The earths Ionosphere
Processes and measurement techniques

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Definition

- ionized part of Earth's upper athmosphere
- from 60 km to 1000 km
- ionization process driven by the solar radiation
- highly variable

History

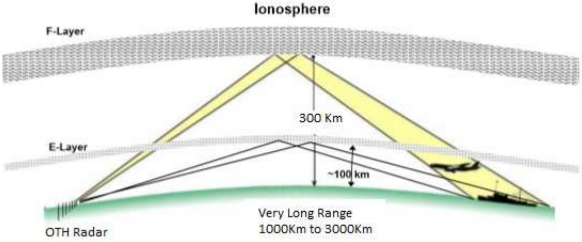
- 1839 Gauss: Electrical conducting region
- 1901 Marconi: Transatlantic radio transmission. Over the Horizion, Signal had to be reflected twice on the Ionosphere
- The name Ionosphere was introduced in 1926 by Scottish physicist Robert Watson-Watt: "...for the region in which the main characteristic is large scale ionisation with considerable mean free paths..."

History

ELECTRICAL ENGINEERING MILESTONE
TRANSATLANTIC RADIO SIGNALS
AT SIGNAL HILL ON 12 DECEMBER 1901, GUGLIELMO MARCONI AND HIS ASSISTANT, GEORGE KEMP, CONFIRMED THE RECEPTION OF THE FIRST TRANSATLANTIC RADIO SIGNALS. WITH A TELEPHONE RECEIVER AND A WIRE ANTENNA KEPT ALOFT BY A KITE, THEY HEARD MORSE CODE FOR THE LETTER "S" TRANSMITTED FROM POLDHU, CORNWALL. THEIR EXPERIMENTS SHOWED THAT RADIO SIGNALS EXTENDED FAR BEYOND THE HORIZON, GIVING RADIO A NEW GLOBAL DIMENSION FOR COMMUNICATION IN THE TWENTIETH CENTURY.
OCTOBER 1985
INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS

Technical applications

- naval communication
- over the horizon radars
- powering of satellites



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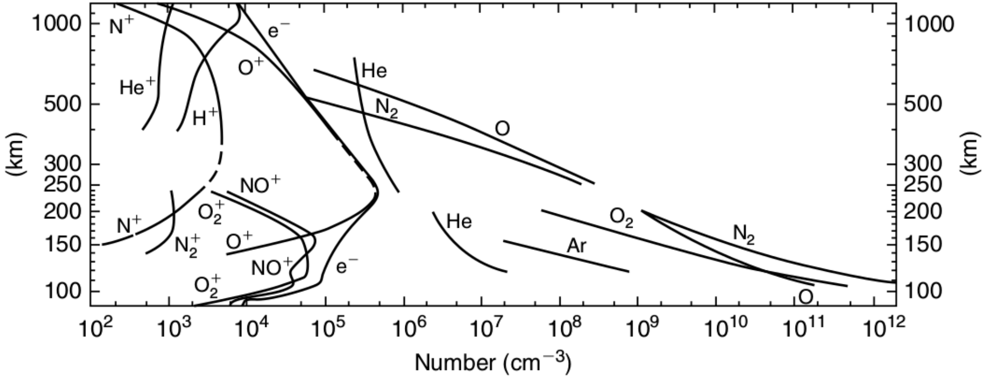
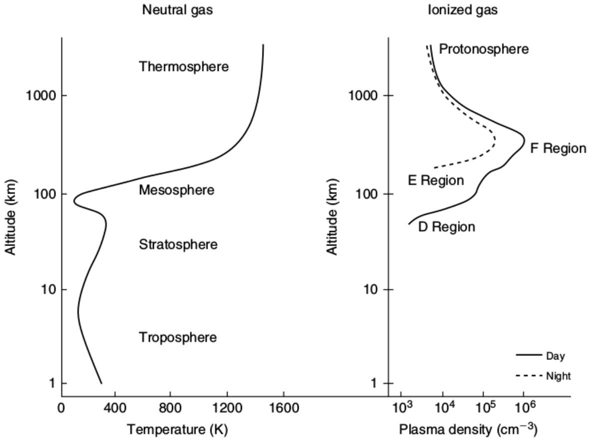


The composition is mainly determined by the height and temperature.

