code based range estimates are too long and carrier phase based range estimates are too short
- Index of refraction in the ionosphere changes as a function of the electron density

  => ionosphere error in satellite navigation varies as a function of the time of the day, latitude, time of the year, and the solar cycle

GNSS navigation signals (1/2)

- Measured pseudorange [meters]

$$\rho = \left|\bar{r}_{rx}(t_r) - \bar{r}_{tx}(t_r)\right| - \frac{\left[\bar{r}_{rx}(t_r) - \bar{r}_{tx}(t_r)\right] \cdot \bar{v}_{tx}}{c} + c\Delta t_{ntrl} + \boxed{c\Delta t_{ion}} + ct_{rx} - ct_{tx} - ct_{rel} + \varepsilon_{\rho}$$

- First two terms represent the geometrical distance between the receiver and the transmitting satellite
- _t_{ntrl} = the impact of the neutral atmosphere
- t_{ion} = the group delay caused by the ionosphere
- t_{rx} = the transmitter clock error
- t_{tx} = the receiver clock error
- t_{rel} = relativistice effects due to the different gravity potential and the transmitter velocity
- _${}_p$ = noise

GNSS navigation signals (2/2)

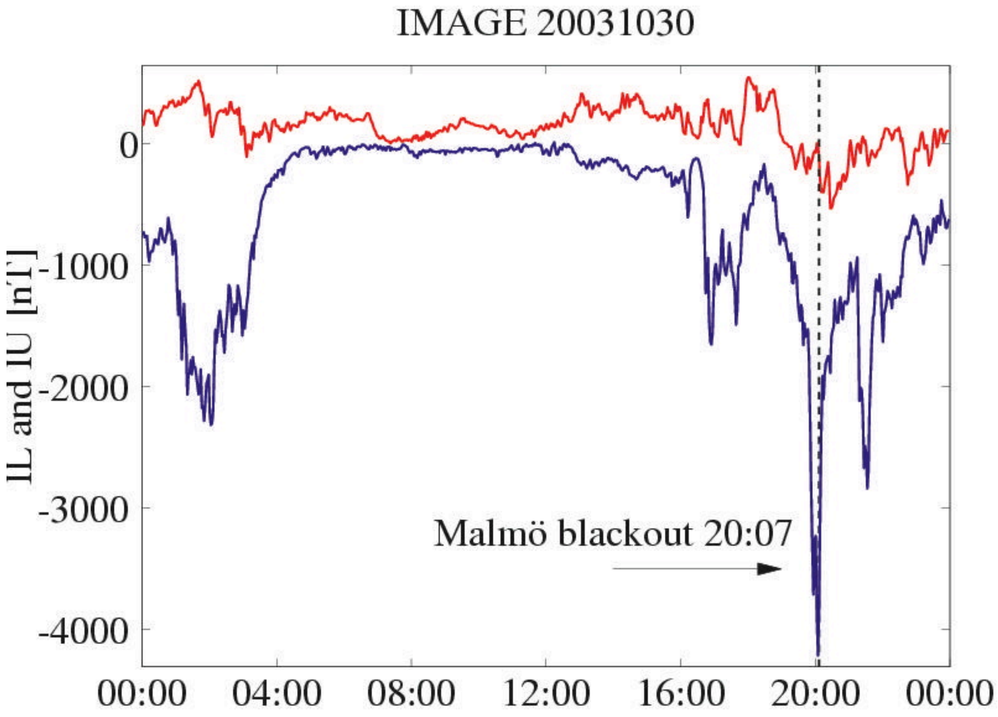
- Signal carrier phase [cycles]

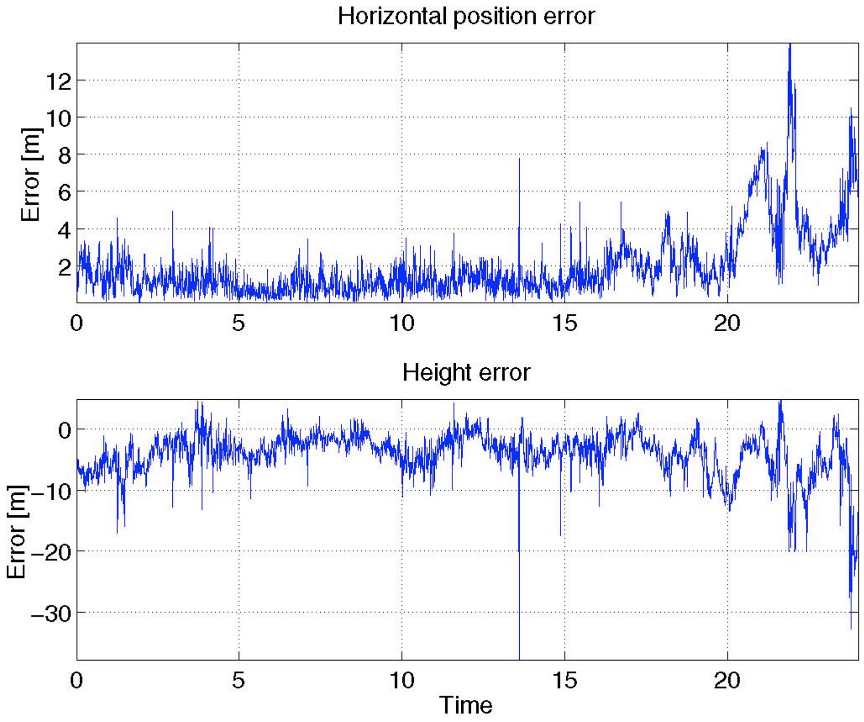
$$\ddot{o} = \frac{f}{c}\left[\left|\bar{r}_{rx}(t_r) - \bar{r}_{tx}(t_r)\right| + c\Delta t_{ntrl} - c\Delta t_{ion} + ct_{rx} - ct_{tx} - ct_{rel} + N + \varepsilon_{\varphi}\right]$$

- N is a phase ambiguity due to the short wavelength of the carrier (20 cm)
- Transmitter position vector and clock error estimate are transmitted in the navigation signal
- Relativistic effects can be mitigated based on transmitter position and rough receiver location
- Tropospheric errors can normally not be removed
- Phase ambiguity can be reduced but not completely removed from individual samples
- Noise can be decreased by increasing the receiver integration time

Space weather impact on navigation solution

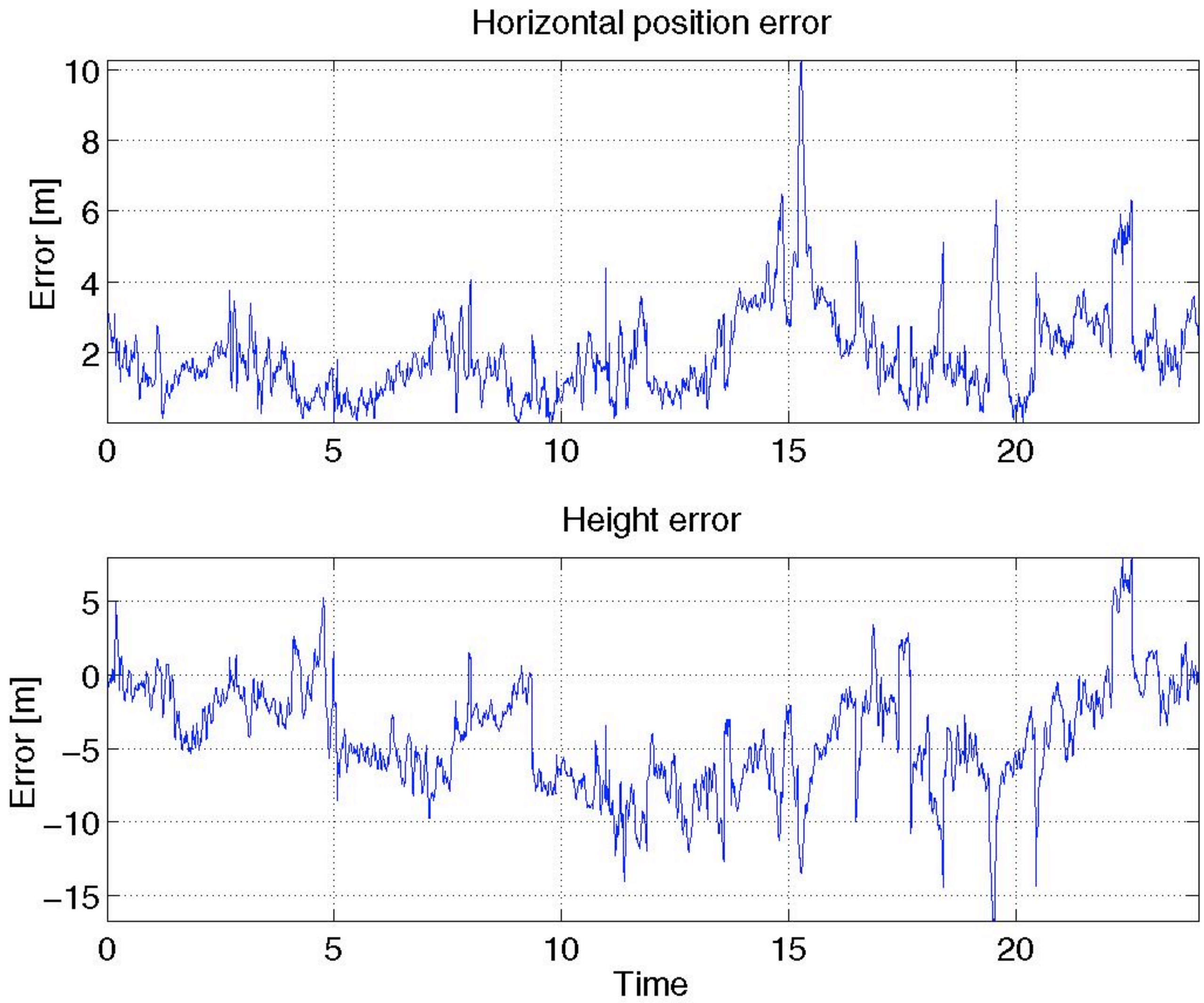
Halloween storm 2003





GPS data from Tromsø

Diurnal cycle during “quiet” conditions



Metzoki dragot, Israel, 7 Feb 2005

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Ionosphere correction (1/4)

