International School of Space Science
L'AQUILA - ITALY

- Ionosondes and GNSS network (instruments and data)-

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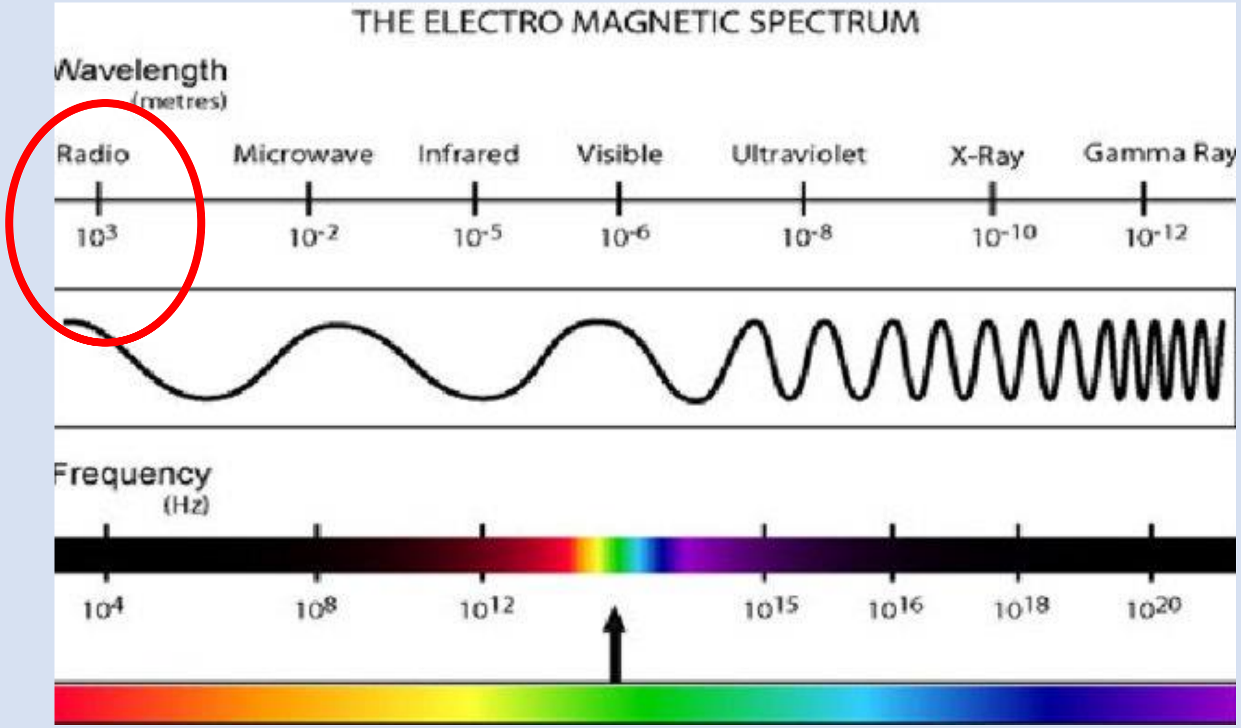
Istituto Nazionale di Geofisica e Vulcanologia

TRAINING COURSE ON
THE POLAR UPPER ATMOSPHERE: FROM SCIENCE TO OPERATIONAL ISSUES
L'Aquila (Italy), 16-21 Sept. 2018

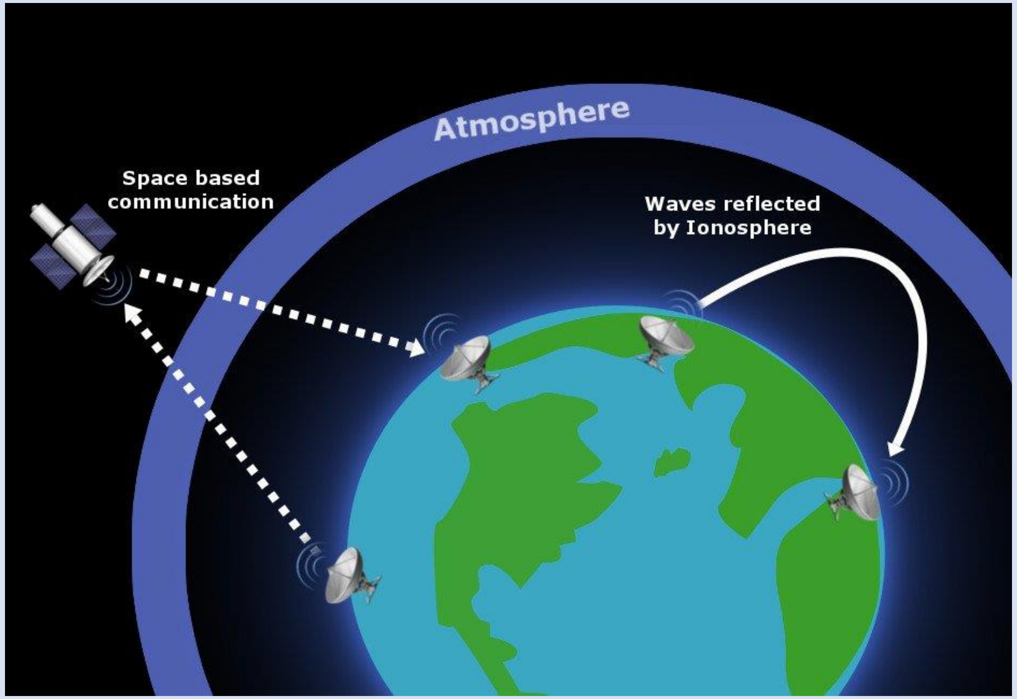
Most of the methods to study the geophysical environment are based on the use of **electromagnetic waves**

In particular the **radio waves modifications** when they interact with the medium they pass through

The **ionosphere** is no exception, either the waves are emitted from the ground or from a satellite



The **ionosphere** is the part of the upper atmosphere in which sufficient ionization exists to influence the propagation of **radio waves.**



1. Below the ionosphere:

radio wave pulses are emitted into the ionosphere, the echo signal contains information about the layers in which it may be refracted, reflected or absorbed.

2. Above the ionosphere:

GNSS radio waves (1 GHz= 10^9 Hz) emitted from satellites are affected by the medium they pass through.

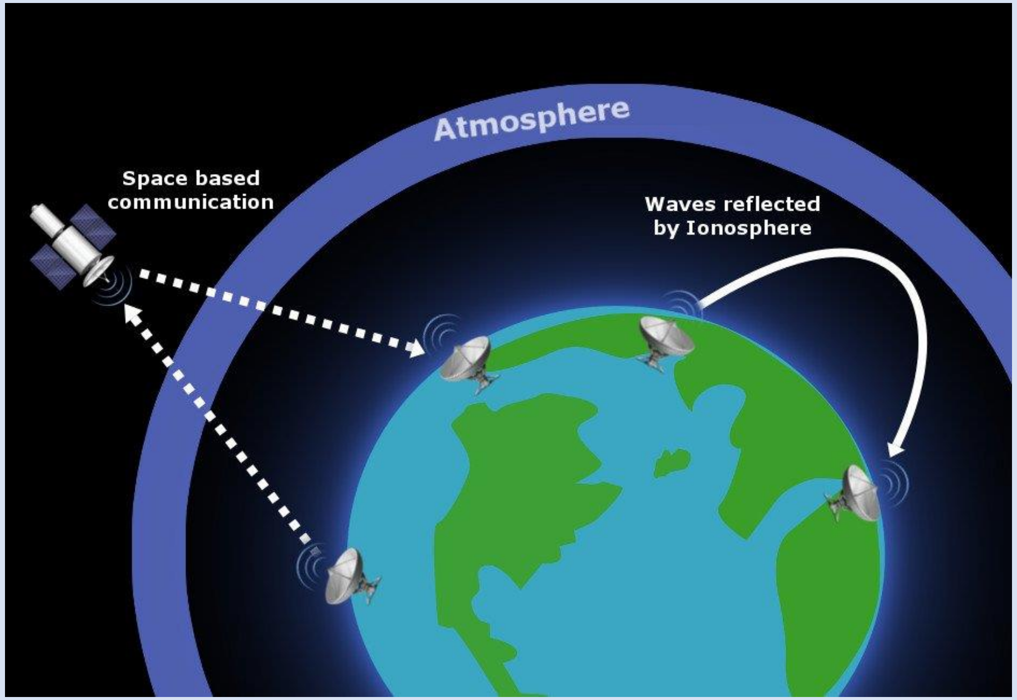
plasma frequency $f_p = 8.98\sqrt{N_e}$ Hz

N_e affects the dielectric constant ε thence the refractive index

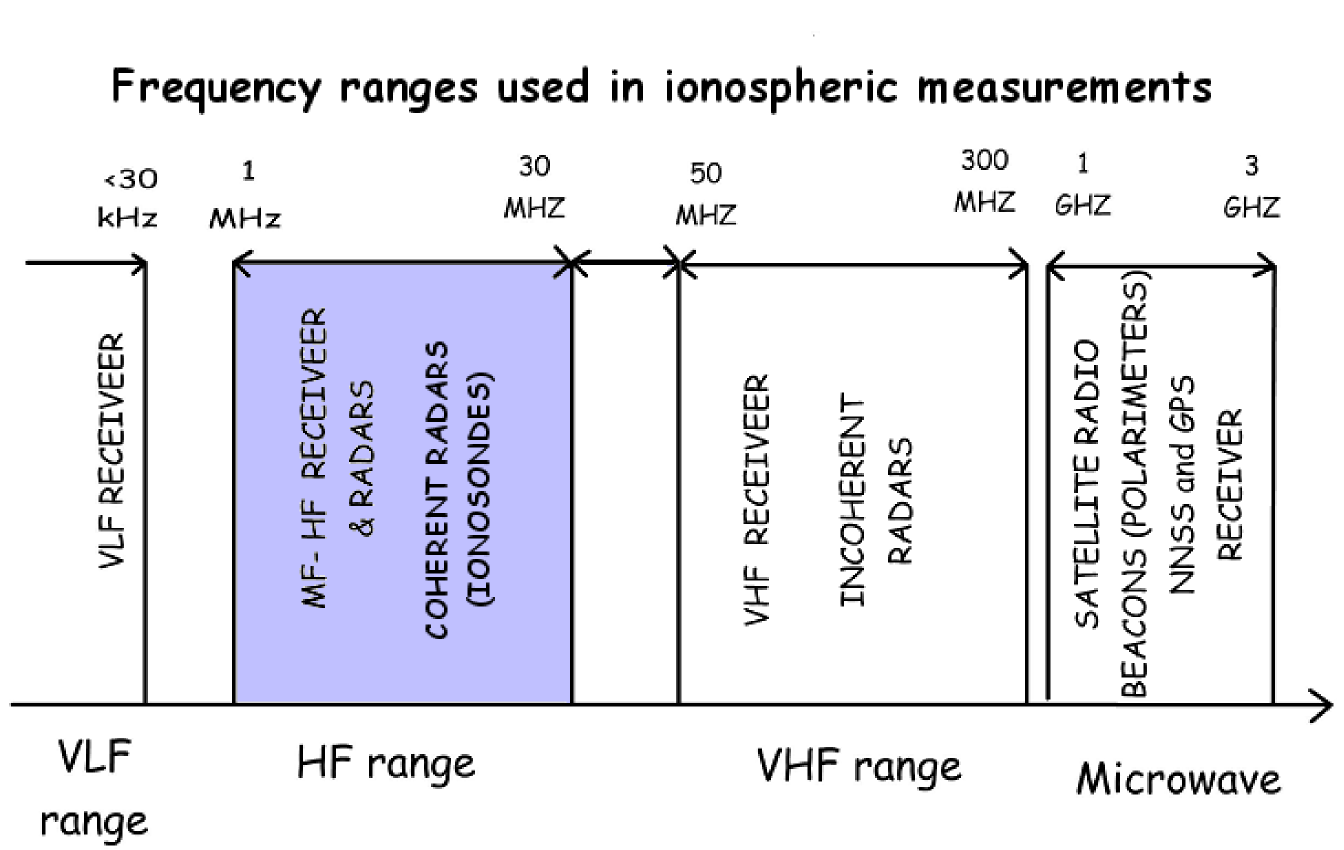
N_e (max around 300-500 km) => $f_{p\,(max)} \approx 10^6$ Hz

Waves with $\mathbf{f > f_p}$ will be able to cross the ionosphere
Waves with $\mathbf{f < f_p}$ will be reflected

Part I – Ionosonde



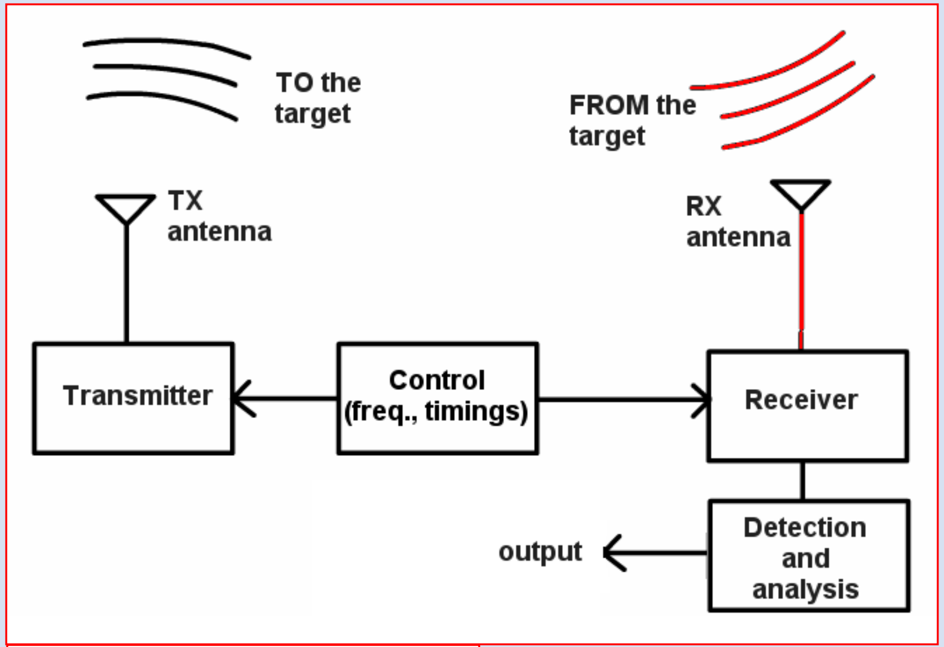
ELF	SLF	ULF	VLF	LF	MF	HF	VHF	UHF	SHF	EHF
3 Hz	30 Hz	300 Hz	3 kHz	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz
30 Hz	300 Hz	3 kHz	30 kHz	300 kHz	3 MHz	30 MHz	300 MHz	3 GHz	30 GHz	300 GHz



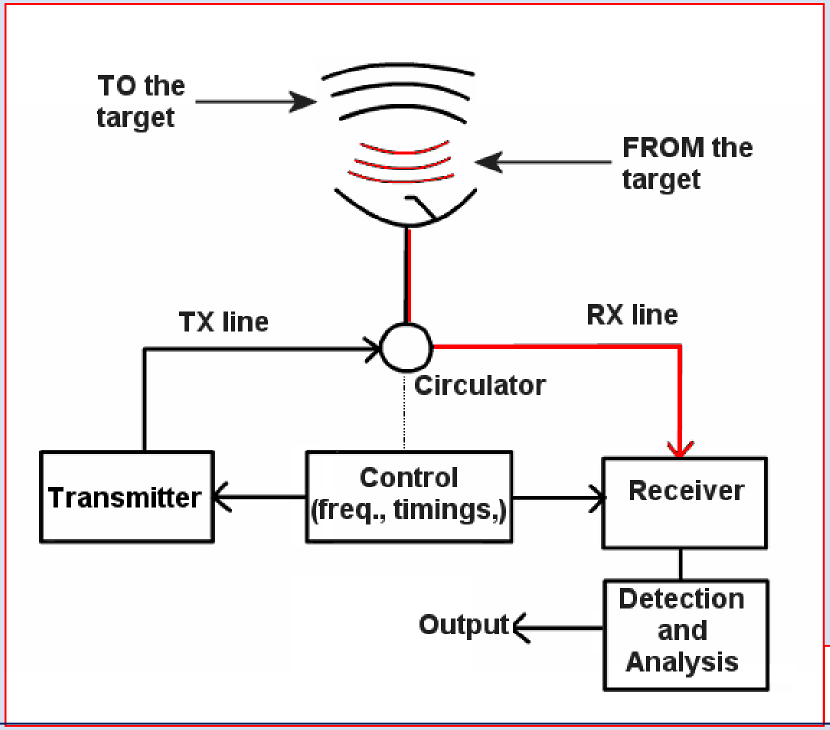
RADAR Theory

RAdio Detection And Ranging

Using e.m. pulses of proper frequency and amplitude it is able to find targets and to reveal the distance from the radar itself.