- $\sim 0.1\%$ ionized
- recombination rate depends fast for molekuar ions, slow for atomic ions.

Ionization/Recombination processes



- D region not existent at night
- E region weaker during night
- less variation in the F region

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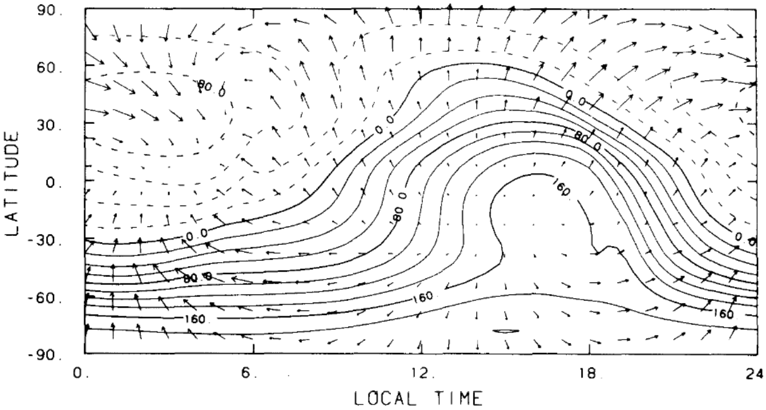
Forcing form up



- Maximum windspeed $\approx 120m/s$
- Contours: change of temperature, in K

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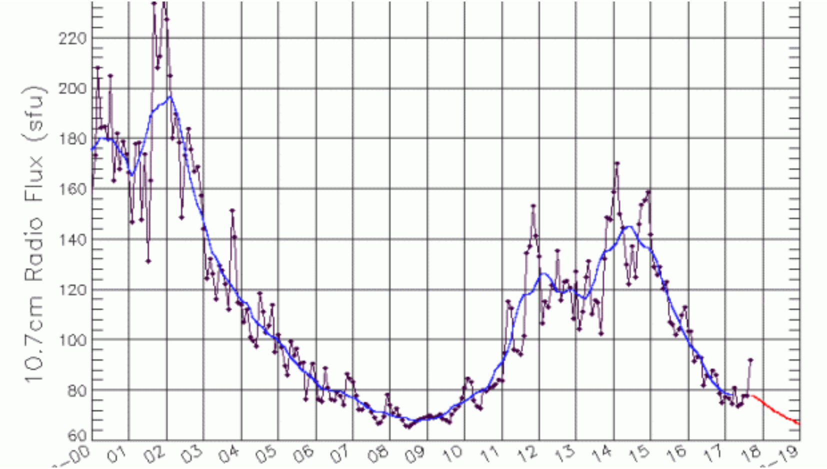
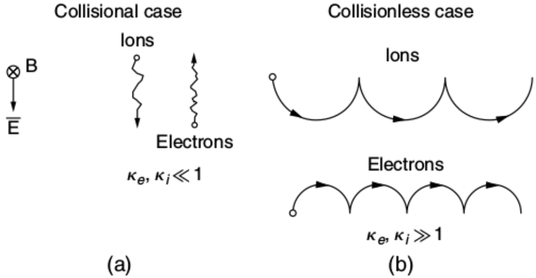
$F10.7$-**Index**

Indicator for the ionization by the sun



Electrodynamics

Magnetic field causing gyromotion of charges particles



In presence of an electric (E) and magetic field (B), particles drift in $E \times B$ direction

