Earth Observation Using GNSS

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Trieste 07,04,2010

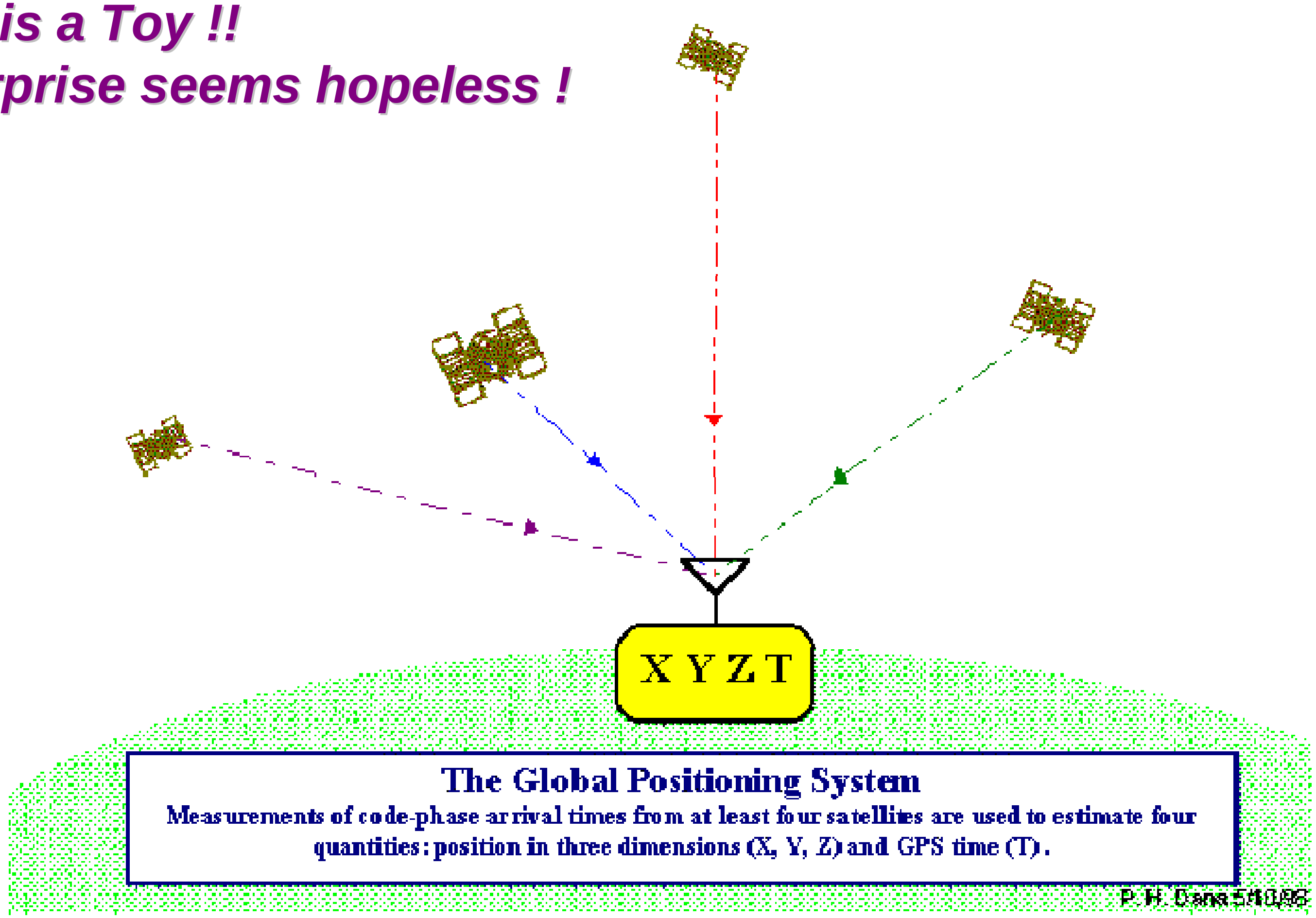
II Workshop on Satellite Navigation
Science and Technology for Africa

Earth Observation Using GNSS

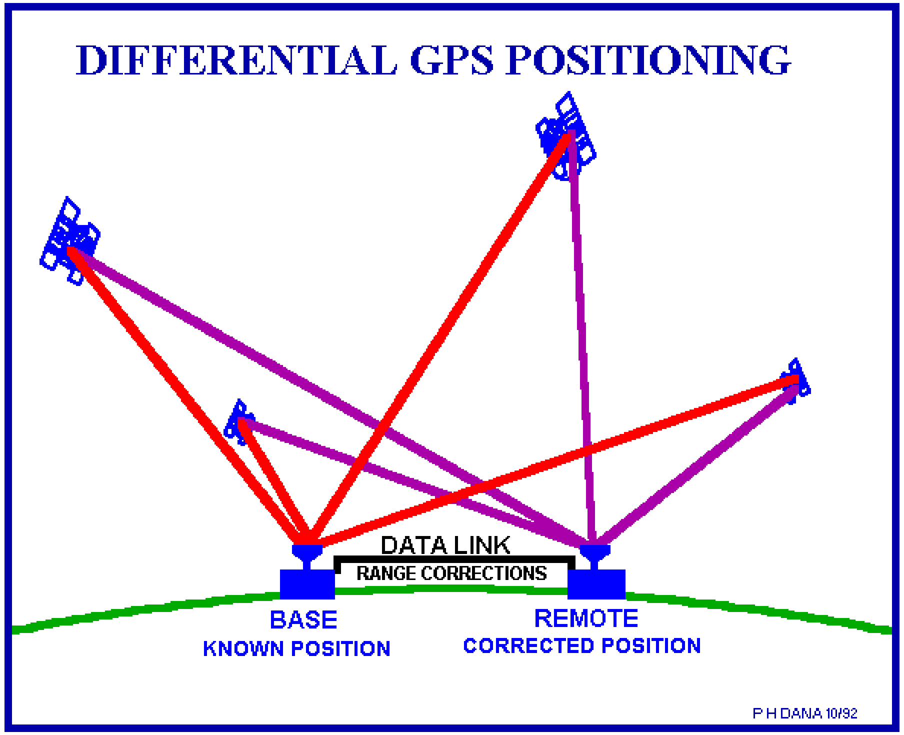
- EO with ground GNSS facilities
- EO with spaceborne GNSS
- ASI projects in GNSS Radio Occultation Activities

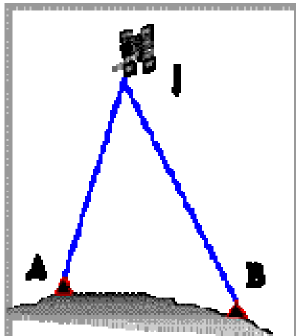
The Global Navigation Satellite Systems: The Principles

Accuracy ” few meters
The GPS is a Toy !!
The enterprise seems hopeless !
But…..

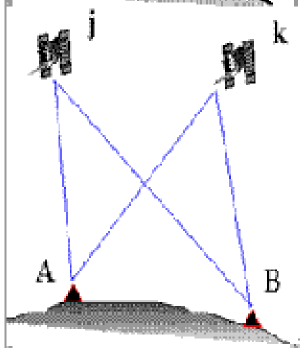


The Differential Approach

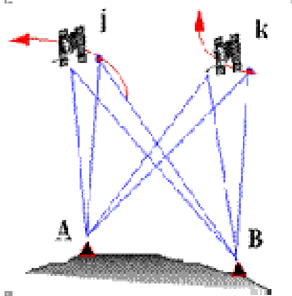




Single Differences
These are used to reduce satellite clock and orbit errors, and localised atmospheric errors.
This is the technique used by DGPS.



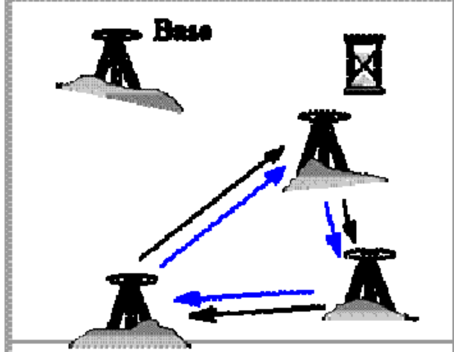
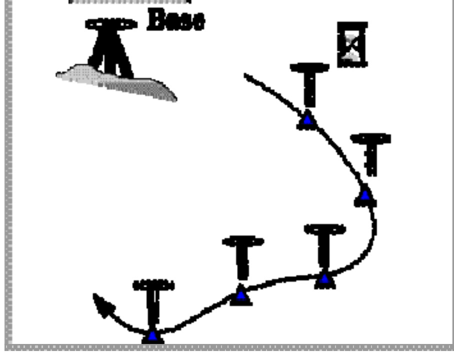
Double Differences
These are used to reduce satellite clock and orbit errors, localised atmospheric errors, and receiver clock errors.
This is usually the technique adopted by the final carrier phase GPS solution. Relative GPS also uses this approach.



Triple Differences
This is the difference between two double differences from measurements recorded at subsequent epochs.
Assuming no cycle slips, or loss of lock has occurred, this eliminates the integer ambiguity. It is therefore used to detect for cycle slips and loss of lock.

The uncertainties are reduced at few mm level !! GNSS can be used for scientific purposes

Survey modes

	**Continuous Kinematic** After initialisation, or resolution of the ambiguities, one receiver is allowed to roam. You must however keep track of the satellites so that lock is not lost, and only few cycle slips occur.
	**Pseudo Kinematic** This allows you to compute the coordinates of a large number of points without observing a static network. You set up for approximately one minute twice on each of the points you wish to be coordinated. The two occupations of a point must be separated by at least one hour in time.
	**Semi Kinematic/Stop and Go** Here you spend a few minutes on each point. When moving between points you must still keep lock on the satellites, although positions are not computed.

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GNSS principles

Maintainance of the Terrestrial Reference Frame

ITRFxx

Seismicity and Landslides

Mean Sea level

Ionosphere

Neutral Atmosphere (Meteorology & Climate)

Space Applications

- Radio Occultation
- Gradiometry

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International Space Geodesy Coordination

Satellite/Lunar Laser Ranging

International Laser Ranging Service

Very Long Baseline Interferometry

IVS

Global Positioning System

IGS

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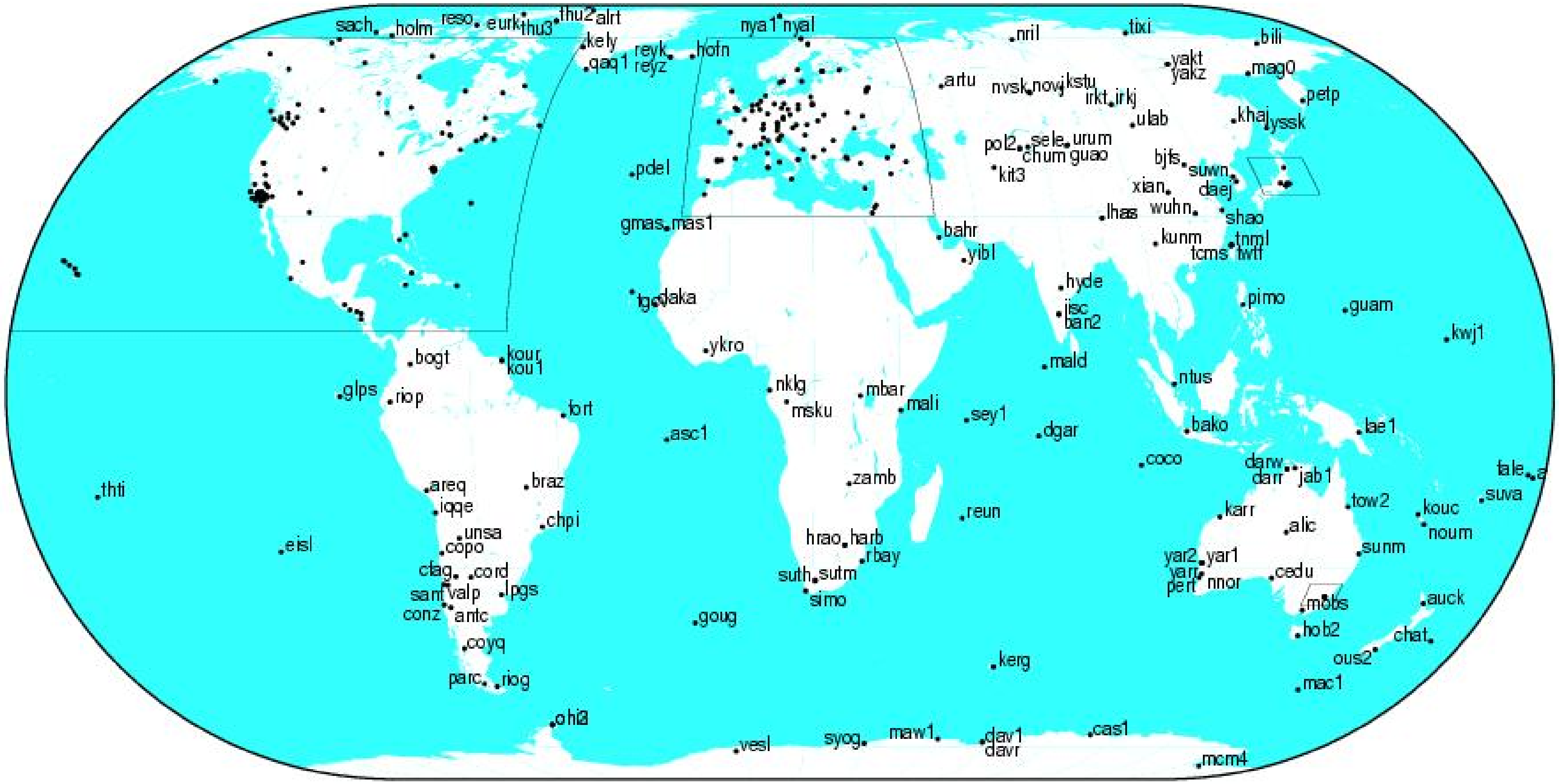
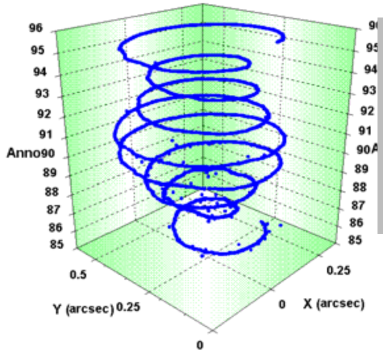
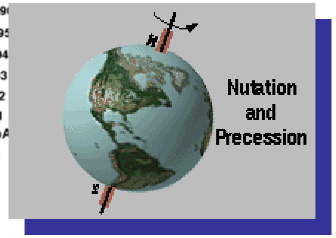
IGS Network