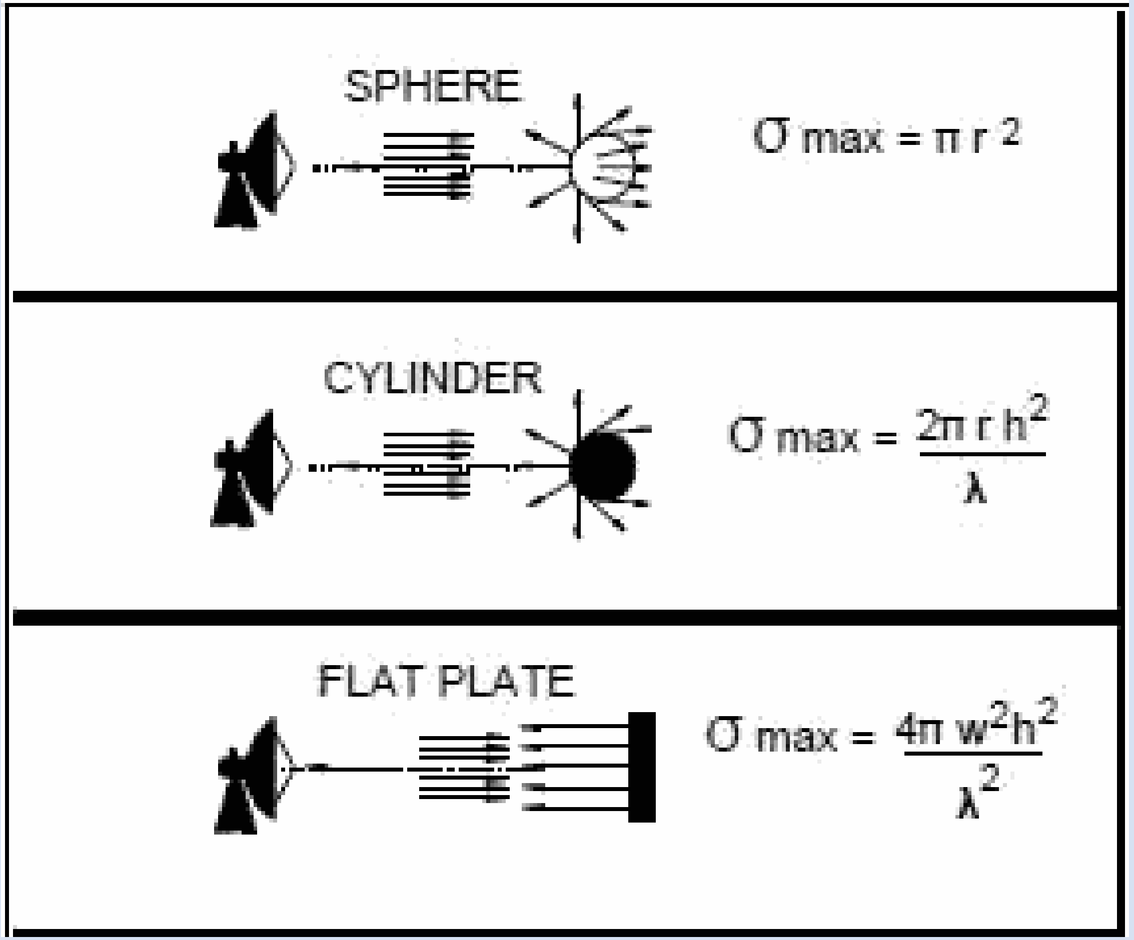
bistatic: two antennas



monostatic: one antenna (circulator to direct energy)

Independently of the type the control section communicates with both the TX and RX section so that the receiver can be tuned properly.

The power that will return to the receiver antenna depends:



Different shapes react to radar in different ways

$$P_r = \frac{(\lambda G_d)^2 \sigma P_{rad}}{(4\pi)^3 r^4}$$

Radar cross section

$$\sigma = 4\pi r^2 \frac{P_s}{P_i}$$

where

r distance;

P_i incident density power on the target;

P_s scattered density power at a distance *r* from the target.

Pulse technique

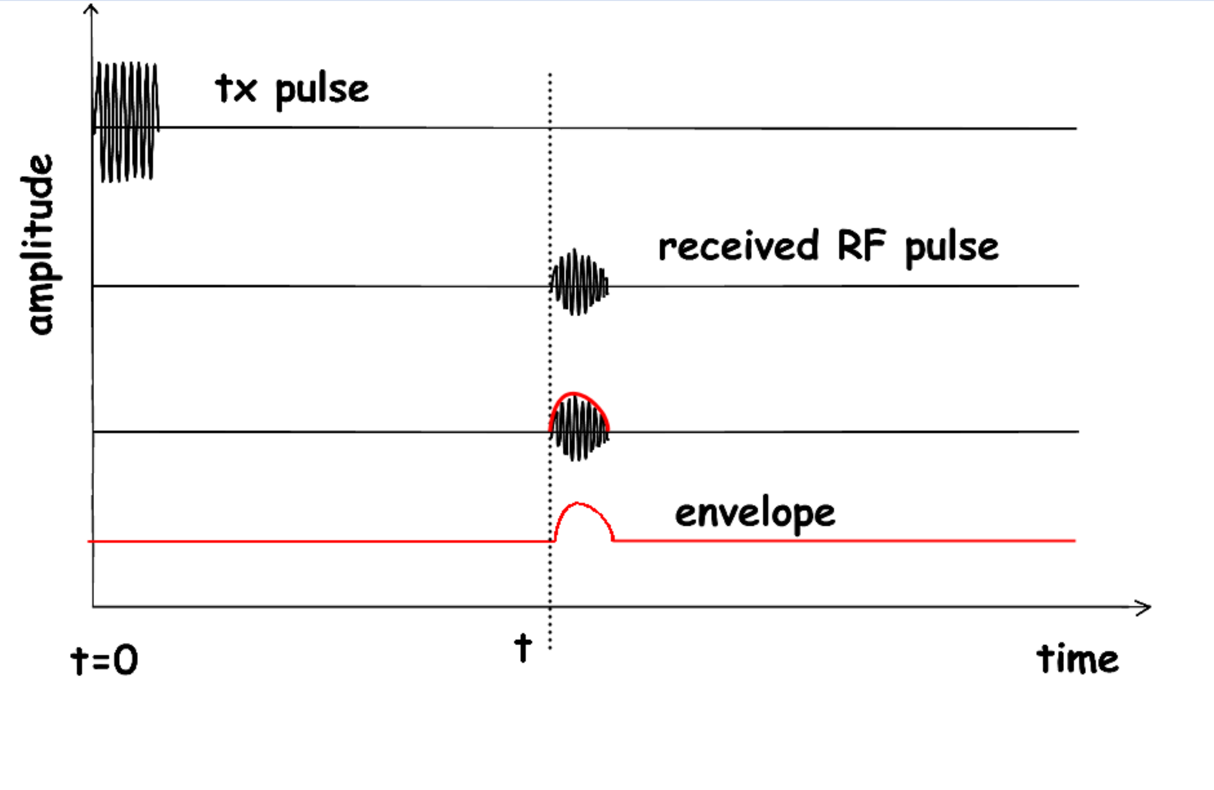
Pulses of proper amplitude and duration are emitted by the antenna in the target direction.

After a time "t" a possible echo reaches the receiver of the radar.

The delay time between the emitted and the received pulse.

$$d = \frac{v \cdot t}{2}$$

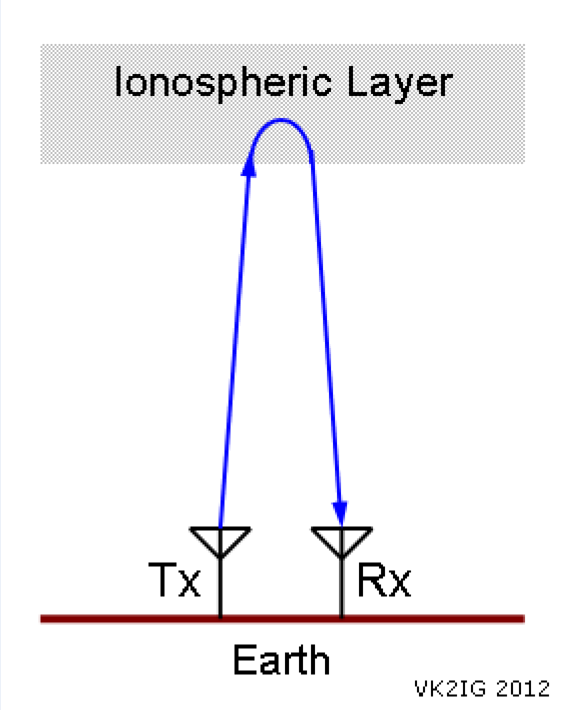
The measure is the time of flight of a packet of radio frequency energy



The early model of radars were based on the envelope technique.
The receiver that is tuned on the emitted frequency is able to follow the relative maxima of the signal generating an electric signal that "envelopes" the received echo.

A particular radar: the ionosonde

The measure technique is based on sending pulses of energy at different frequencies towards the ionosphere and in measuring the backscattered echo delay to properly evaluate the position of ionospheric layers.



frequency range: (1 - 20) MHz with a step of 50 kHz or 100 kHz

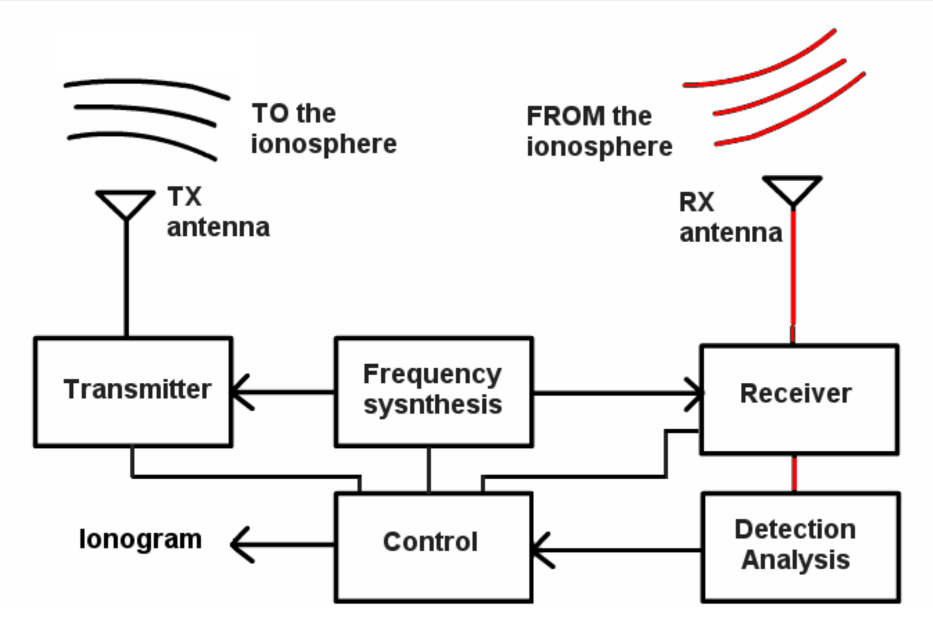
resolution should be less than 20 km

minimum height is around 90 km
maximum height could be be above 600 km

the target is an infinite reflecting planes (ionized layers) the radar cross section is not in the equation. This yields the equation radar to become

$$P_r = \frac{(\lambda G_d)^2 \sigma P_{rad}}{(4\pi)^3 r^4} \longrightarrow P_r = \frac{(\lambda G_d)^2 P_{rad}}{(4\pi r)^2 L}$$

The ionosonde is, generally, a bistatic radar, with antennas in the same site (often on the same mast).



Control system: enables the TX to emit energy and, after that, enables the receiver starting the so called "listening time".

Frequency synthesizer: generates the frequency to be transmitted tuning the receiver on that frequency.

Transmitter: amplifies small signals to a proper amplitude.

Receiver: converts information at different frequencies to a more comfortable value (etherodyne principle).

Detection and Analysis: recognizes good echoes amongst the noise evaluating the delay times of echoes.