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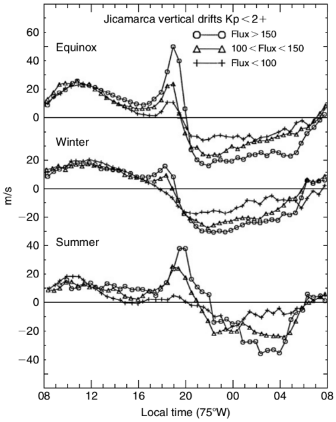
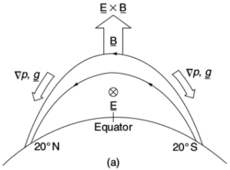
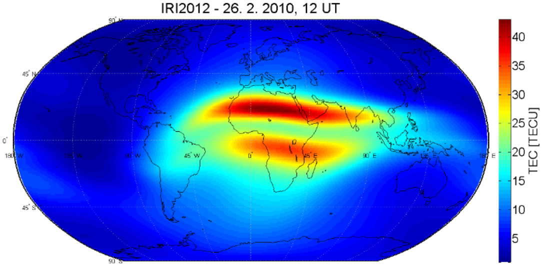
Dynamics







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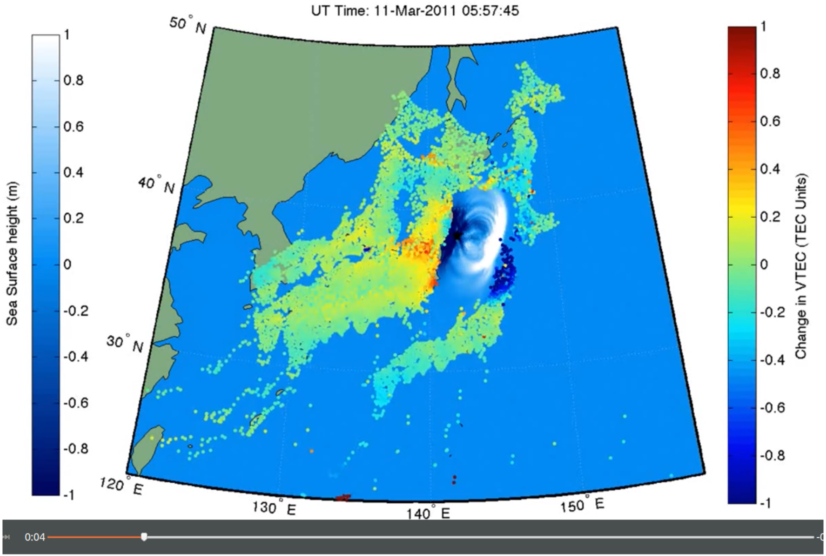
Forcing from below



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Measurements

Radar (Jicamarca Radio Observatory)

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Radars

- high quality velocity and density measurements
- expensive to build
- only a few site

Ionosondes

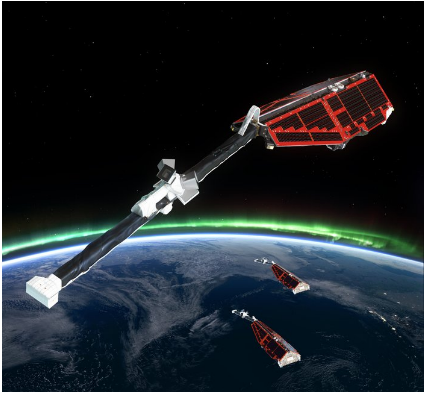
Ionosondes (HAARP: High Frequency Active Auroral Research Program)

Ionosondes

- Less expensive
- provide density profiles
- only capable of measuring up to the peak density
- small number of sites (~ 100)

GPS receivers

Ground or space based



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Constellation

32 sattelites in 60° inclined planes.

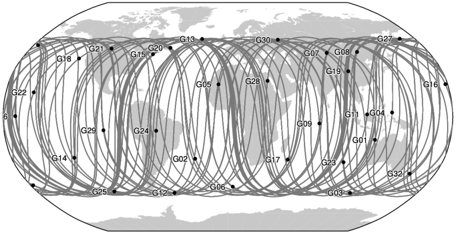
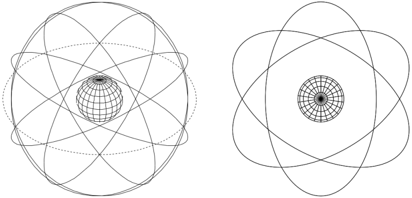


Figure 2.2.: Groundtrack of the GPS constellation during 10 days in September 2015.