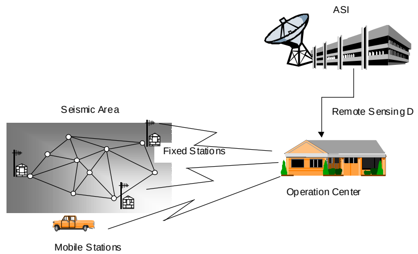
GMT Mar 23 17:22:02 2004

Tectonics

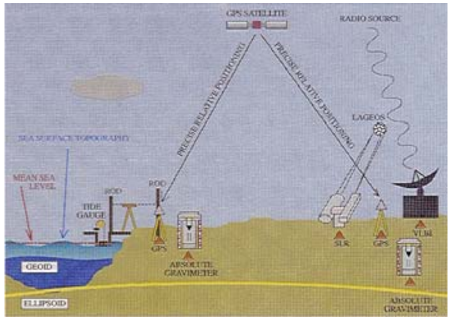




Polar Motion and Orientation

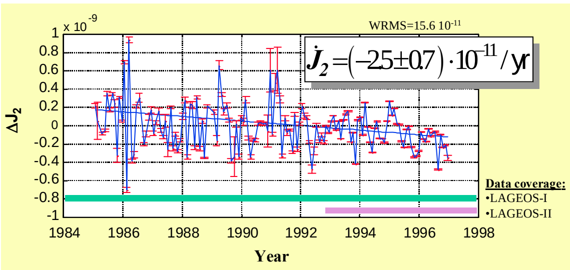


Areas Liable to Seismic and/or Landslides Hazards

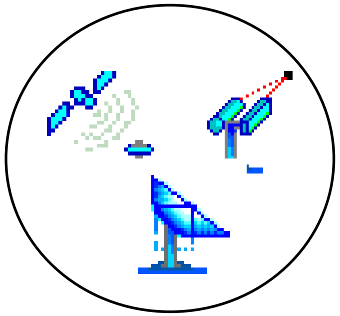


Mean Sea Level

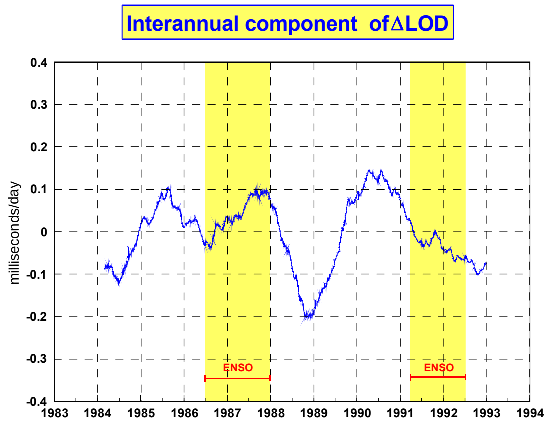
Data analysis ITRF- Earth



Gravity Field



Combined SLR-VLBI-GPS Solutions



Length of Day

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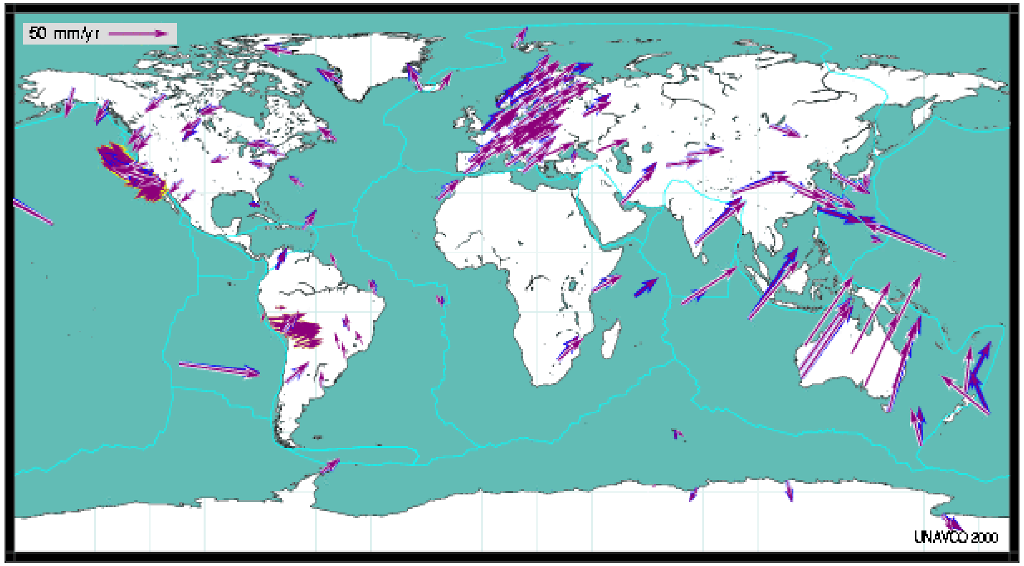
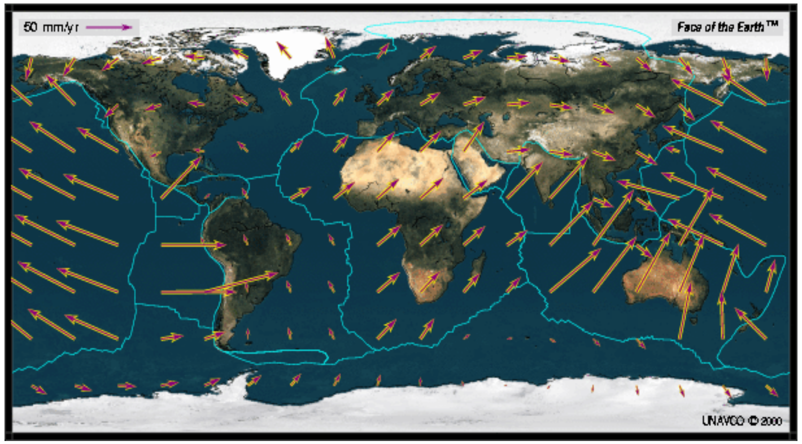
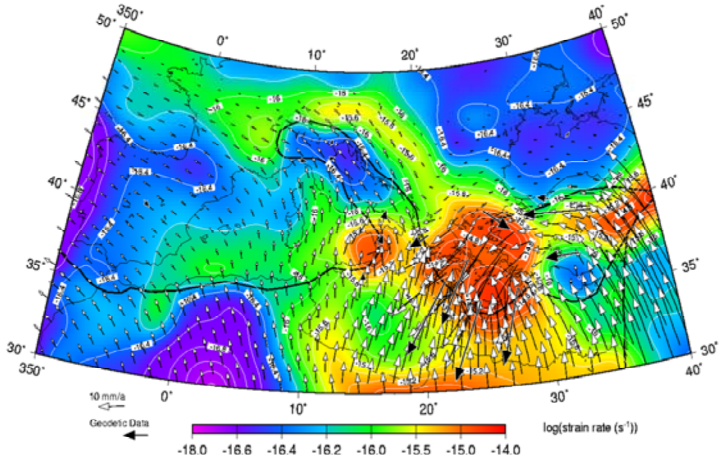
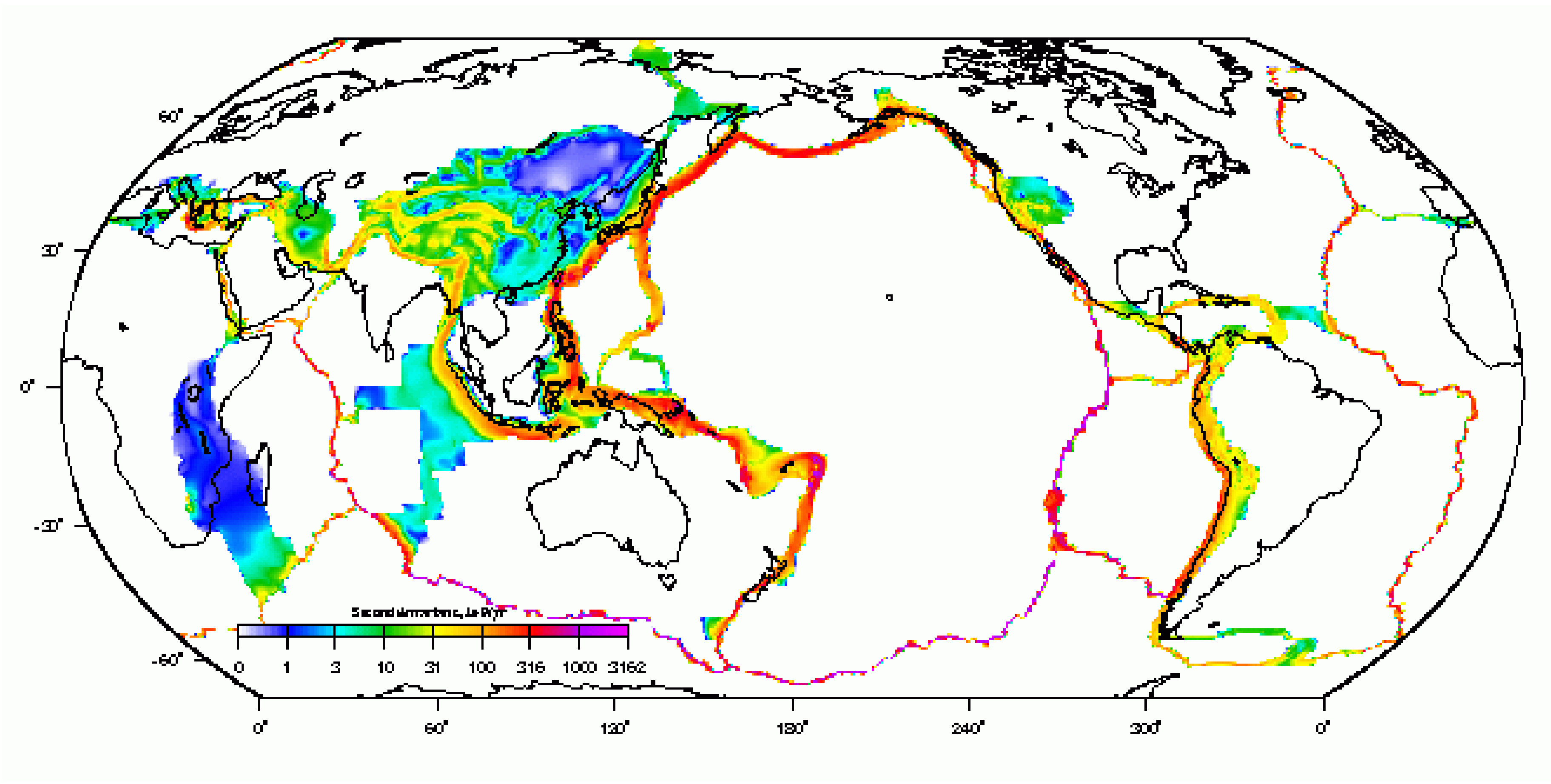
TRF & Tectonics



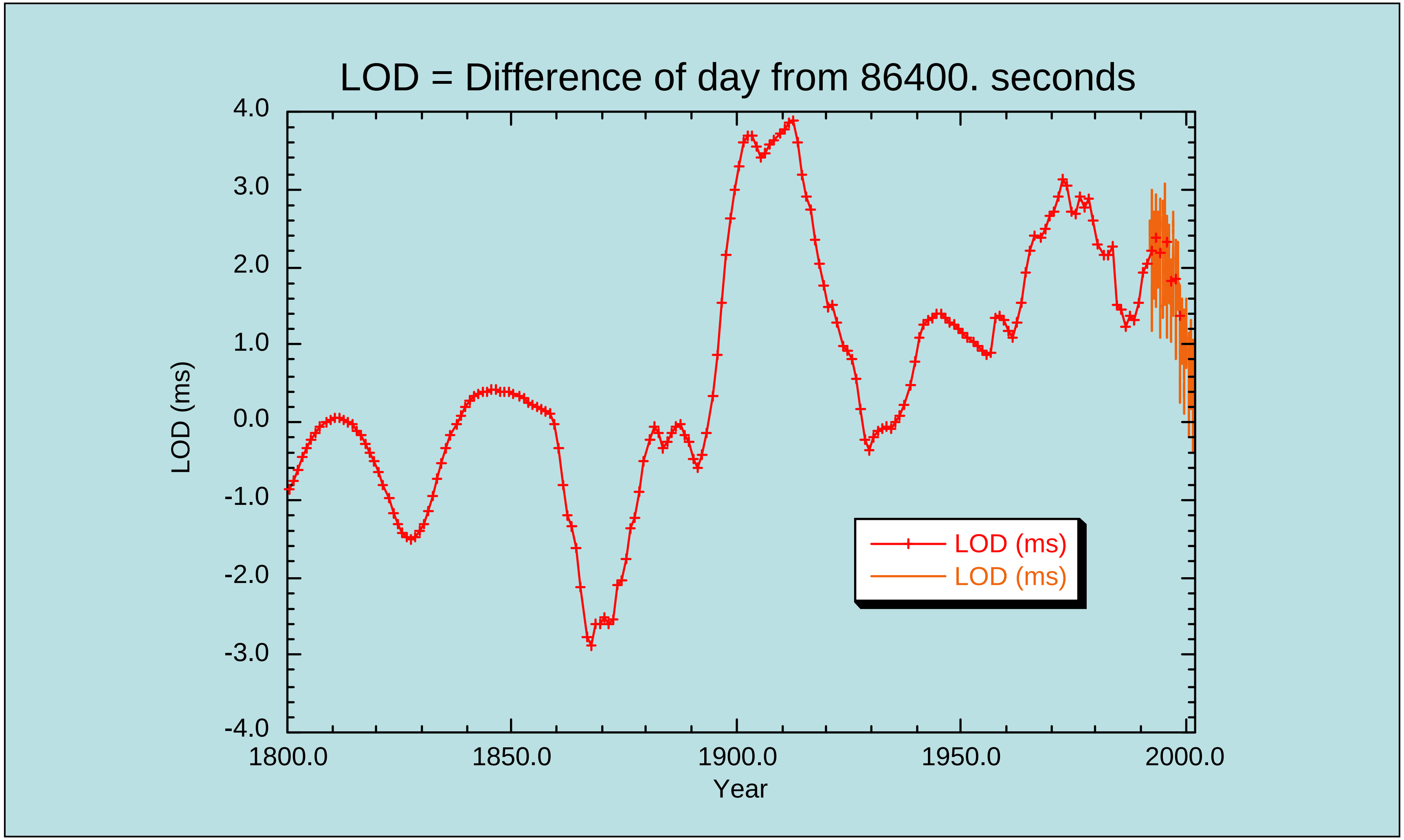




Global Strain Rate



Length of day (LOD)



GNSS principles

Maintainance of the Terrestrial Reference Frame ITRFxx

Seismicity and Landslides

Mean Sea level

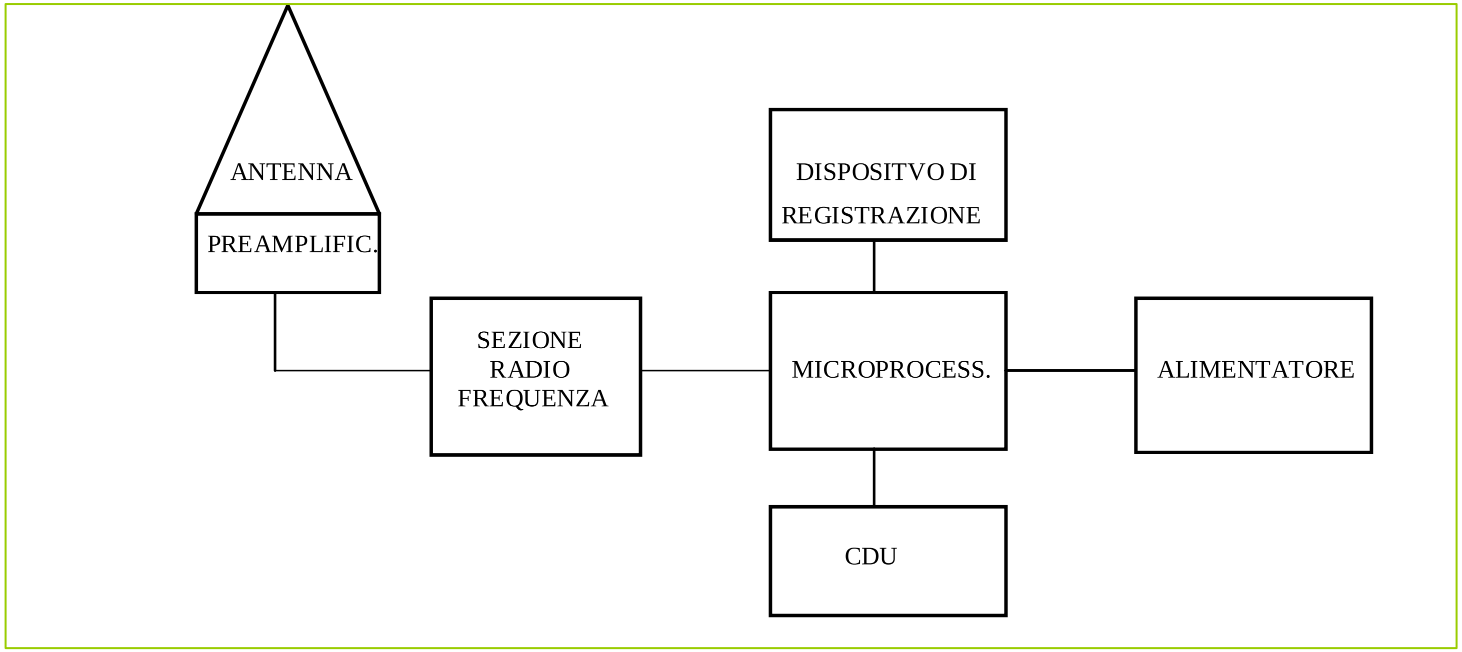
Ionosphere

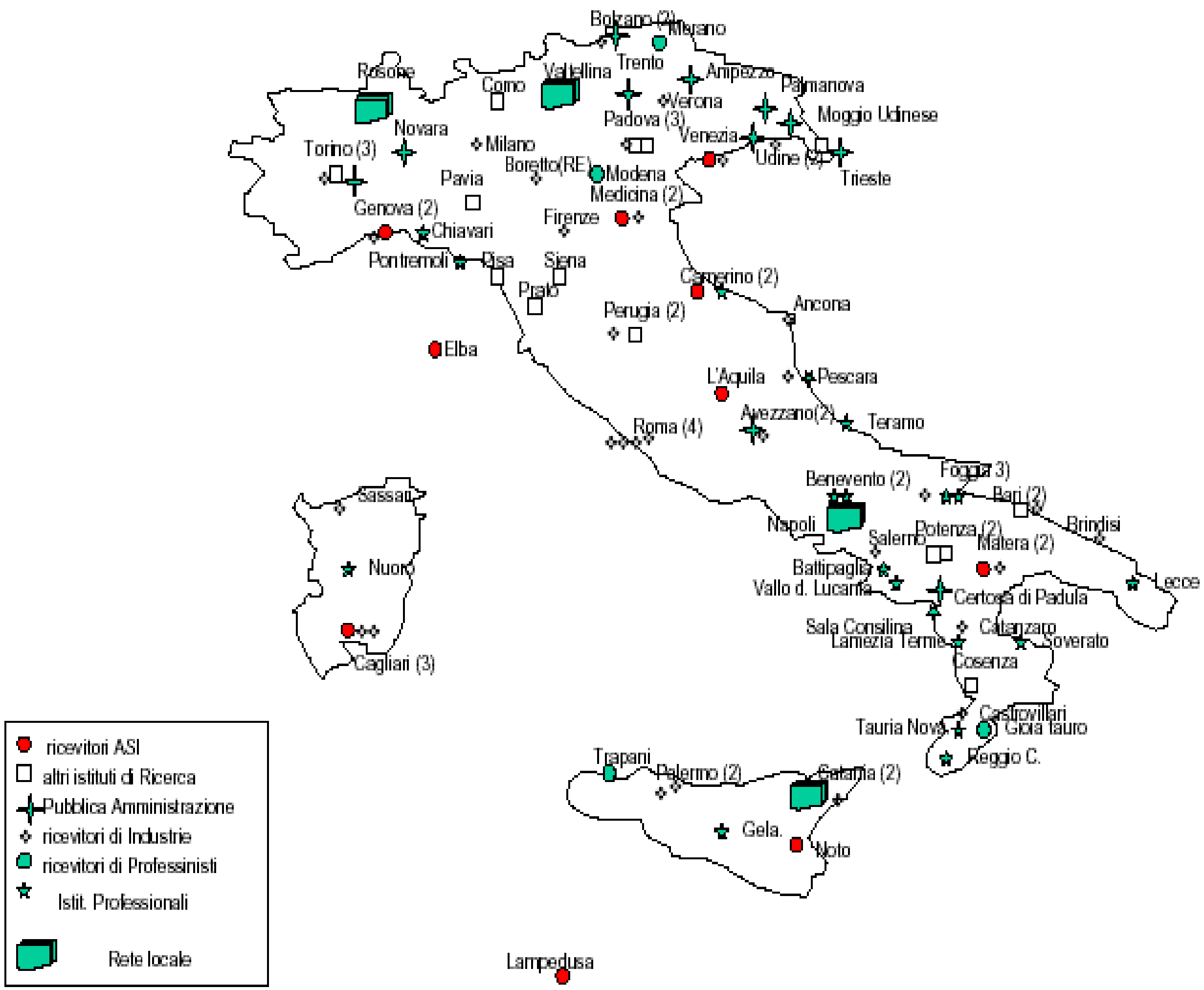
Neutral Atmosphere (Meteorology & Climate)

Space Applications

- Radio Occultation
- Gradiometry

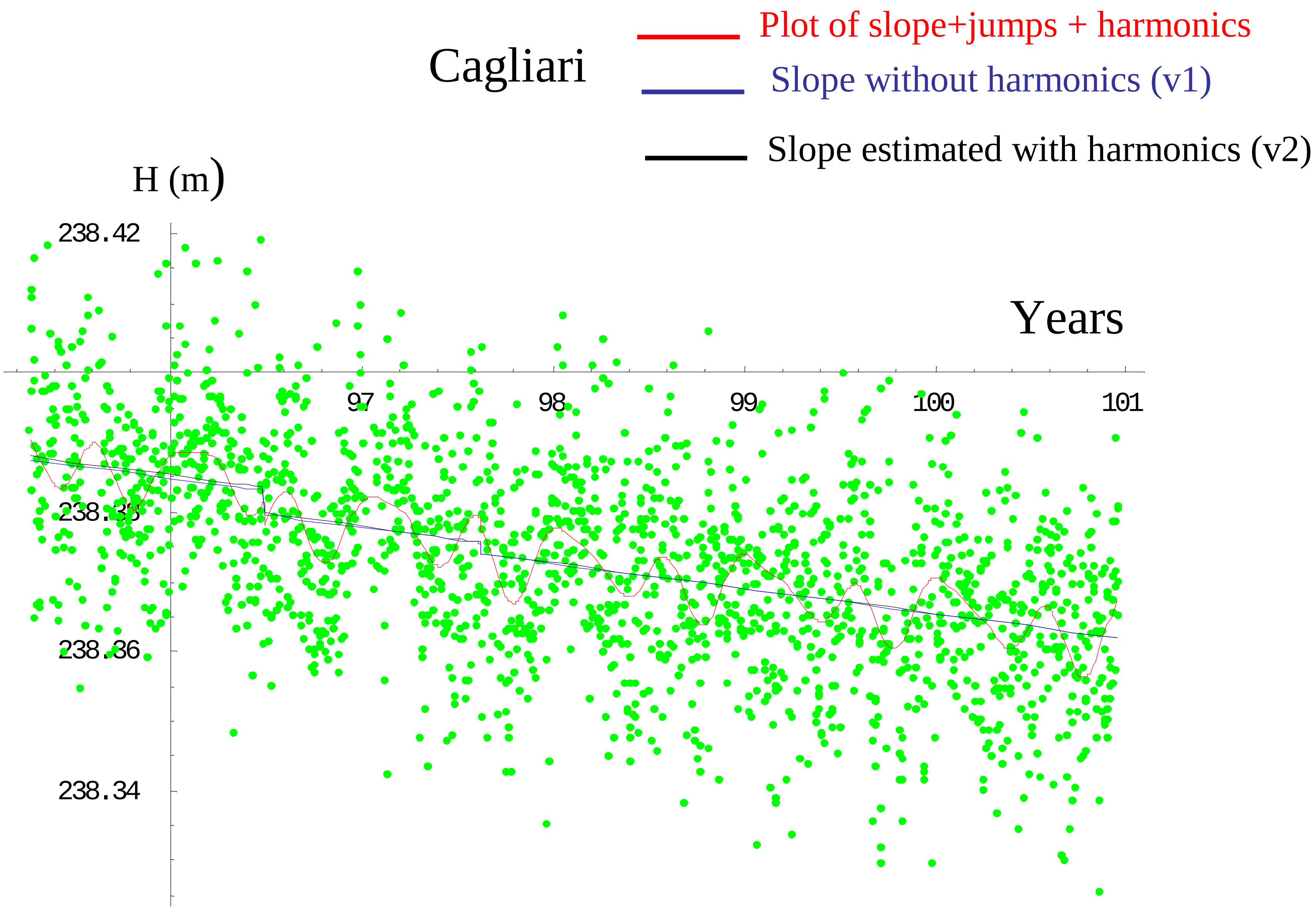

Bolzano
Trento
Basovizza
Torin
o
Novara
Padova
Venezia
Genova
Boretto
Medicina
Camerino
Prato
Perugia
Ancona
Elba
L'Aquil
a
Fucino
Roma
Foggia
Tirana
Matera
Potenza
Vallo d. Lucania
Cagliari
Cosenza
Scanzano
Reggio C.
Noto
Lampedusa
ASI receivers
Institutes collaborating with ASI
others


