GNSS Ionosphere: How and Why (*brief visual discovery*)

Manuel Hernandez Pajares(1,2), Germán Olivares-Pulido(1)
on behalf of **many UPC-IonSAT colleagues & collaborators**

(1) UPC-IonSAT, Barcelona, Spain; (2) IEEC, Barcelona, Spain.

contact e-mail: manuel.hernandez@upc.edu

EUREF 2024 Tutorial: GNSS contributions to Space Weather monitoring
Barcelona, Spain, 04 June 2024, 12h30m-14h30m

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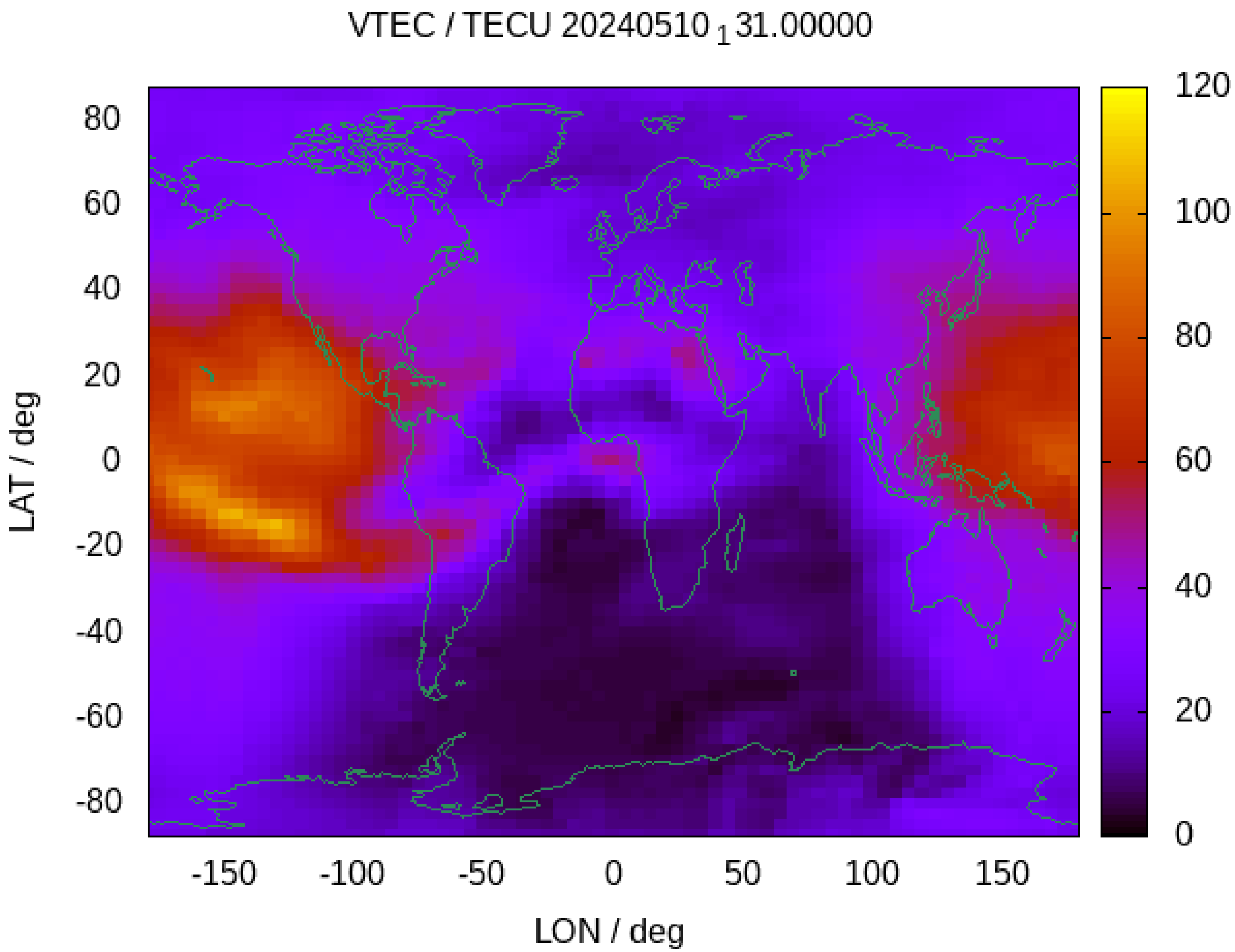
What is this?

Movie of the vertically integrated electron number density (AKA Vertical Total Electron Content, VTEC) of the partially ionized part of the Earth atmosphere (ionosphere) obtained from worldwide Global Navigation Satellite System (GNSS) multifrequency measurements (10 May, day 131, of 2024, starting at the end a huge ionospheric storm)



Do you wish to check the present global VTEC, from RT UPC-IonSAT GIMs? If yes:

http://chapman.upc.es/tomion/real-time/quick/last_results.uadg/RT-DAILY-VTEC-MOVIE.gif

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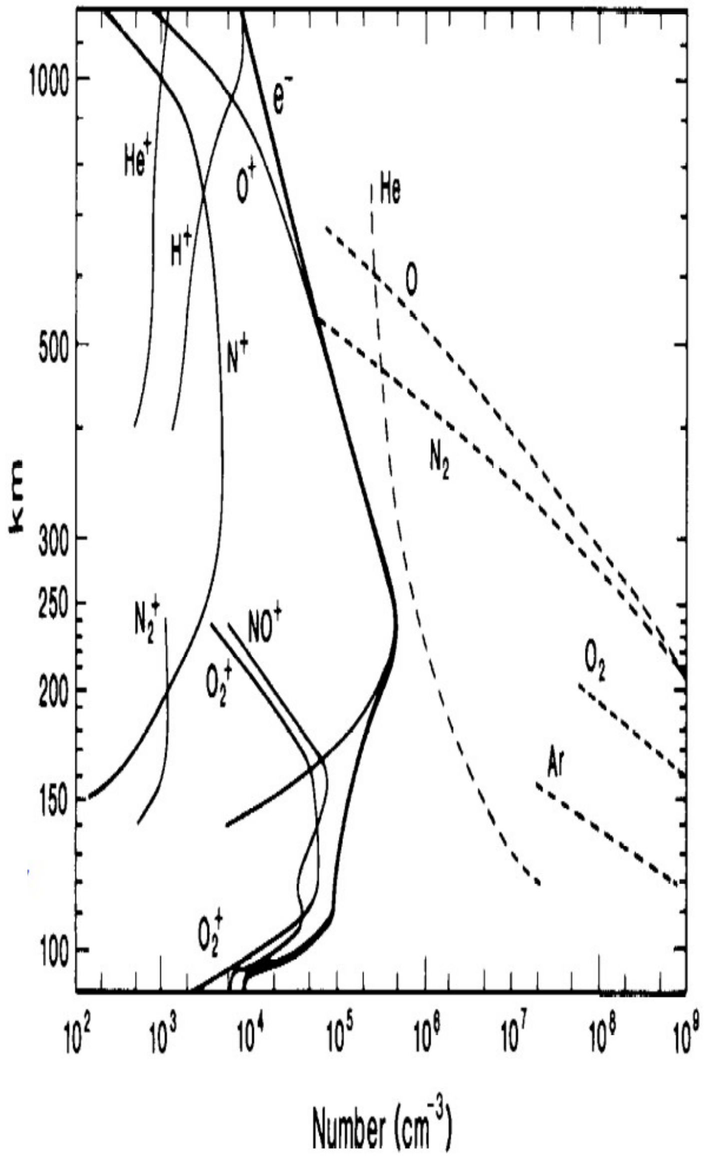
Why there are free electrons within the Earth atmosphere?