- Ionosphere error can be removed by combining data measured at two frequencies

$$\rho_{L1} = R_g + c(t_{rx} - t_{tx}) + c\Delta t_{ion}(f_{L1})$$

$$\rho_{L2} = R_g + c(t_{rx} - t_{tx}) + c\Delta t_{ion}(f_{L2})$$

- If we make a linear combination

$$\rho_{L1,L2} = x_1 \rho_{L1} + x_2 \rho_{L2}$$

- and demand that

$$x_1 c\Delta t_{ion}^{L1} + x_2 c\Delta t_{ion}^{L2} = 0$$

- the solution is

$$\Delta\rho_{L1} = \left(\frac{f_2^2}{f_2^2 - f_1^2}\right)(\rho_{L1} - \rho_{L2}) \quad \Delta\rho_{L2} = \left(\frac{f_1^2}{f_2^2 - f_1^2}\right)(\rho_{L1} - \rho_{L2})$$

Ionosphere correction (2/4)

- Ionosphere correction does not work perfectly because
  - the dispersion of the ionosphere forces the two signals to propagate along separate paths

    => signals transmitted at the same time arrive at different times

    => the linear combination actually combines signals transmitted at different times
  - the ionosphere refractive index along the propagation paths may be different
  - one signal may propagate through one or more ionosphere "bubbles"
  - the signals may experience different multipath during the propagation

Ionosphere correction (3/4)

- Ionosphere correction can also be made with a sufficiently accurate ionosphere model because [Seeber, 1989]

$$n_p \approx 1 + \frac{c_2}{f^2}$$

- and

$$c_2 \approx -40.3 N_e$$

- and

$$STEC = \int N_e ds_0 .$$

- Then

$$\Delta\rho_{Li} = -\frac{40.3}{f_i} STEC \qquad \Delta\varphi_{Li} = \frac{40.3}{f_i} STEC$$

Ionosphere correction (4/4)

- Model assisted ionosphere correction has had modest success in the past
- The residual ionosphere error with a statistical model typically 2 – 5 m
- Many statistical models exist:
  - Klobuchar (used in the GPS system)
  - NeQuick (ITU)
  - IRI (International Reference Ionosphere from COSPAR)
- Current challenge is to use ground based and space borne GPS observations to update a (near) real time numerical ionosphere model
- Improved ionosphere models may allow very accurate navigation without the two frequency linear combination

HF radio and space weather

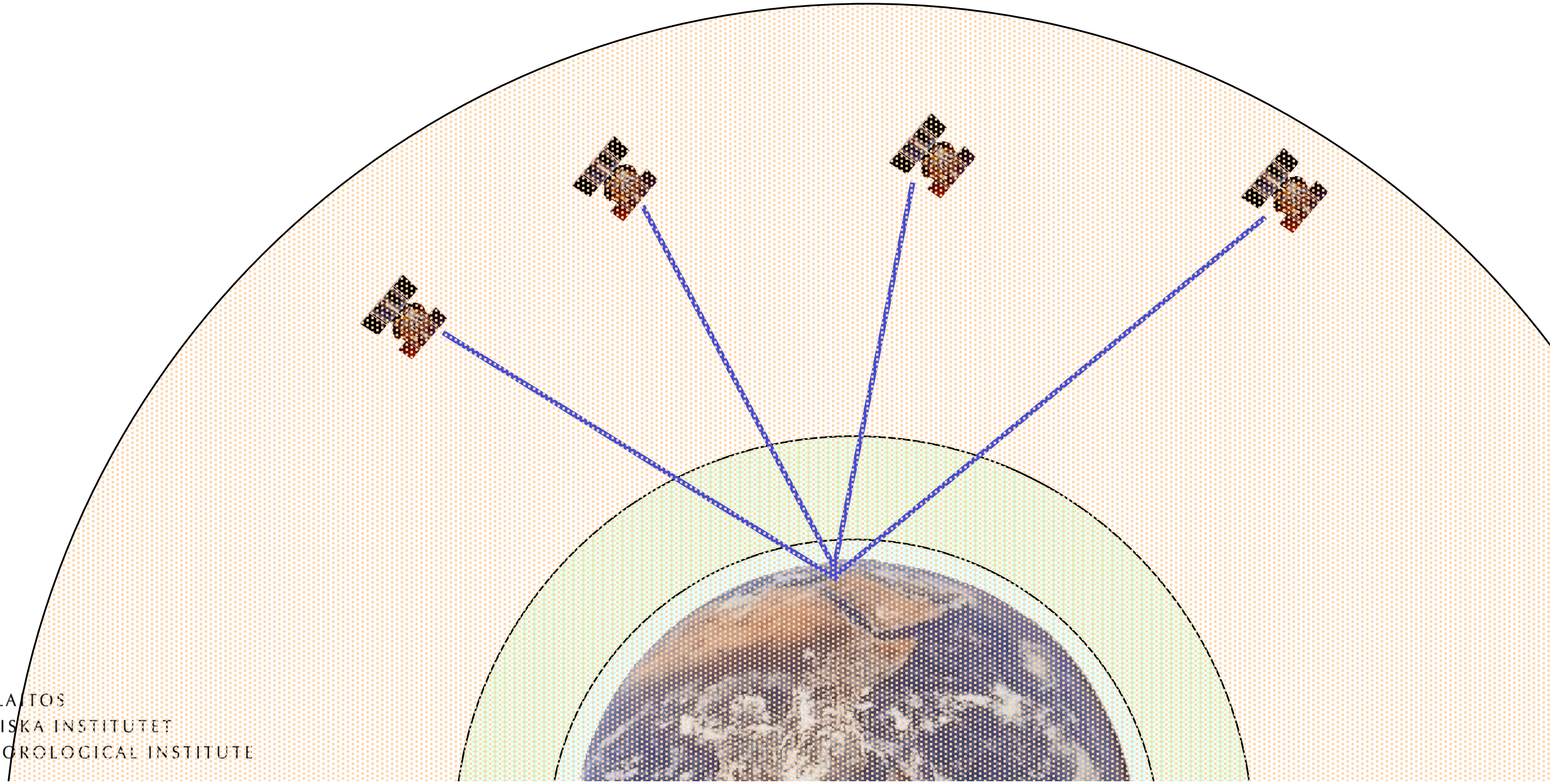
- The space weather impacts on HF radio transmission are not directly connected to the previously discussed GNSS impacts
- HF radio disturbances are mostly caused by
  - ionization in the lower ionosphere causing radio signal phase shifts and increased absorption
  - interference caused by unexpected reflections from the ionosphere
  - ionospheric irregularities causing signal fluctuations (scintillation) and signal path distortion
  - Polar Cap Absorption (PCA) from protons and electrons entering upper atmosphere near magnetic poles
- HF radio interference is a real problem to commercial airlines flying in polar regios because a continuous radio connection is required by flight rules

  => flights must be cancelled or delayed during heavy magnetic storms
- Space weather interference can also be a nuisance to e.g. radio amateurs, and civil users of HF radios

Can satellite navigation be used for something interesting?