ANTENNA
PREAMPLIFIC.
SEZIONE RADIO FREQUENZA
DISPOSITVO DI REGISTRAZIONE
MICROPROCESS.
ALIMENTATORE
CDU



Bolzano (2)
Merano
Rosone
Valtellina
Trento
Ampezzo
Palmanova
Como
Verona
Moggio Udinese
Novara
Padova (3)
Venezia
Torino (3)
Milano
Udine (2)
Trieste
Boretto(RE)
Modena
Pavia
Medicina (2)
Genova (2)
Firenze
Chiavari
Pontremoli
Pisa
Siena
Camerino (2)
Prato
Perugia (2)
Ancona
Elba
L'Aquila
Pescara
Avezzano(2)
Roma (4)
Teramo
Benevento (2)
Foggia (3)
Sassari
Bari (2)
Napoli
Brindisi
Salerno
Potenza (2)
Matera (2)
Nuoro
Battipaglia
Vallo d. Lucania
Lecce
Certosa di Padula
Sala Consilina
Catanzaro
Lamezia Terme
Soverato
Cagliari (3)
Cosenza
Castrovillari
Tauria Nova
Gioia Tauro
Reggio C.
Trapani
Palermo (2)
Catania (2)
Gela
Noto
Lampedusa
ricevitori ASI
altri istituti di Ricerca
Pubblica Amministrazione
ricevitori di Industrie
ricevitori di Professinisti
Istit. Professionali
Rete locale

Contribution to the ITRF Maintainance (IGS/EUREF)



Cagliari

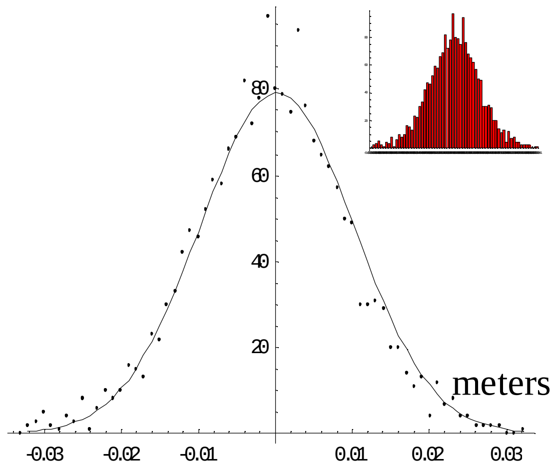
V1= -3.61±0.36 mm/yr rms=12.5 mm

V2= -3.64±0.35 mm/yr rms=12.0 mm

👎t ¤ 10.5 yr

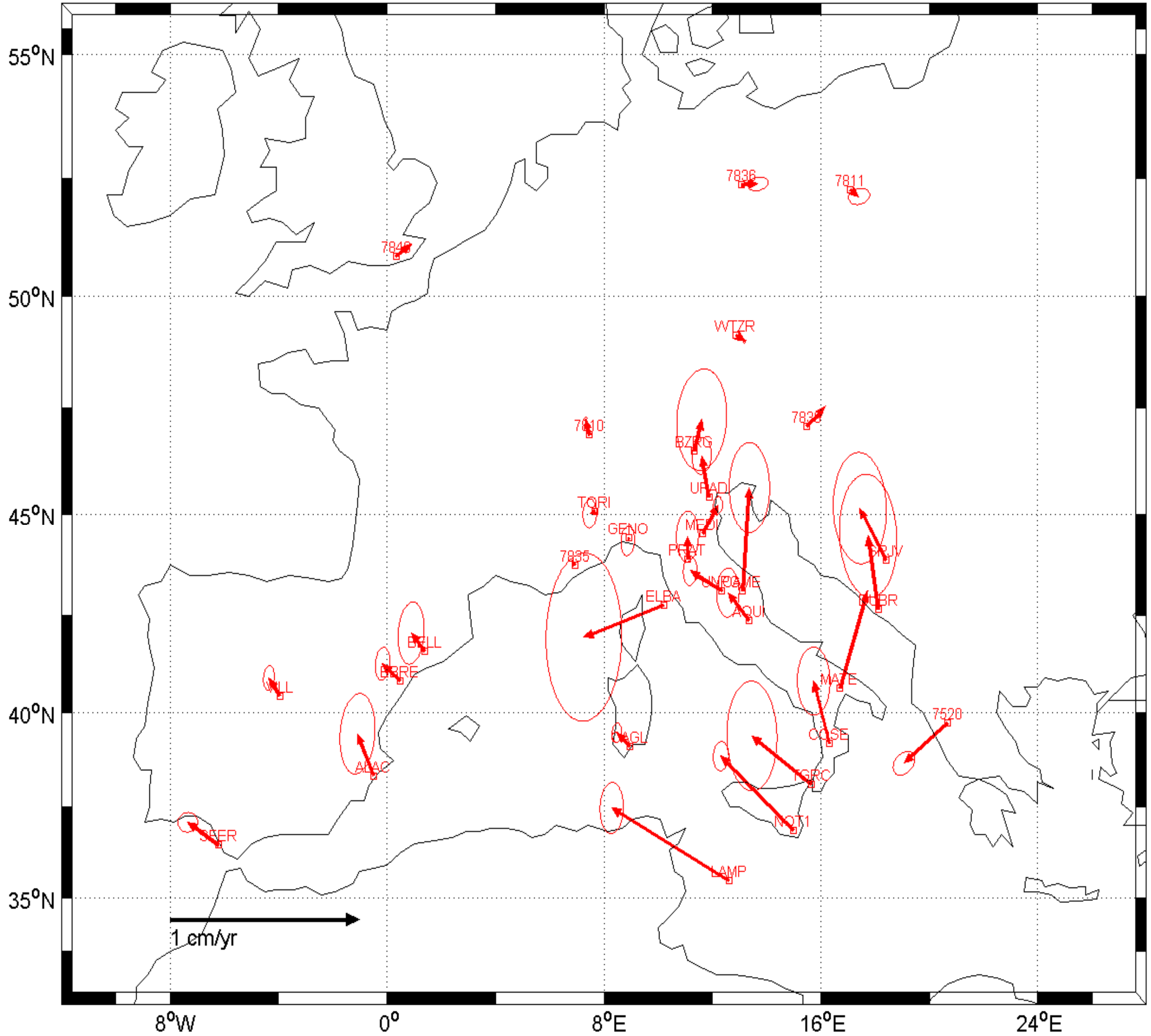
$$\Delta t \geq 3 * (scatter \quad of \quad the\ fit) / V_h$$

Period (days)	amp (mm)
359	2.2
180	3.7
121	1.8



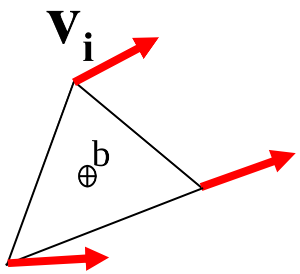
$$V_{tot} = V_t + V_{sl} + V_c + V_{pgr} + V_{hl} + V_a$$

Velocity residuals w.r.t. Eurasian Eulerian Pole ITRF2000



Strain Rate Computation

1 The planar (x,y) velocities in the vertices of each selected triangle are expanded at the first order by means of the **velocity gradient tensor L**

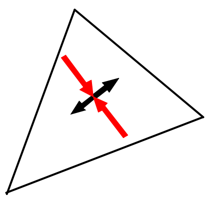


$$\mathbf{v_i} = \mathbf{L}\,\Delta\mathbf{x_i} + \mathbf{v_b}$$

$$L = \begin{bmatrix} \dfrac{\partial V_x}{\partial x} & \dfrac{\partial V_x}{\partial y} \\ \dfrac{\partial V_y}{\partial x} & \dfrac{\partial V_y}{\partial y} \end{bmatrix}$$

2 Estimation of the **tensor L** in a least squares sense

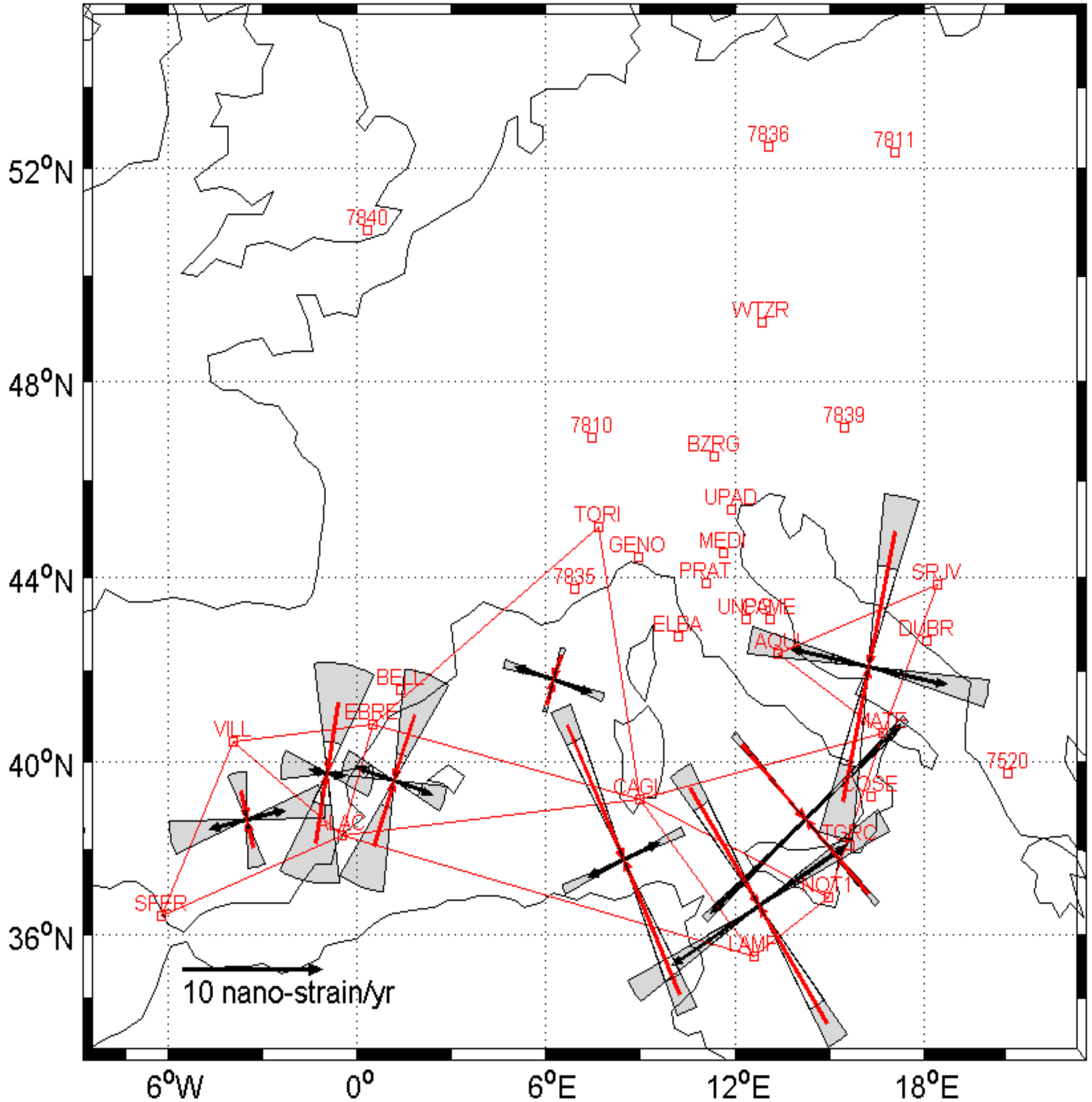
3 **Strain rate (E)** computation



$$\mathbf{E} = \frac{1}{2}\left(\mathbf{L} + \mathbf{L}^{\mathrm{T}}\right)$$

4 Measurement unit of strain rate: 1 nano-strain/yr is equal to a deformation of 1mm/yr per 1000 Km

Strain rate in the Western Mediterranean Area



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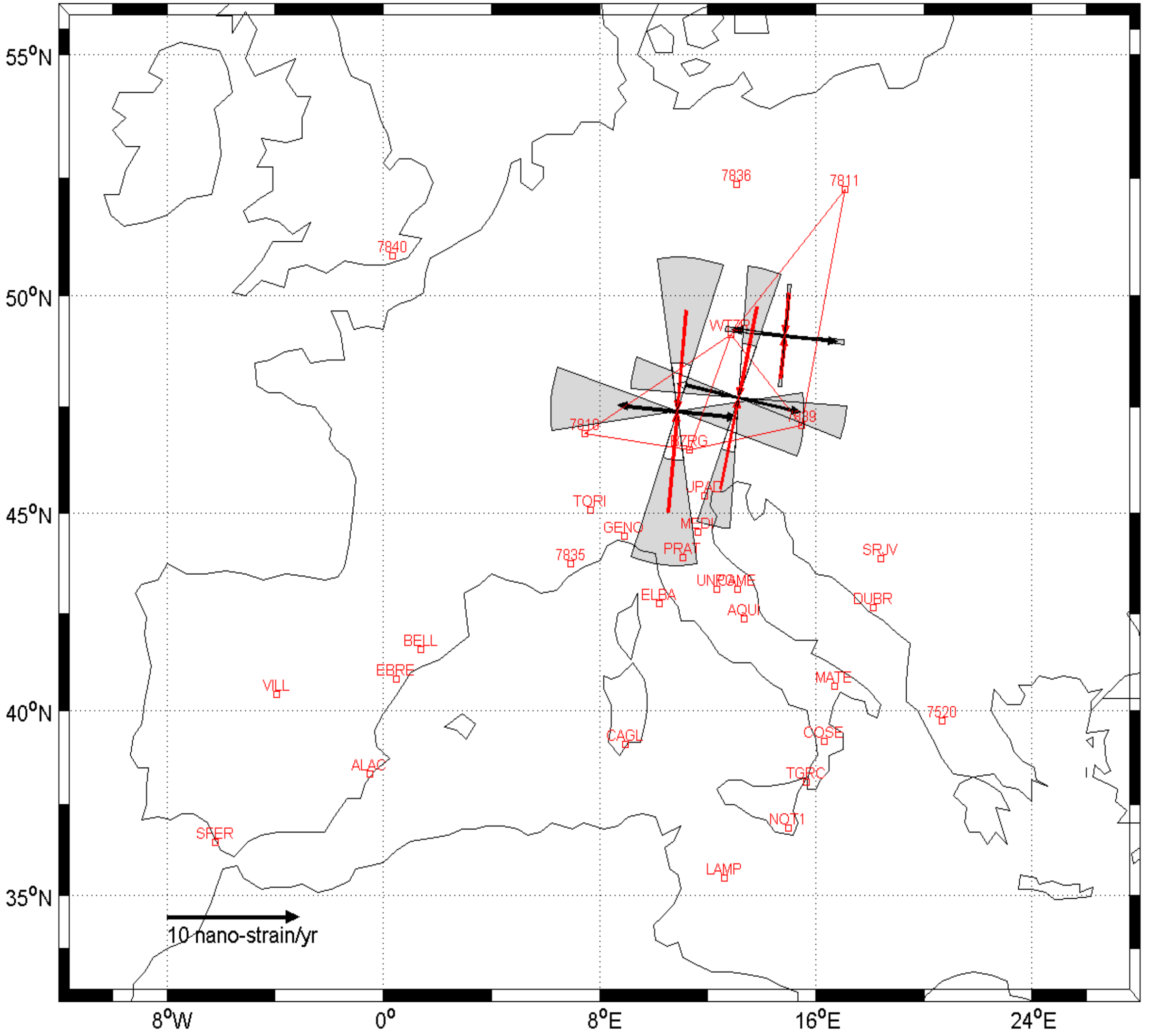
Strain rate in the Alpine region