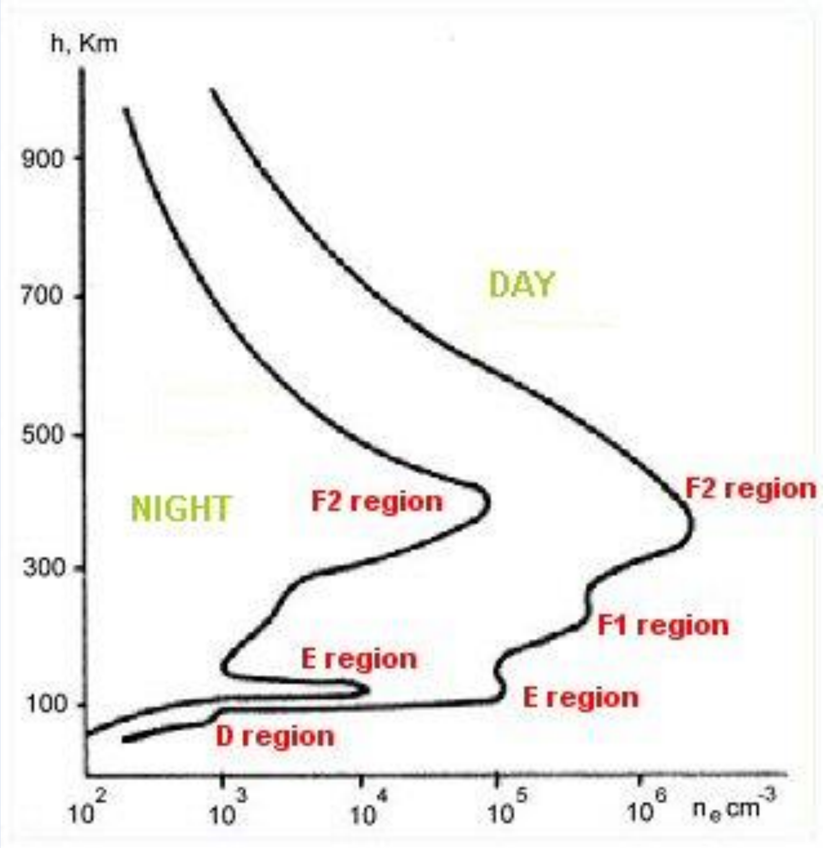
The vertical sounding principle

For every used frequency, f, the reflection will happen when the **refraction index n=0**;

N that varies with the height we have reflections from different altitudes.

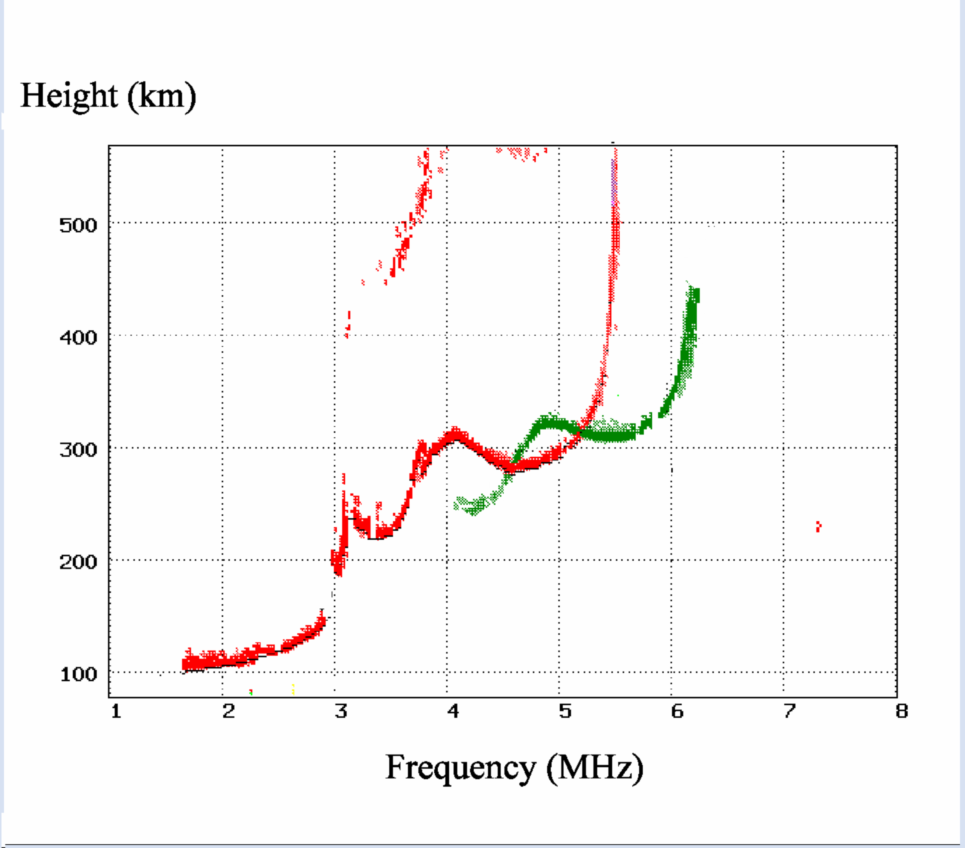
$$f_p = \sqrt{\frac{N e^2}{4\pi^2 \varepsilon_0 m}} \approx 9\sqrt{N}$$

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2$$



Ionogram

the ionogram is the plot of echo's delay times (or heights) versus frequency.

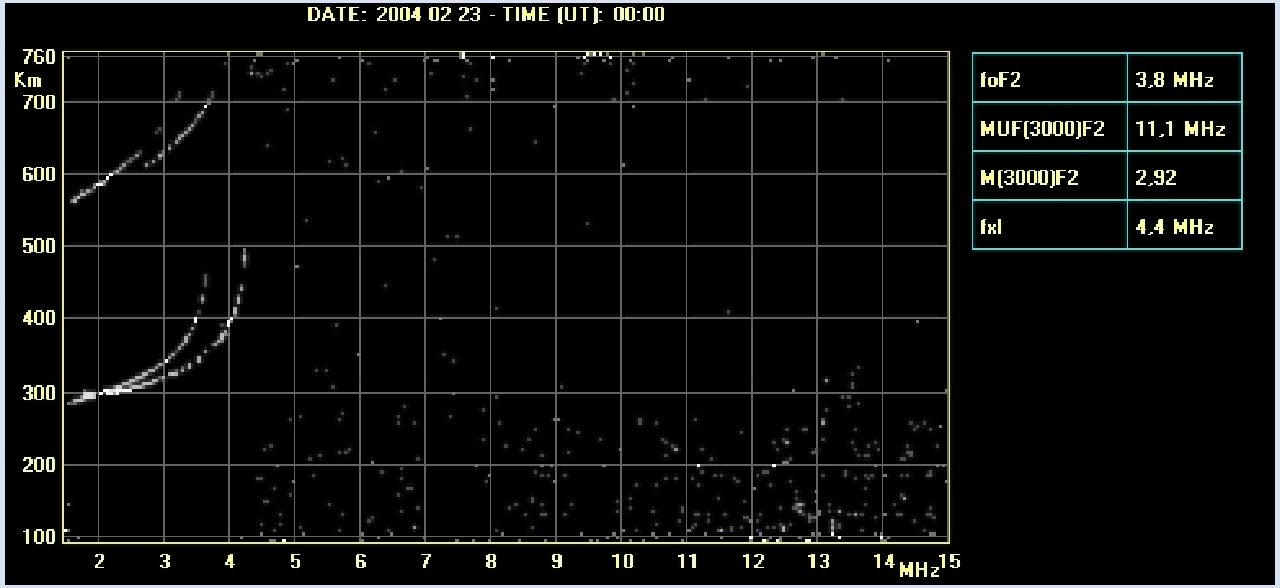


We use the term "**virtual**" because we are not measuring the real position of the layer.

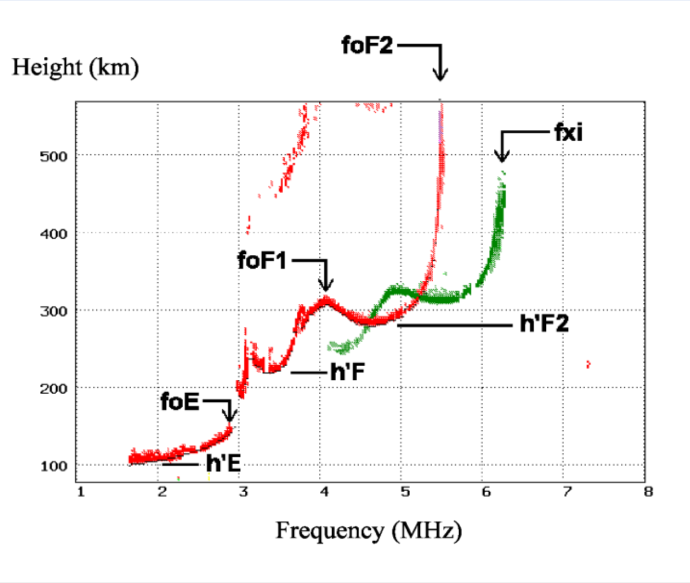
The instrument converts the delay time into kilometres using the light speed in the vacuum and the relationship

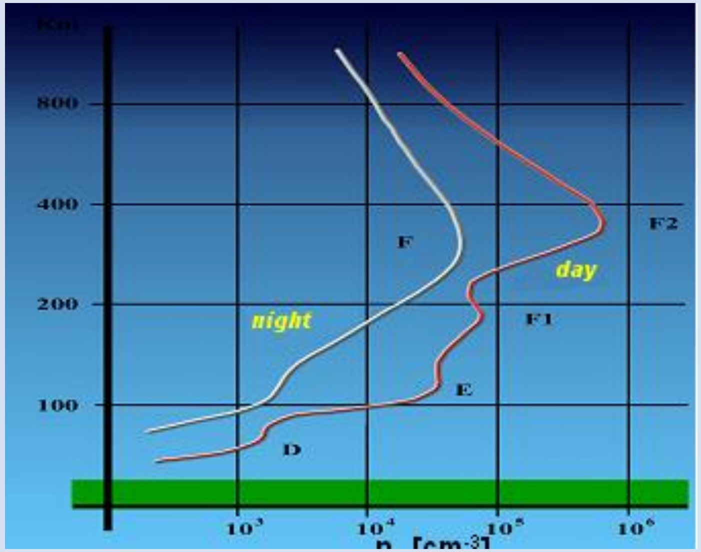
$$h' = \frac{c \cdot \Delta t}{2}$$

While penetrating the plasma the speed decreases so that h < h'


DATE: 2004 02 23 - TIME (UT): 00:00
760
Km
700
600
500
400
300
200
100
2 3 4 5 6 7 8 9 10 11 12 13 14 MHz 15

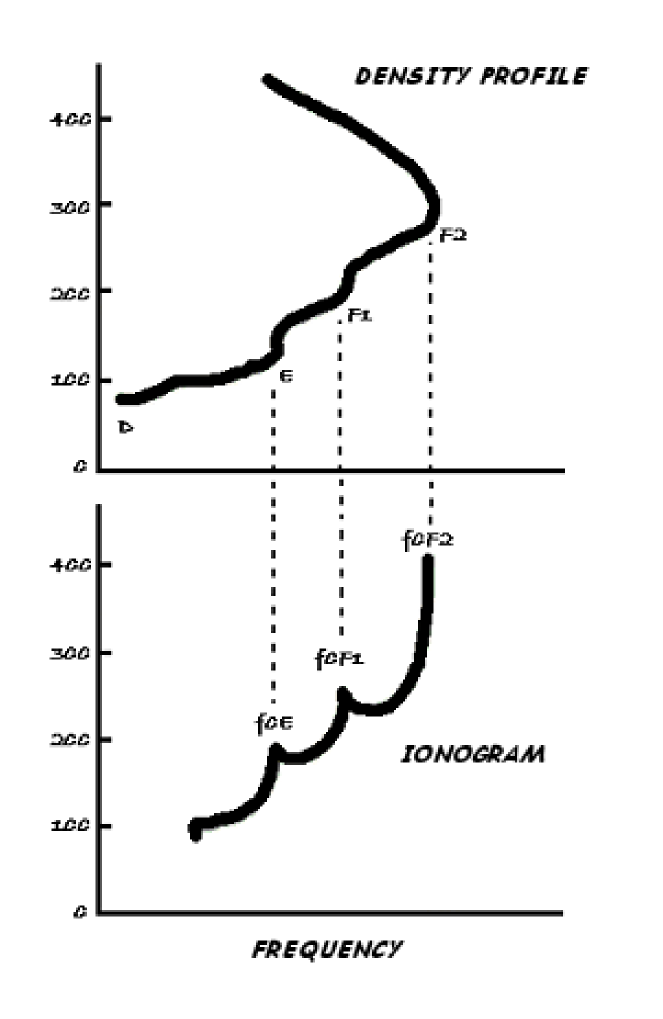
foF2	3,8 MHz
MUF(3000)F2	11,1 MHz
M(3000)F2	2,92
fxI	4,4 MHz


Height (km)
foF2
fxi
foF1
h'F2
h'F
foE
h'E
500
400
300
200
100
1 2 3 4 5 6 7 8
Frequency (MHz)


800
400
200
100
F2
F
day
F1
night
E
D
10^3 10^4 10^5 10^6

From ionogram to the density profile

•To better describe the ionosphere we need to know the electron density profile.

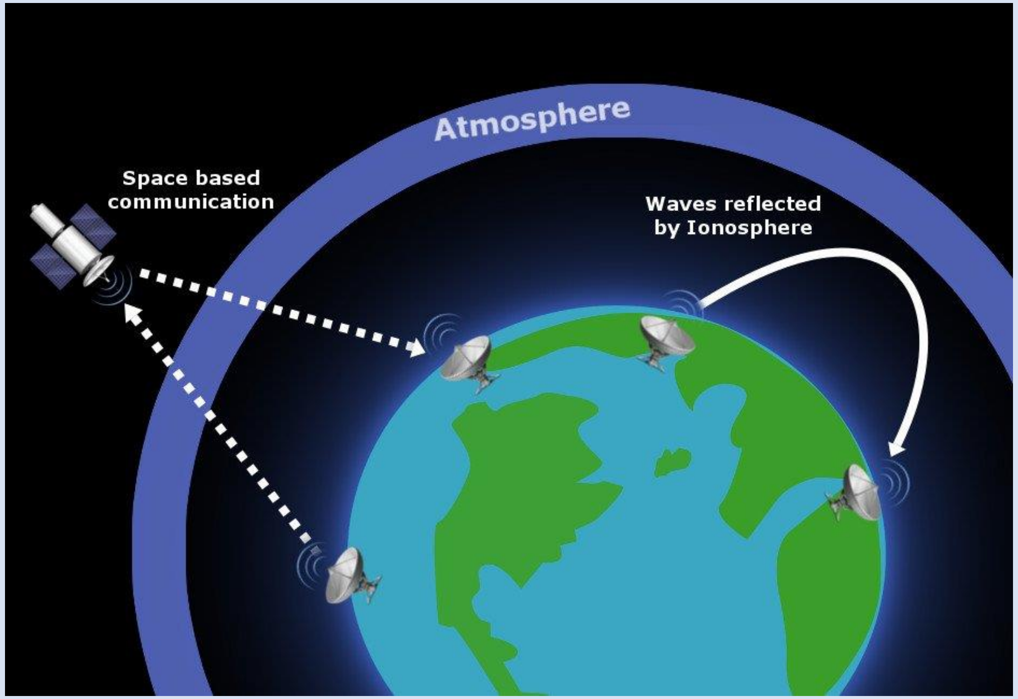


•Knowing the ionogram point by point (virtual height-frequency couples) we can invert the ionogram to obtain the electron density profile.