Monitoring ionosphere from ground

- Signals received by ground based GPS receivers pass always through the ionosphere and most of the plasmasphere
- The measurement should contain information about the space weather



Retrieving ground based TEC

- GNSS range measurements contain the ionospheric term

  => if we already know where the receiver is, TEC can be solved

$$\rho_l = \left|\bar{r}_{rx}(t_r) - \bar{r}_{tx}(t_r)\right| - \frac{\left[\bar{r}_{rx}(t_r) - \bar{r}_{tx}(t_r)\right]\cdot \bar{v}_{tx}}{c} + c\Delta t_{ntrl} + c\Delta t_{ion} + ct_{rx} - ct_{tx} - ct_{rel} + \varepsilon_\rho$$

Remove geometrical range => $\rho_l = c\Delta t_{ntrl} + c\Delta t_{ion} + ct_{rx} - ct_{tx} - ct_{rel} + \varepsilon_\rho$

↓

Clock correction => $\rho_l = c\Delta t_{ntrl} + c\Delta t_{ion} - ct_{rel} + \varepsilon_\rho$

↓

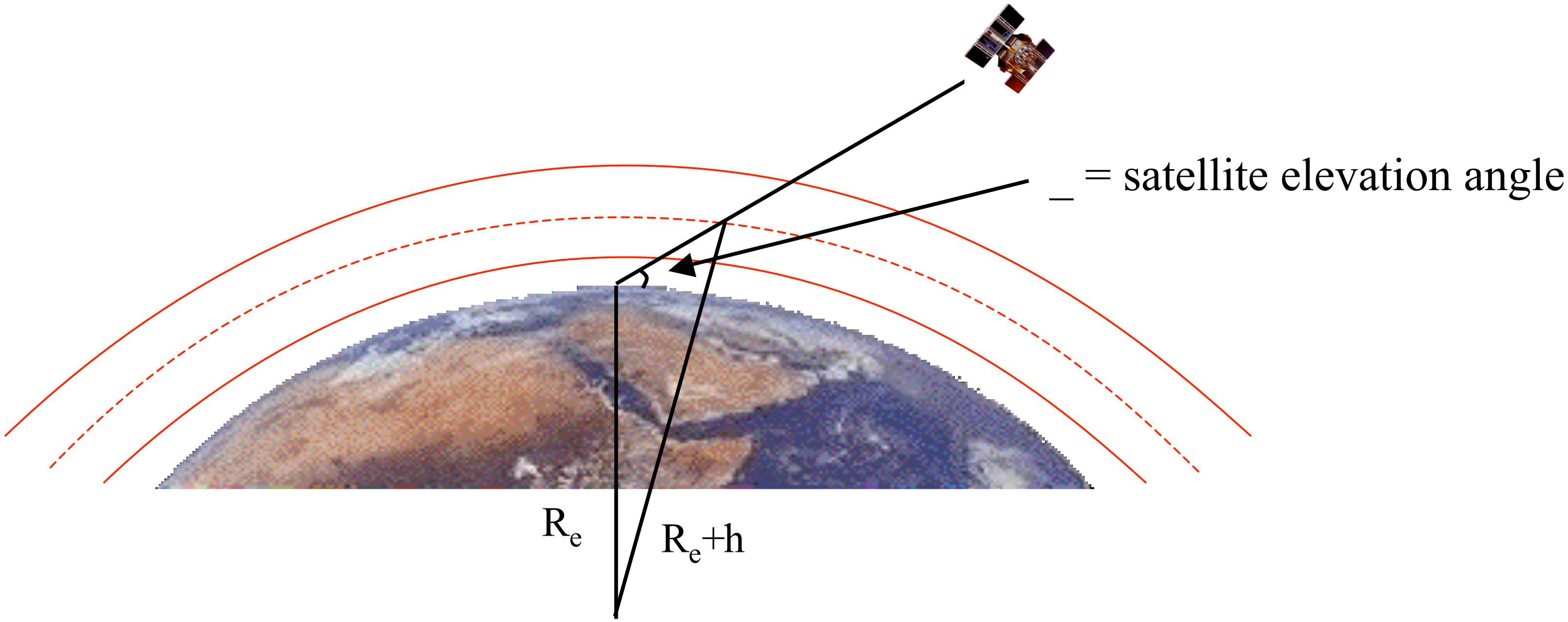
Relativistic corrections (taking POD into account) => $\rho_l = c\Delta t_{ntrl} + c\Delta t_{ion} + \varepsilon_\rho$

↓

TEC retrieval <=> $STEC_\rho = \frac{1}{d}\frac{f_{L1}^2 f_{L2}^2}{\left(f_{L1}^2 - f_{L2}^2\right)}\left(\rho_{l2} - \rho_{l1}\right)$

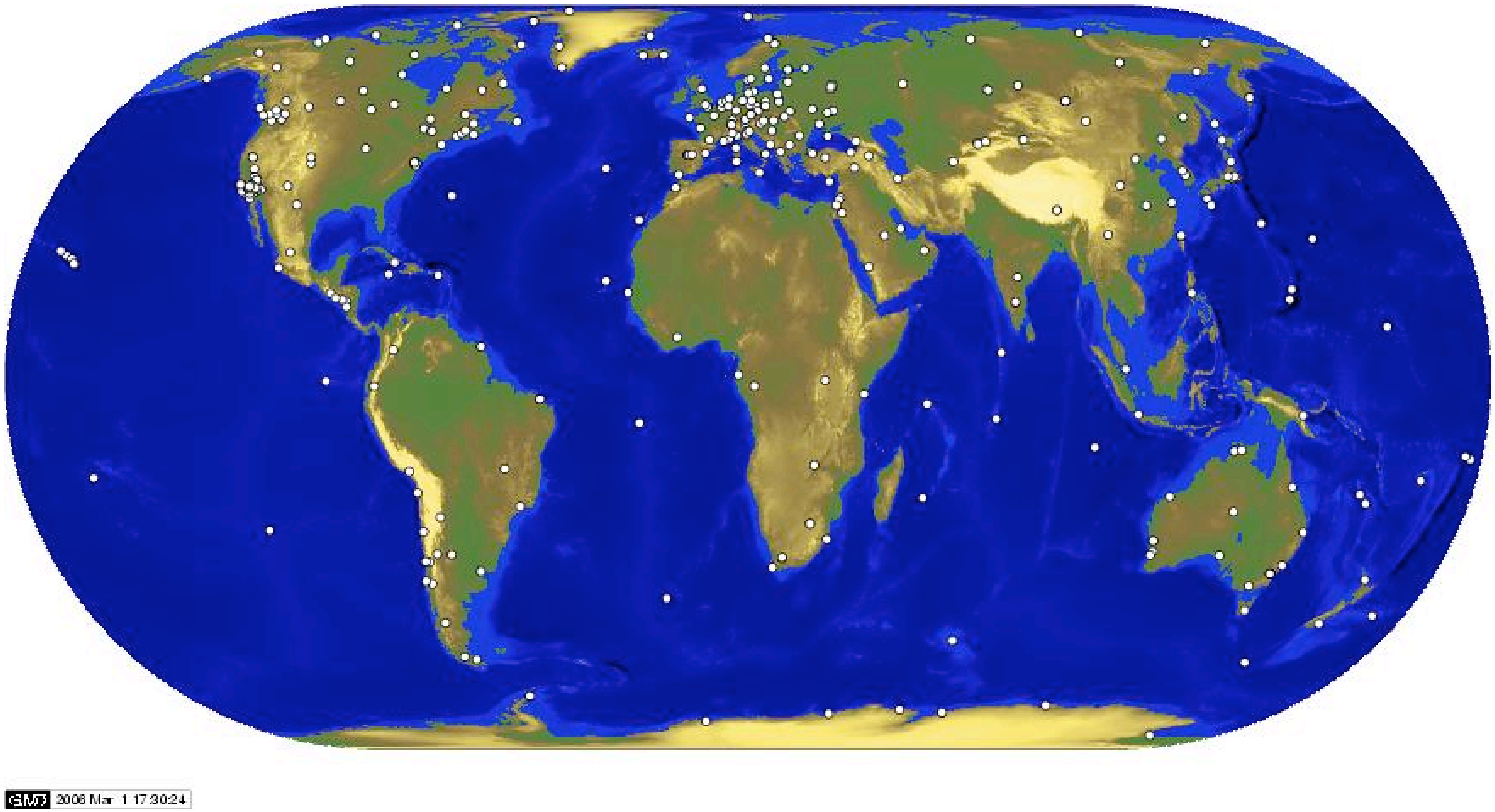
Mapping STEC into VTEC

- The retrieved STEC corresponds to the slant measurement
- Mapping to VTEC (Vertical TEC) is performed with a mapping function