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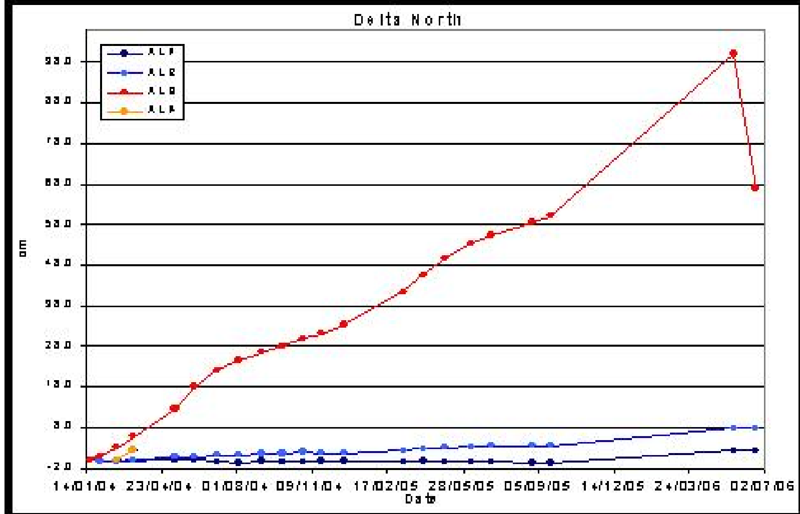
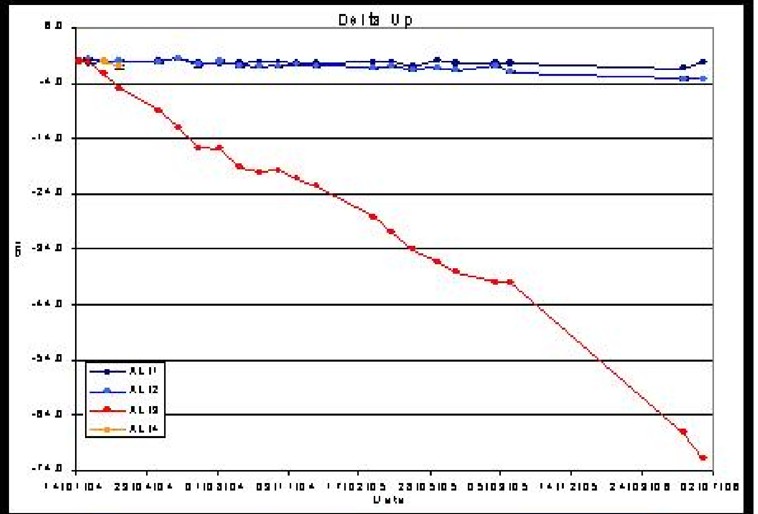
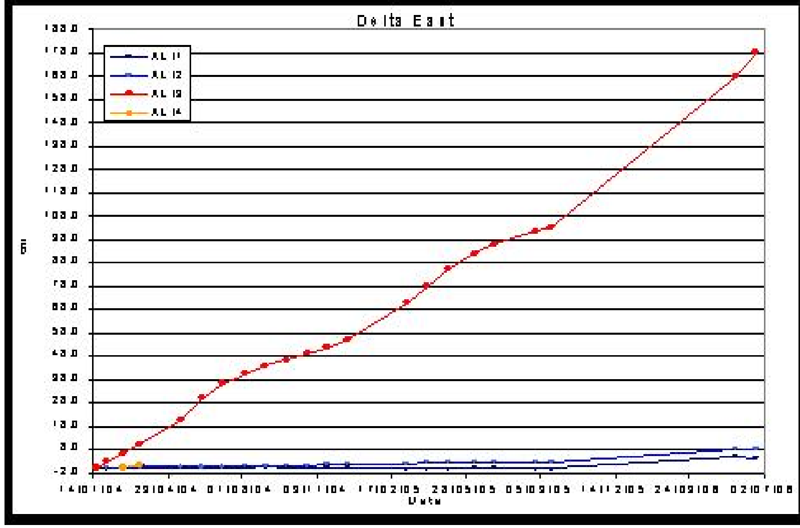
Landslides

Aliano



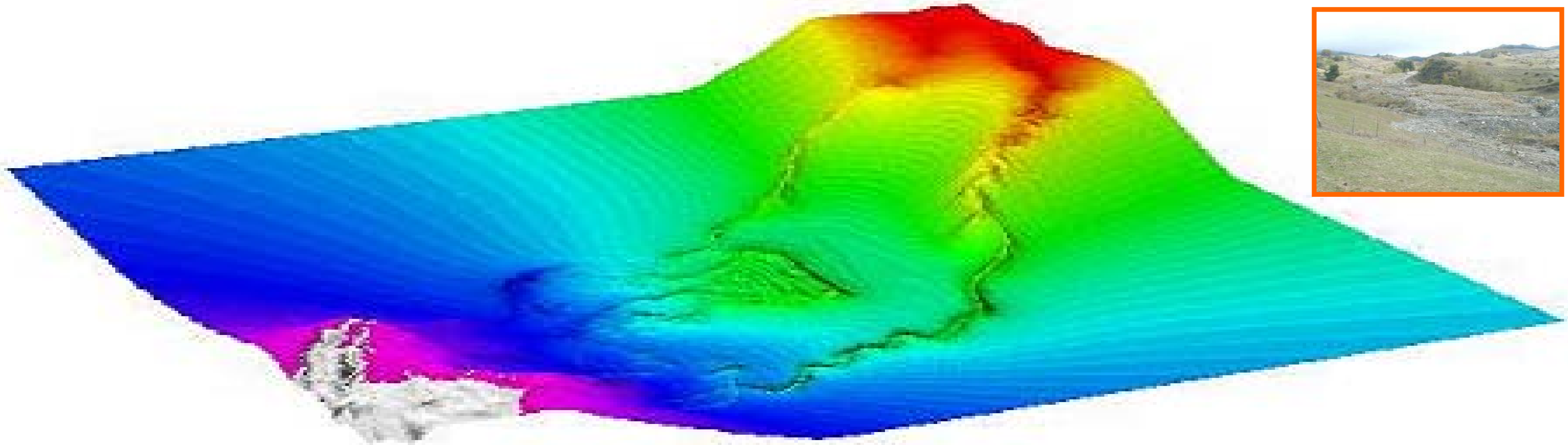


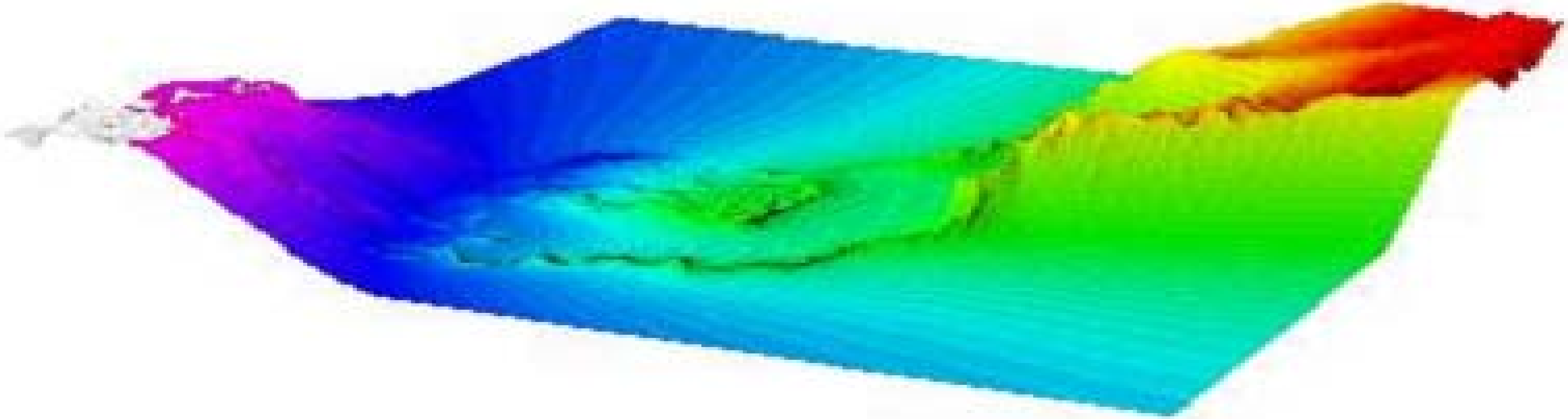


Extension of the experiment to Craco (Mt)

A site candidates to be Included in WMF list

DTM built with GPS RTK





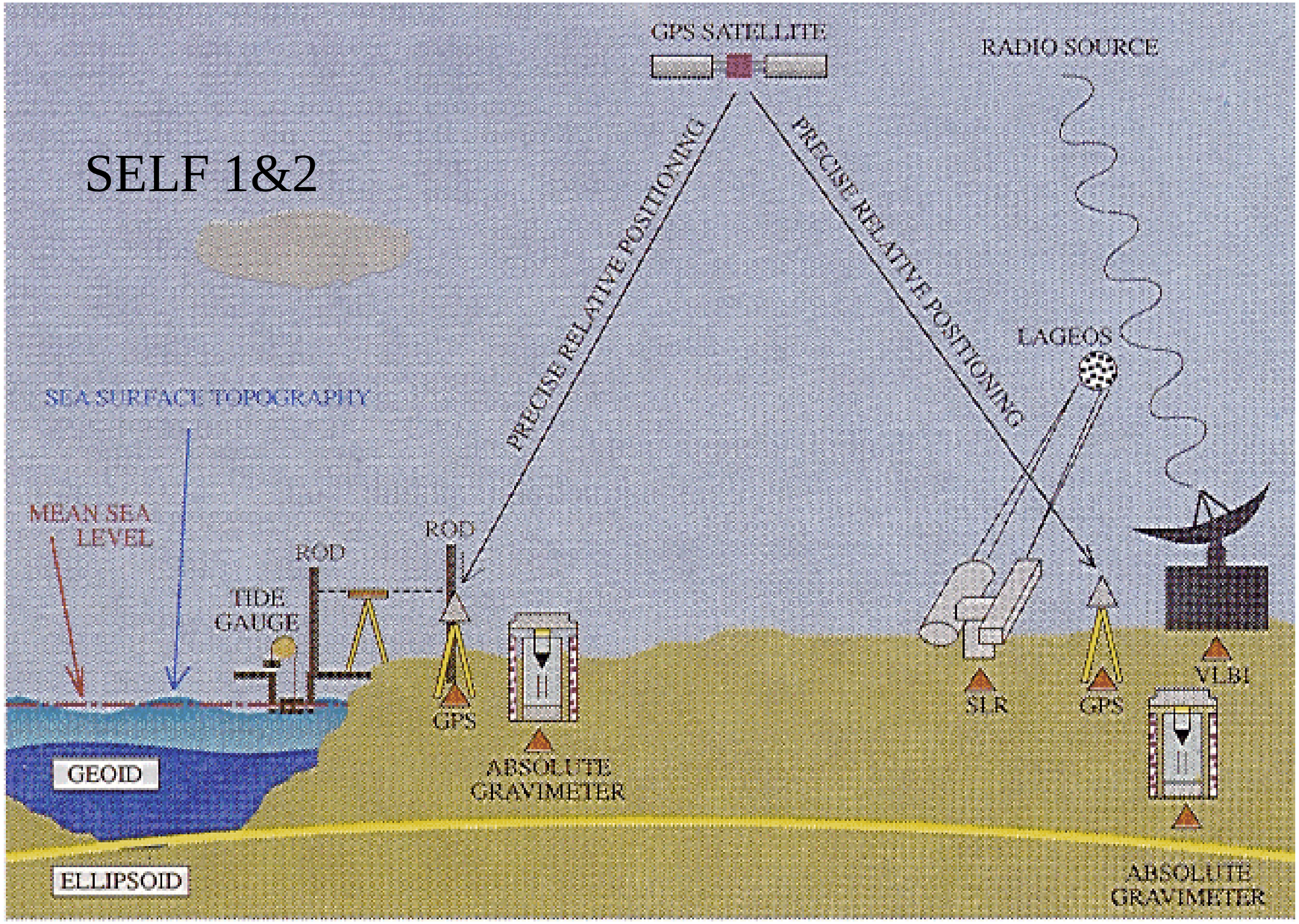
- GNSS principles
- Maintainance of the Terrestrial Reference Frame ITRFxx
- Seismicity and Landslides
- Mean Sea level
- Ionosphere
- Neutral Atmosphere (Meteorology & Climate)
- Space Applications
  - •Radio Occultation
  - •Gradiometry

Why do we study MSL?

- Climate
- Geodesy: Vertical Datum
- Shore and Sea Instabilities (Subsidence, Erosion, water loading etc.)
- Topography, Cartography etc.

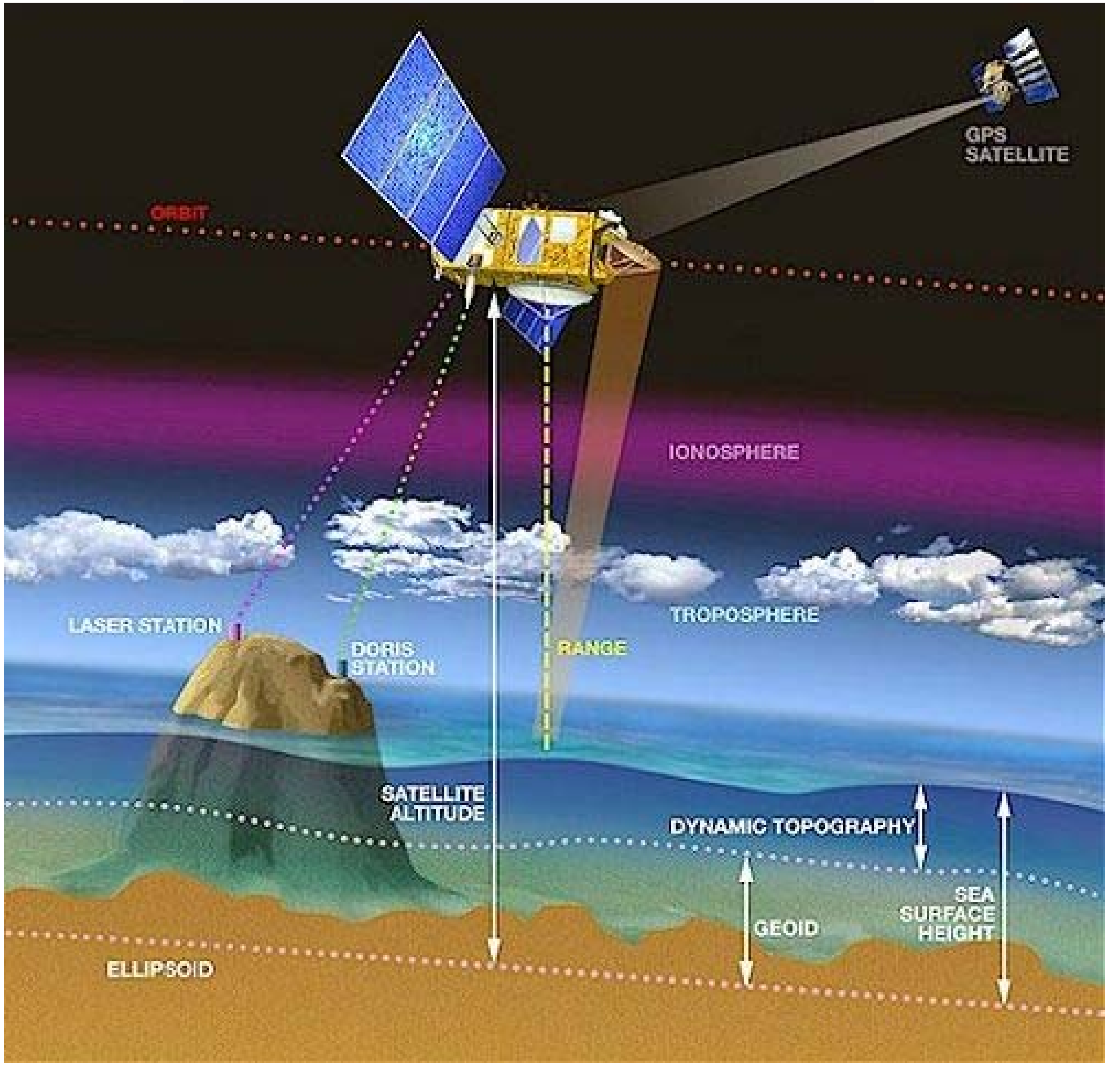
We do need a simphony of different techniques

- Tide-gauges:
  - Relative MSL against the ground
- GPS local network co-located with tide-gauges
- Bathymetry
- Global GPS network to link the local one to ITRF
- Ocean circulation and waves-motion monitoring with SAR, Radar Altimeter, GPS buoys etc.

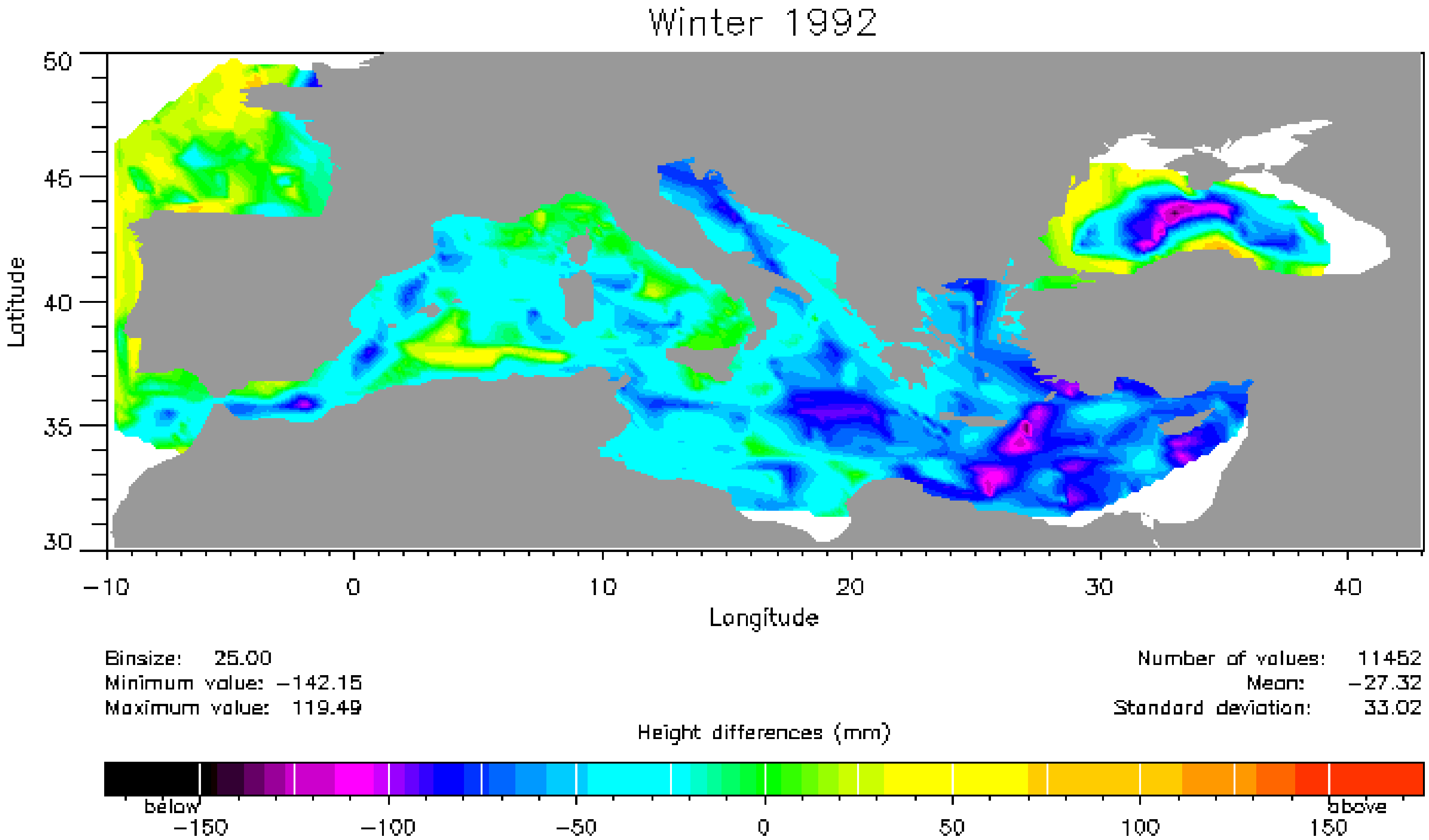


SELF 1&2
GPS SATELLITE
RADIO SOURCE
PRECISE RELATIVE POSITIONING
PRECISE RELATIVE POSITIONING
LAGEOS
SEA SURFACE TOPOGRAPHY
MEAN SEA LEVEL
ROD
ROD
TIDE GAUGE
GPS
ABSOLUTE GRAVIMETER
SLR
GPS
VLBI
GEOID
ELLIPSOID
ABSOLUTE GRAVIMETER

How altimetry works:



Altimetry principle



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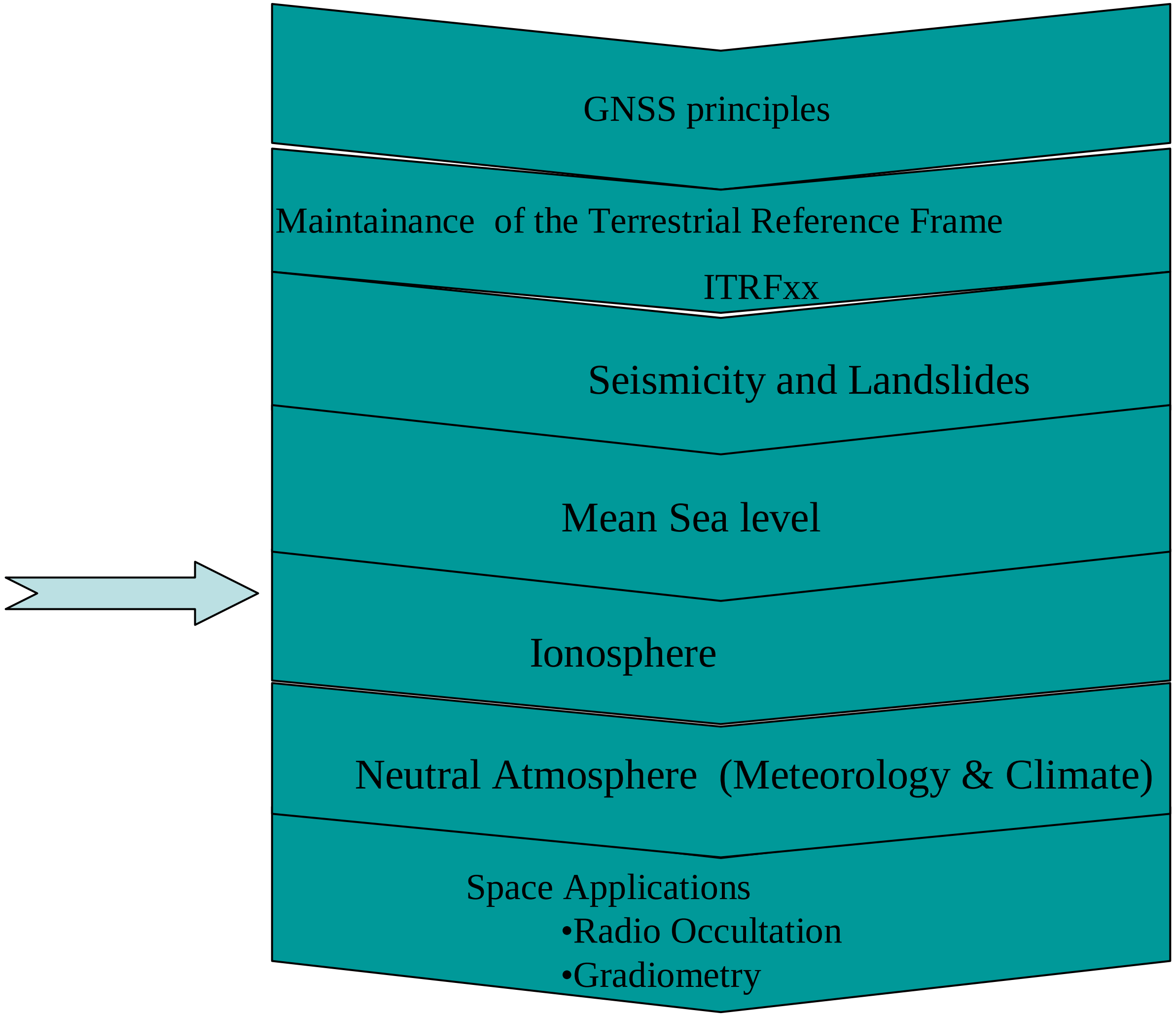
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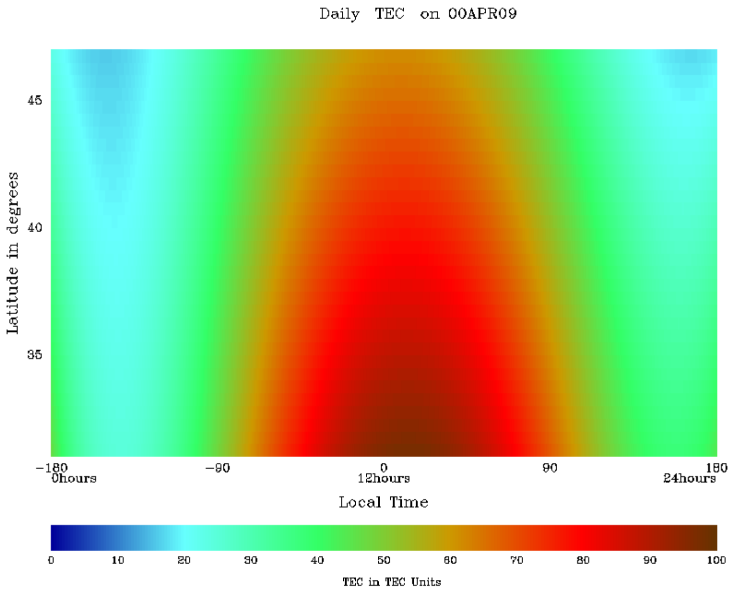
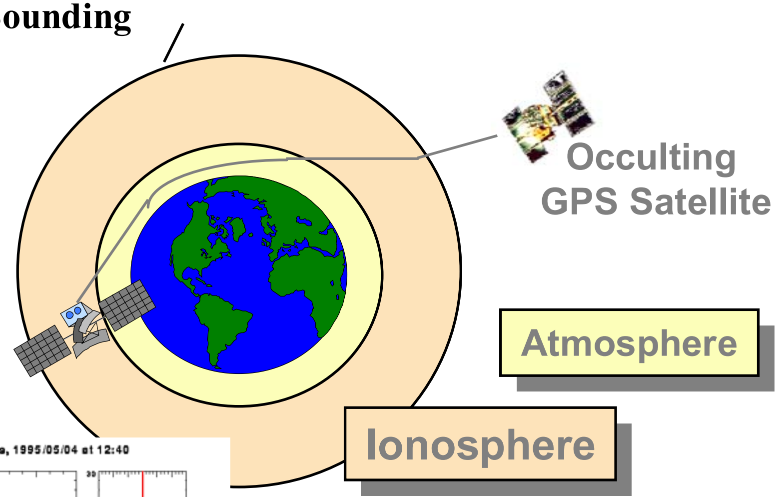
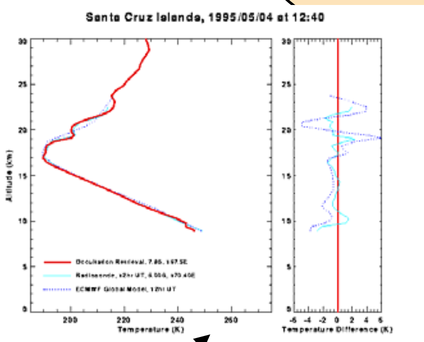


GPS Limb Sounding



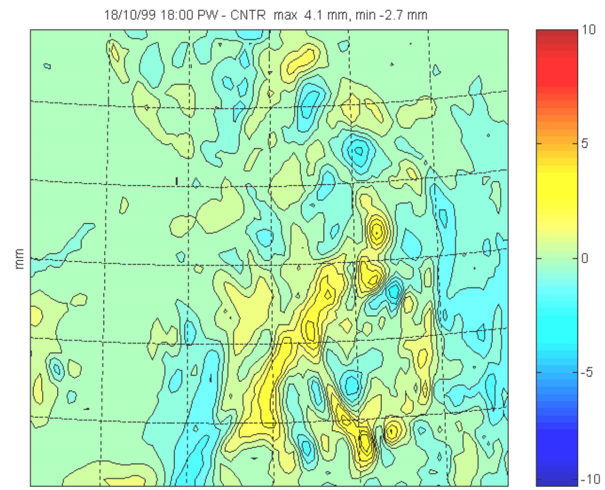


$$\Delta f = \frac{f}{c}\left[\left(\mathbf{v}_T \cdot \mathbf{e}_T - \mathbf{v}_R \cdot \mathbf{e}_R\right) - \left(\mathbf{v}_T \cdot \mathbf{e} - \mathbf{v}_R \cdot \mathbf{e}\right)\right]$$

$$n(a) = \exp\left\{ -\frac{1}{\pi}\int_a^\infty \ln\left(\frac{x}{a} + \left(\frac{x^2}{a^2} - 1\right)^{\frac{1}{2}}\right)\frac{d\gamma}{dx}\,dx \right\}$$

$$N = (n-1)\cdot 10^6 = 77.6\,\frac{P}{T} + 3.73\cdot 10^5\,\frac{e}{T^2} + \ldots$$

GPS PW influence w.r.t the model



Ionosphere

Data analysis Atmosphere

GPS for Meteorology

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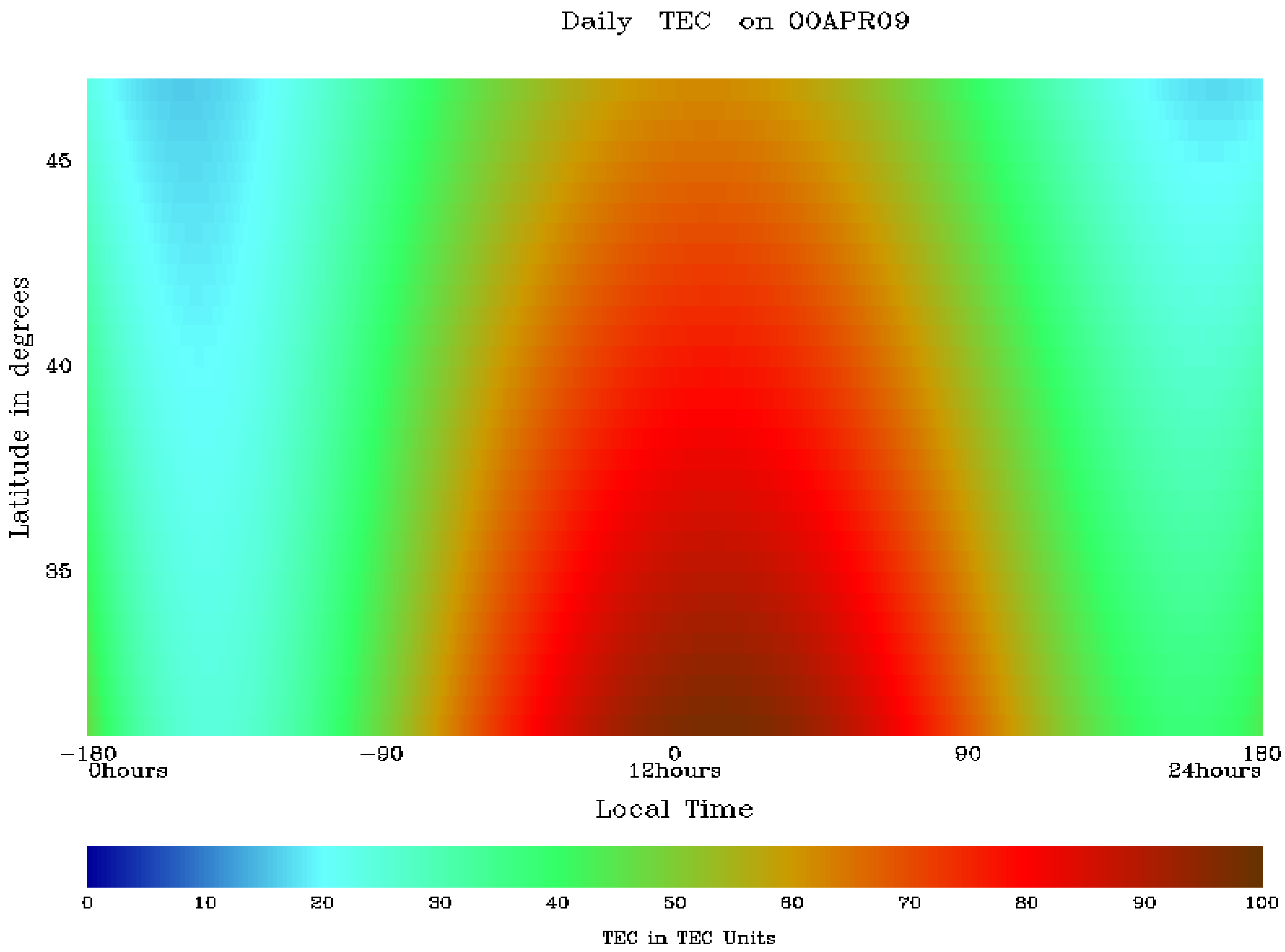
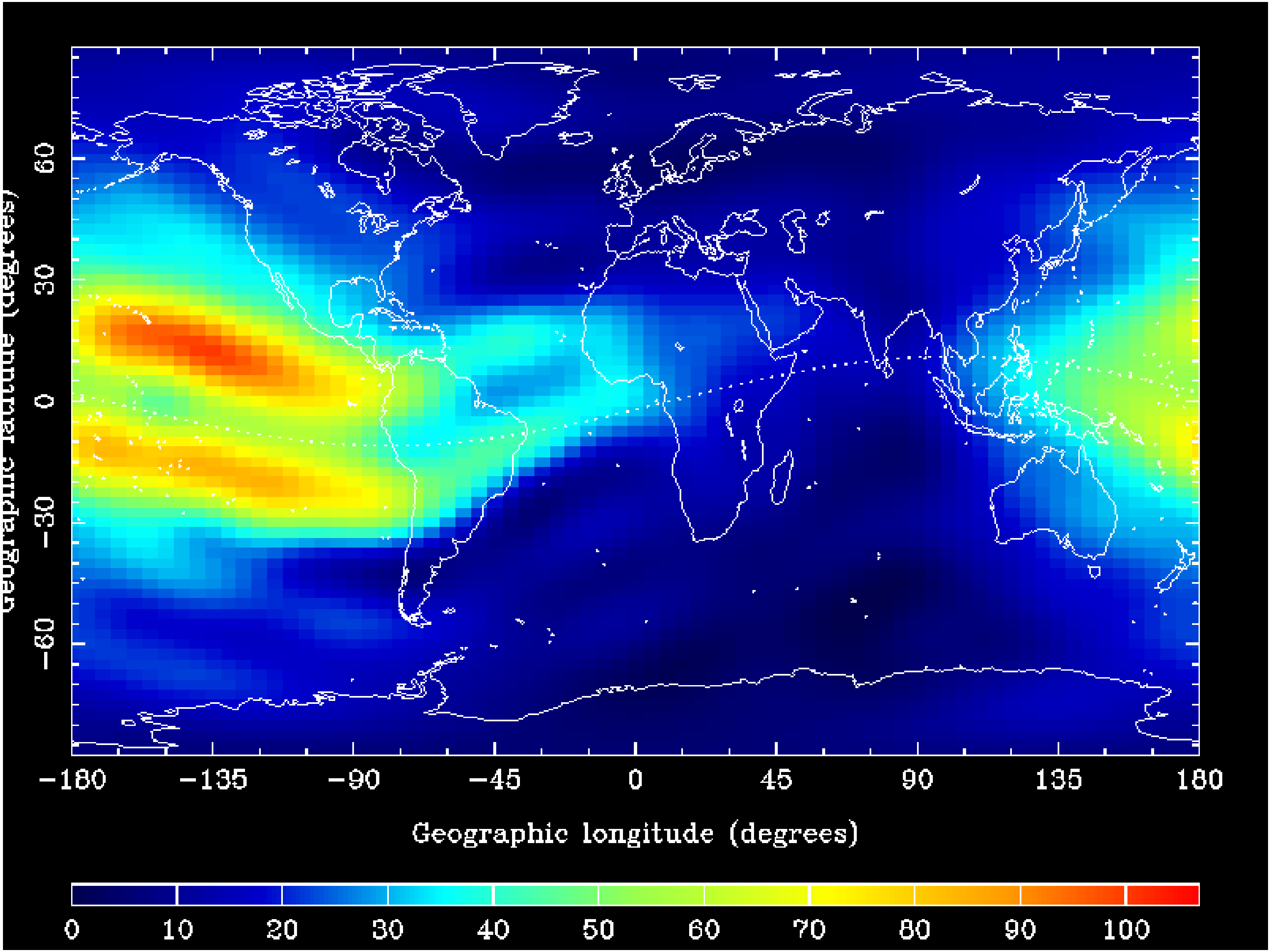


Daily TEC on 00APR09
45
40
35
Latitude in degrees
−180
0hours
−90
0
12hours
90
180
24hours
Local Time
0
10
20
30
40
50
60
70
80
90
100
TEC in TEC Units



Geographic latitude (degrees)
60
30
0
−30
−60
−180
−135
−90
−45
0
45
90
135
180
Geographic longitude (degrees)
0
10
20
30
40
50
60
70
80
90
100

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GNSS principles

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- Gradiometry

From GPS TD to Num. Weather Pred.