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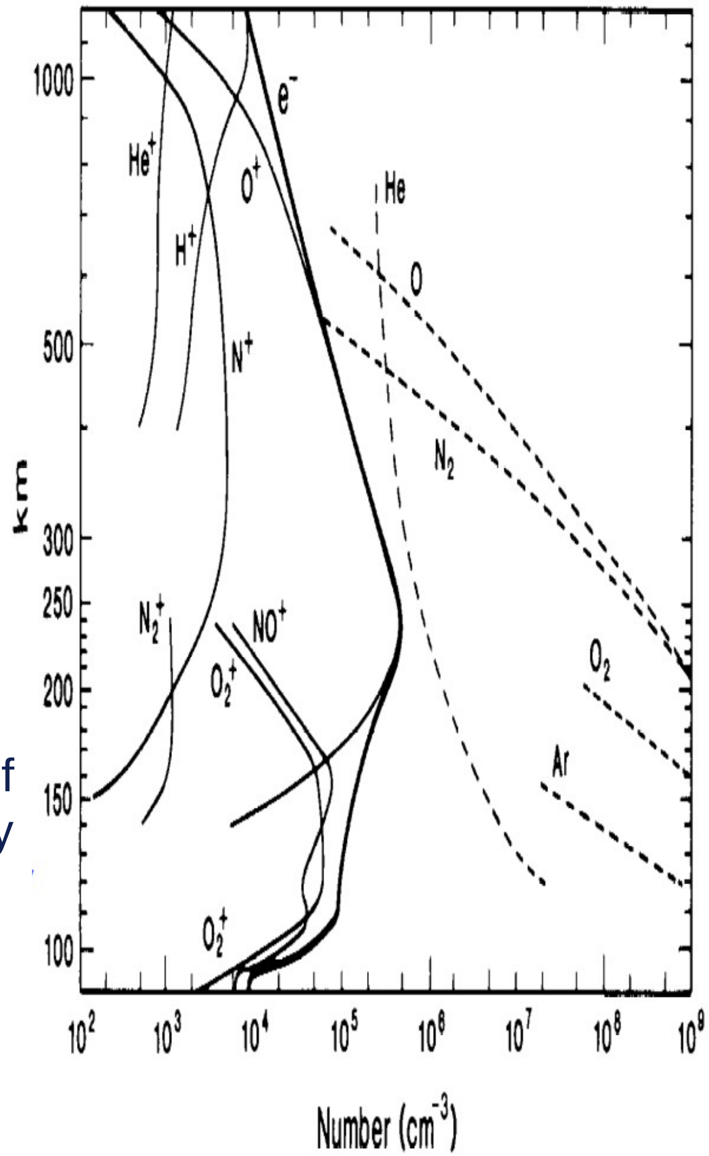
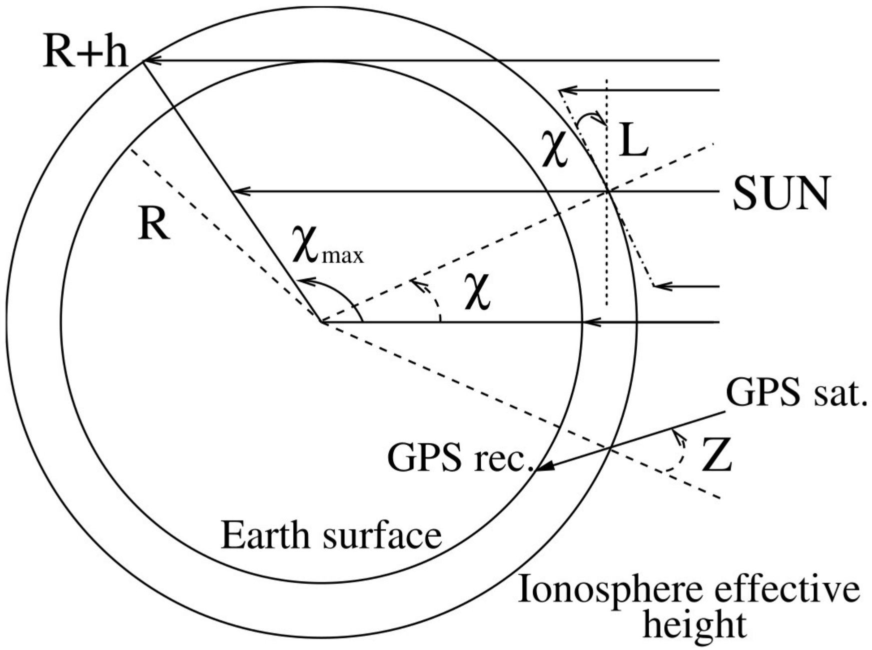
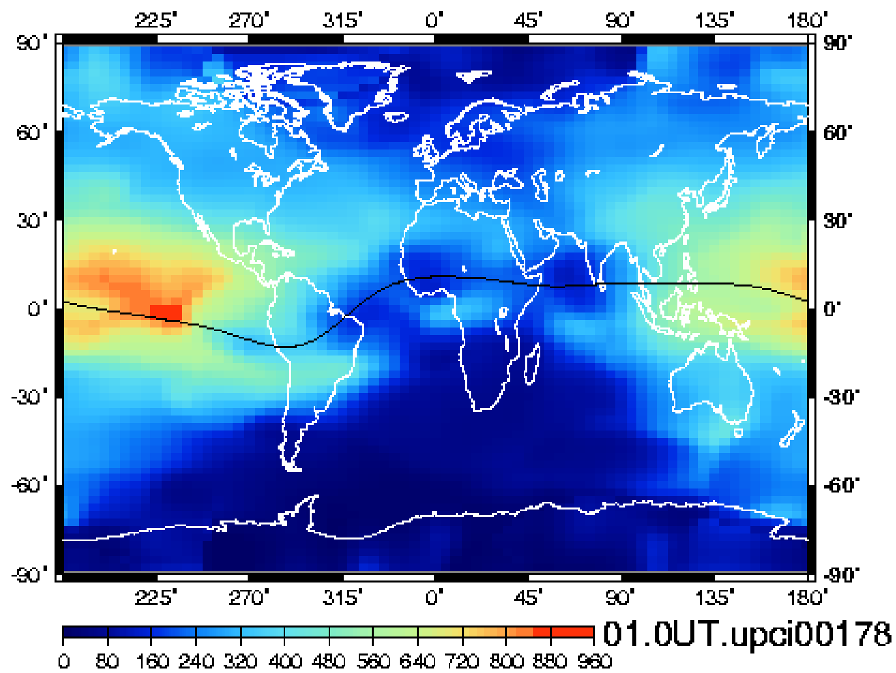
Why there are free electrons within the Earth atmosphere?

The chemical reactions on the Earth atmosphere of dissociation of different molecules at different heights by solar photons (mostly in EUV and X-ray bands).



How can the VTEC distribution be explained?





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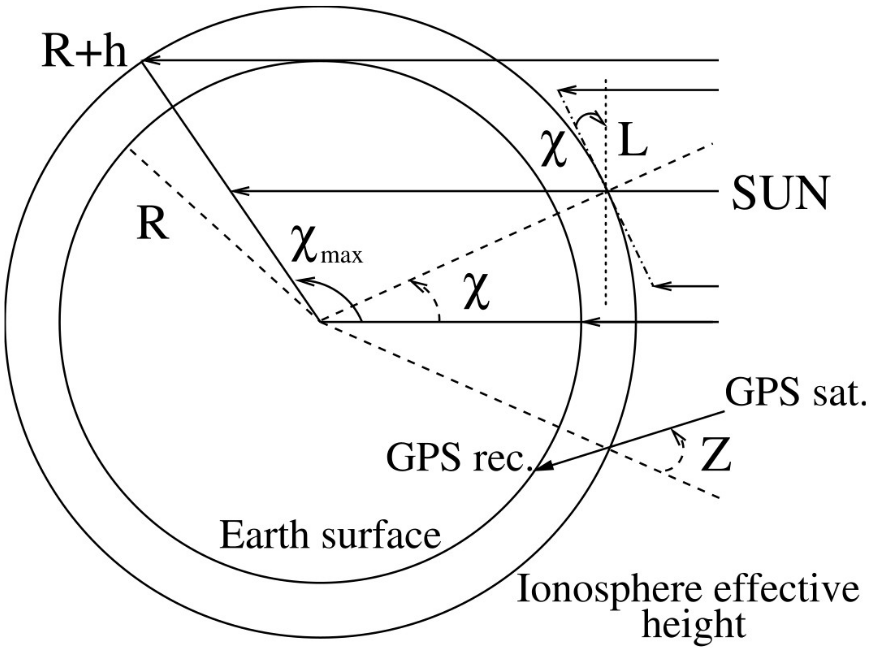
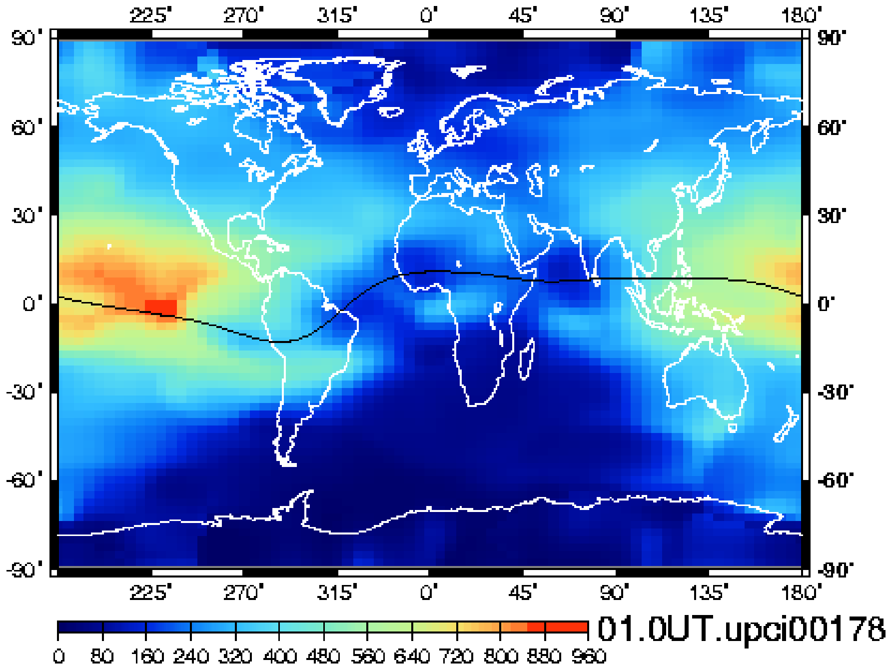
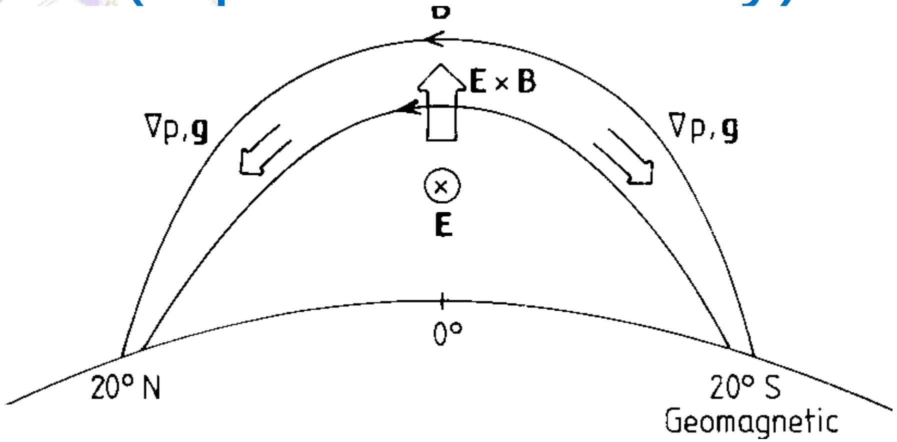