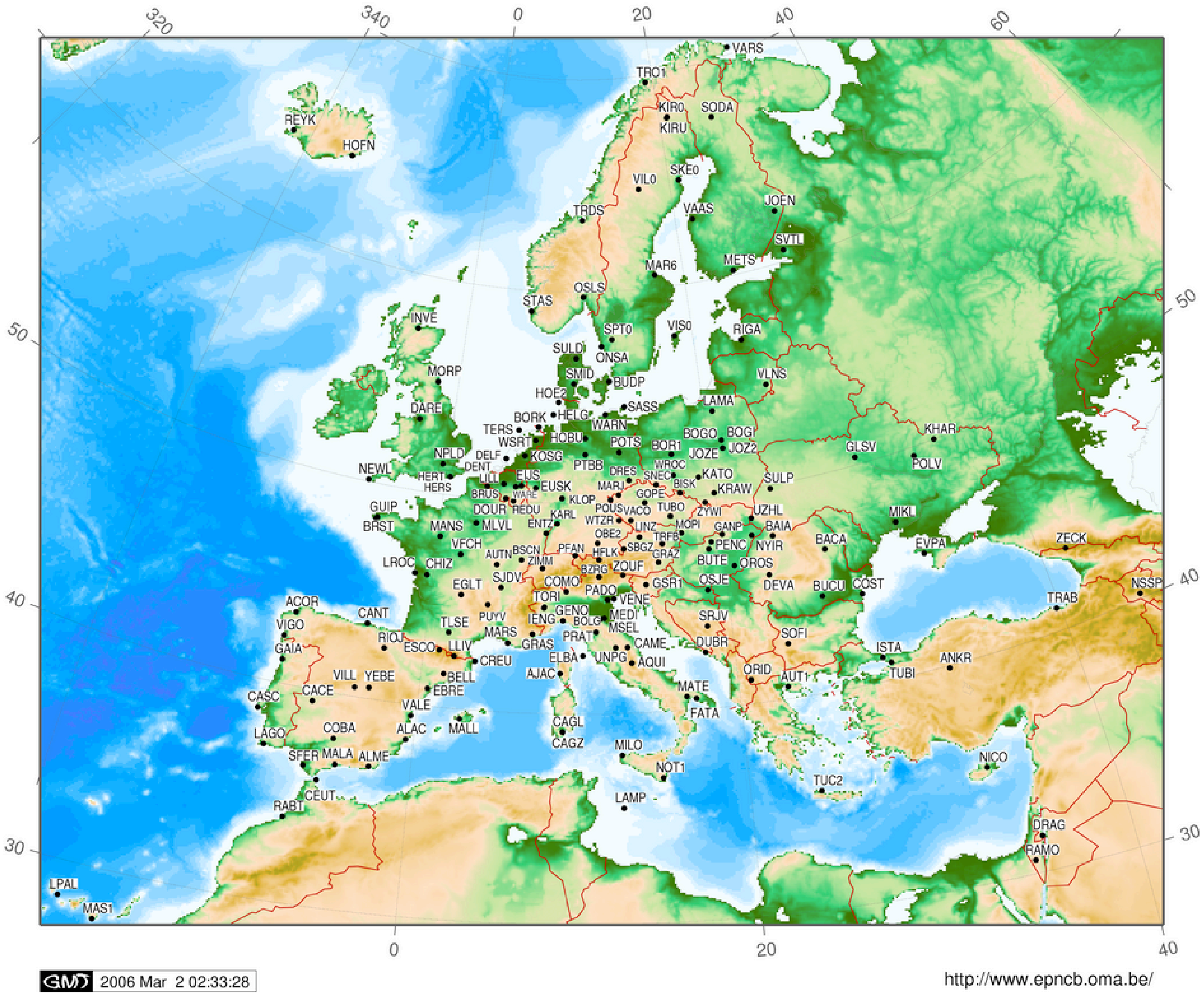


$$VTEC = \frac{1}{\sqrt{1-\left(\cos\theta \frac{R_e}{R_e+h}\right)^2}} STEC$$

International GNSS Service (IGS) GPS tracking network



EUREF permanent tracking network



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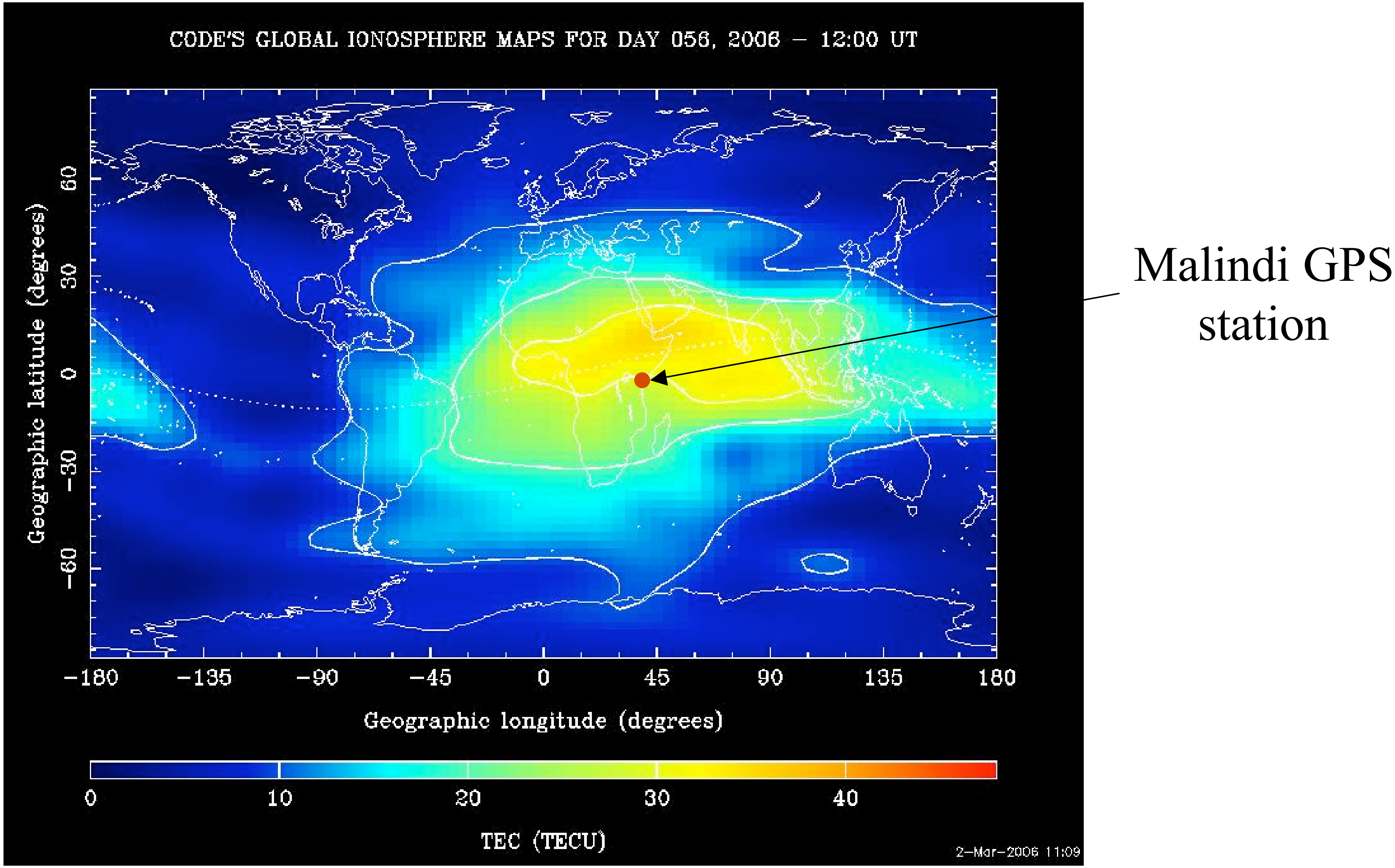
VTEC map from ground based GNSS data