GPS observables

$$\Phi = \rho + c(dt - dT) + \lambda A - d_{ion} + d_{trop} + \varepsilon$$

data reduction

$$d_{trop} \cong ZTD \cdot m(el)$$

$$ZTD \cong 10^{-6} \int N dz$$

ZTD

ZTD possono essere assimilati direttamente (HIRLAM)

separation

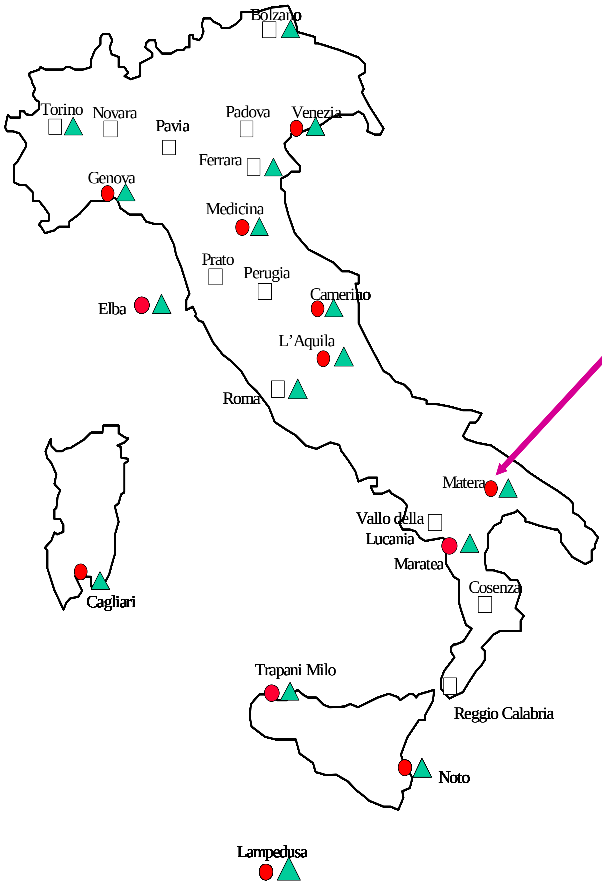
IWV

$$IWV \cong \Pi(T_m) ZWD = \Pi(T_m)\,(ZTD - ZHD)$$

assimilation

Meteo Forecasts

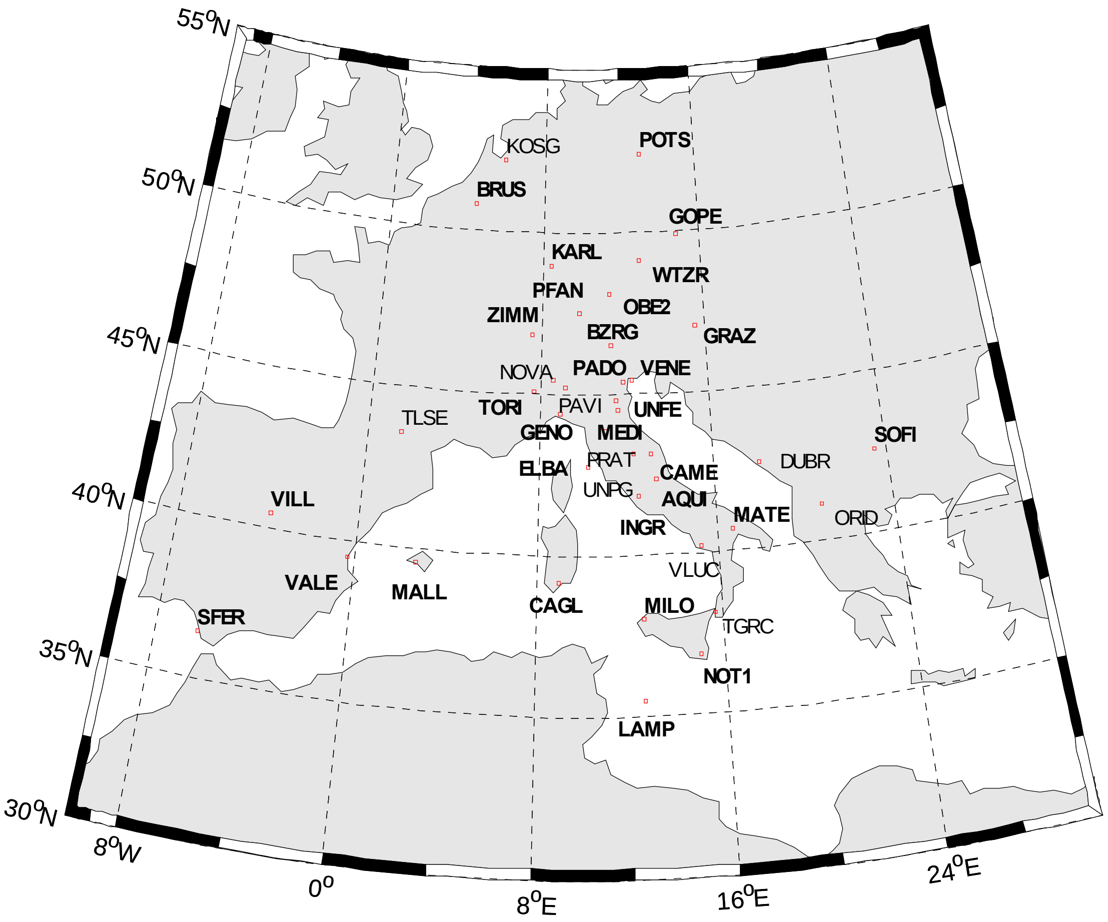
Italian GPS Fiducial Network



Matera ASI-CGS

- 12 ASI SITES
- 12 OTHER INSTITUTION SITES
- 16 HOURLY SITES

ASI Analyzed GPS Ground Network



40 stations in Post-Processing Mode

30 stations in Near-Real Time Mode

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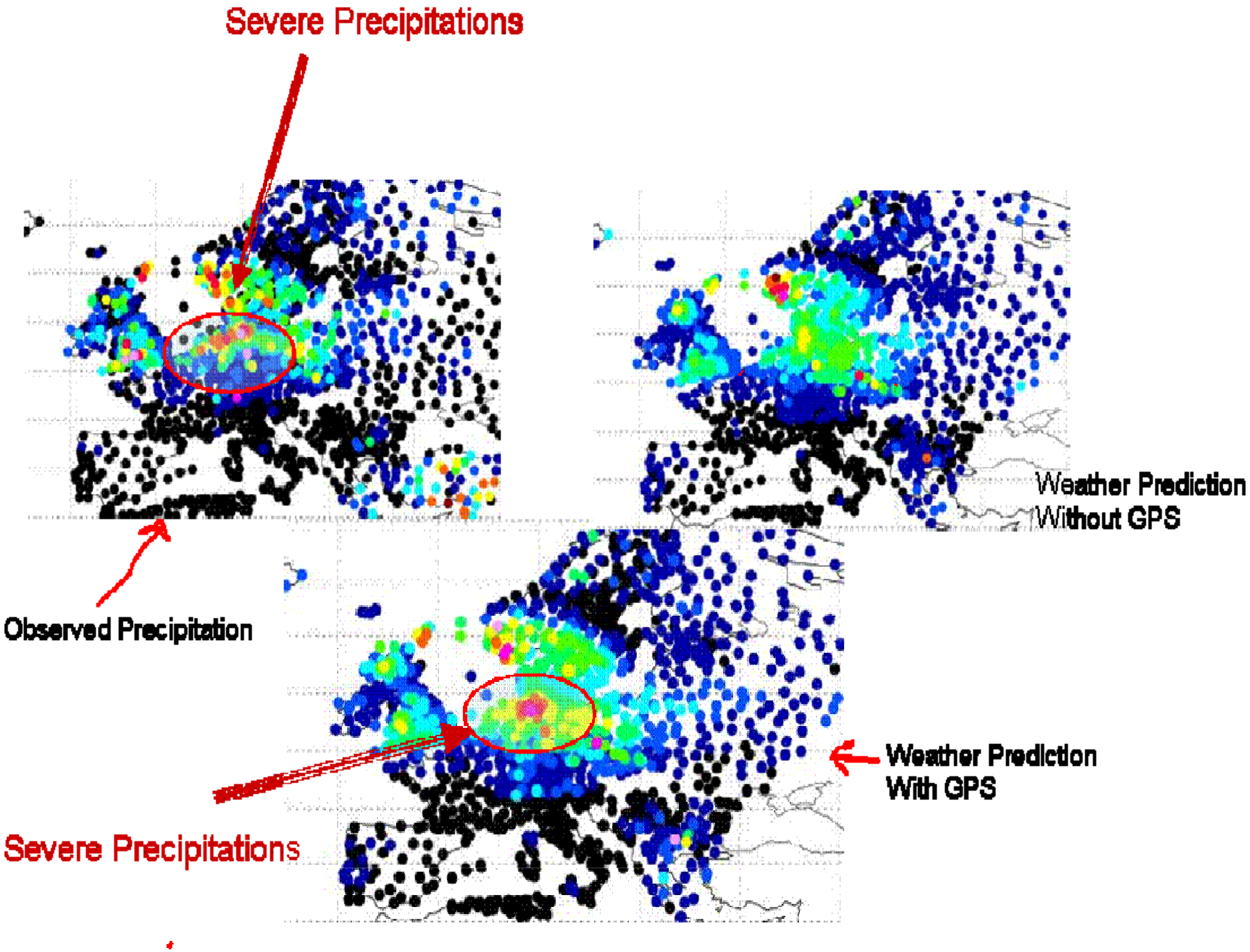
II Workshop on Satellite Navigation Science and Technology for Africa

Meteorology



GNSS principles

Maintainance of the Terrestrial Reference Frame ITRFxx

Seismicity and Landslides

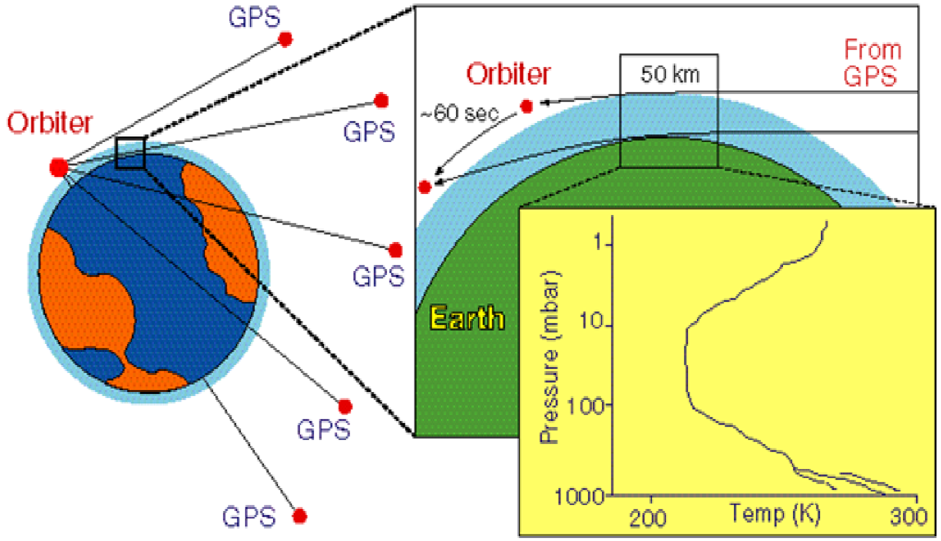
Mean Sea level

Ionosphere

Neutral Atmosphere (Meteorology & Climate)

Space Applications
- Radio Occultation
- Gradiometry

Radio Occultation with GPS

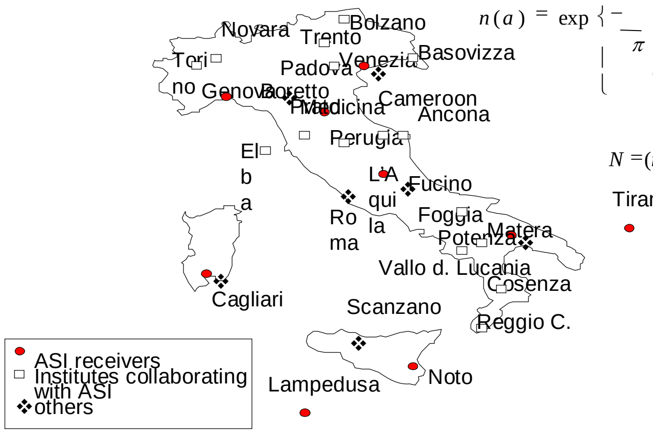


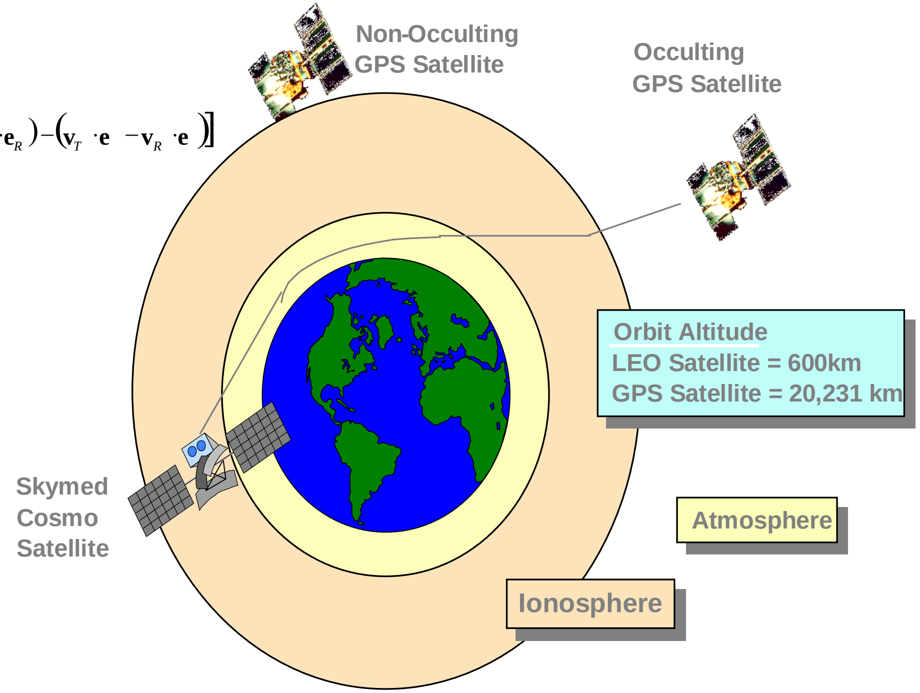
Radio Occultation Principle

$$\Delta f = \frac{f}{c}\left[\left(\mathbf{v}_T \cdot \mathbf{e}_T - \mathbf{v}_R \cdot \mathbf{e}_R\right) - \left(\mathbf{v}_T \cdot \mathbf{e} - \mathbf{v}_R \cdot \mathbf{e}\right)\right]$$

$$n(a) = \exp\left\{ -\frac{1}{\pi} \int_a^\infty \ln\left[\frac{x}{a} + \left(\frac{x^2}{a^2} - 1 \right)^{\frac{1}{2}} \right] \frac{d\gamma}{dx} dx \right\}$$

$$N = (n-1)\cdot 10^6 = 77.6\frac{P}{T} + 3.73\cdot 10^5 \frac{e}{T^2} + \ldots$$





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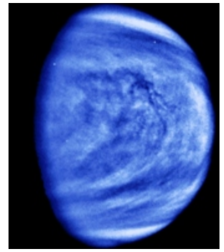
Mariner V Occultation at Venus:
Separate Stanford & JPL Experiments



One-way: Earth –> Venus

50 & 423 MHz uplinks

50 MHz data were not usable; the 423 MHz receiver lost lock at about 37 km altitude

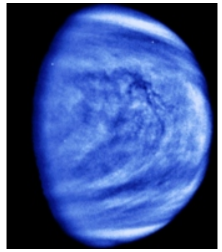
One-way: Venus –> Earth

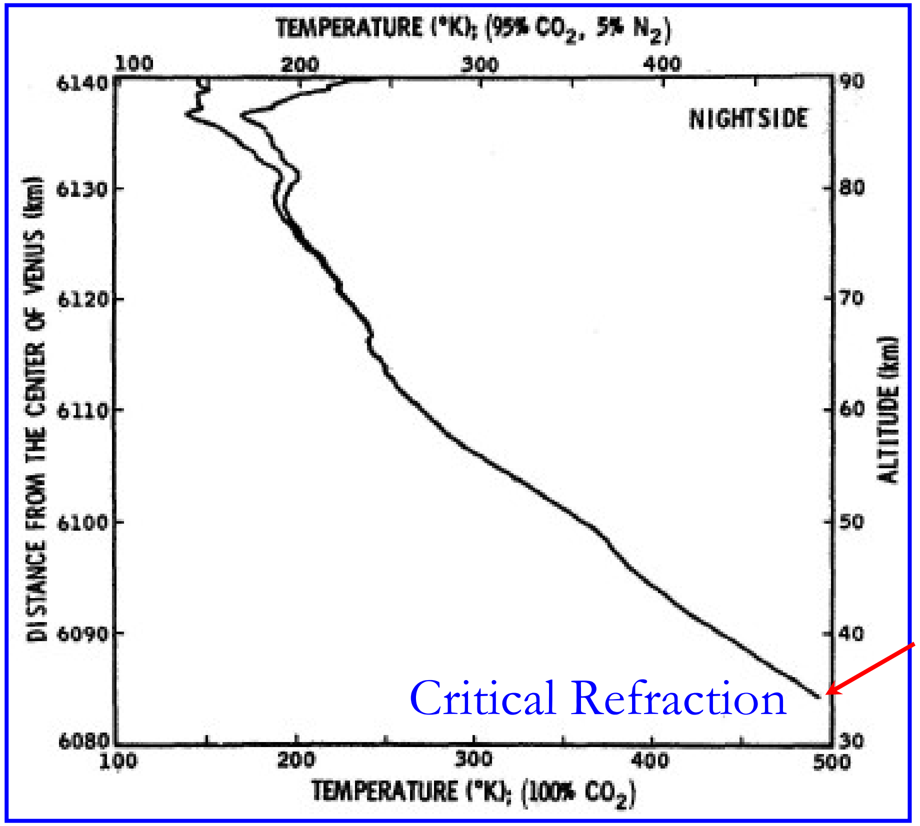
2.3 GHz downlink

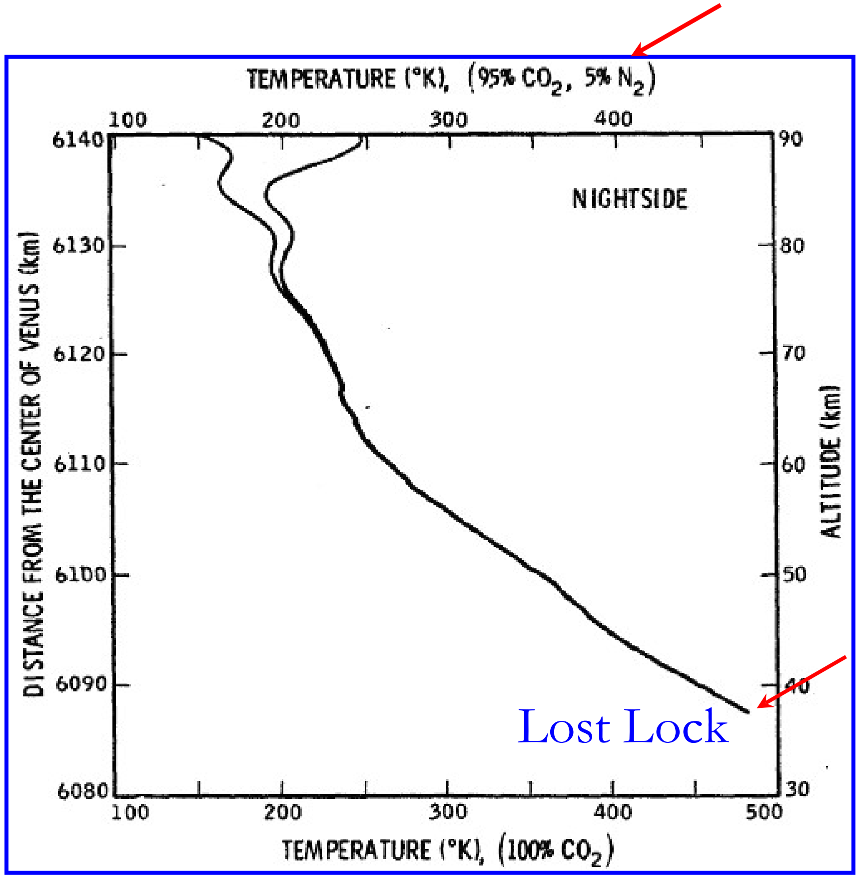
Obtained data from 90 to ~34 km altitude, then encountered critical refraction