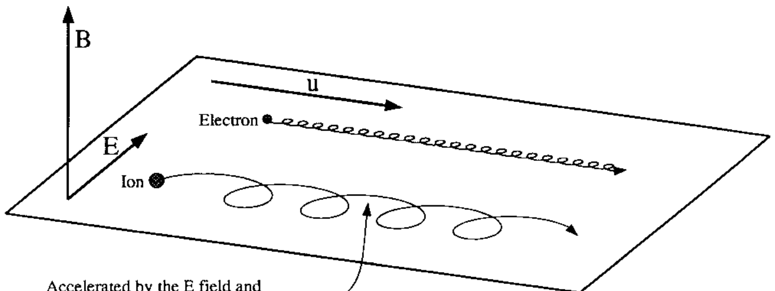


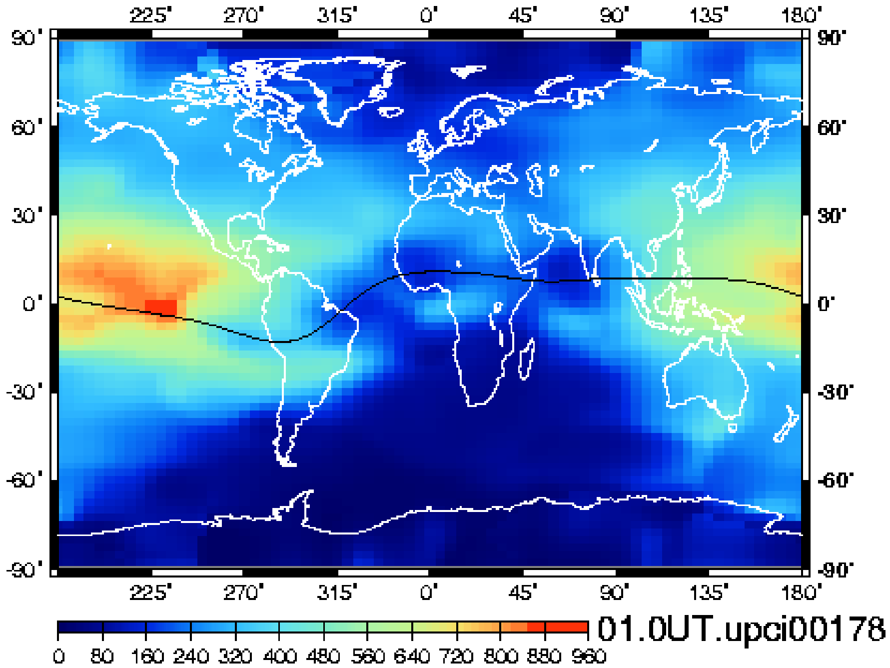
- In principle, taking into account with different solar irradiance in function of the latitude

- (And the Earth rotation!)

Anything else to be explained? What about the double VTEC peak (equatorial anomaly)?







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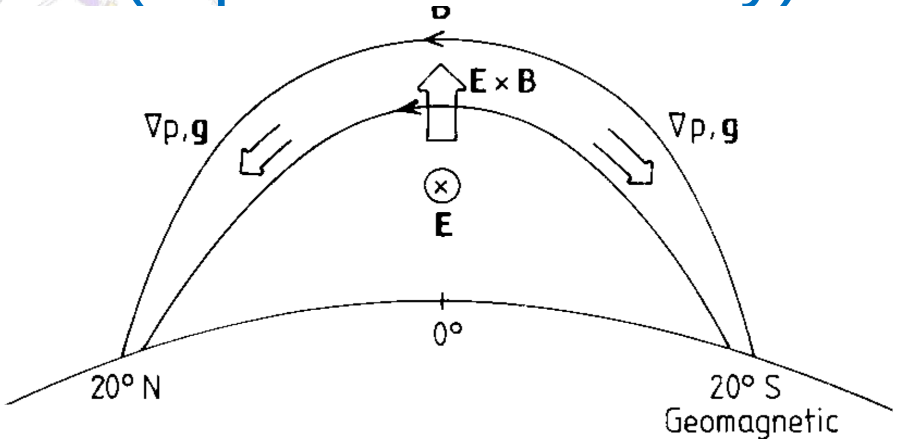
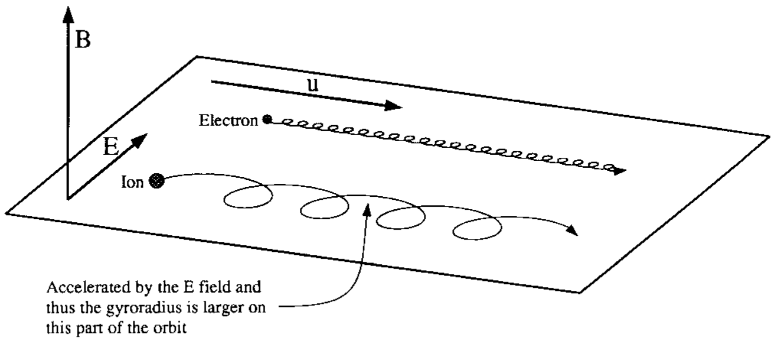
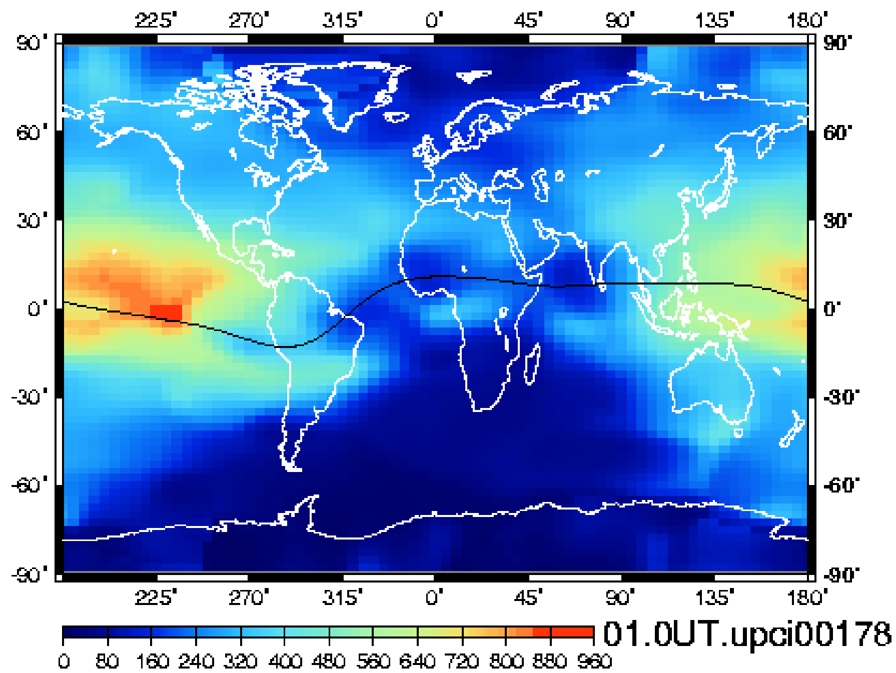
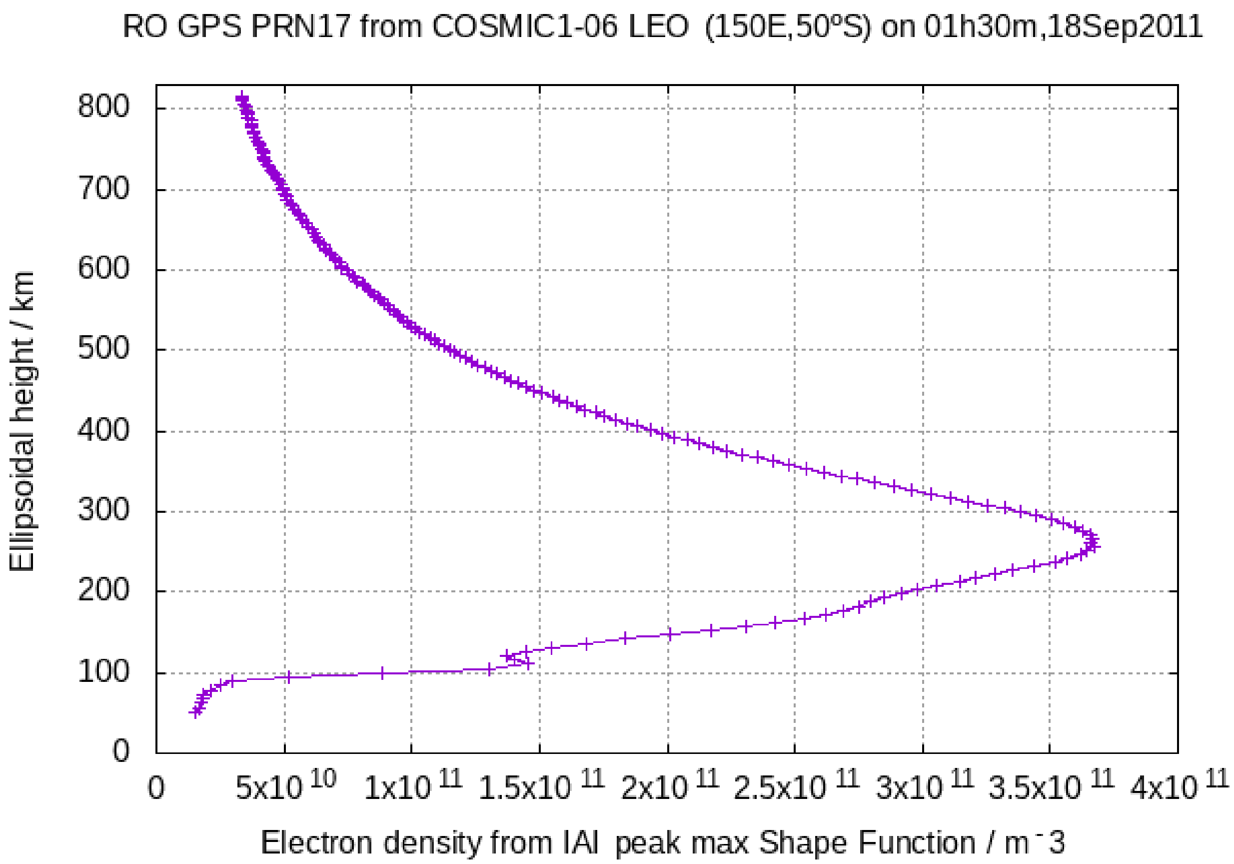






ExB drift, generates the fountain effect, and then, the equatorial anomaly and double peak, with a central role of the magnetic field, the magnetic equator in particular, in the distribution of the free electrons of the Earth ionosphere.