Map by Astronomisches Institut, Universität Bern

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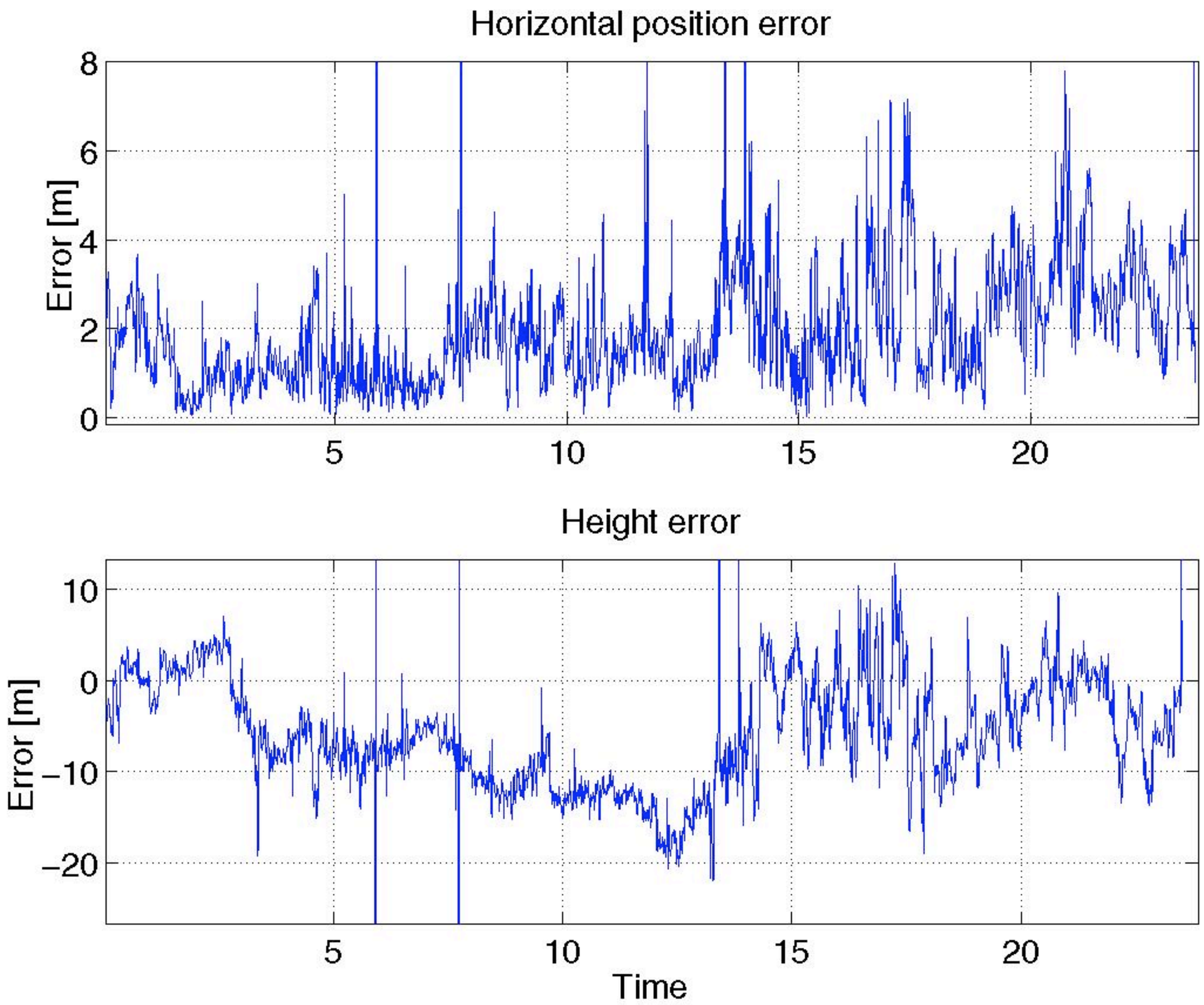
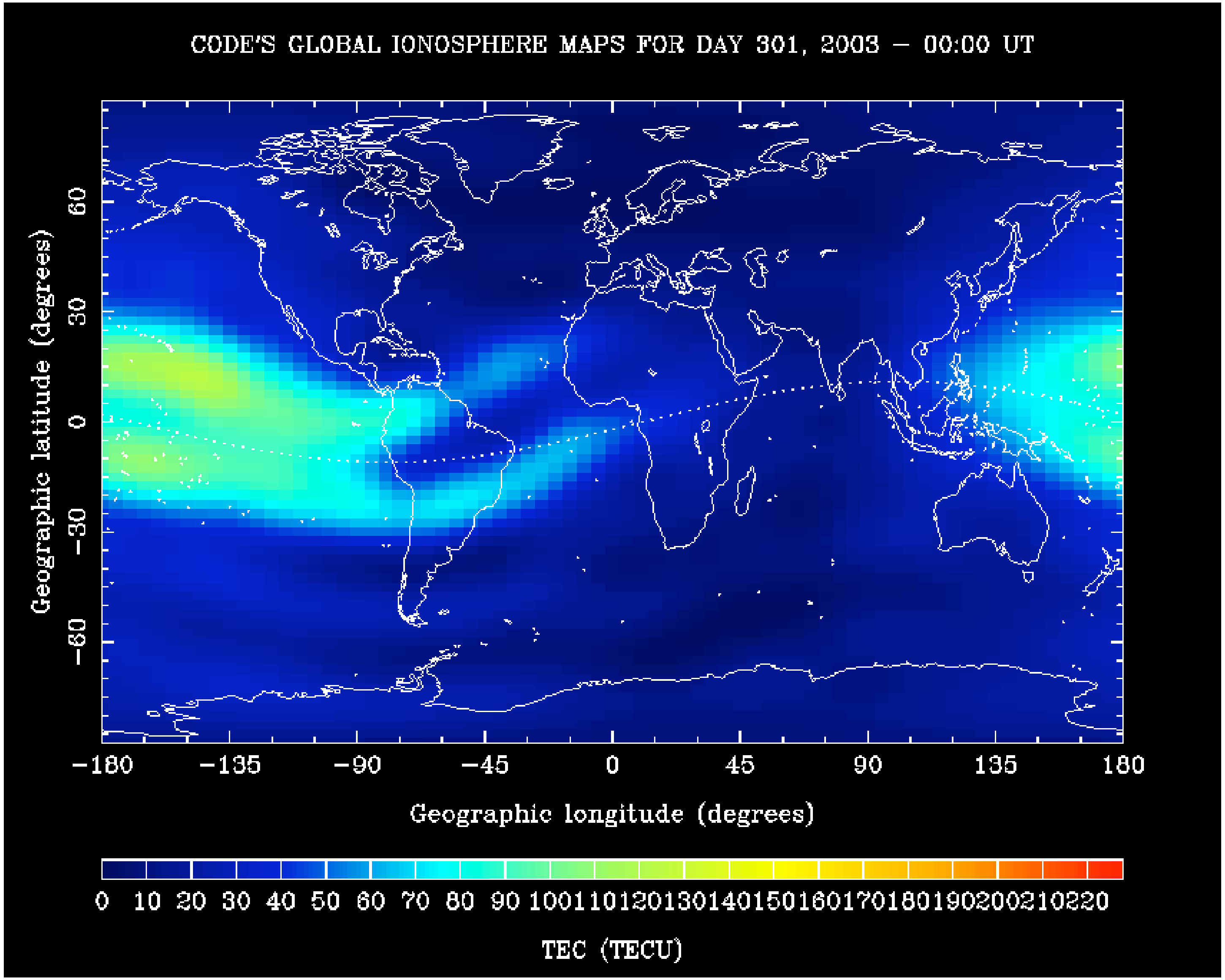
Ionospheric navigation error at Malindi station



VTEC maps during Halloween storm 2003



Map by Astronomisches Institut, Universität Bern

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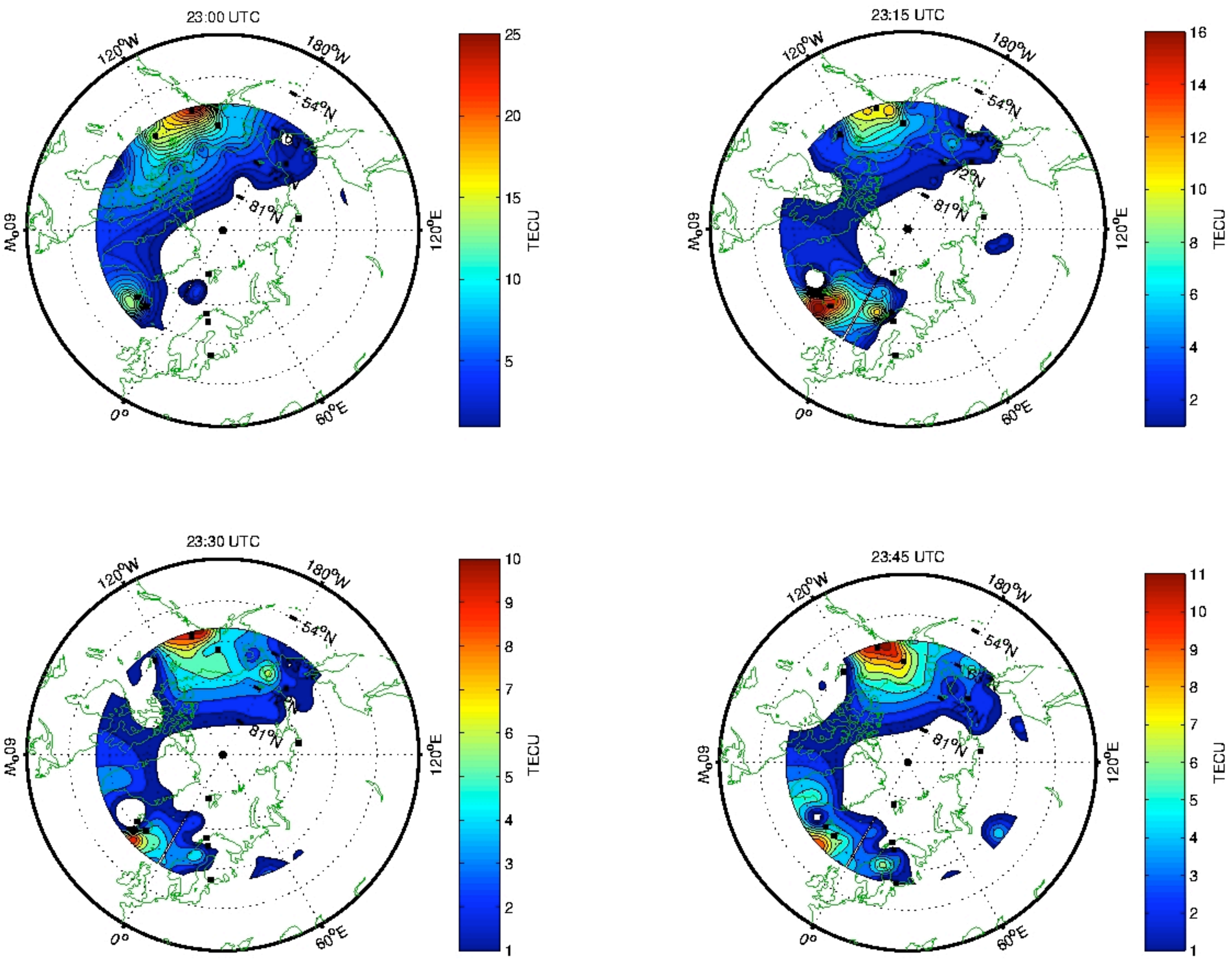
VTEC snapshots on 30 October 2003