Amplitude and phase based retrievals

Mariner V Occultation at Venus:
Temperature Profile Comparison

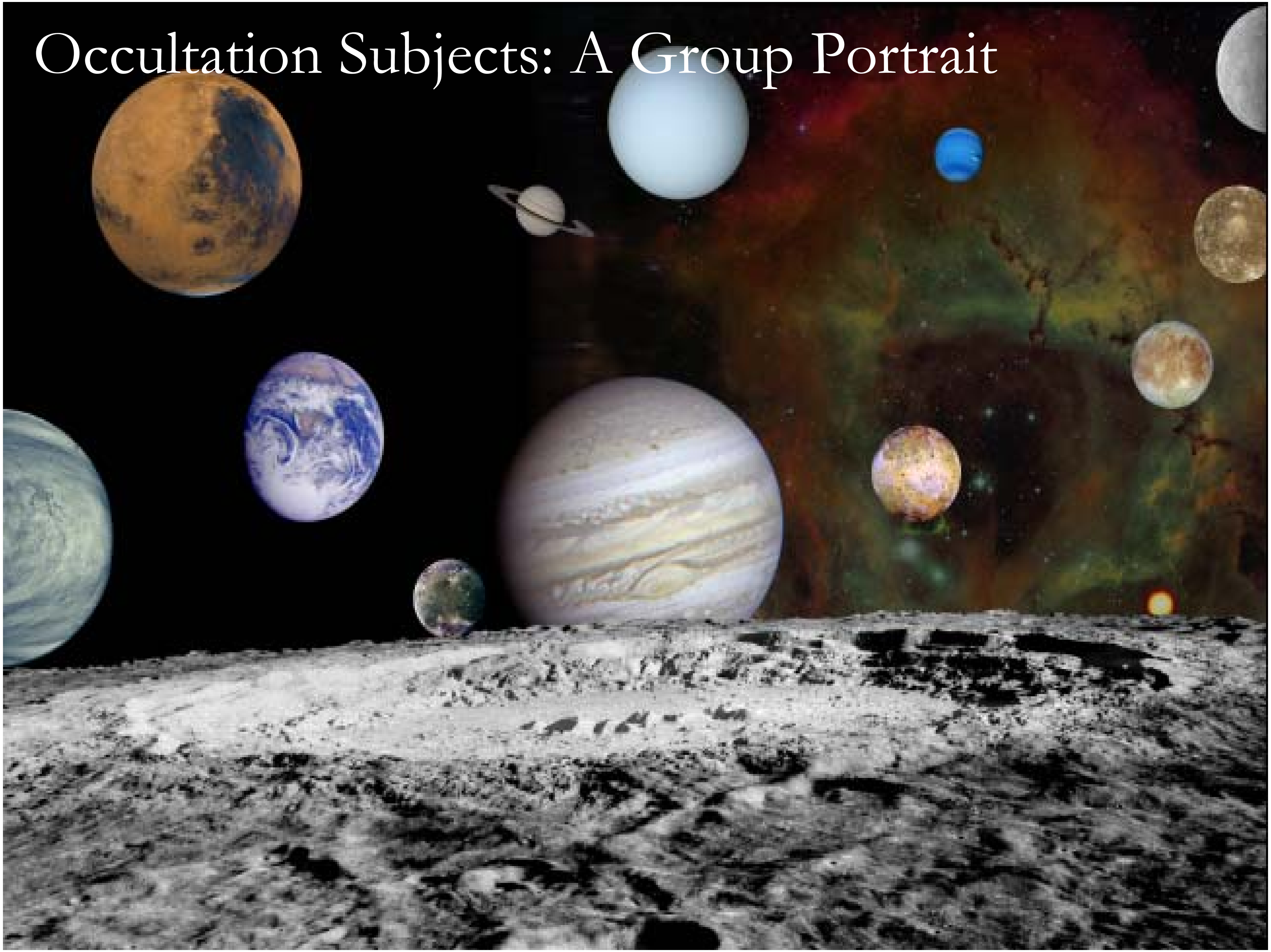


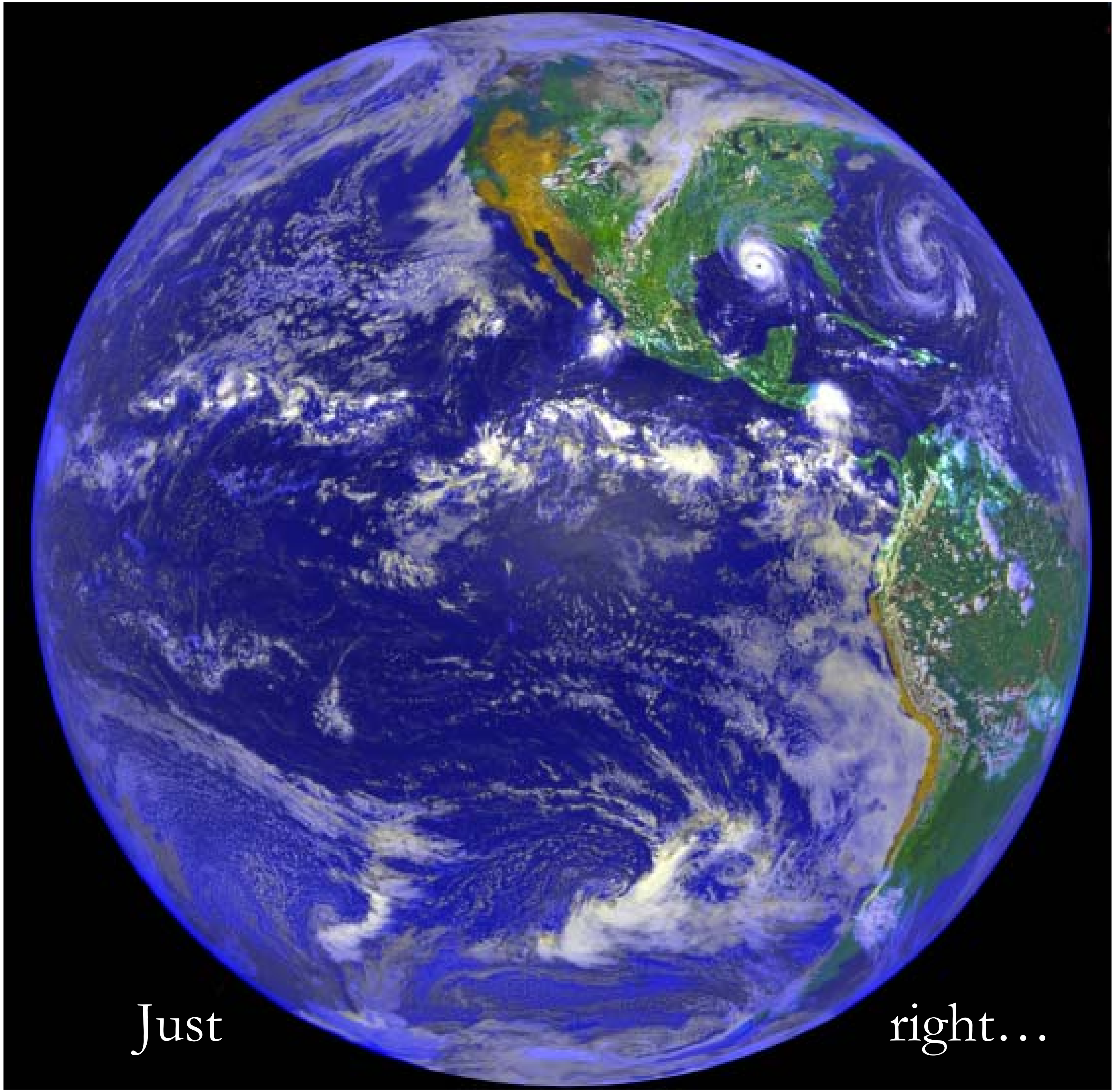




Fjeldbo et al., 1971

Occultation Subjects: A Group Portrait




Just
right…

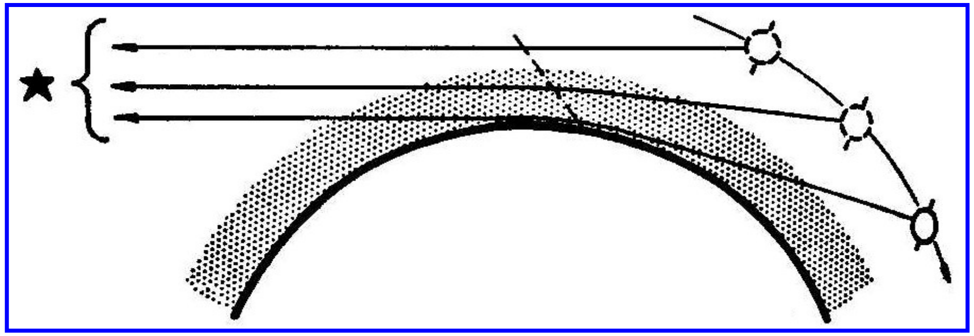
What took so long…?

Need a lot of transmitters and a lot of LEO receivers

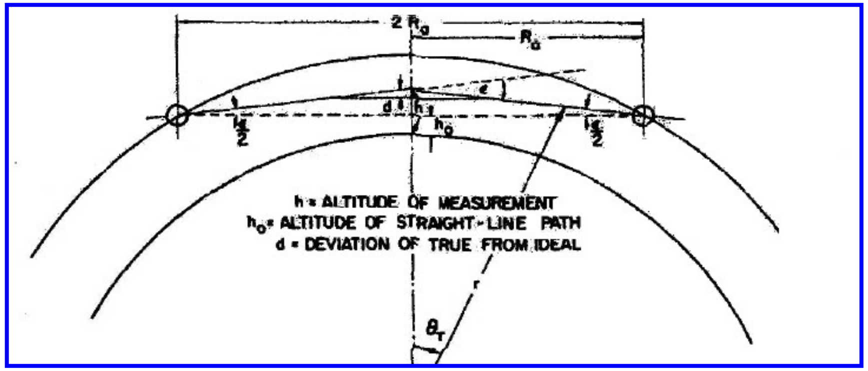
GPS did not fit the paradigm:
- One-way only
- Need flight USOs?
- Dithered GPS signal
- Need classified receiver?
- Suppressed GPS carrier
- Crude pseudorange only?
- Multipath a major concern
- Need high-gain antennas?

Earth Occultation – Early Concepts

Fishbach, 1965:
Stellar occultation from LEO



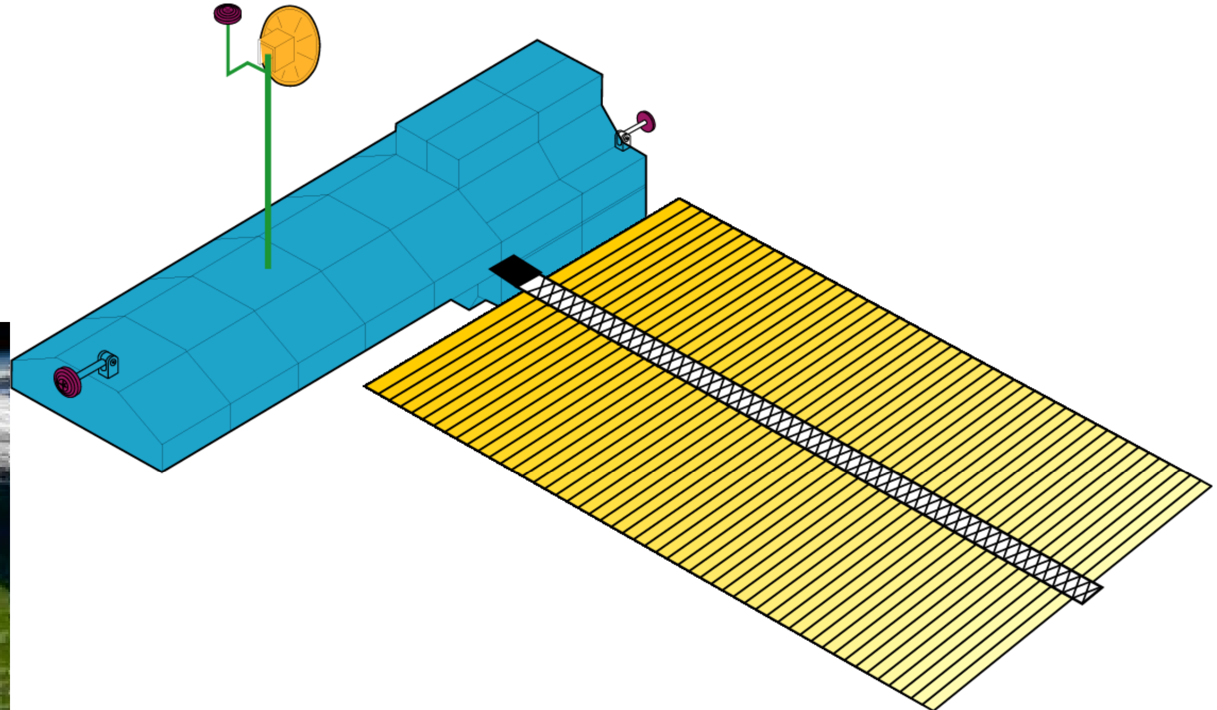
Lusignan et al., 1969: Radio sounding with tandem LEO's at a fixed separation



Gurvich and Krasil'nikova, 1987: Navigation satellites for sensing Earth atmosphere

GPS Geoscience Instrument

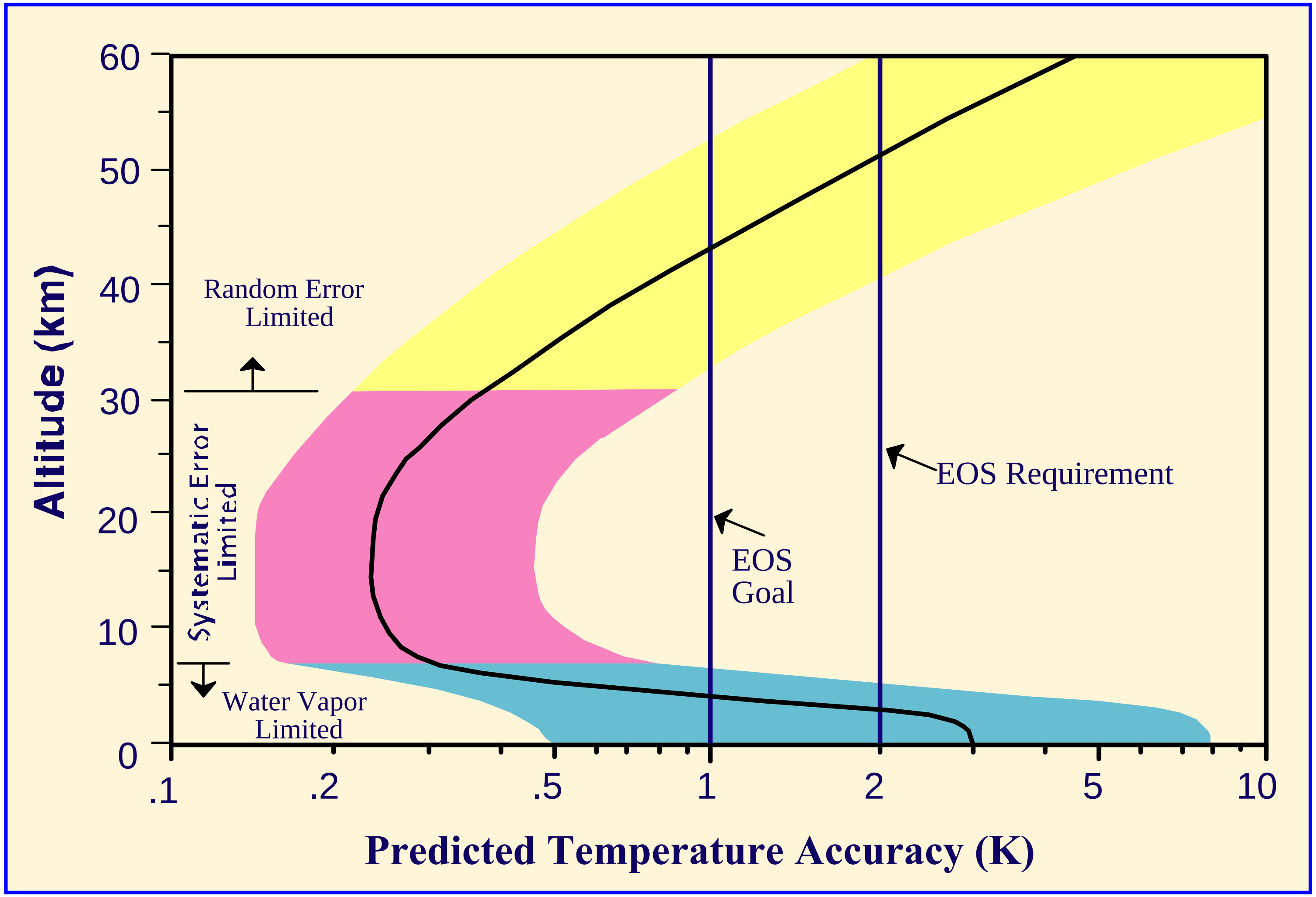
EOS-A, EOS-B and Space Station
(1988-1992)

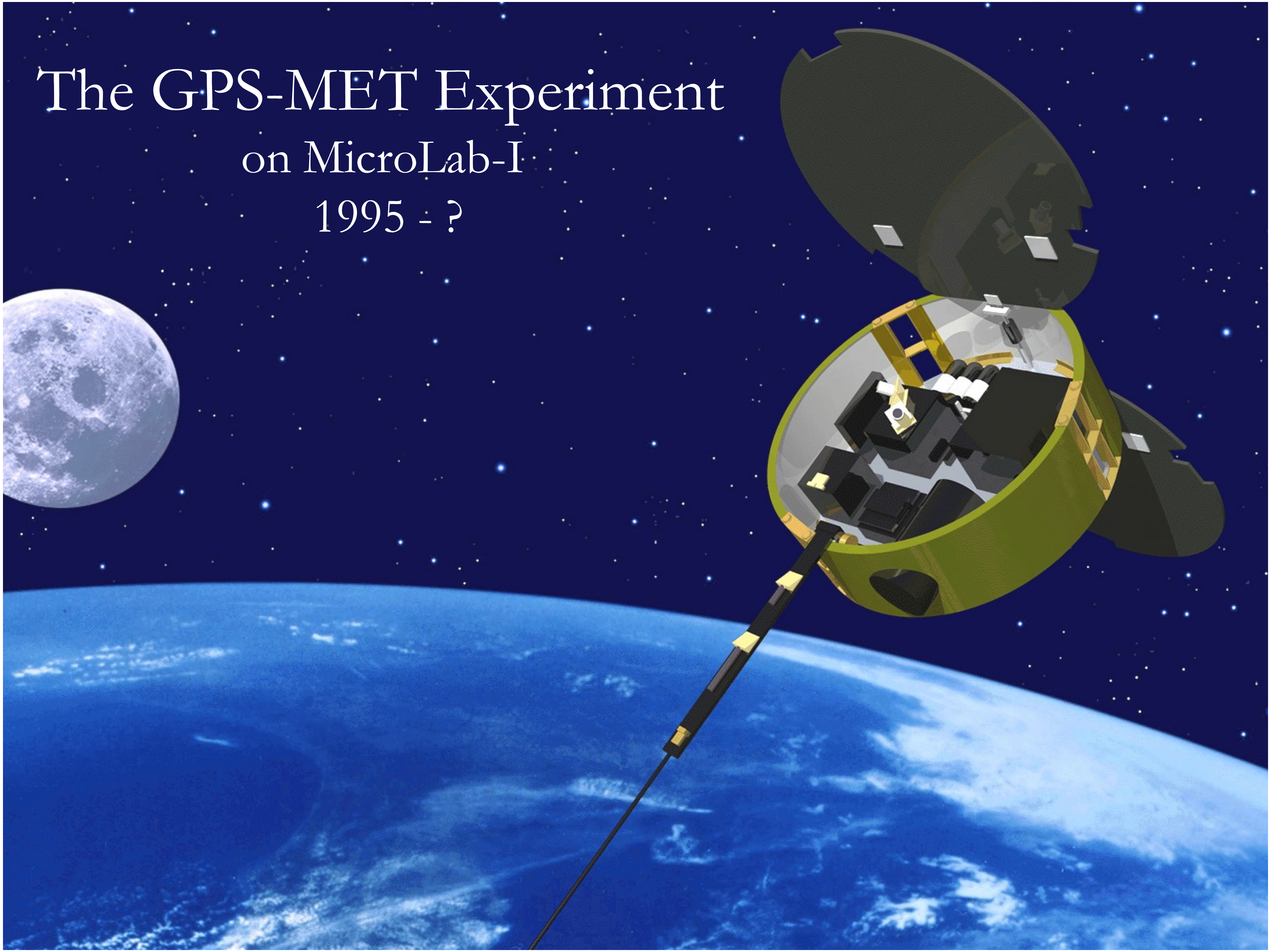


POD
Geodesy
Ionosphere Mapping
Atmospheric Occultation

GPS Geoscience Instrument

EOS-A, EOS-B and Space Station
(1988-1992)




The GPS-MET Experiment
on MicroLab-I
1995 - ?