•There are models partially empirical able to describe analytically the different ionospheric regions from elio-geophysical and ionospheric quantities.

•There are methods that derive the density profile automatically: they are particular interesting in real time mapping of ionosphere.

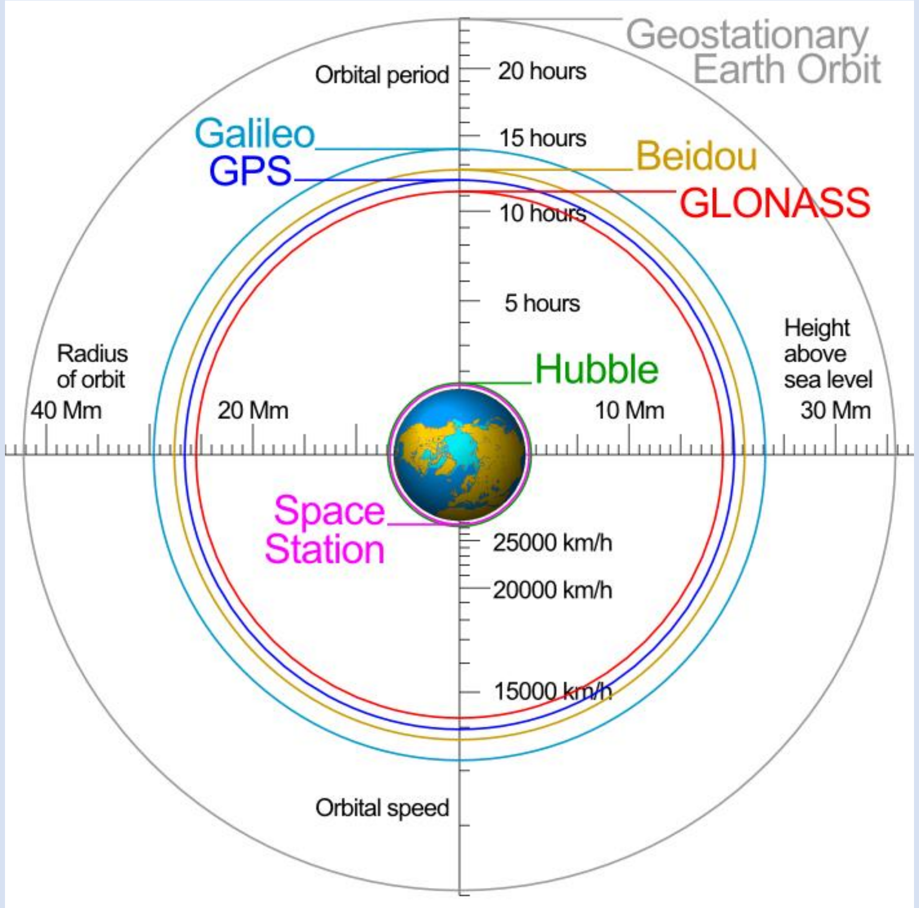
Part II – GNSS measurements



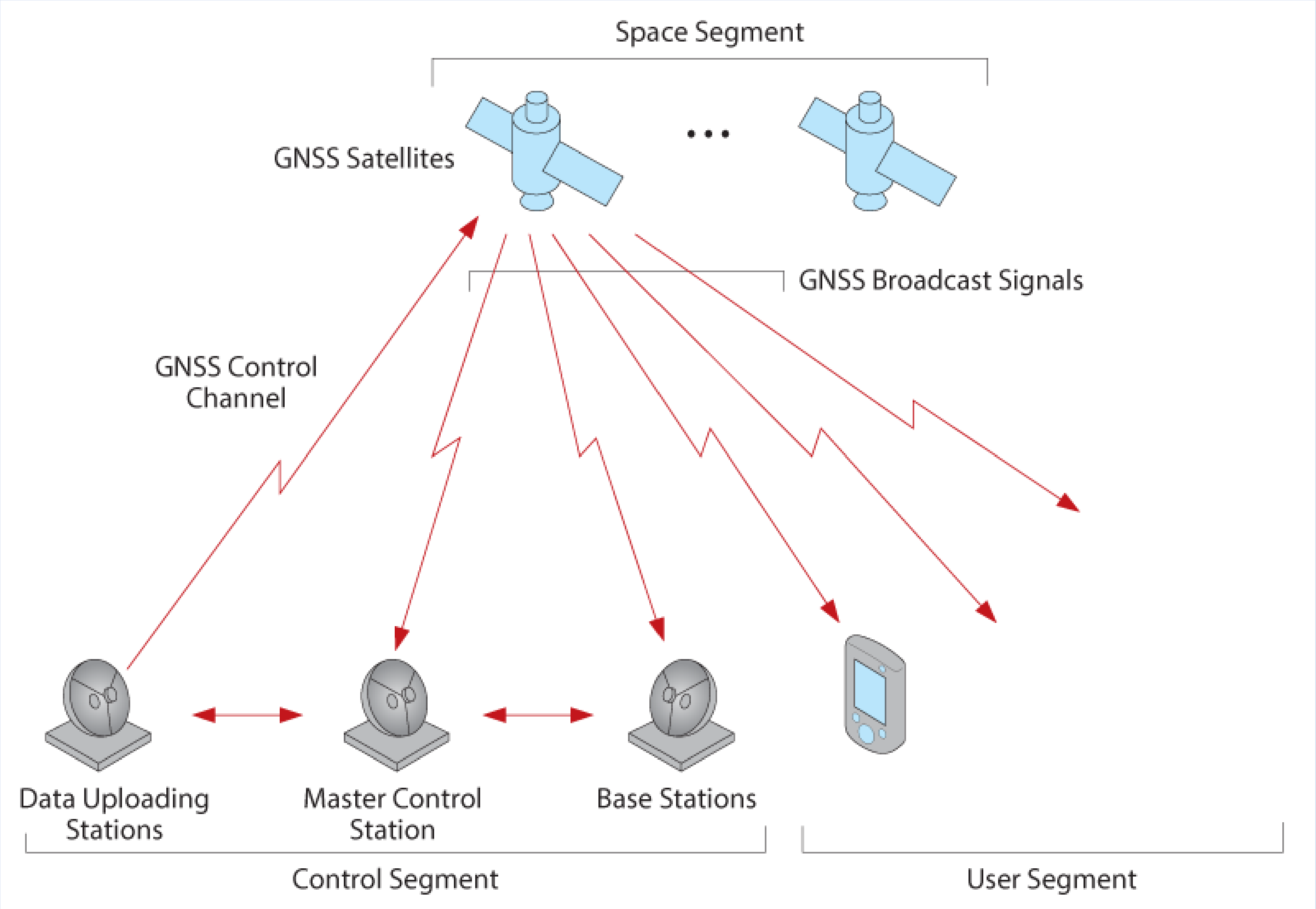
Global Navigation Satellite System (GNSS)

GNSS is the standard term for satellite navigation systems that provide **autonomous geo-spatial positioning with global coverage**. Includes the global GPS, GLONASS, Galileo, and Beidou and other regional systems.

	GPS	GLONASS	GALILEO	BEIDOU
Number of Satellites	21 + 3	21 + 3	27 + 3	35 5 GEO 27 MEO 3 IGSO
Number of orbital planes	6	3	3	
Semi-major axis	26600 km	25440 km	29600 km	27878 km
Orbital revolution period	11:58 H	11:15 H	14:07 H	
Inclination	55 deg	64 deg	56 deg	55 deg
Satellite Mass	1100 kg (IIR)	1400 kg	700 kg	1000 kg



GNSS segments



Master Control Staions:

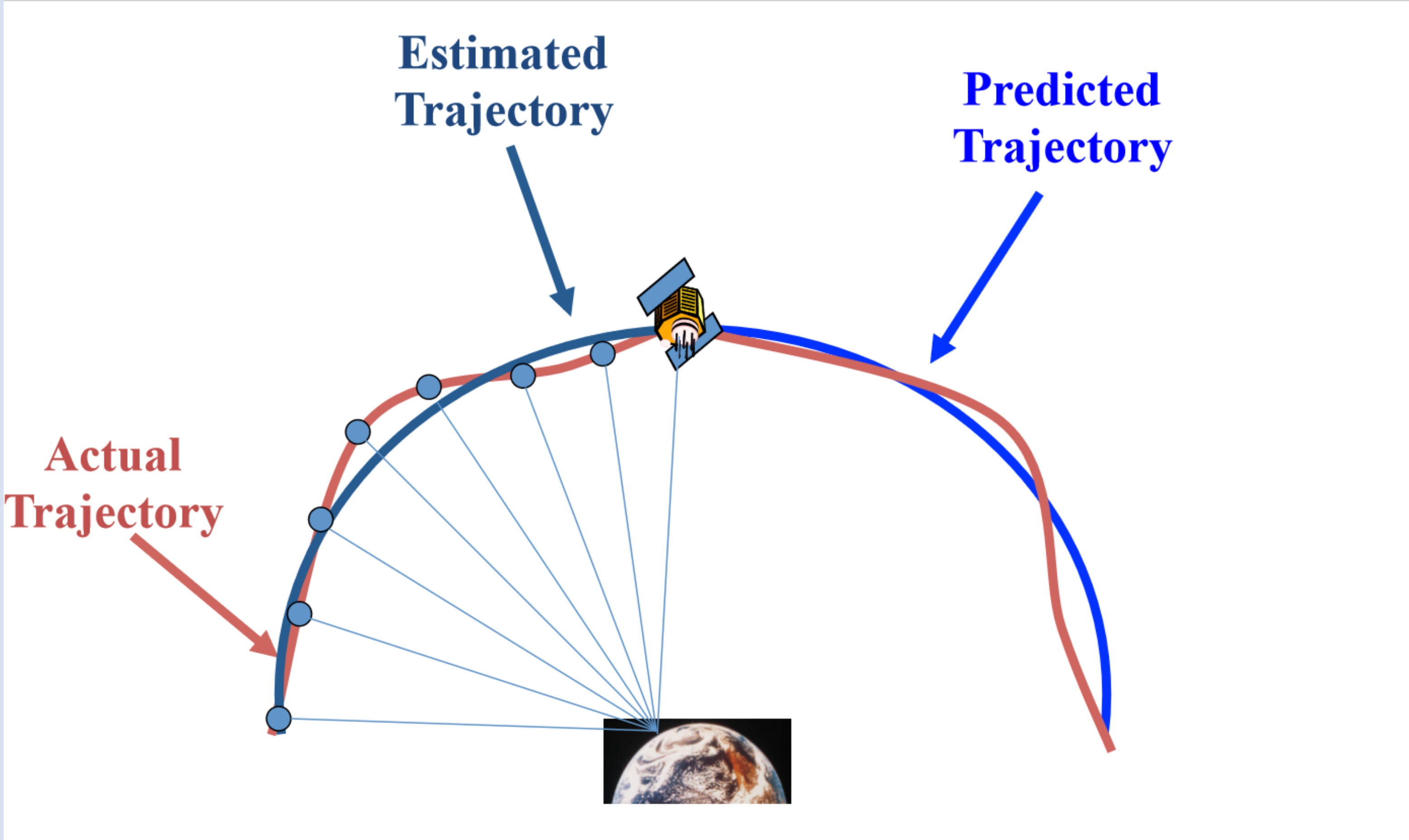
GPS: Schriever Air Force Base Colorado Springs , Colorado

Galileo:
Oberpfaffenhofen (Germany)
Fucino (Italy).

GLONASS: Krasnoznamensk (near Moskow

BEIDOU: ?

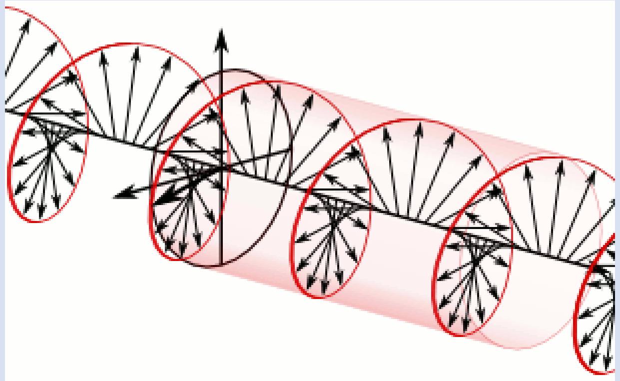
GNSS control segments



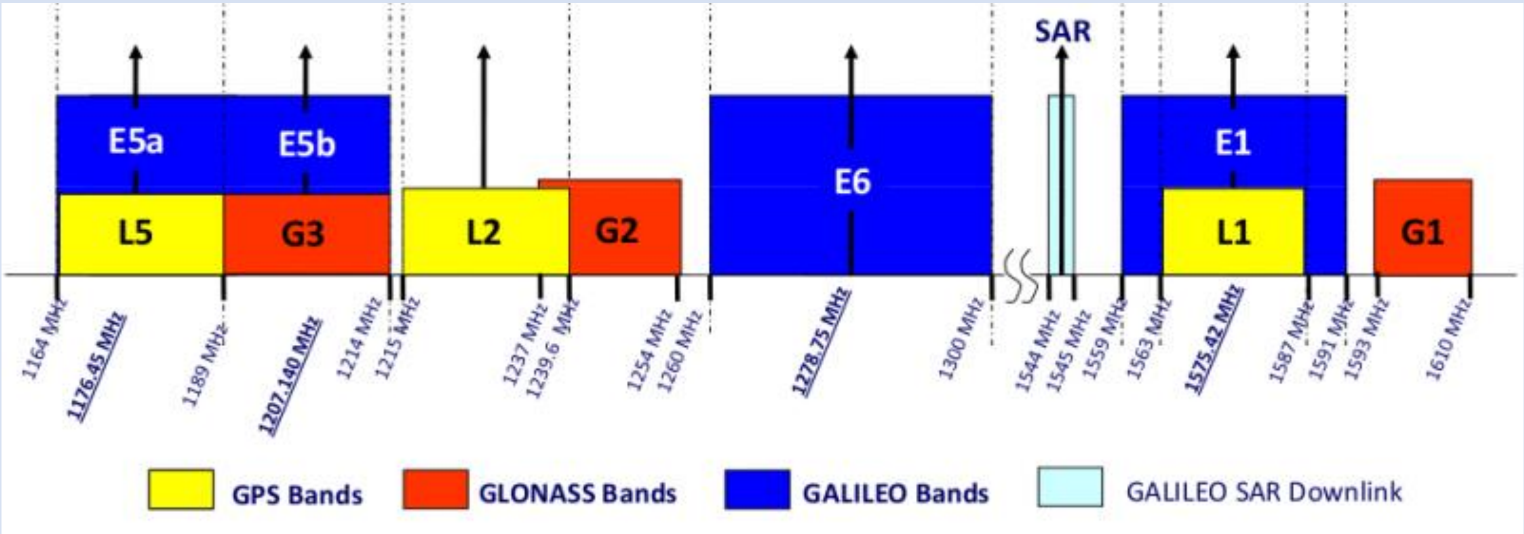
J. Raquet

Space segment - GNSS signals

Each satellite transmits signal in (at least) 2 different L-band (1-2 GHz) frequencies