(a) Viewed from a latitude of $\phi = 35^\circ$. **(b)** Viewed from a latitude of $\phi = 90^\circ$.

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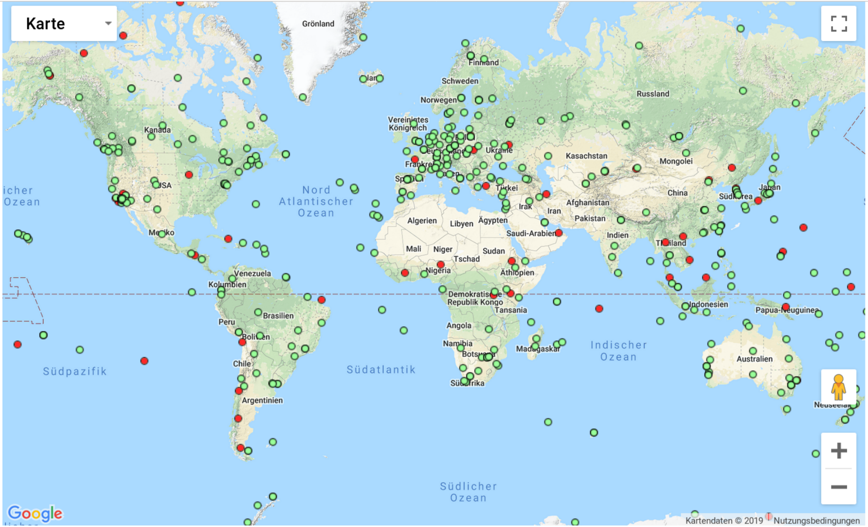
International GNSS Service Network.



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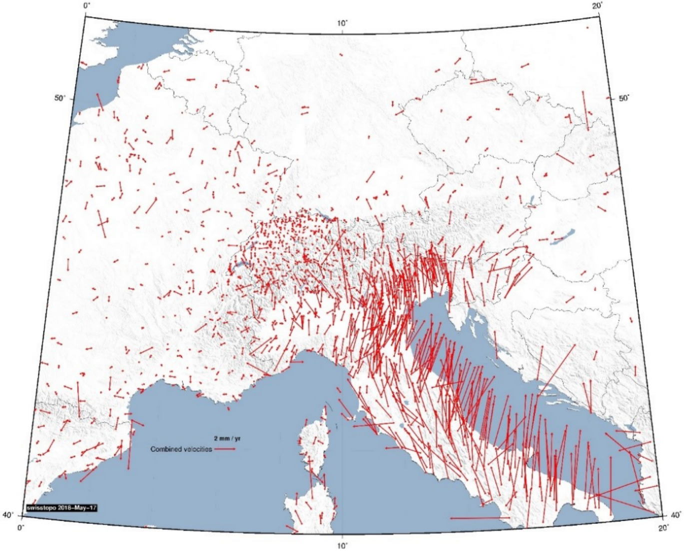
Networks

Dense networks to measure station drift.



Dual Frequency GPS

Electromagnetic wave transmitted at two frequencies:
$f_1 = 1575.42 MHz$
$f_2 = 1227.60 MHz$

$$P^i_{1k} = \rho^i_k + I^i_k(f_1) + T^i_k + c\delta_k - c\delta^i$$
$$P^i_{2k} = \rho^i_k + I^i_k(f_2) + T^i_k + c\delta_k - c\delta^i$$
$$L^i_{1k} = \rho^i_k - I^i_k(f_1) + T^i_k + c\delta_k - c\delta^i + \lambda_1 n^i_{1k}$$
$$L^i_{2k} = \rho^i_k - I^i_k(f_2) + T^i_k + c\delta_k - c\delta^i + \lambda_1 n^i_{2k}$$