And this? How can it be explained?



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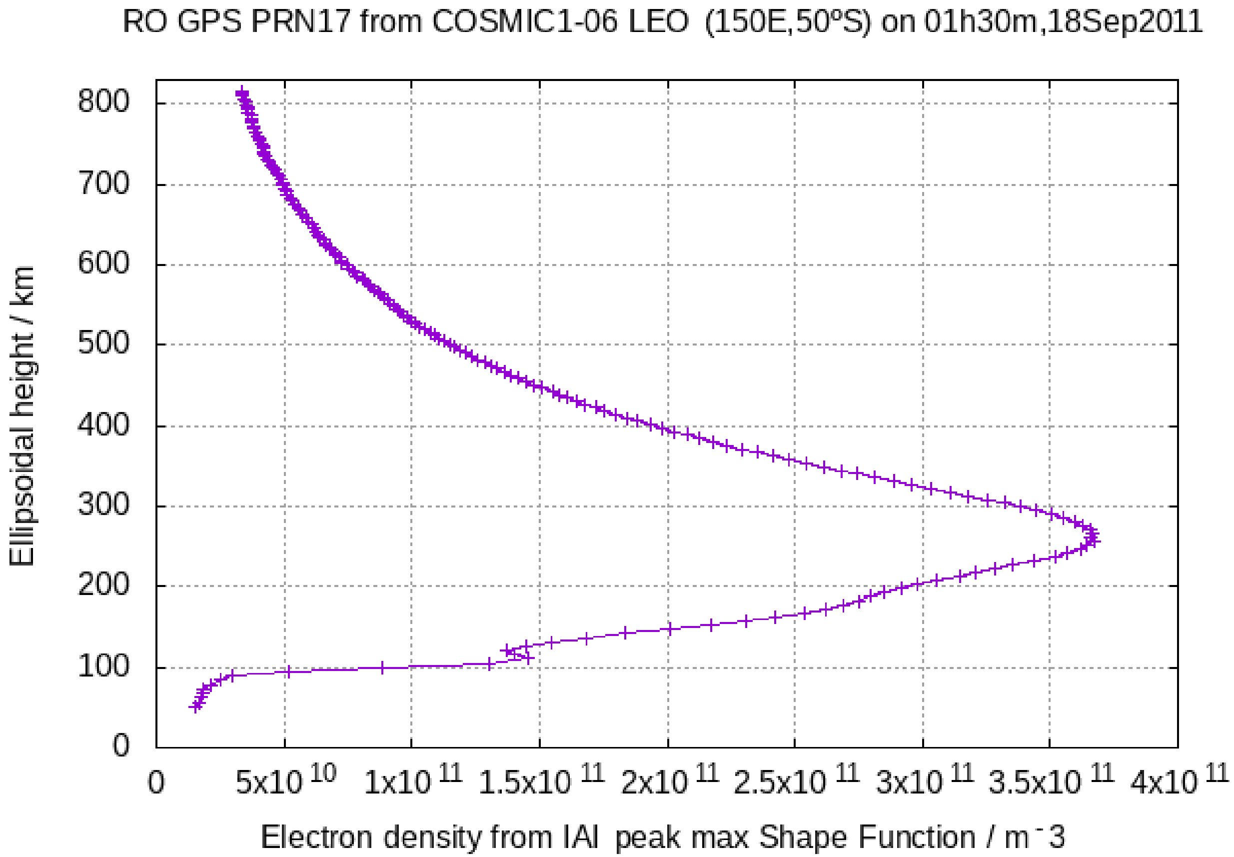
And this? How can it be explained?

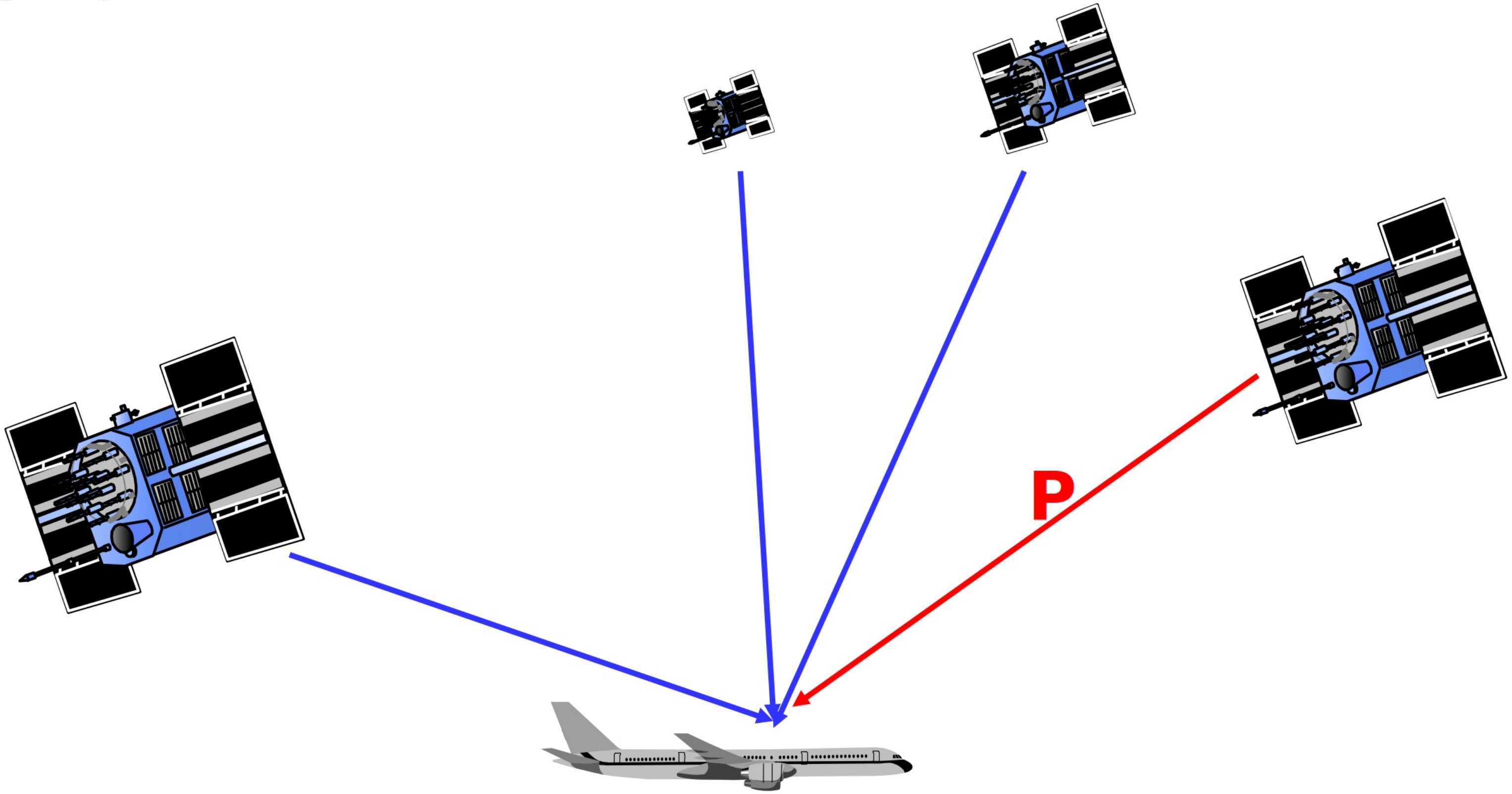
- The electron number density (hereinafter electron density) vs height(*).

- The intermediate electron density peak height can be understood as the optimal height of production of free electrons, a compromise between enough number of target molecules and enough ionizing solar radiation, specially in EUV.

(*) Estimated thanks to GNSS receivers flying on a Low Earth Orbiting satellite -in this case FORMOSAT-3/COSMIC- measuring multifrequency GNSS signals from transmitters below the LEO local horizon (radio-occultation scenario).



And what about this? Any guess?