Right-hand circularly polarization



Examples of Wavelenghts: L1 = 19 cm, L2 24 cm, L5 25 cm

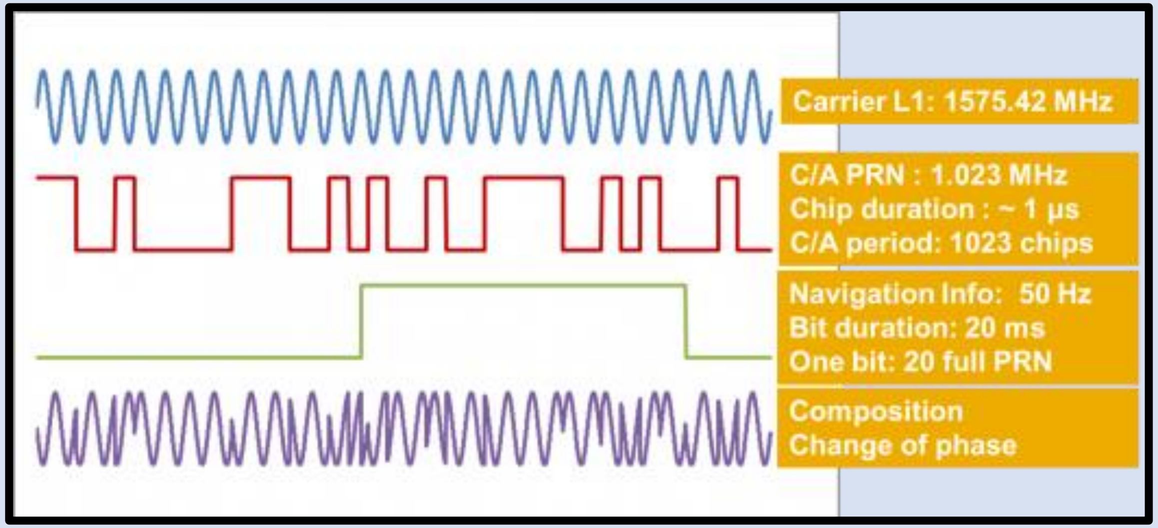
Right-hand circularly polarization to avoide the **Faraday rotation** that results from the **electron plasma** of the **ionosphere** and the presence of Earth's magnetic field.

A linearly polarized radio wave passing through the ionosphere will gradually rotate in the plane perpendicular to the direction of propagation

=> the wave would arrive to the receiver with an undetermined polarization

=> loss in power

Space segment - GNSS signal



https://gssc.esa.int

The main signal components :

•***Carrier***: Radio frequency sinusoidal signal at a given frequency

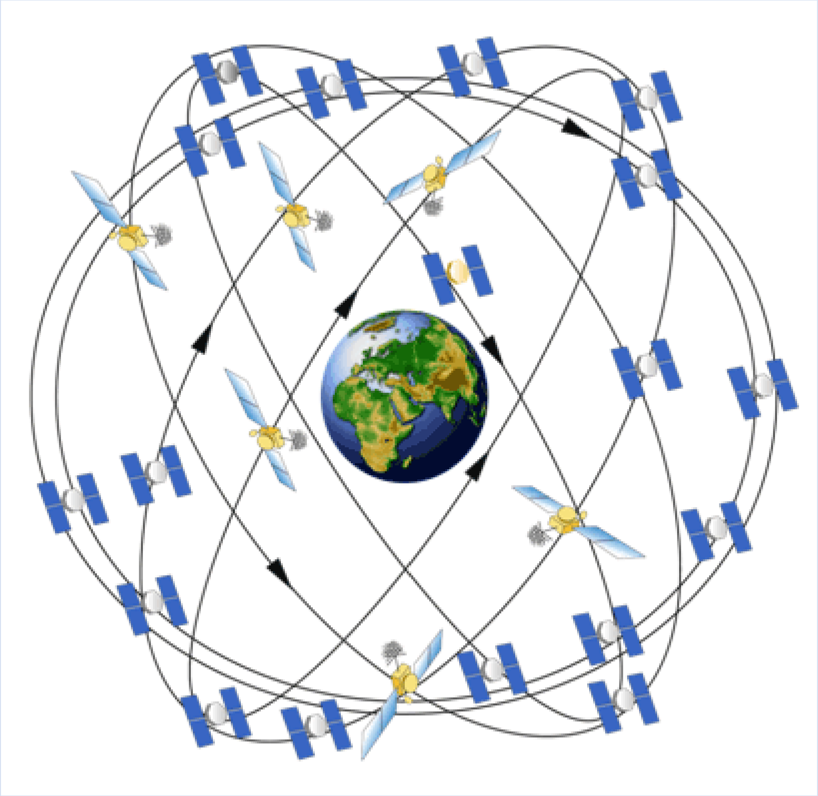
•***Pseudo-Random*** *Noise sequences or PRN codes*: Sequences of 0s and 1s, which allow the receiver to determine the travel time of radio signal from satellite to receiver.
Each satellite is assigned with a PRN code

•***Navigation data***: A binary-coded message providing information on the satellite ephemeris (satellite position and velocity), clock bias parameters, almanac (with a reduced accuracy ephemeris data set), satellite health status, and other complementary information.

On board the satellite there are atomic oscillators with high daily stabilities (cesius or rubidium).
The satellite clock offsets are continuously estimated by the Ground Segment and transmitted to the users to correct the measurements $\Delta f / f \approx 10^{-14}$

The observable in a GNSS system is the time required for a signal to travel from the satellite to the receiver

$$R = c\, t$$

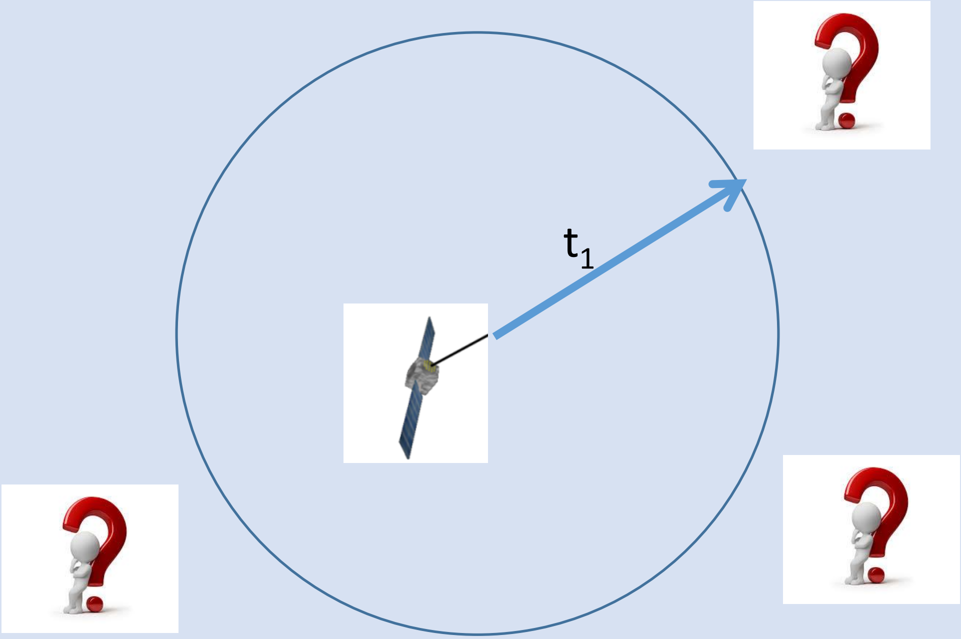


Why do we need so many satellites?

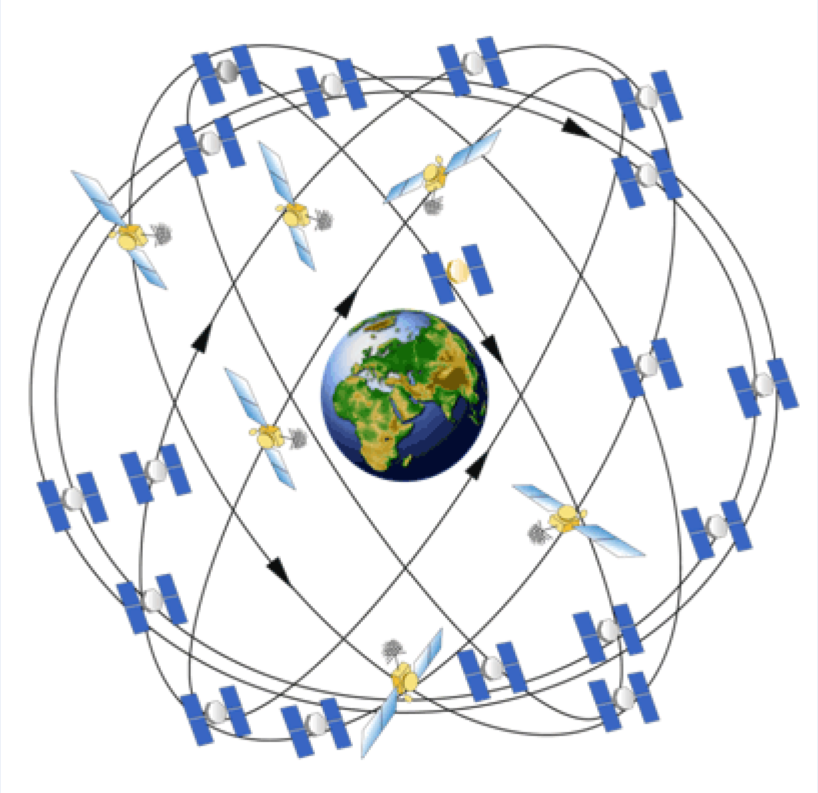
If the clocks of the receiver is perfeclty synchronized with the satellites:

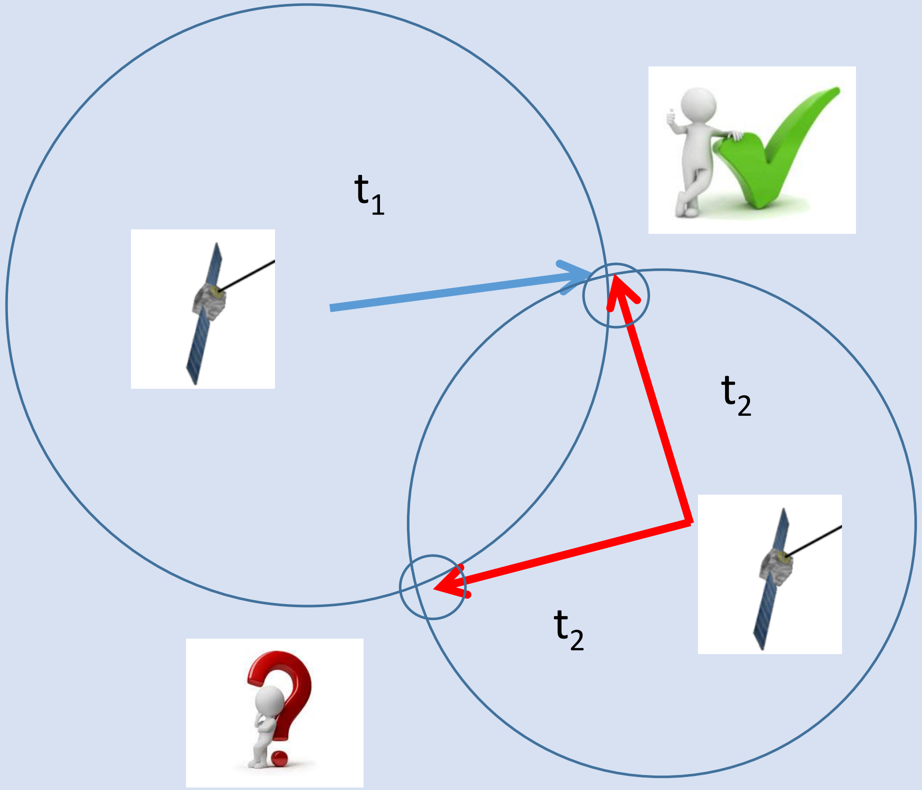
The range R is :