ρ^i_k: Slant range
I^i_k: Ionospheric code delay/phase advance
T^i_k : Tropospheric delay
δ_k, δ^i: Receiver/transmitter clock correction
n^i_{1k}, n^i_{2k}: ambiguities

Forming differences

$$P_{1k}^i = \rho_k^i + I_k^i(f_1) + T_k^i + c\delta_k - c\delta^i$$
$$P_{2k}^i = \rho_k^i + I_k^i(f_2) + T_k^i + c\delta_k - c\delta^i$$
$$L_{1k}^i = \rho_k^i - I_k^i(f_1) + T_k^i + c\delta_k - c\delta^i + \lambda_1 n_{1k}^i$$
$$L_{2k}^i = \rho_k^i - I_k^i(f_2) + T_k^i + c\delta_k - c\delta^i + \lambda_1 n_{2k}^i$$

$$L_{3(k)}^i = \frac{1}{f_1^2 - f_2^2}(f_1^2 L_{1k}^i - f_2^2 L_{1k}^i)$$:ionosphere-free linear combination

$$L_{4(k)}^i = L_{1k}^i - L_{2k}^i$$:geometry-free linear combination

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CODE vs. Phase

- Code provides absolute Measurements (no ambiguity)
- P Code only semi-code-less trackable (encrypted)
- C/A CODE RMS $\sim 10m$ only 1 frequency
- P CODE RMS $\sim 1m$
- L1/L2 Phase RMS $\sim 1cm$

TEC

- TEC: Total Electron Content
- Integrated vertical electron density
- unit: $1\ TECU = 10^{16} electrons/m^2$

$$I_k^i(f_j) \approx \frac{1}{f_j^2} 40.3 \int_{REC}^{GPS} N_e dl$$

$$\Rightarrow TEC \approx \frac{f_1^2 - f_2^2}{40.3} \cdot L4 + const.$$

TEC determination

- Cycle slip correction and arc decomposition
- Sat. P1-P2 time bias (CODE-Product)
- Arc-wise phase leveling using corrected code measurements
- P1-P2 Receiver bias estimation

An error of 1 cycle implies an error of $19/25$ cm which equals an error of $1.8/2.4 TECU$

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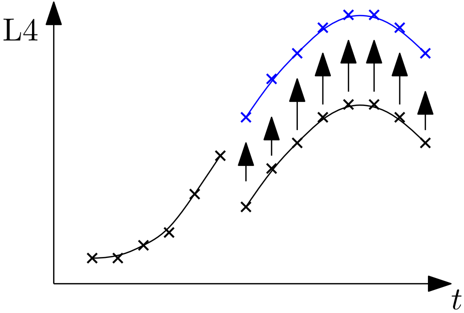
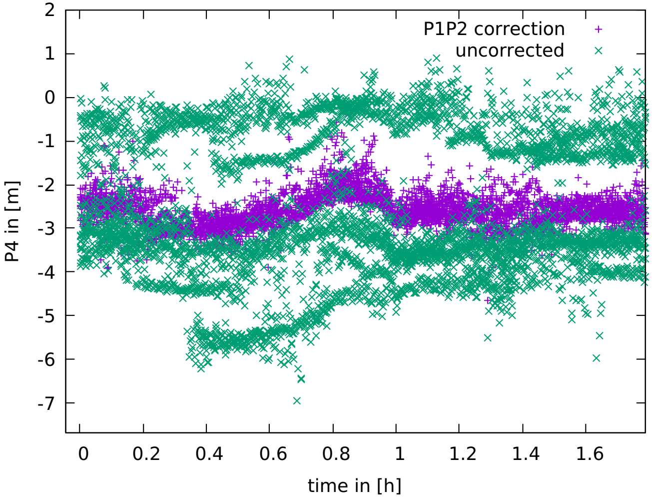
Cycle slip correction and arc decomposition

Jumps in the observations due to receiver artifacts or loss of lock.