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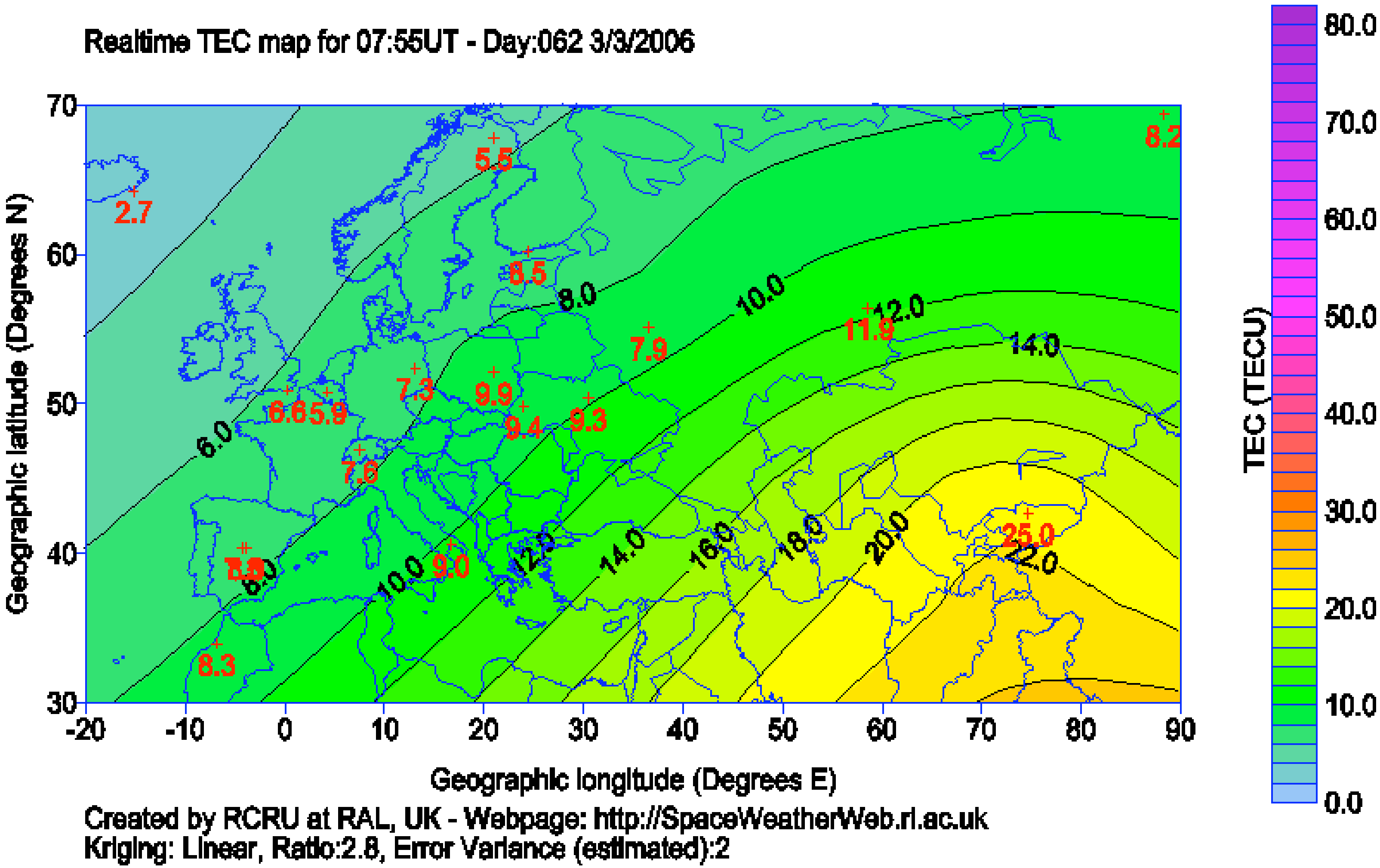
30 October 2003 23:00 – 24:00

Local VTEC maps from Europe

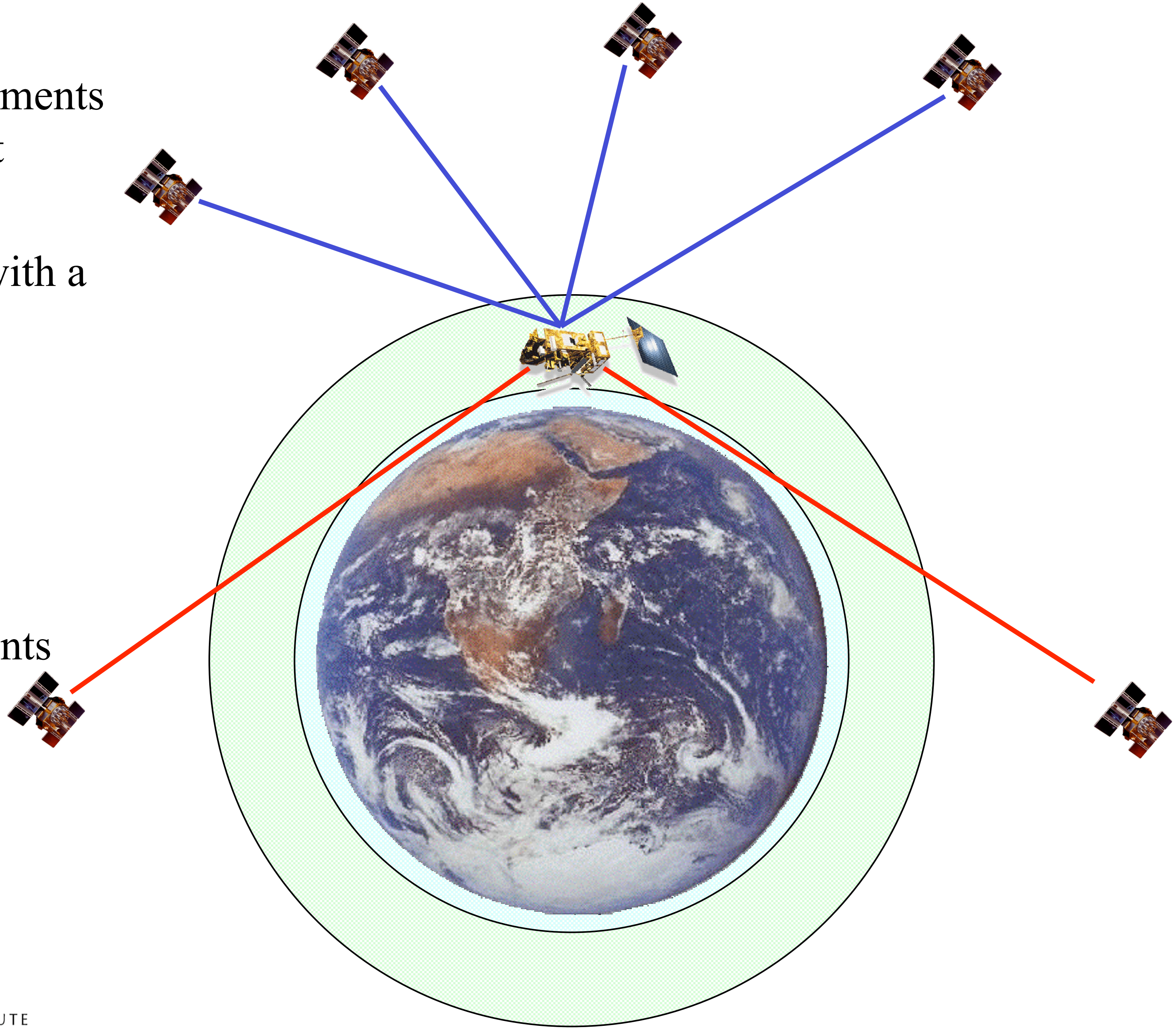


Space borne ionosphere sounding with GNSS

- GNSS receivers are already used in Low Earth Orbit (LEO) satellites for orbit determination
- Just like ground based measurements, space borne GNSS measurements can be used for sounding of the ionosphere (and also for neutral atmosphere)
- Currently e.g. the German CHAMP satellite is performing space borne ionosphere soundings
- CHAMP is also performing Radio Occultation (RO) soundings to measure the neutral atmosphere

Space borne GNSS sounding geometry

- Navigation measurements for the satellite orbit determination
- Any LEO satellite with a GNSS receiver will perform these measurements



- Occultation (limb sounding) measurements
- Only a dedicated RO missions are likely to perform these