$$R = c\ t$$

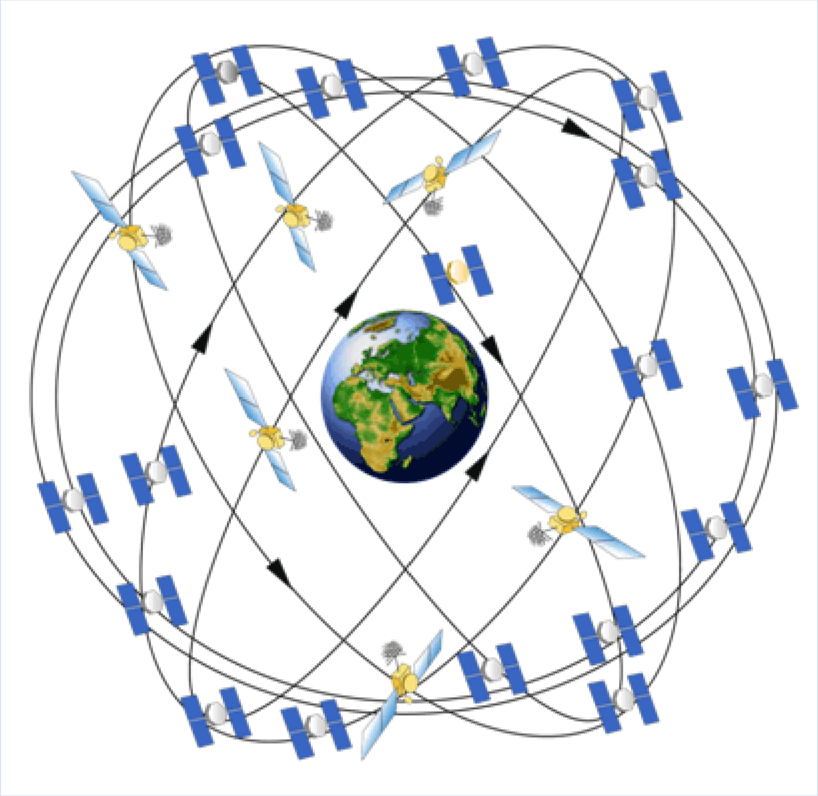


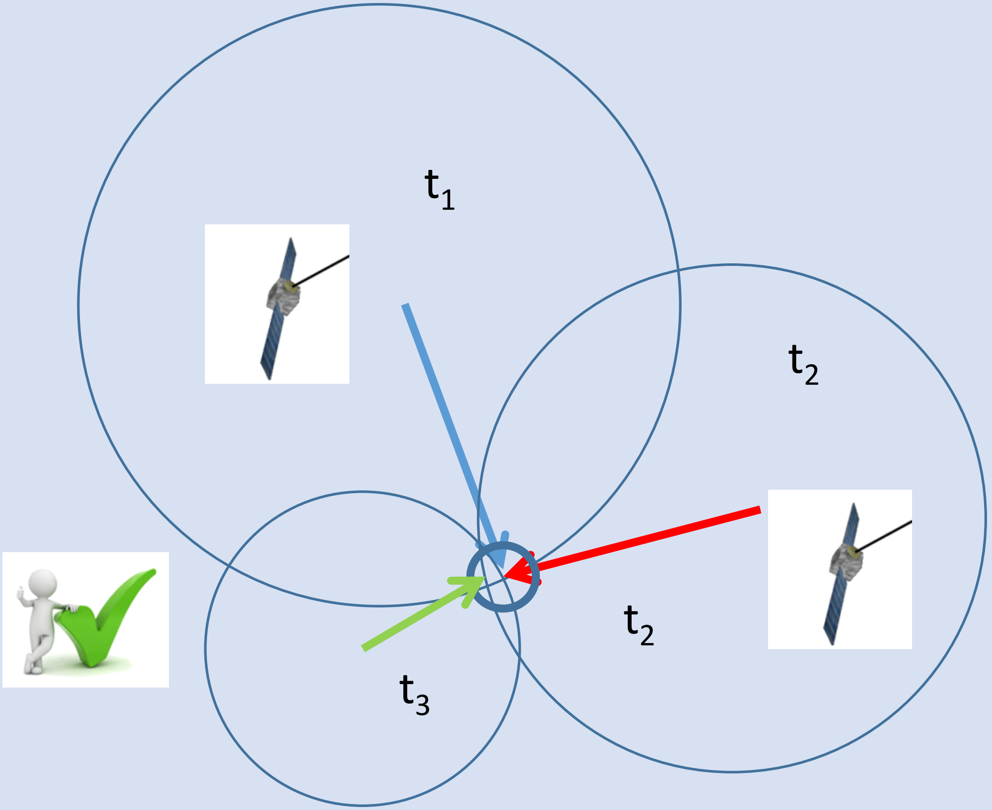
With one satellite you could be anywhere on the circle





Two possible solutions





Now there is a unique solution

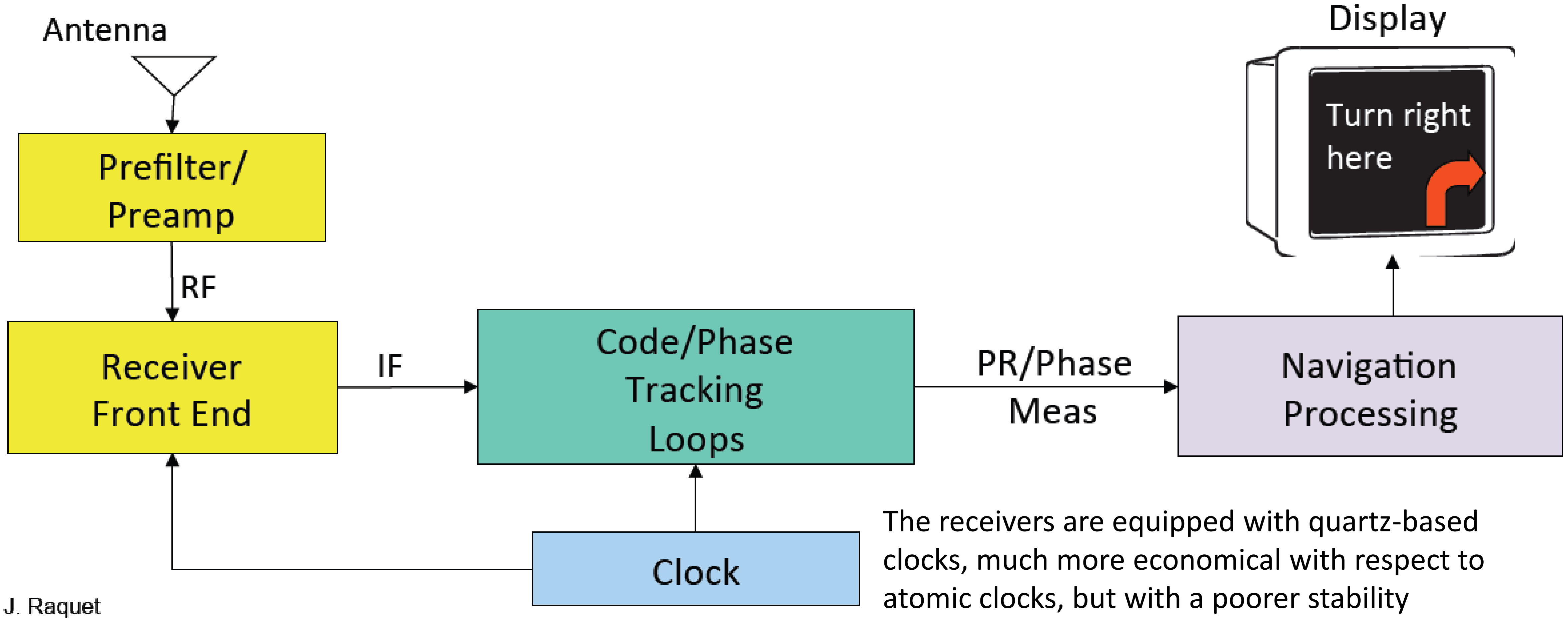
Unfortunately the clocks are not synchronized, we actually measure a **pseudo-range**, a range with error

$$R' = c\,(t + \delta t)$$

Moreover there is the troposphere, ionosphere, electronic noise, multipath, antenna rotation, doppler effect……….

GNSS User segment

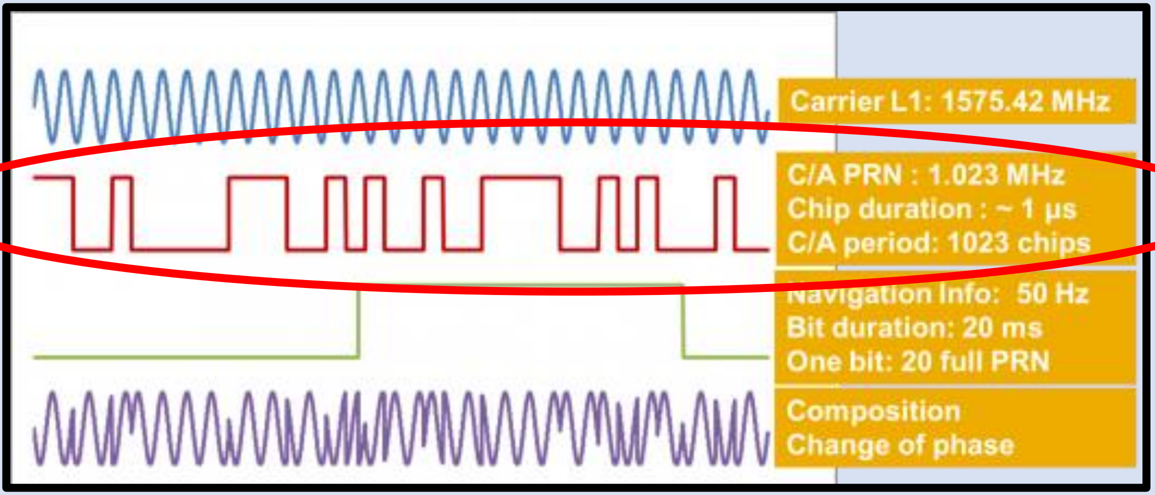
- **Typical GPS receiver components**



The receivers are equipped with quartz-based clocks, much more economical with respect to atomic clocks, but with a poorer stability

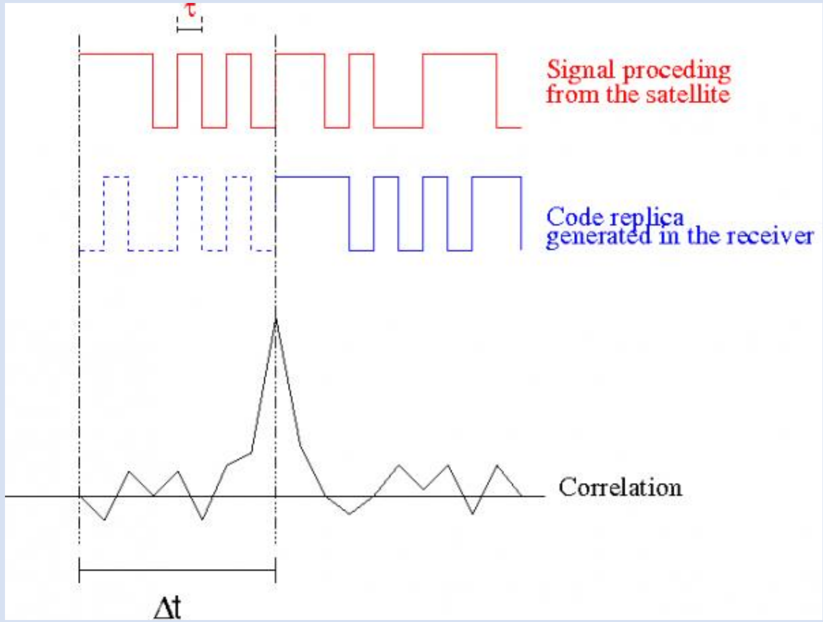
J. Raquet

The duties of the GNSS receivers: 1 and 2



1. Get the signal after a propagation time of 60-70 ms

   24.001,25 Km / 300.000 Km/s = 0,080005 s



Emitted at a rate of
1.023 M bits/sec

2. Compute measurements for all sat/signal pairs:

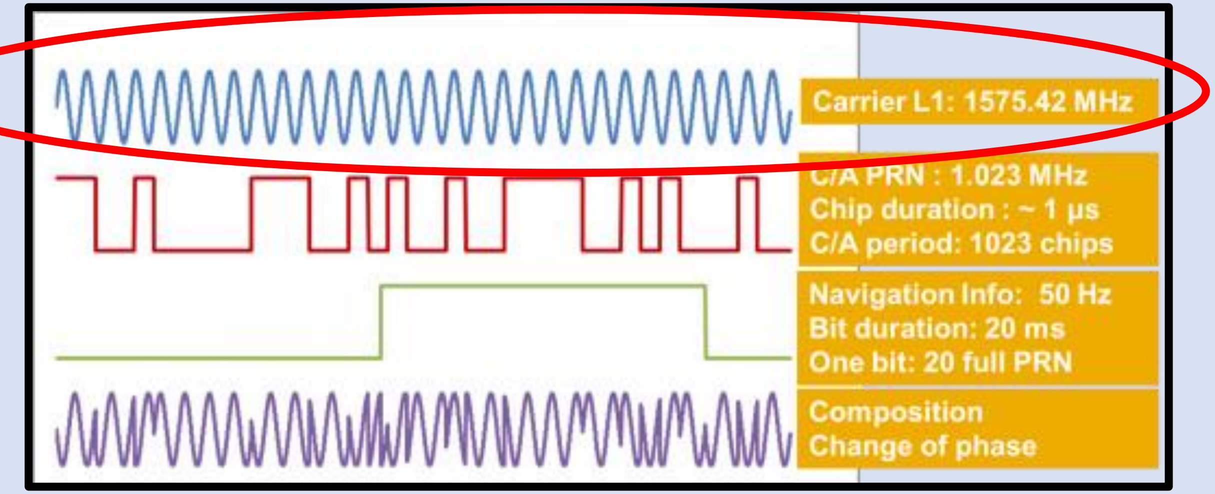
   Pseudorange measurements (code delay) in meters

Geometric range | Rec and Sat clock offset | Tropospheric delay | Ionospheric delay | Rec and Sat instrumental delay | Multipath | Receiver noise

$$R_P = \rho + c(dt_r - dt^s) + T + \alpha_f\, STEC + K_{P,r} - K_P^{\,s} + \mathcal{M}_P + \varepsilon_P$$

R’ = c (t + δt)

The duties of the GNSS receivers: 1 and 3



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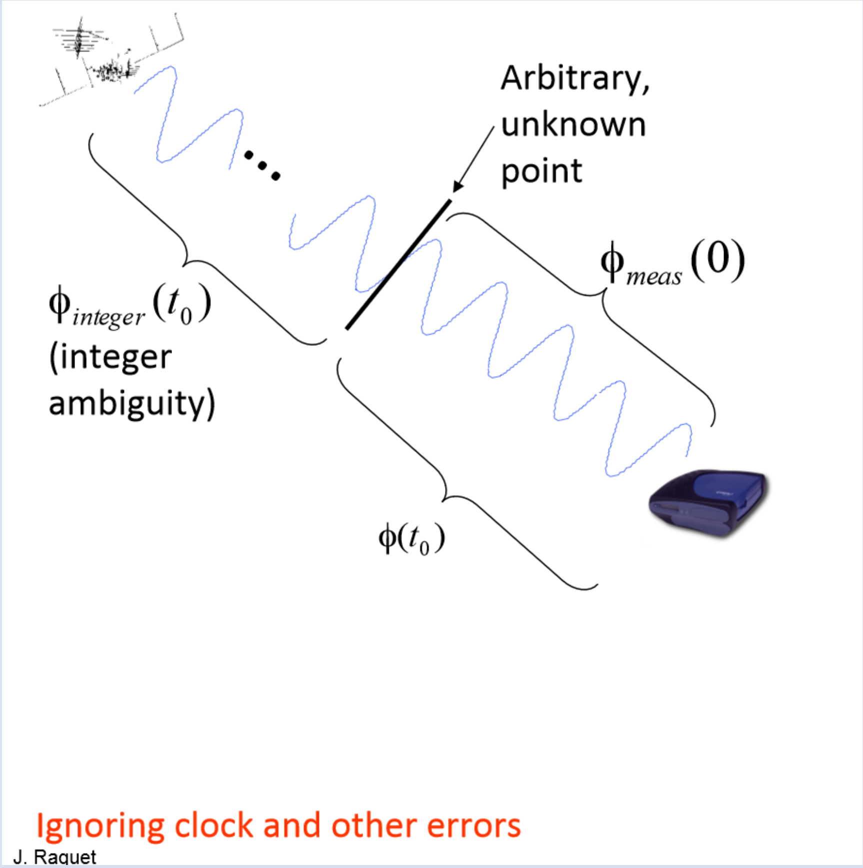