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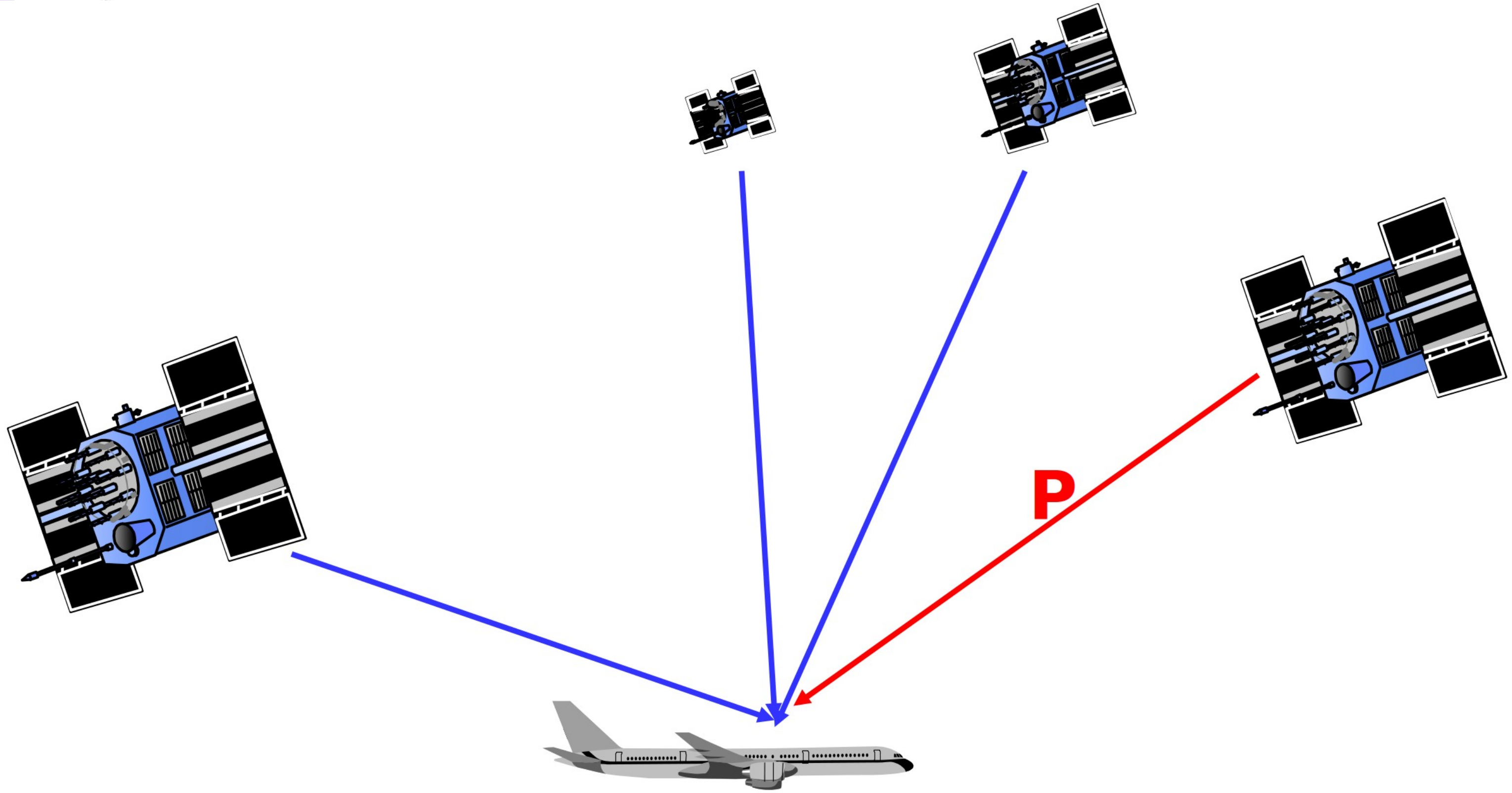
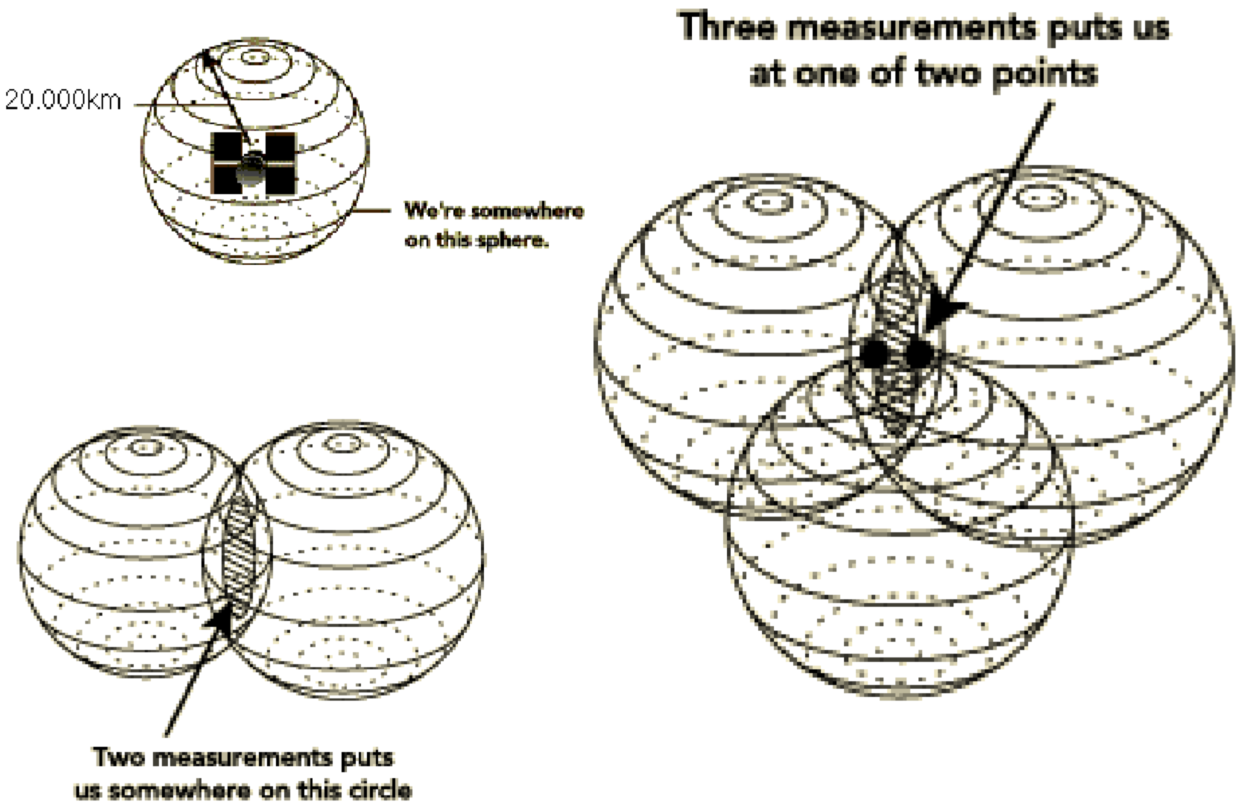


Yes, these are four Global Positioning System (GPS) transmitter providing pseudodistance signals to a receiver on board an airplane (this an “artistic” composition NOT following the real distance scale).

And now, who can explain these layouts?



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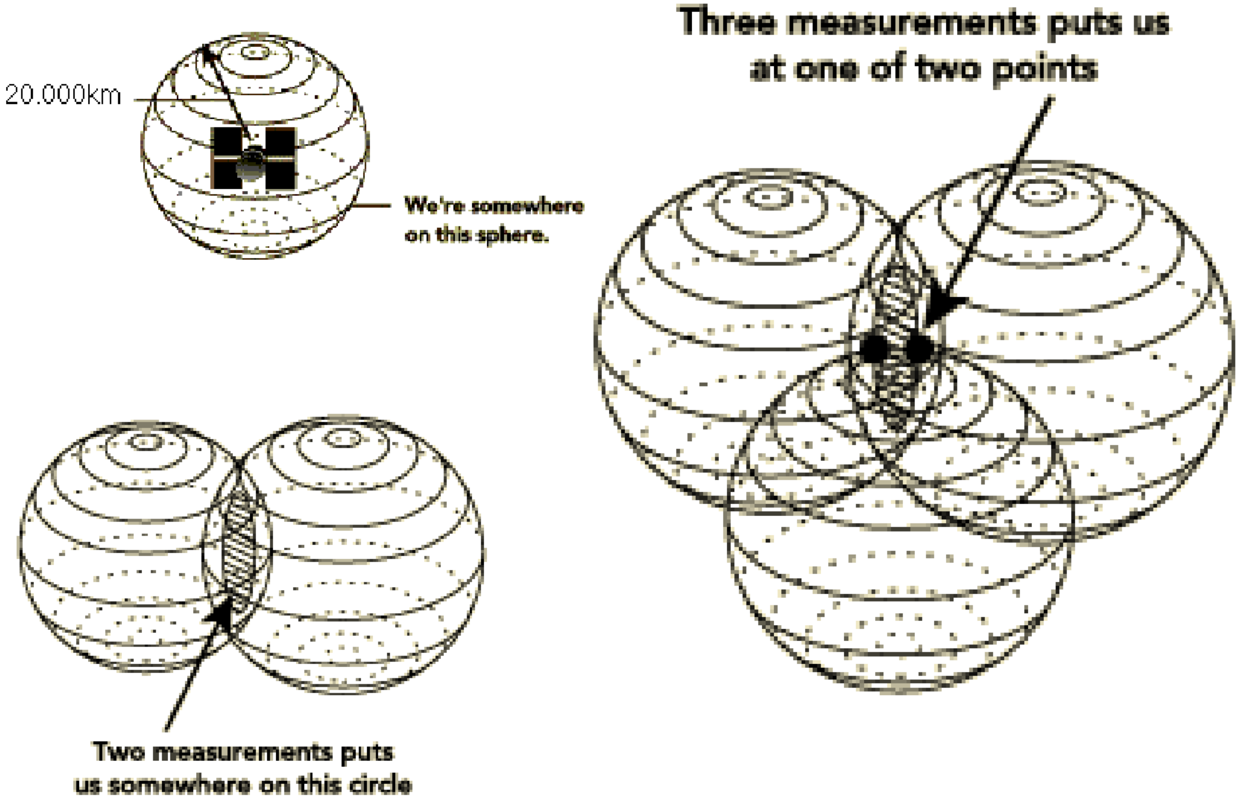
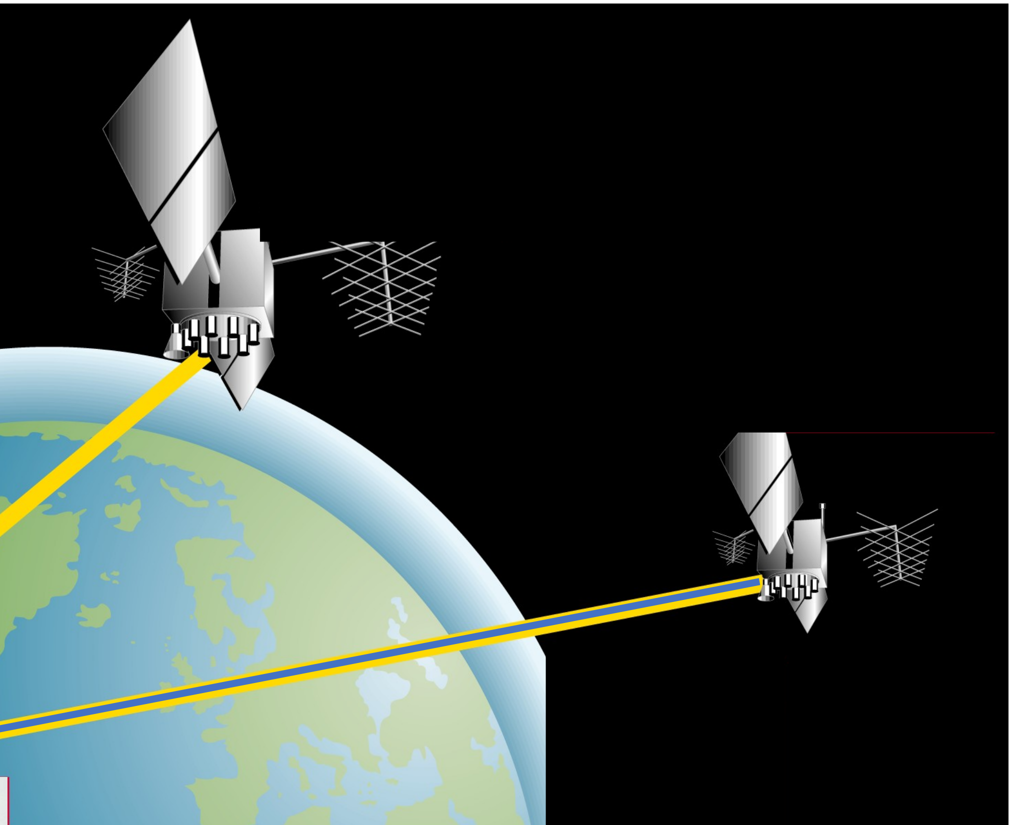
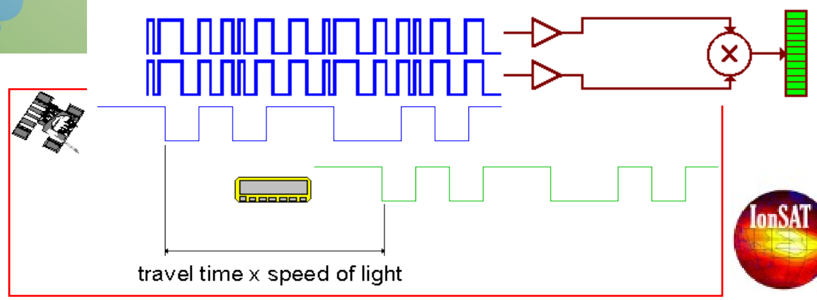