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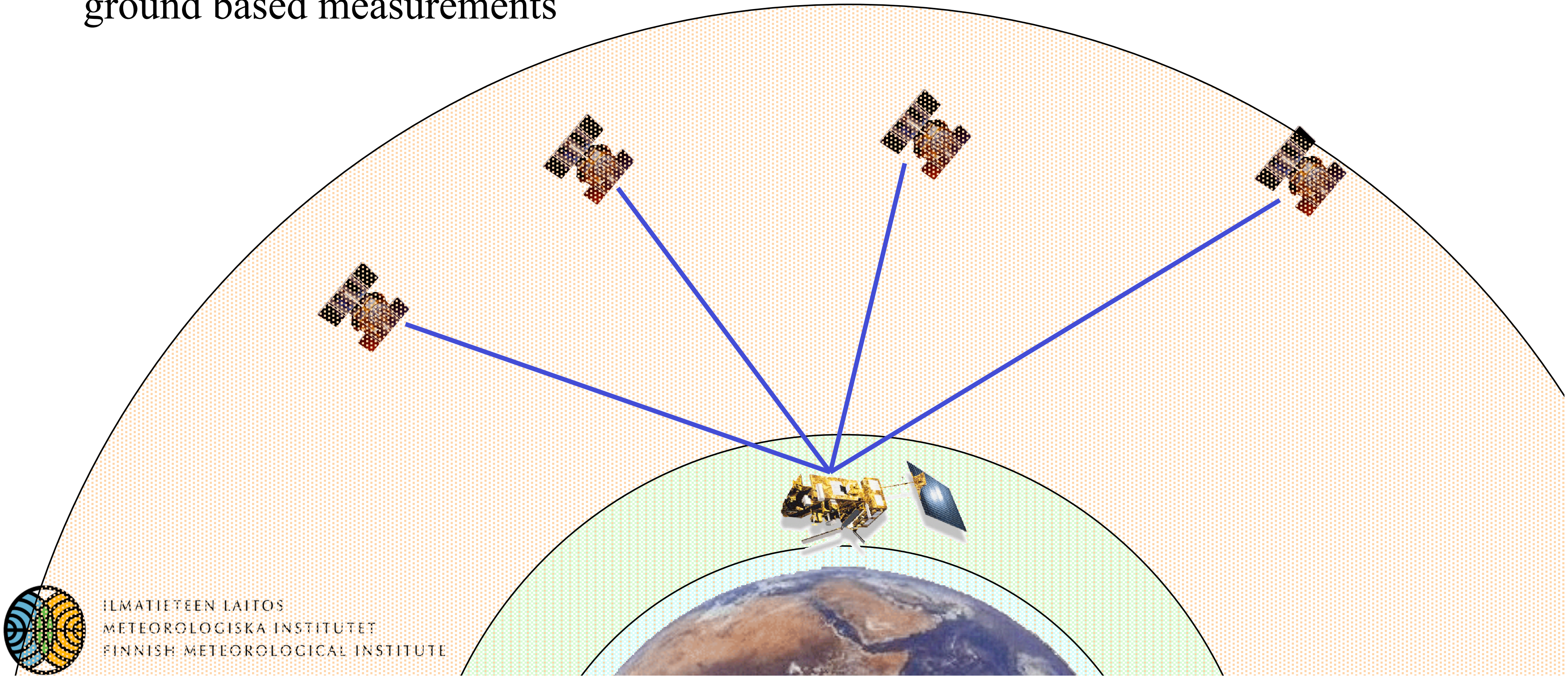
GNSS navigation measurements

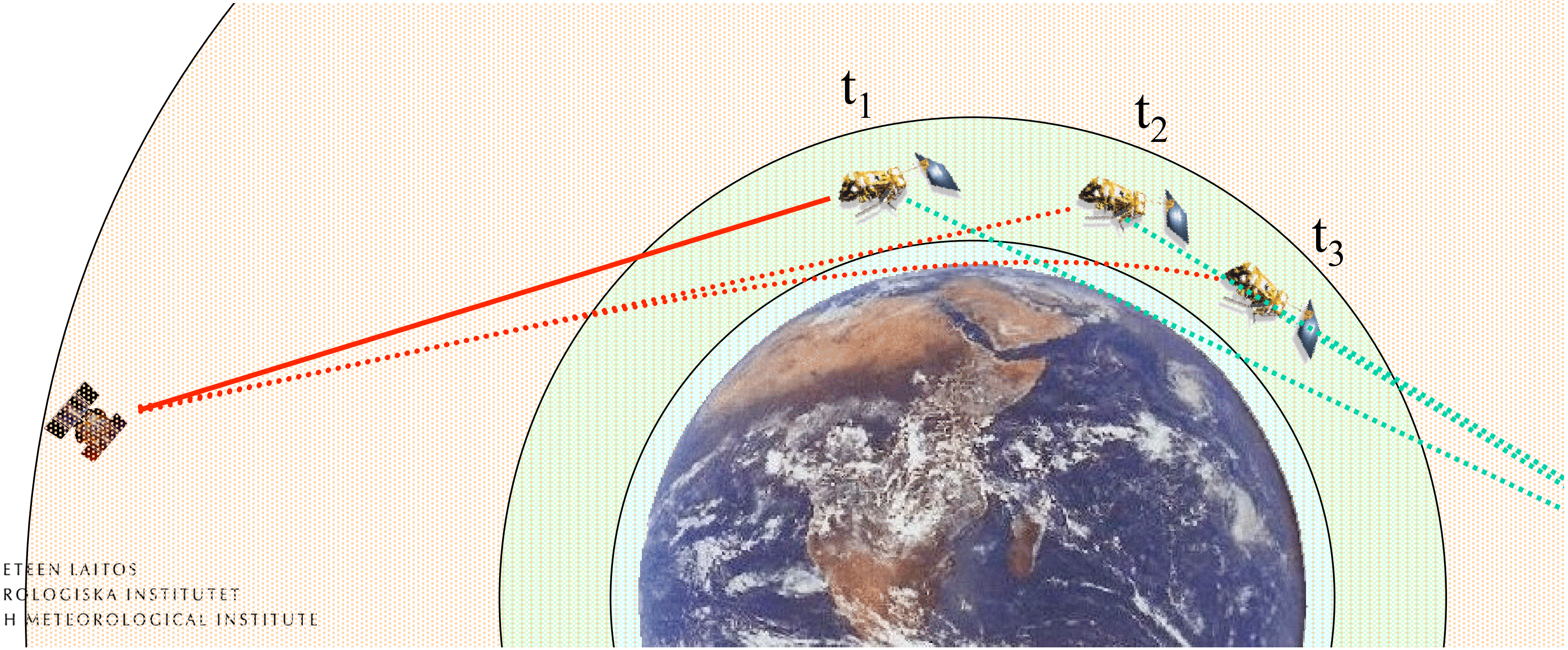
- The navigation measurements will contain information about the ionosphere and plasmasphere above the satellite orbit: typically 400 – 1200 km
- Because navigation measurements are limited to elevations above 10º – 20º, the measurement of the peak of the electron density in the F region is difficult or impossible
- Navigation measurements can be processed essentially in the same way as ground based measurements



GNSS radio occultation soundings

- Occultation measurements measure horizontally through the ionosphere and the plasmasphere
- The RO data is an integral of all ionosphere and plasmasphere layers along the signal propagation path
- The information “peaks” at the region of the highest electron density along the path
- The motion of the LEO spacecraft changes the height of the ray tangent point

=> RO sounding provides some vertical information about the electron density



Processing of RO soundings (1/2)

- Basically the processing is the same as with ground based data
- Determining the receiver position is in this case much more difficult, especially if the retrieval is performed in near real time
- The RO signal is typically weaker than the ground based signal due to the much longer distance

  => both the pseudorange and the carrier phase measurements are used in the TEC retrieval
- The TEC can be retrieved independently from the pseudorange and from the carrier phase
- The TEC from the carrier phase contains a bias due to the phase ambiquity term

$$\ddot{o} = \frac{f}{c}\left[\left\|\bar{r}_{rx}(t_r) - \bar{r}_{tx}(t_r)\right\| + c\Delta t_{ntrl} - c\Delta t_{ion} + ct_{rx} - ct_{tx} - ct_{rel}\right] + \boxed{N} + \varepsilon_{\varphi}$$

Processing of RO soundings (2/2)

- TEC estimate can be calculated from carrier phase and from pseudorange

$$STEC_{\varphi} = \frac{1}{d} \frac{f_{l1}^2 f_{l2}^2}{\left(f_{l1}^2 - f_{l2}^2\right)} \left(\varphi_{l2} - \varphi_{l1}\right) + B \qquad \text{(biased)}$$

$$STEC_{\rho} = \frac{1}{d} \frac{f_{l1}^2 f_{l2}^2}{\left(f_{l1}^2 - f_{l2}^2\right)} \left(\rho_{l2} - \rho_{l1}\right) \qquad \text{(noisy)}$$

- The bias term B can be estimated with a least squares fit of $TEC\_$ to TEC_{PR}
- Measurement geometry means that the result contains about 30 000 km of integrated ionosphere data

  => interpretation of the results is difficult without using data assimilation and a a numerical ionosphere model