3. Carrier-phase measurements (in meter)

Is ambigous by an unknown integer number of wavelengths λN. It is two order of magnitude more precise than the code measurements

$\Phi_L = \lambda_L \phi_L$

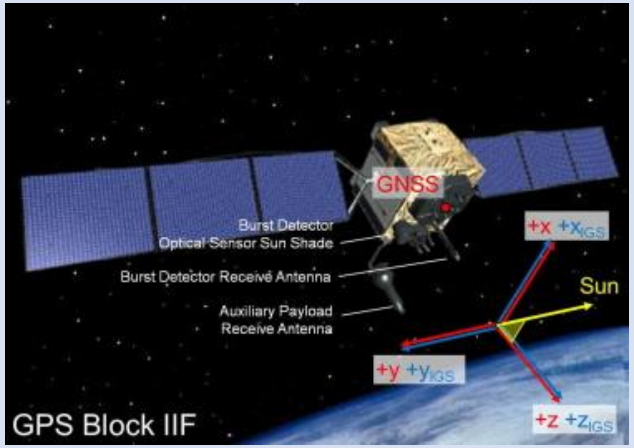
Geometric range; Rec and Sat clock offset; Tropospheric delay; Ionospheric delay; Rec and Sat instrumental delay; Integer ambiguity; Wind-up; Receiver noise

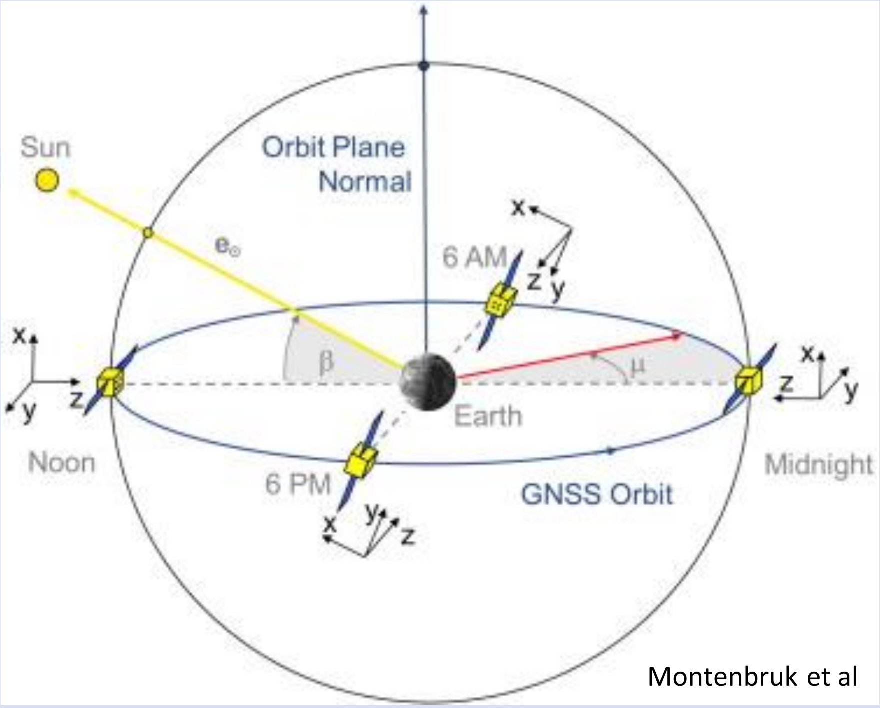
$$\Phi_L = \rho + c(dt_r - dt^s) + T - \alpha_f\, STEC + k_{L,r} - k_L{}^s + \lambda_L N_L + \lambda_L w + m_L + \epsilon_L$$

The duties of the GNSS receivers: 1 and 3 continues

Wind-up Effect

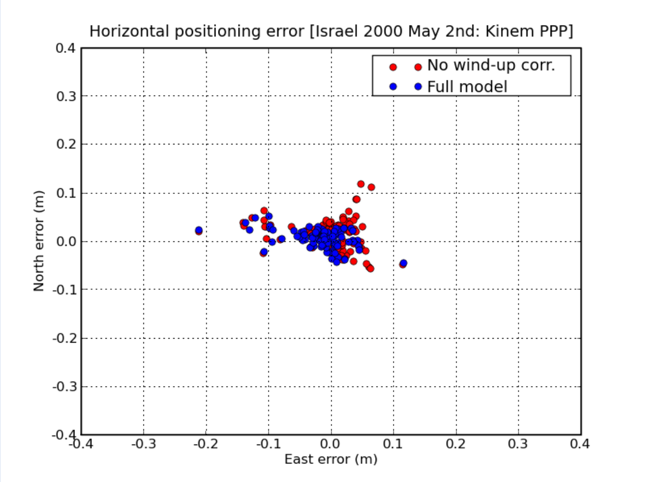
affects only to the **carrier-phase** measurements,

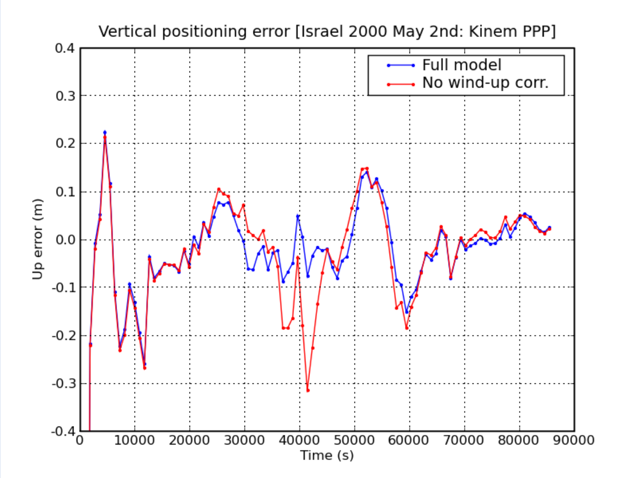




It is due to the e.m. nature of circular polarized waves depends on the relative orientation of satellite and receiver antennas and the direction of the line of site

A rotation of 360 degrees of the receiver antenna introduces a variation of one wavelength in the phase-obtained measurement of apparent distance between the receiver and the satellite





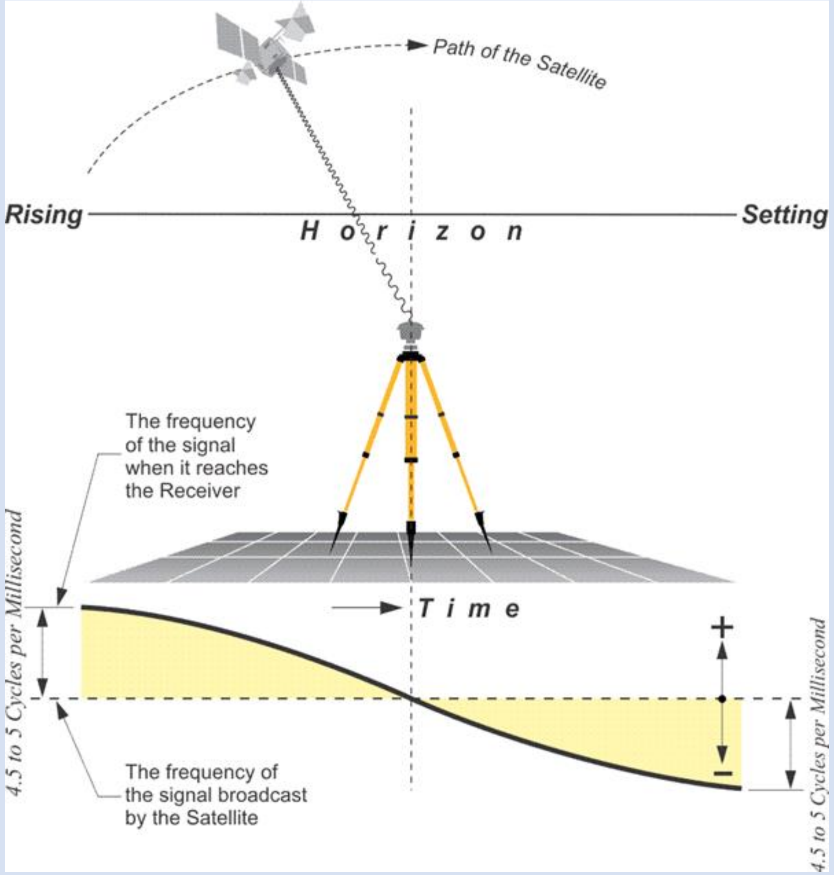
The duties of the GNSS receivers: 4

4. Doppler measurements (in Hz)

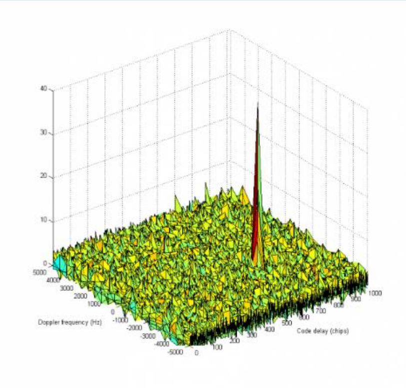
The correlation principle is first used to search for the satellites in view

Because the signal is originated by moving satellites, there is a Doppler and code delay effect observed in the received signals.

To search for the signals, different local replicas (corresponding to different **code delay / Doppler frequency pairs**) are generated and correlated with the input signals.



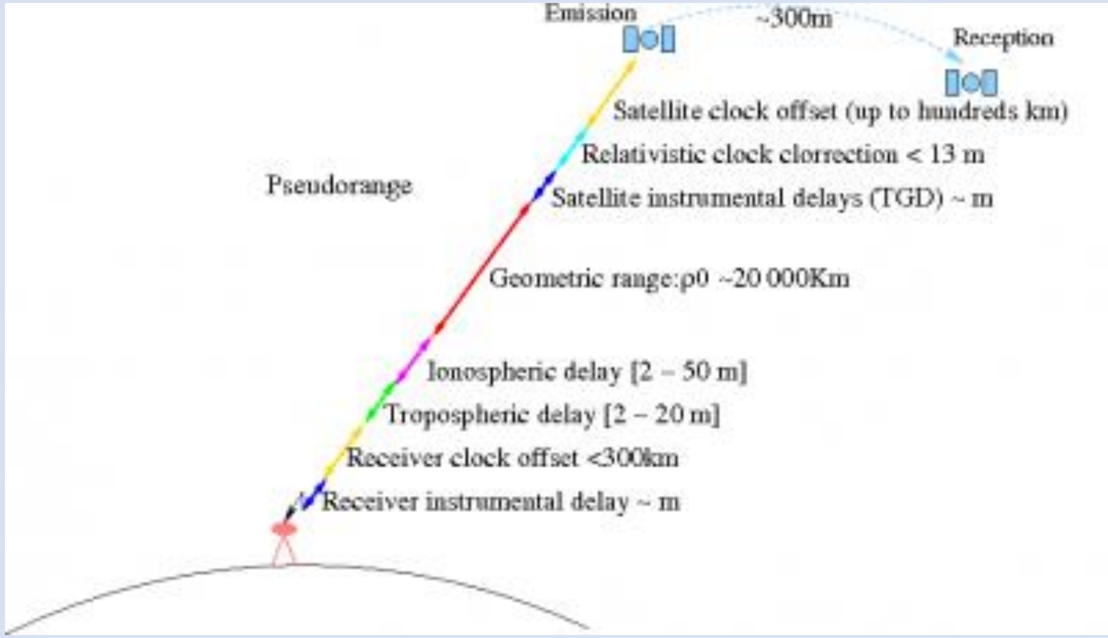
When the local replica and the incoming signal are aligned, their correlation generates a peak and the code delay / Doppler frequency pair corresponding to this peak is assumed to be a good estimate to initialize the **tracking** process.



Code measurements equations (for each f_i)

Geometric range
Rec and Sat clock offset
Tropospheric delay
Ionospheric delay
Rec and Sat instrumental delay
Multipath
Receiver noise

$$R_P = \rho + c(dt_r - dt^s) + T + \alpha_f\, STEC + K_{P,r} - K_P^{\,s} + M_P + \varepsilon_P$$



Carrier phase measurements equations (for each f_i)

Geometric range
Rec and Sat clock offset
Tropospheric delay
Ionospheric delay
Rec and Sat instrumental delay
Integer ambiguity
Wind-up
Multipath
Receiver noise

$$\Phi_L = \rho + c(dt_r - dt^s) + T - \alpha_f\, STEC + k_{L,r} - k_L^{\,s} + \lambda_L N_L + \lambda_L w + m_L + \epsilon_L$$

The ionosphere is a dispersive medium, it means that the group and phase refraction are different and depend on f
This causes on the code and carrier signal an opposite amount of delay

code delay (the code measurement will be larger than in vacuum),

phase advance (the carrier phase measurement will be smaller than in vacuum)

The duties of the GNSS receivers: 5 and 6

5. Obtain satellite position and time from navigational messages

6. Compute receiver position, velocity and time (PVT)

The ionospheric free combination removes the first order (99%) of the ionospherc effects that depends on the inverse of squared signal frequency

It is used for Precise Point Positioning

Ionosphere-free combination

$$R_C = \rho + c(\delta t_{rcv} - \delta t^{sat}) + Tr + \mathcal{M}_C + \varepsilon_C$$

$$\Phi_C = \rho + c(\delta t_{rcv} - \delta t^{sat}) + Tr + B_C + \lambda_N w + m_C + \epsilon_C$$