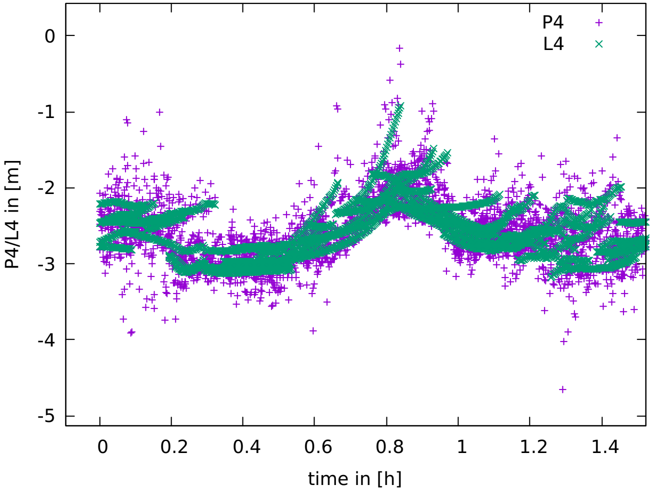
Sat. P1-P2 time bias (CODE-Product)

Transmitter corrections for the GPS satellites.



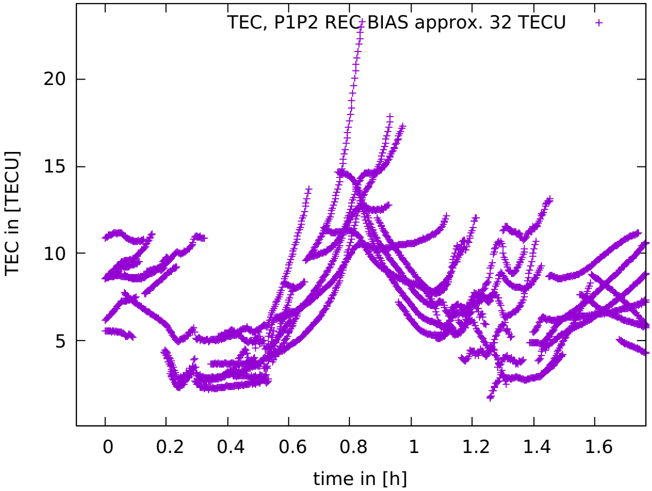
Arc-wise phase leveling

Estimate ambiguities by using code measurements as reference.



P1-P2 Receiver bias estimation

Scale from m to TECU and estimate receiver offset



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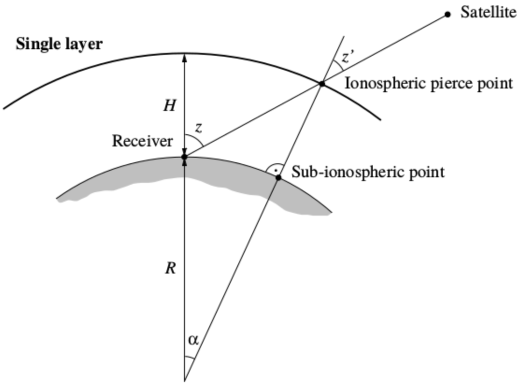
TEC Mapping

Single Layer Model: Map the measured slant TEC to the ionospheric piercing point. (usually between 350 km to 450 km)



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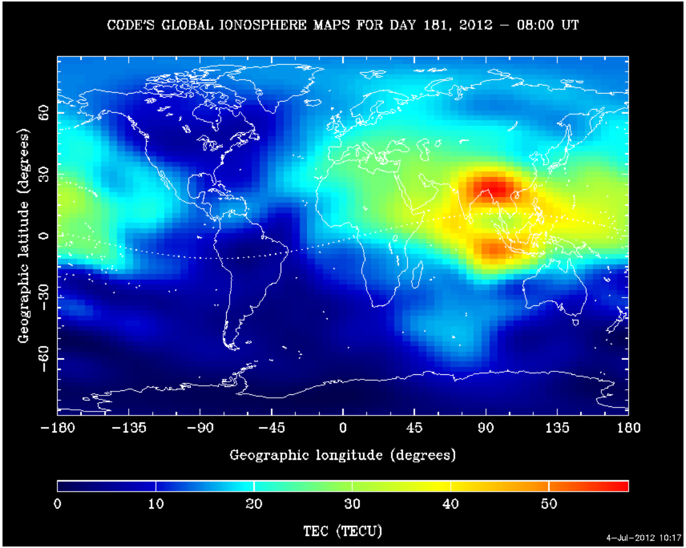
CODE TEC map