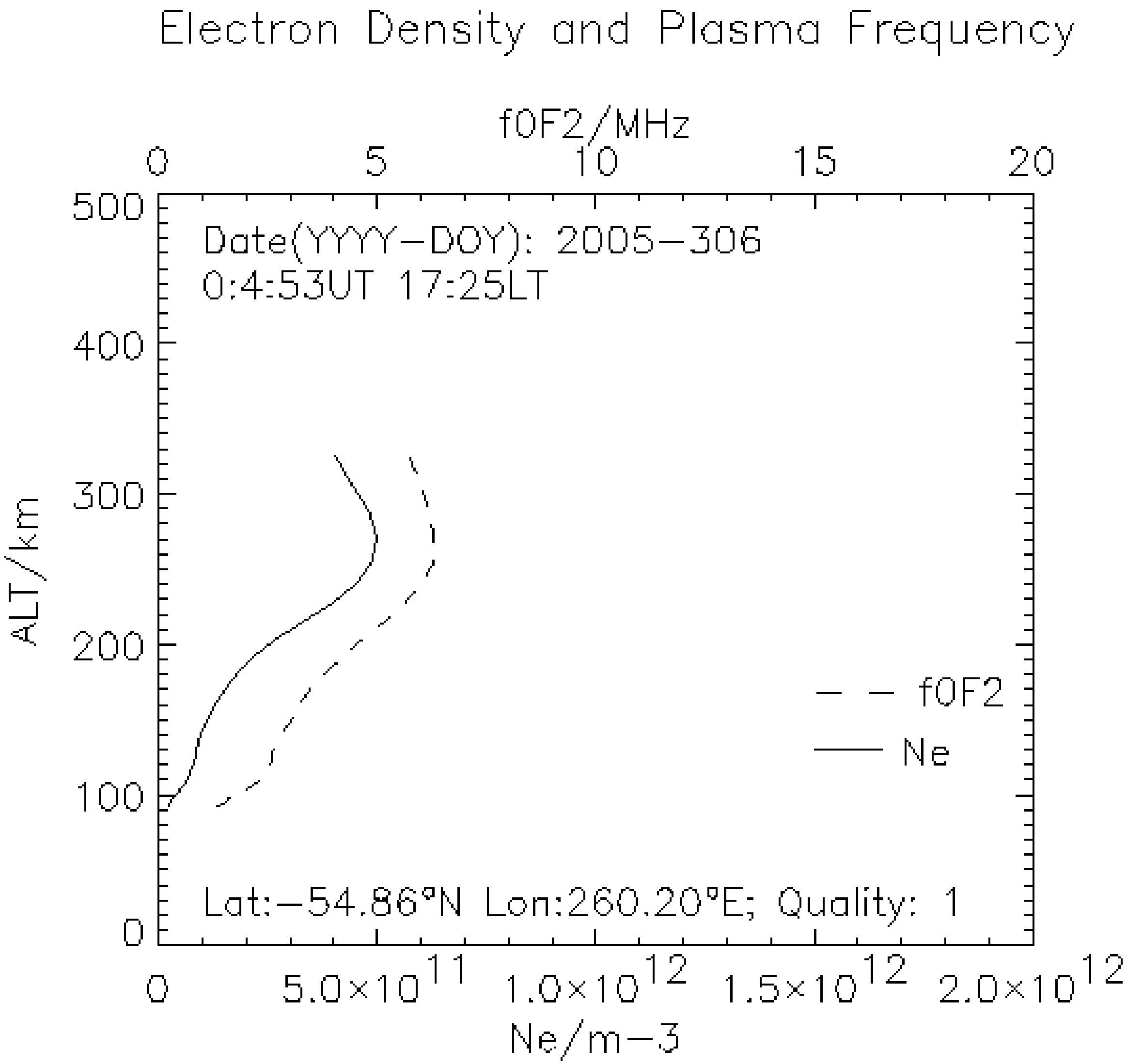
What is space borne GNSS ionosphere data good for?

- RO missions can provide
  - ionosphere data in 80 - 1000 km height range
  - plasmasphere data in 1000 – 22000 km height range
- Below 80 km ionosphere and neutral atmosphere signatures are mixed => no useful information
- Current research objective is to make ionosphere forecasts feasible
- RO ionosphere data alone only marginally useful

  => combined RO and ground based data assimilated into a 3D numerical ionosphere model may be the correct approach
- Commercial GNSS applications (e.g. transportation) require ionosphere information in (near) real time or even as a forecast

  => NWP type ionosphere forecasting service?

GPS TEC products



Electron density profile from CHAMP RO data

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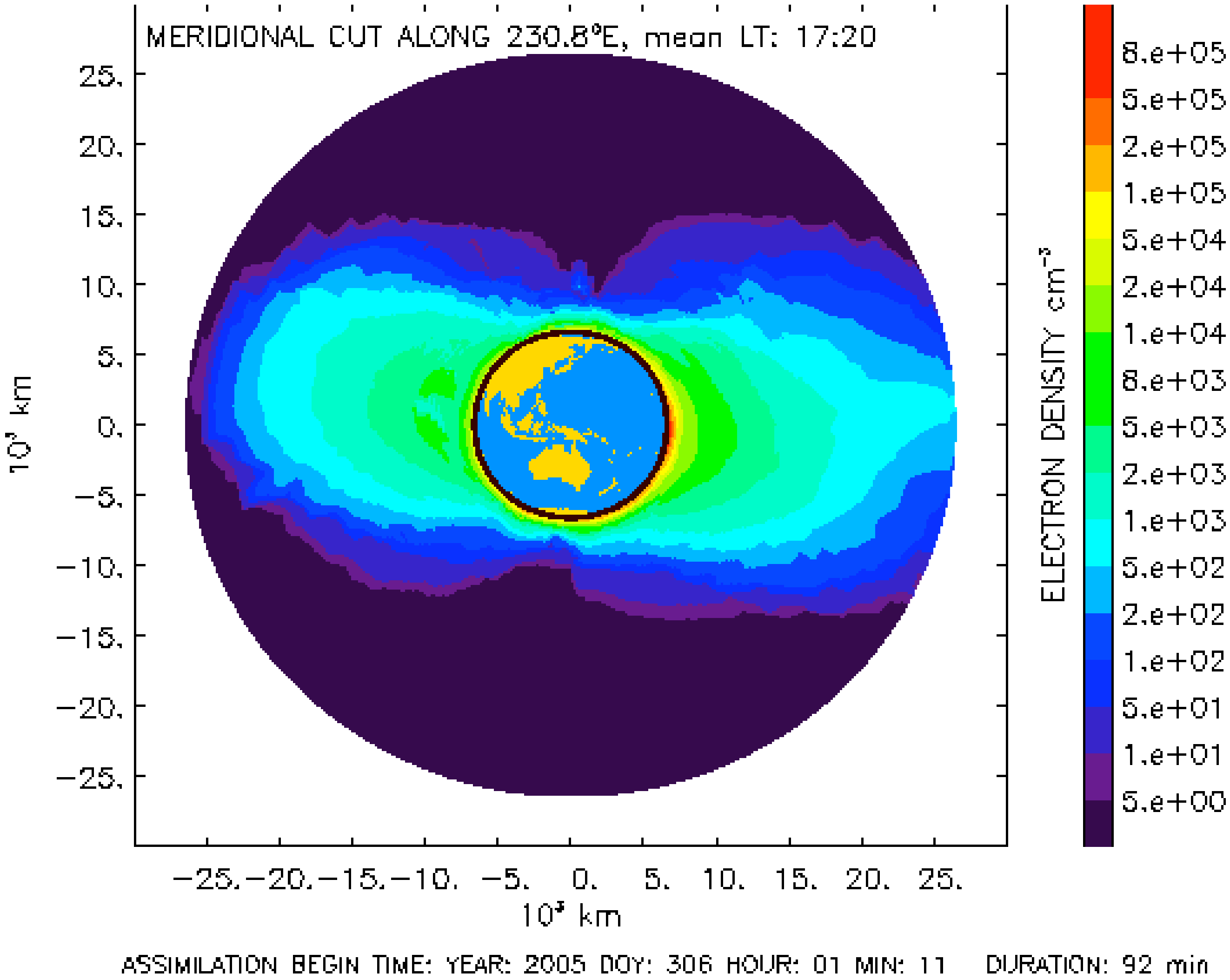
Picture by the SWACI project: http://www.kn.nz.dlr.de/swaci/

Combined 2D TEC map



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TEC maps produced by SWACI project: http://www.kn.nz.dlr.de/swaci/

Current “hot topics” in GNSS applications

- Improved numerical ionosphere models allowing near real time TEC derivation
- Efficient use of ground based and space borne GNSS data
- Potential provided by the dense GNSS ground based measurement networks currently under development
- Forecasting of the ionosphere state and scintillations
- Potential use of numerical model assisted ionosphere correction in commercial single frequency navigation applications

Some useful web pages

GNSS data:

- International GNSS Service: http://igscb.jpl.nasa.gov/
- EUREF permanent network: http://www.epncb.oma.be/

GNSS based TEC maps:

- Astronomisches Institut der Universität Bern: http://www.aiub.unibe.ch/igs.html
- Space weather application center – ionosphere (SWACI): http://www.kn.nz.dlr.de/swaci/html-seiten/haupt.html

Other links:

- European Space Agency:
  - Space weather: http://www.esa-spaceweather.net/
  - Galileo: http://www.esa.int/esaNA/galileo.html
- EU/EC Galileo: http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm

Exercises:

- Kick-off: March 15, 10-12, 1D23c (Dynamicum ATK class, to the right from the front door)
- Be at the front desk at 10 o'clock sharp, you need a visitor badge
- If you have not chosen the exercise, select it from http://www.ava.fmi.fi/~minna/researchseminar/exercise and contact minna.palmroth@fmi.fi