Yes, it illustrates the trilateration concept, foundation of GNSS for positioning: knowing the position of the center of at least three(*) spheres in different directions -GNSS transmitters on MEOs- and the radius of such spheres -from the pseudorange measurements-, we get the receiver position X,Y,Z -intersection-).

(*) at least four satellites are needed taking into account the receiver clock error

But we need to get pseudoranges, right?



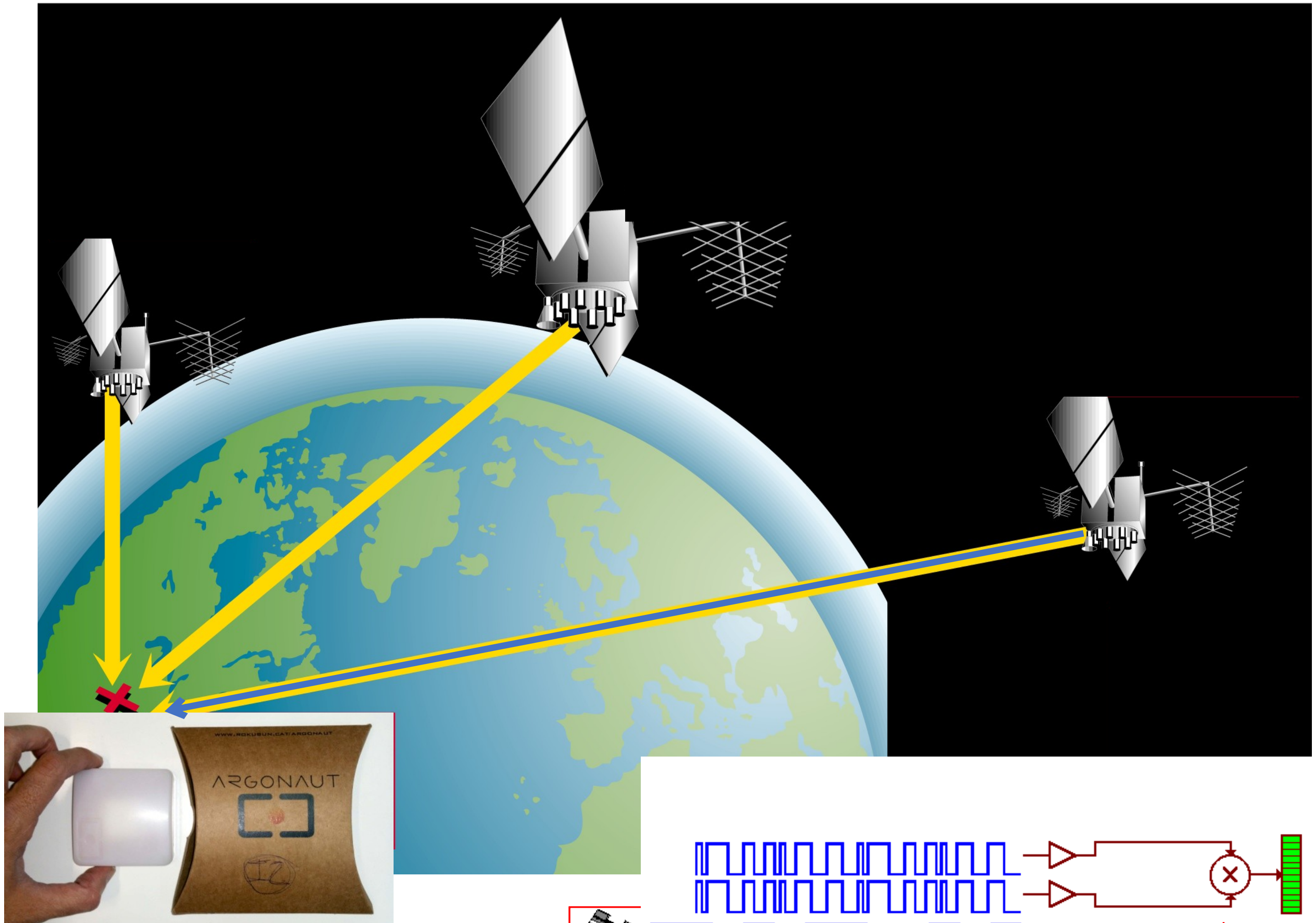


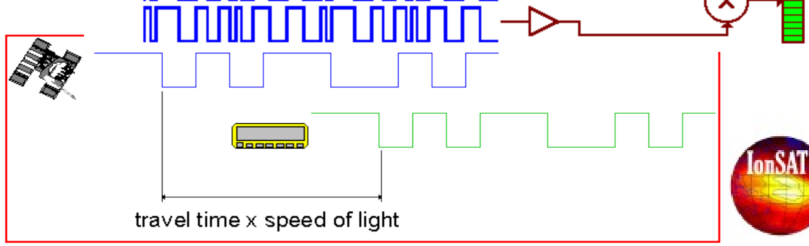
But we need to get pseudoranges, right?

- "Pseudoranges" are computed from the apparent traveling time from GNSS transmitter to GNSS receiver.

- The pseudo-random noise transmitted signal, function of the atomic transmitter clock, is correlated at the receiver with its replica, generated from its typically quartz clock.

- Several "error" sources quickly arises, not only the transmitter and receiver clock errors, but also the atmospheric ones, including the ionospheric delay, all under the "pseudo" part of the observable pseudorange name.





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1. Code or pseudorange: This measurement is given by the apparent travel time τ of the EM signal propagated from GPS transmitter to receiver, scaled by the speed of light in the vacuum, c. This value can be partially considered as a range, i.e., a pseudorange $\tilde{\rho}$:

$$P \equiv c\tau = \tilde{\rho} \quad (3)$$

And we have a second “invited” type of measurement to the “GNSS party”, very interesting, very precise: the carrier phase

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2. Carrier phase: This measurement is computed in the receiver by continuously integrating the frequency Doppler shift, primarily due to the relative velocity, clocks, and tropospheric and ionospheric drifts. This value is scaled in unit lengths in such a way that it represents the pseudorange $\tilde{\rho}$ and basically refers to the last time the carrier phase was locked by the receiver t_L (i.e., the pseudorange change since the last "cycle-slip" or the first acquisition epoch).

And we have a second “invited” type of measurement to the “GNSS party”, very interesting, very precise: the carrier phase

$$\int_{t_L}^{t} \dot{\tilde{\rho}}\, \mathrm{d}t = -\frac{c}{f} \int_{t_L}^{t} \delta f \cdot \mathrm{d}t. \qquad (5)$$

Thus, the carrier phase is finally defined as:

$$L \equiv -\lambda \int_{t_L}^{t} \delta f \cdot \mathrm{d}t = \tilde{\rho}(t) - \tilde{\rho}(t_L) = \tilde{\rho} + B_f, \qquad (6)$$

where B_f is the carrier phase ambiguity for frequency f and $\lambda = c/f$ is the corresponding carrier wavelength.