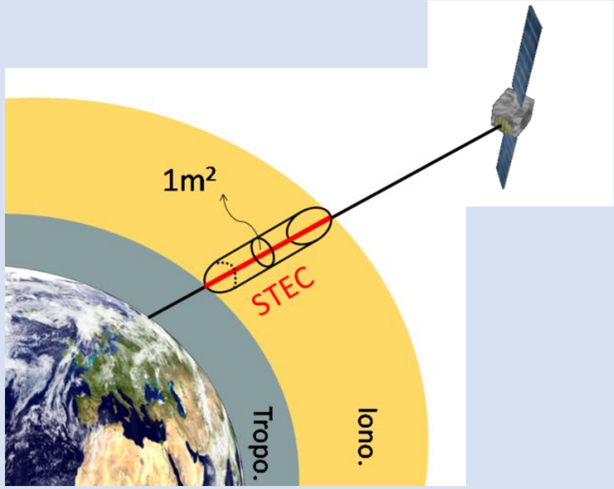
GNSS TEC measurements and calibration

$$I_{ph,f} = -40.30 \frac{STEC}{f^{2}}$$

$$I_{gh,f} = 40.30 \frac{STEC}{f^{2}}$$

$$STEC = \int_{receiver}^{satellite} N_e \, ds$$

$$vTEC = STEC \, \chi(\vartheta)$$



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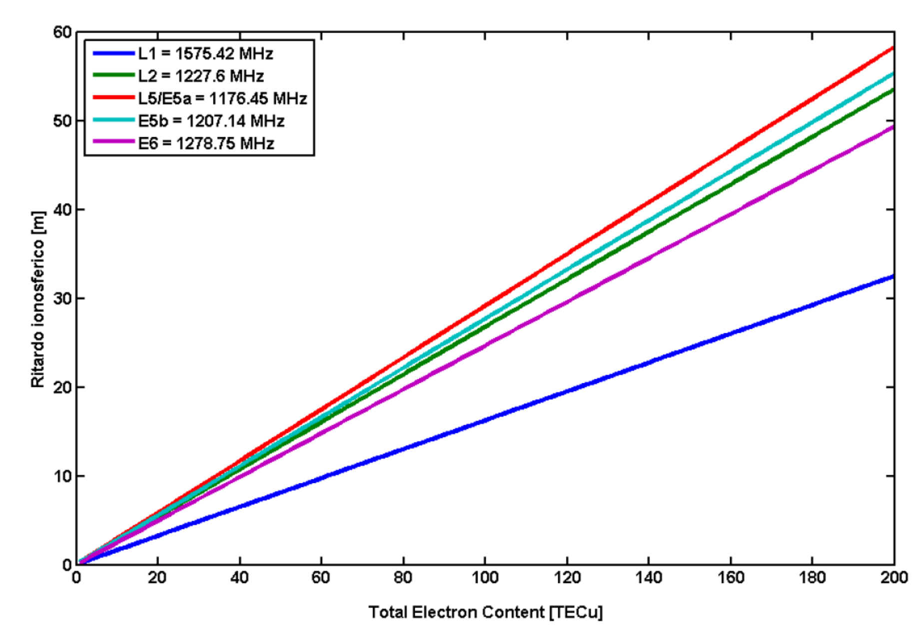
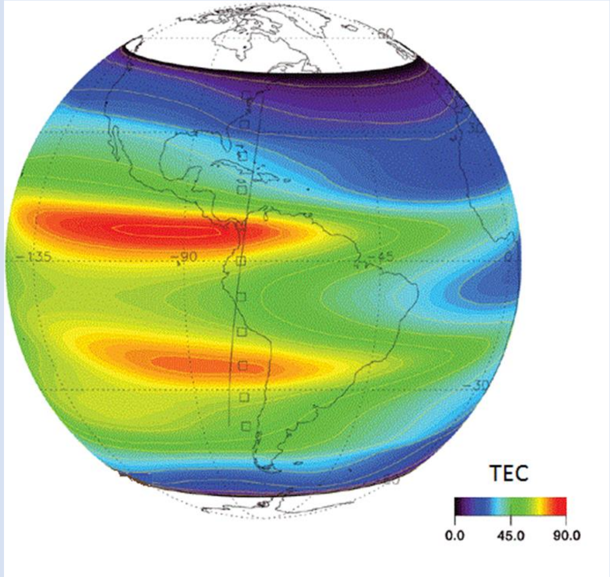


Ionospheric delay for GPS and Galileo



Extracting TEC with GNSS with dual frequency measurements: Geometry-free combination

A combinations of code and/or phase measurements

$$\Phi_{LI} = \Phi_{L1} - \Phi_{L2} \quad ; \quad R_{PI} = R_{P2} - R_{P1}$$

Frequency independent effect are eliminated (ρ, clock errors tropospheric delay)

leaving all the frequency-dependent effect

Ionospheric delay
Phase Wind-up
Multipath
Noise
Integer ambiguity

$$R_I = I + K_{21} + \mathcal{M}_I + \varepsilon_I$$
$$\Phi_I = I + K_{21} + B_I + (\lambda_1 - \lambda_2)w + m_I + \epsilon_I$$

where the bias B_I is given by:

$$B_I = b_I + \lambda_1 N_1 - \lambda_2 N_2$$

In order to cancel out biases and multipath contributions it is possible to apply a calibration procedure based on phase measurements **leveling procedure** (*Ciraolo et al 2007*)

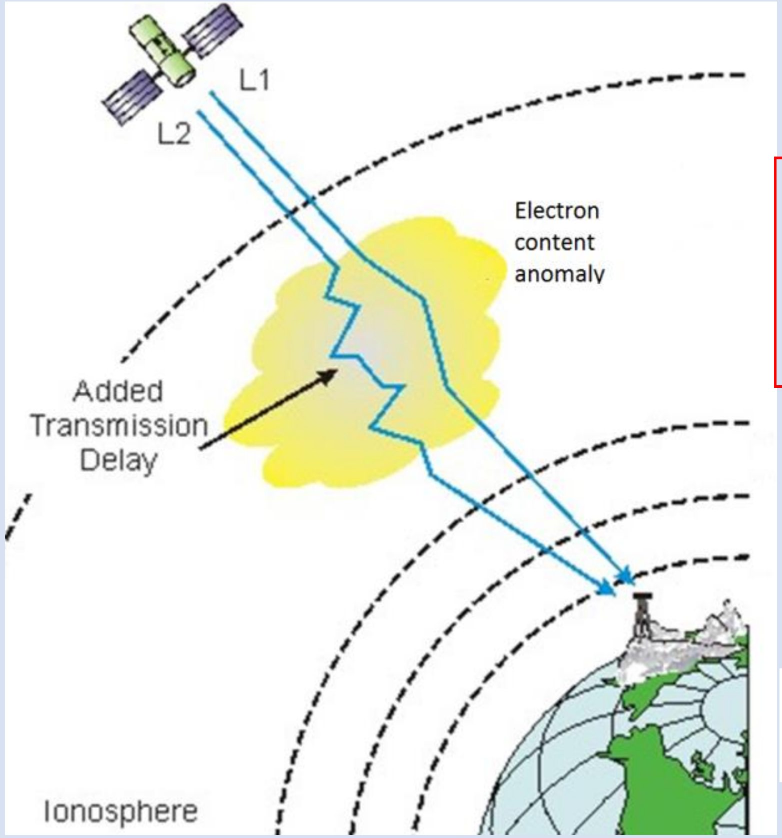
GNSS Ionospheric Scintillation measurements

Scintillations

Sudden fluctuations of amplitude and phase of trans-ionospheric e.m. wave due to small scale electron density anomalies

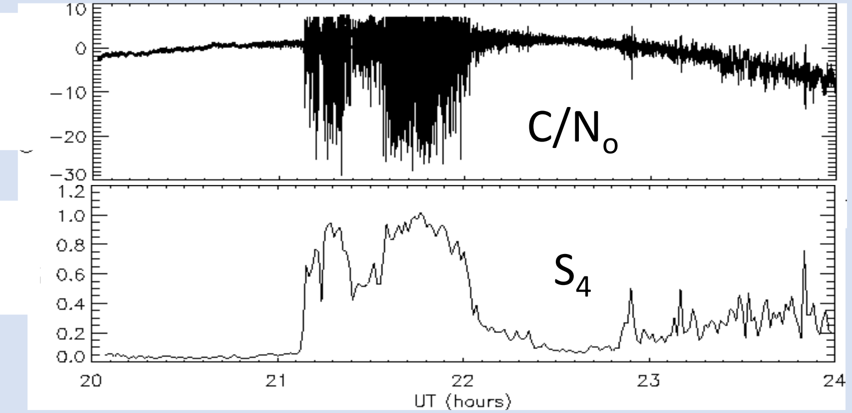
GNSS receivers for scintilliations

- High sampling frequency (50 Hz)
- Multi frequency
- Multi constellation (GPS,GLONASS , GALILEO)

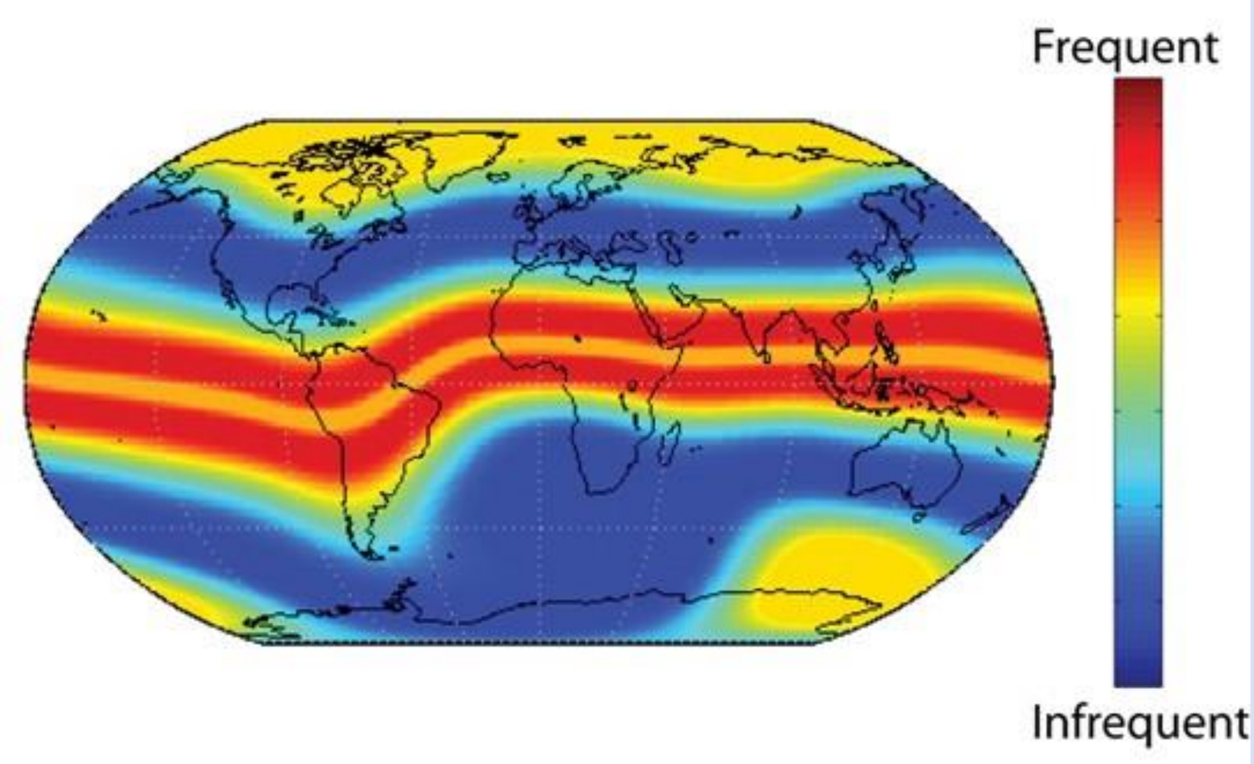


$$\sigma_\varphi = \sqrt{\langle \varphi_i^2 \rangle - \langle \varphi_i \rangle^2}$$

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

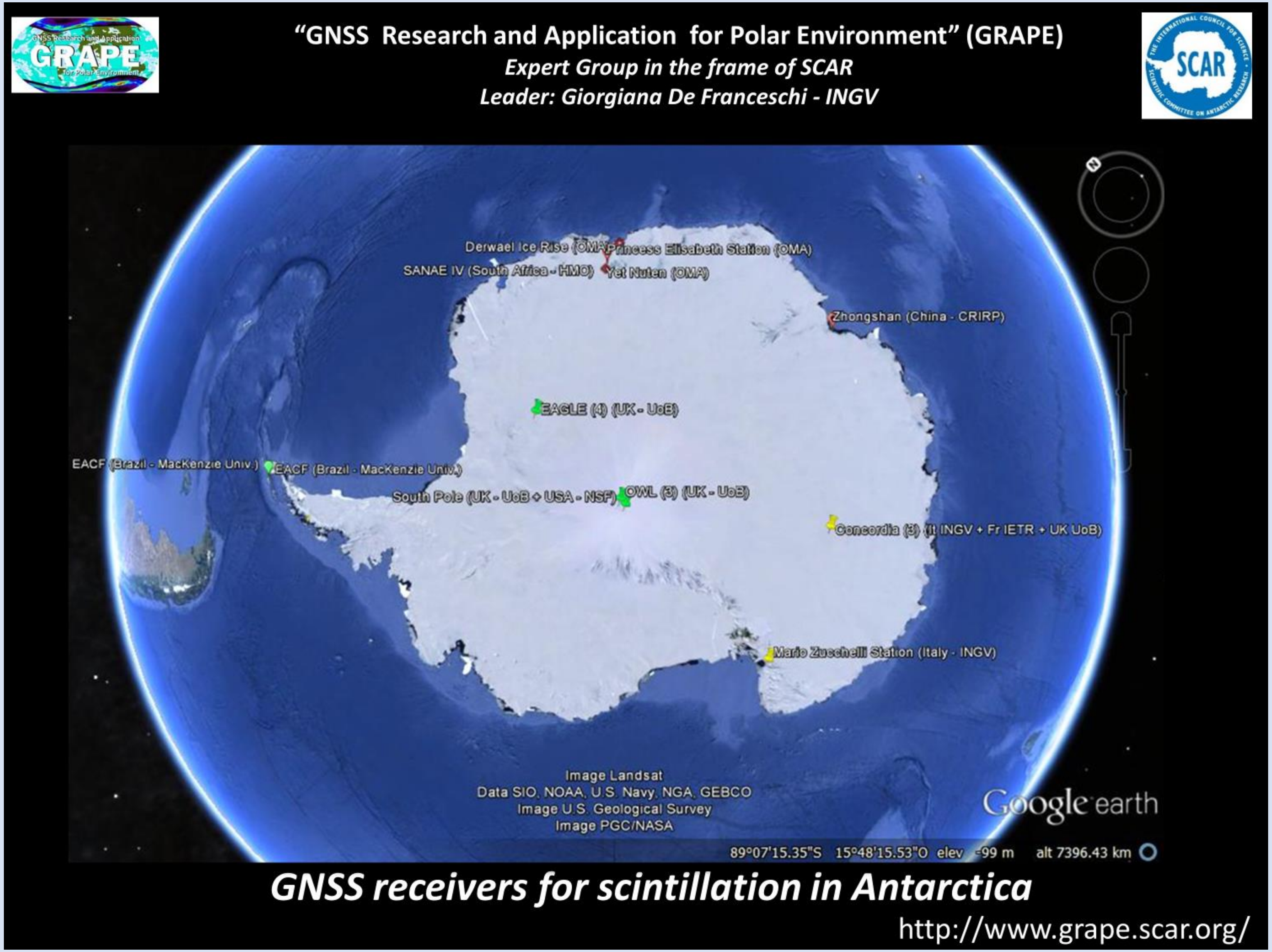


Scintillation map



Suitable Network(s) of ISMR's

Suitable Network(s) of ISMR's



The End