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The ionospheric part

$$I_k^i(f_j) = \frac{q}{f_j^2} + \frac{s}{2f_j^3} + \frac{r}{3f_j^4}$$

$$q = 40.3 \int_{REC}^{GPS} N_e dl$$

$$s = 7527 \cdot c \cdot \int_{REC}^{GPS} N_e B_0 \mid cos(\theta_B) \mid dl$$

$$r = 2437 \int_{REC}^{GPS} N_e^2 dl + 4.74 \cdot 10^{22} \int_{LEO}^{GPS} N_e B_0^2 (1 + cos^2(\theta_B)) dl$$

Using this information we can form the linear combinations:

$$L_{3k}^i = \frac{1}{f_1^2 - f_2^2}(f_1^2 L_{1k}^i - f_2^2 L_{1k}^i)$$:ionosphere free linear combination

$$L_{4k}^i = L_{1k}^i - L_{2k}^i$$:geometry free linear combination

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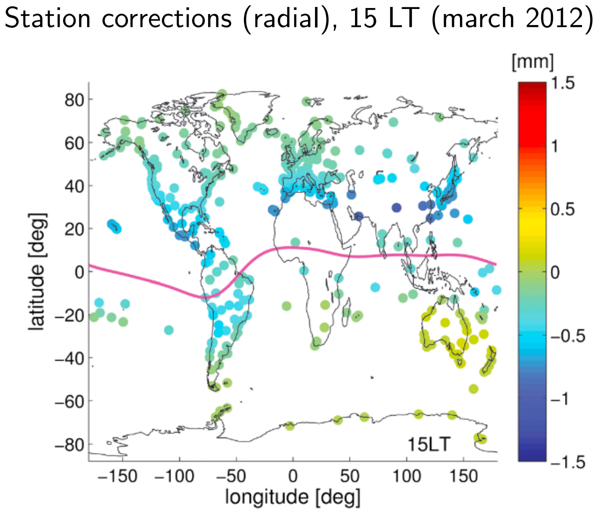
Impact on station positions



- Drift up to 5mm/year
- Ionospheric error 1.5mm

Conclusion

Ionosphere

- Daily, seasonal, and annual Variations
- Maximum ionization in equatorial regions
- $E \times B$ drift lifts plasma

Conclusion

Ionosphere

- Daily, seasonal, and annual Variations
- Maximum ionization in equatorial regions
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GPS-Measurements

- Dense networks
- Provide TEC measurements
- can also benefit from precise ionospheric models

Thank you for your attention!

Images

- http://aerohistory.org/Wireless/marconi-transatlantique.html, slide 3
- http://atlantic-cable.com/NF2001/index.htm slide 4
- http://www.rfwireless-world.com/Tutorials/OTH-Over-The-Horizon-Radar.html, slide 5
- NASA, slide 5
- Kelley, The Earth's Ionosphere, second edition, slide 6,7,9,10
- Blizita, IRI Model, slide 10
- J. E. Titherid, Winds in the Ionosphere, slide 8
- Bernese GNSS Software Manual V5.2, Rolf Dach et. al., slide 19,29
- Jicamarca Radio Observatory (JRO), slide 12
- HAARP, www.haarp.alaska.edu/haarp/photos.html, slide 14
- ESA Swarm, slide 16
- IGS, igs.org/network, slide 18
- Swisstopo, Wabern, Switzerland, slide 19
- Center for Orbit determination Europe, Switzerland, Bern, slide 30
- Astronomical Institue, Bern, slide 16, 30
- F. Zus et. al. The impact of higher-order ionospheric effects on estimated tropospheric paramertes in Precise Point Positioning,slide 32