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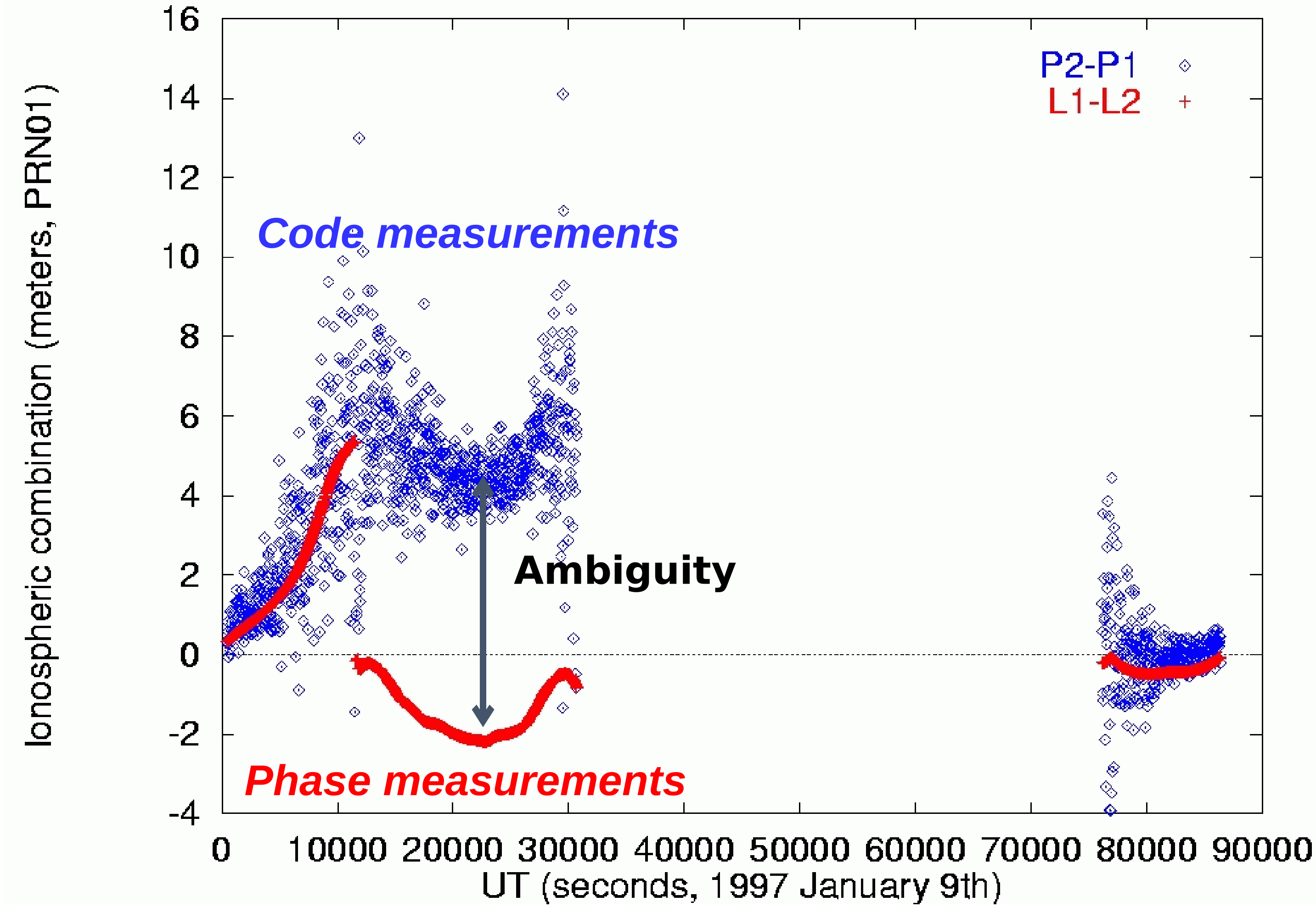
Now, any guess or comment about this plot?



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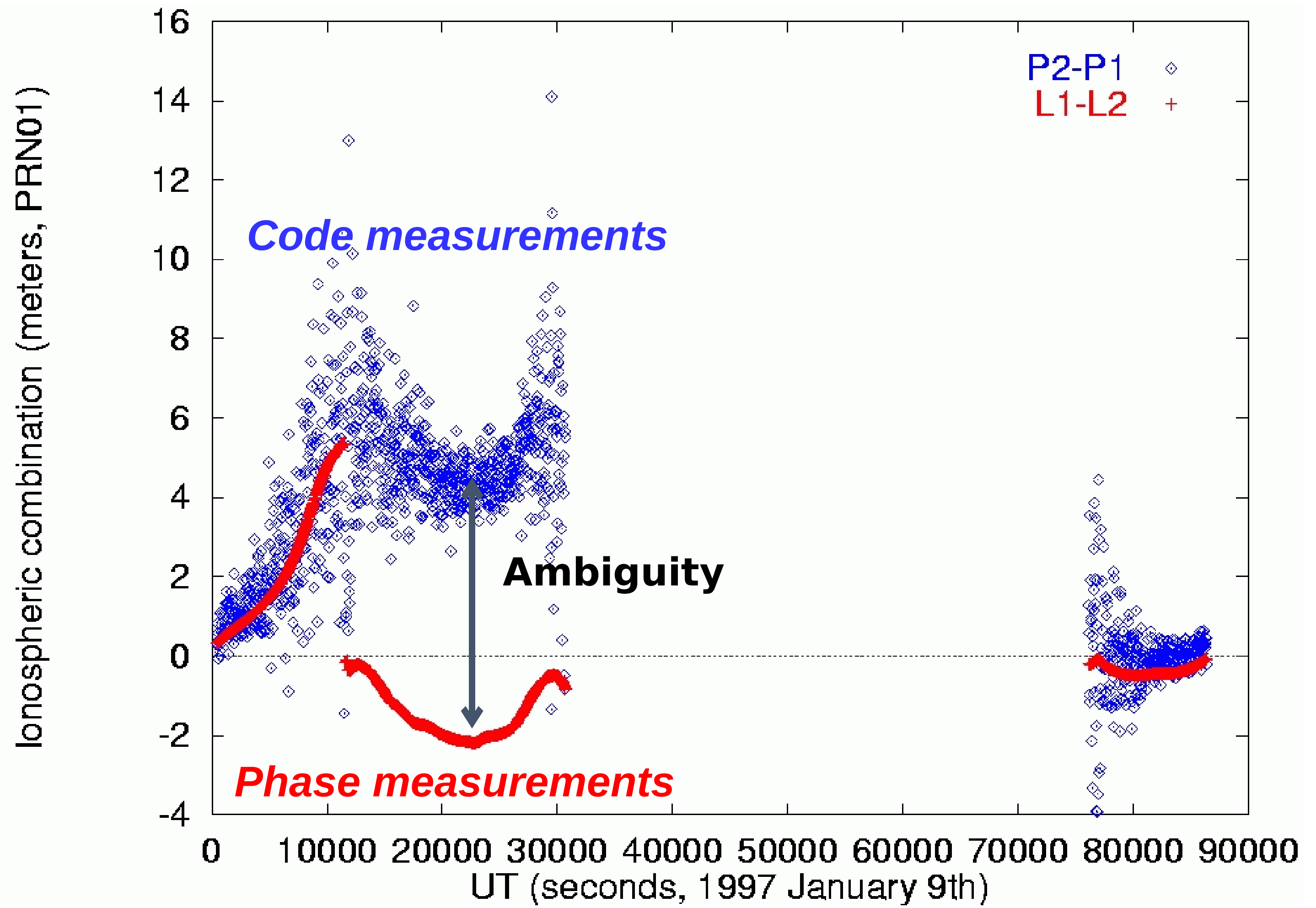
Now, any guess or comment about this plot?

-We can see how the code (i.e. pseudorange) and phase measurements ("ionospheric combination") of a given GPS transmitter ("PRN01") from a given receiver, complement each other very well:

-The code measurements are accurate (pseudorange) but not precise (measurement noise and multipath >~1 m).

-The carrier phase measurements are not accurate (unknown ambiguity = pseudorange at phase lock) but very precise (measurement noise and multipath < 1cm).



Finally, the electron content is inside GNSS measurements!

$$P_m = \rho + c(\mathrm{d}t - \mathrm{d}t') + \frac{40.309}{{f_m}^2} S + T + D_m + D'_m \quad (15)$$

and

$$L_m = \rho + c(\mathrm{d}t - \mathrm{d}t') - \frac{40.309}{{f_m}^2} S + T + B_m + \frac{c}{f_m} \phi \quad (16)$$

$$S = \int_{r_\mathrm{T}}^{r_\mathrm{R}} N_\mathrm{e} \mathrm{dl} \quad (14)$$

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-The first-order approximation of the ionospheric delay term, deduced from the Appleton-Hartree equations of EM propogation, accounts for 99.9% of the the ionospheric delay of GNSS signals (L-band).

- It is positive (delay) for the pseudorange and negative (advance) for the carrier phase. BTW: Is this an issue vs the relativity principle of “maximum velocity” the light speed in the vaccum?.

- The ionospheric delay term is proportional to the Slant Total Electron Content (Slant TEC, STEC) and inverserly proportional to the signal frequency.

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Finally, the electron content is inside GNSS measurements!

$$L_I \equiv L_1 - L_2 = \alpha \cdot S - \beta \cdot \phi + B_I, \quad (17)$$

$$P_I \equiv P_2 - P_1 = \alpha \cdot S + D_I + D'_I + \epsilon_M + \epsilon_T, \quad (18)$$

where $\alpha = 40.309\left(\frac{1}{f_2^2} - \frac{1}{f_1^2}\right) = 1.05 \cdot 10^{-17}\, m^3$, $\beta = c\left(\frac{1}{f_2} - \frac{1}{f_1}\right) = 0.054\,\mathrm{m}$, $B_I = B_1 - B_2$, $D_I = D_2 - D_1$ and $D'_I = D'_2 - D'_1$.[2] In this case, we also made explicit the two main components of the measurement error, both corresponding to the code: the multipath code error ϵ_M and the thermal noise measurement error ϵ_T. Typically, the wind-up term $\beta \cdot \phi$ is a centimeter-level term. For the permanent receivers, this term can be corrected very accurately from their coordinates and orbital information, and it is not discussed explicitly herein.

Finally, the electron content is inside GNSS measurements!

-Then the highly variable ionospheric magnitude, STEC, is directly given by the ionospheric combination of dual-frequency carrier phases and pseudoranges (L_I & P_I): This is the main input data source for GNSS Ionosphere! (among the good performance of single-frequency measurements recently shown for certain ionospheric viewing problems such as plasma bubble detection).

-Other additional terms, are either constant at scales of hours (ambiguity BI, Differential Code Biases, DI, DI') or are small and can be very well modelled (wind-up term $\beta * \phi$).

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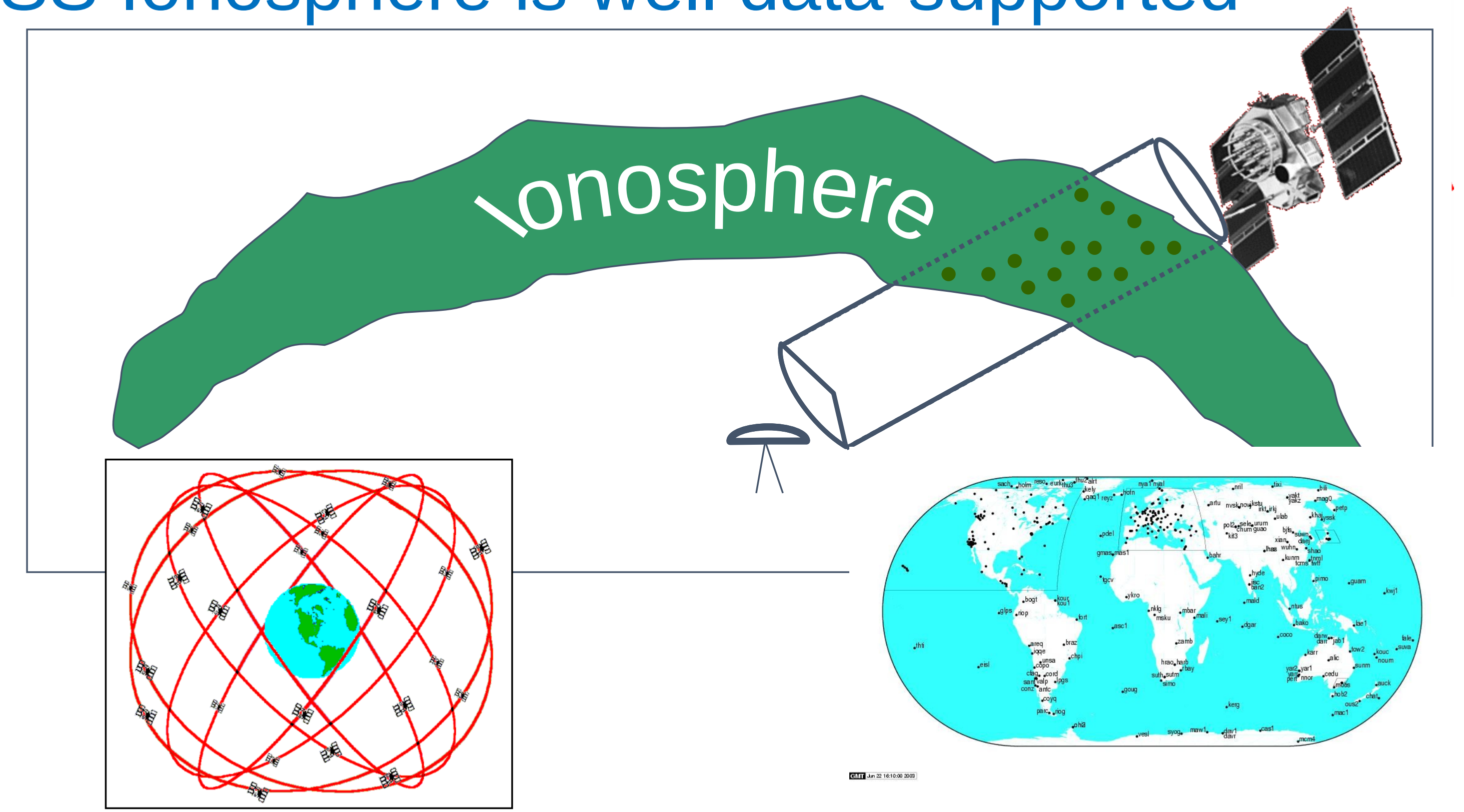
Conclusion: GNSS Ionosphere is well data-supported



~ 100 GNSS trans. & +1000 24/7 static GNSS rec. (+100 in RT)

Worldwide *scanner* of the Ionosphere, an excellent input to generate ***Global Ionospheric Maps (GIMs) of VTEC maps*** (summarizing Big GNSS data), among **many other ways of modelling / studying the ionosphere**

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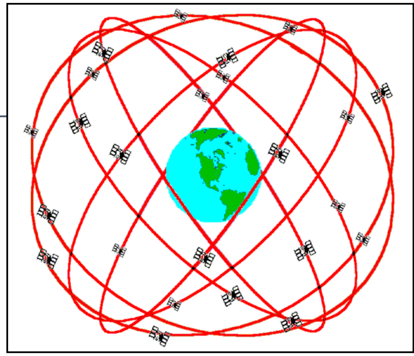
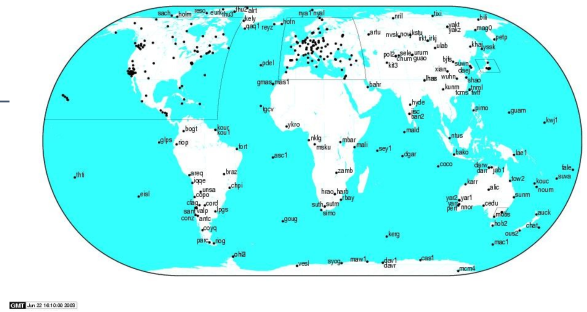
GNSS Ionosphere:

"Effects and computation of the distribution of free electrons, located at the partially ionized part of the atmosphere above 50 km height, from the Global Navigation Satellite Systems (GNSS) measurements, usually multi-frequency, crossing it; and its applications, such as Space Weather monitoring, precise real-time positioning and, in general, precise geodetic modelling among others"





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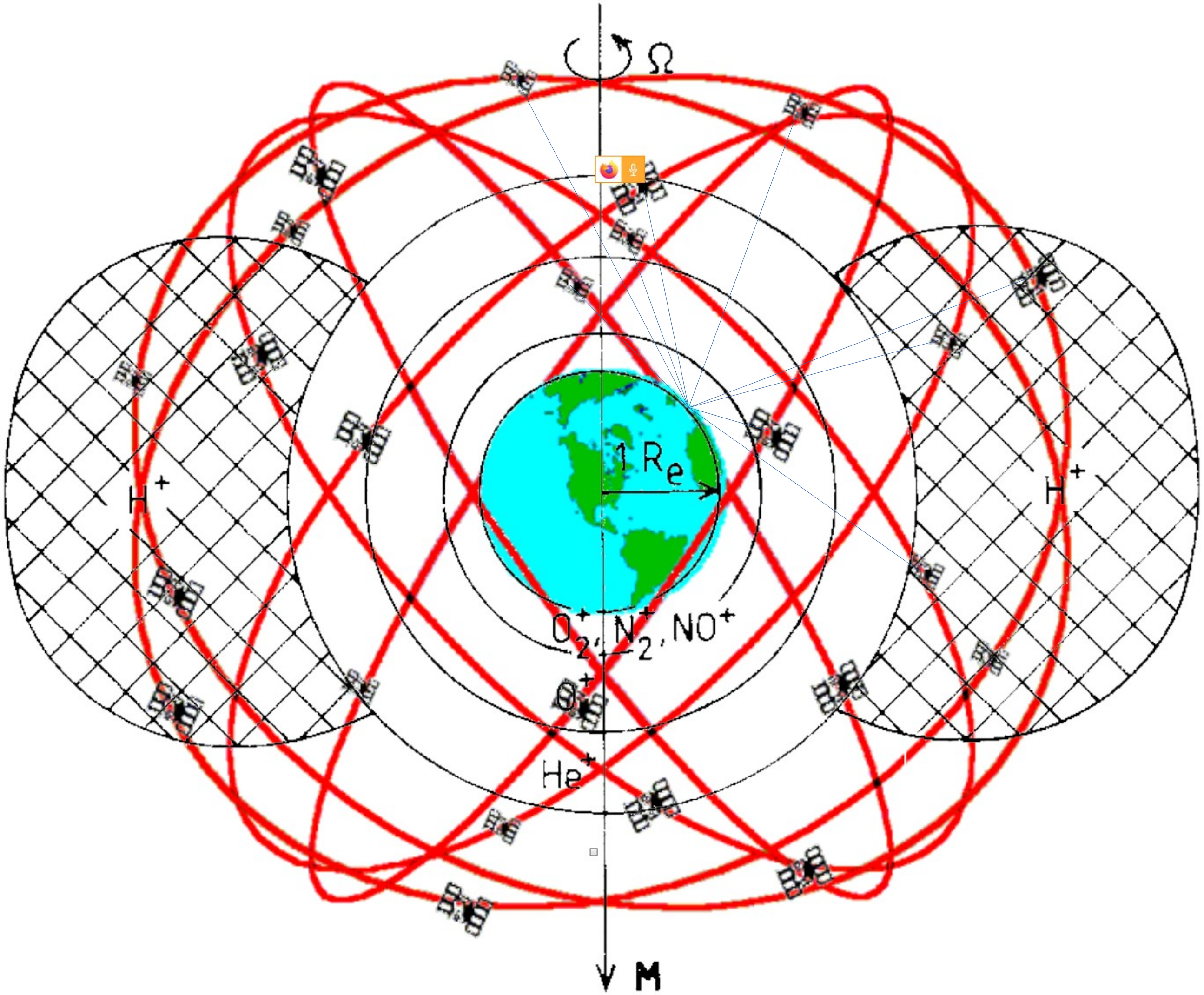

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