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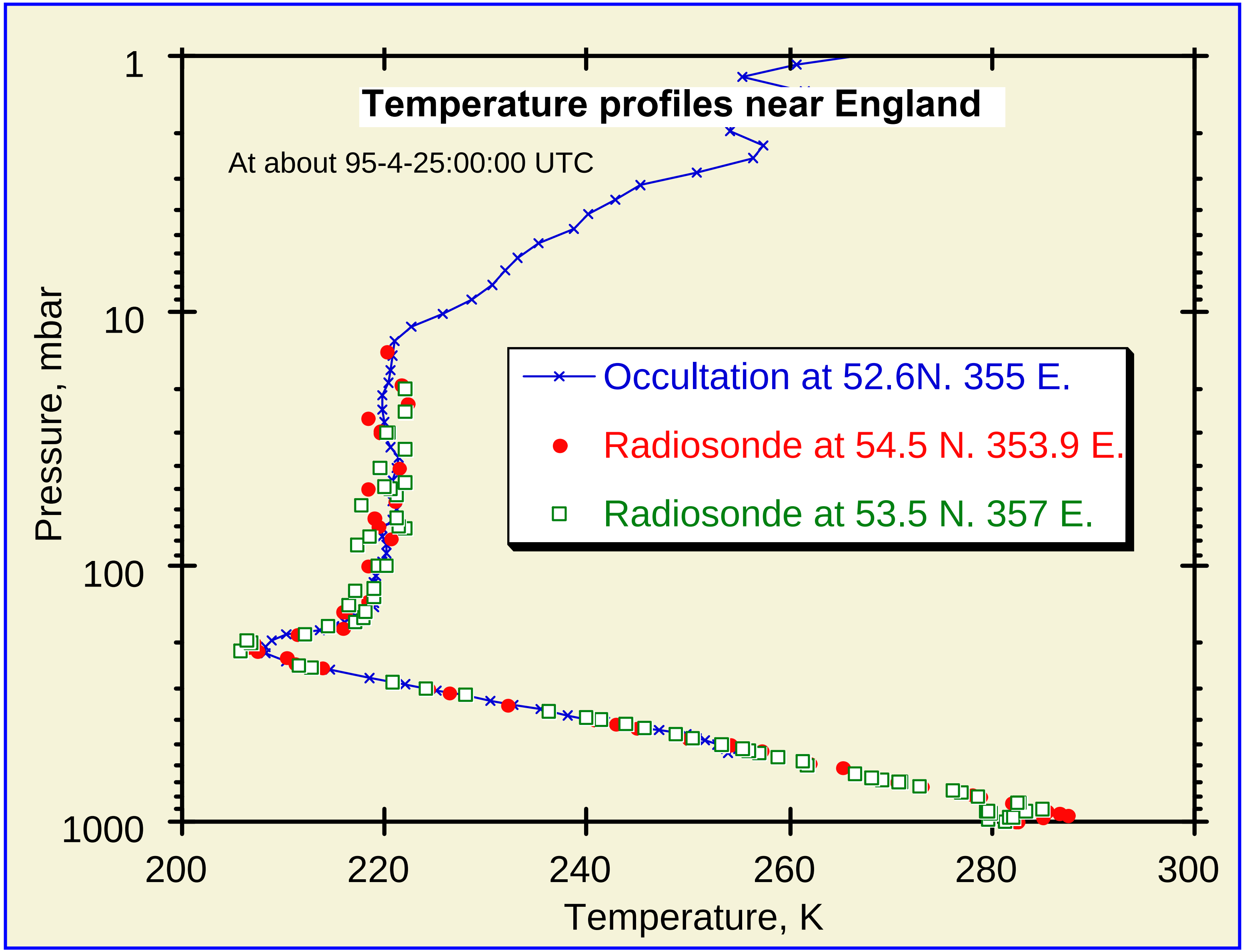
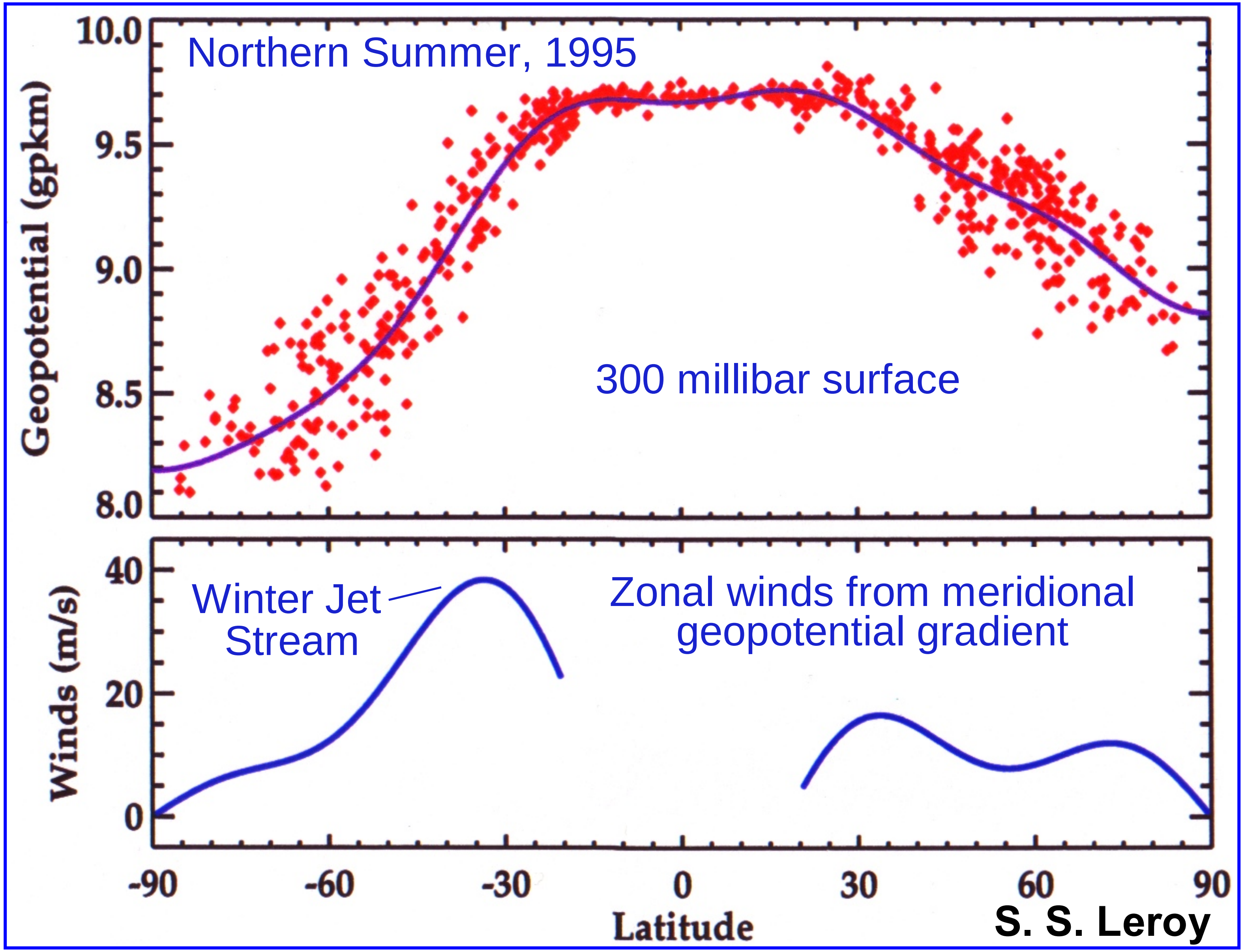
on MicroLab-I 1995 - ?

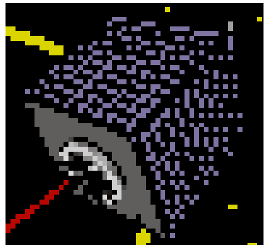


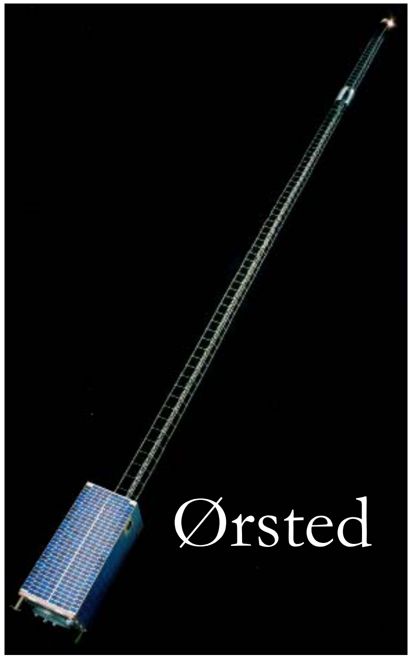
The GPS-MET Experiment
on MicroLab-I 1995 - ?

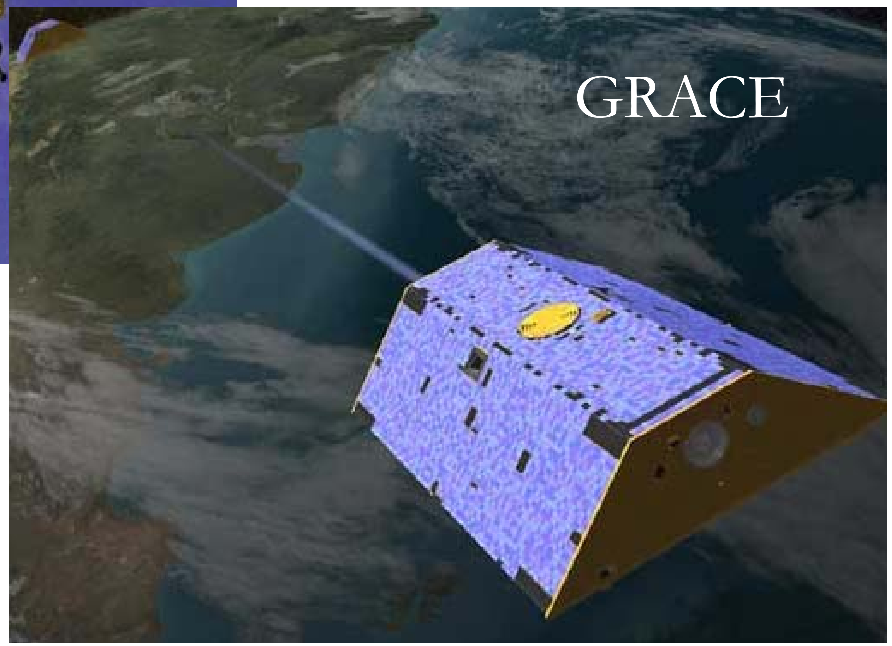


Sunsat

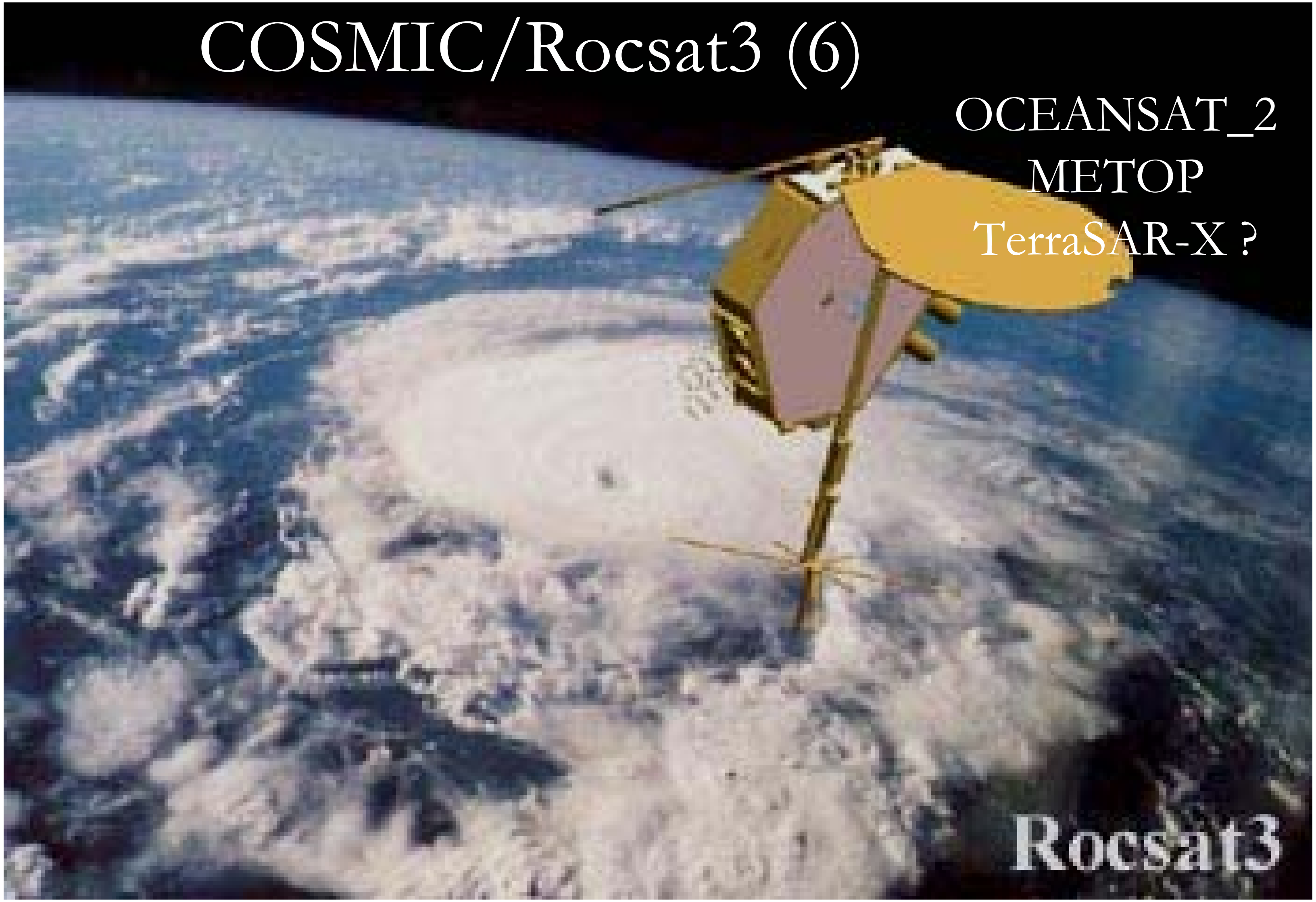
IOX







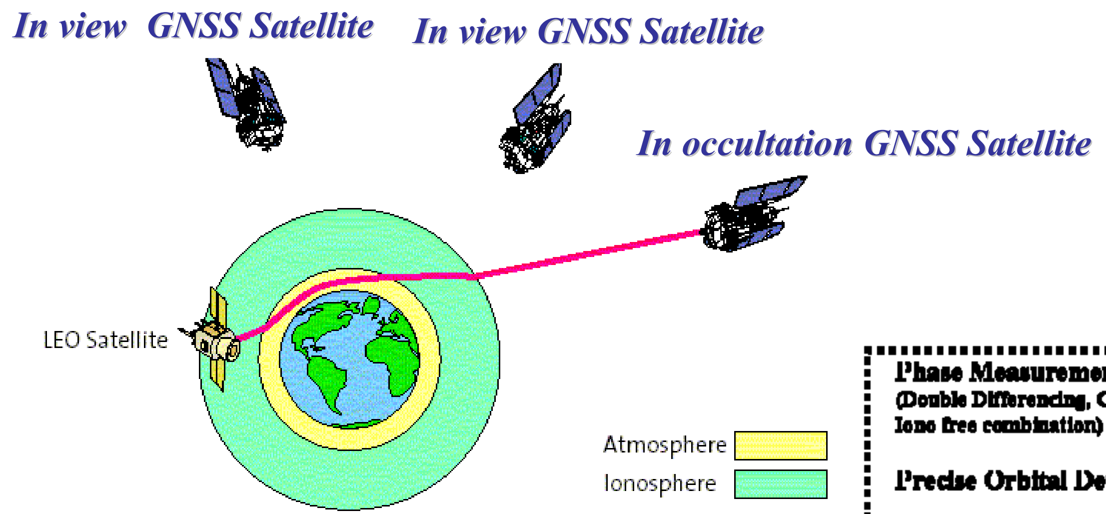
Main Current Attractions…

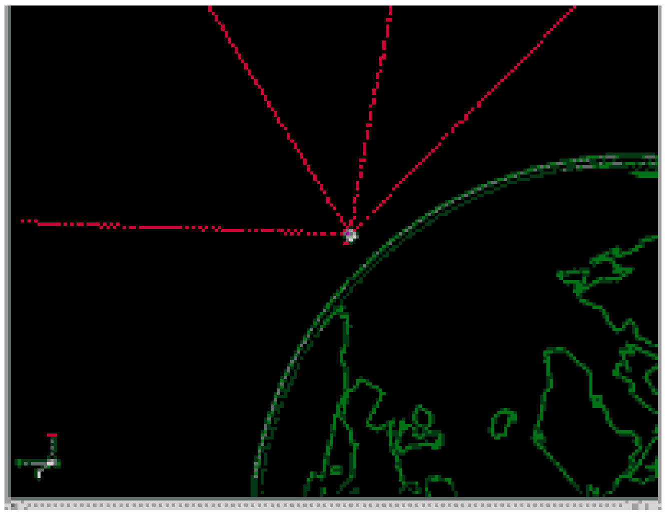


❑Presentation Outline

- ❑The Origin…
- ✓ *Description of the Radio Occultation Technique*
- ❑ Challenging Tasks
- ❑ NRT x LEO-POD
- ❑Conclusions

The GNSS Radio Occultation Technique





Phase Measurement Cleaning
(Double Differencing, Clock Estimation, Iono free combination)

Precise Orbital Determination

(Pre-processing)

Users:
- *Meteorology ?*
- *Climatology*
- *Space Weather*
- *Ionosphere Tomography (?)*
- *Space Geodesy*
- *Geophysics*

Shift Doppler Excess Δf

↓ *ray-tracing equations*

Bending angle $\alpha(a)$

↓ *Abel Inversion*

Refractivity $n(r)$

↓ *Termodinamic Relationships*

$P(r), T(r), P_w$

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Processing Chain

Phase Measurement Cleaning
(Double Differencing, Clock Estimation, Iono free combination)

Precise Orbital Determination
(Pre-processing)

Shift Doppler Excess Δf a)

ray-tracing equations

Bending angle $\alpha(a)$ b)

Abel Inversion

Refractivity $n(r)$ c)

Termodinamic Relationships

$P(r),\ T(r),\ P_w$ d)

Users:

- *Meteorology ?*
- *Climatology*
- *Space Weather*
- *Ionosphere Tomography (?)*
- *Space Geodesy*
- *Geophysics*

To Know Excess Shift Doppler Δf

Doppler Measurement depends on:

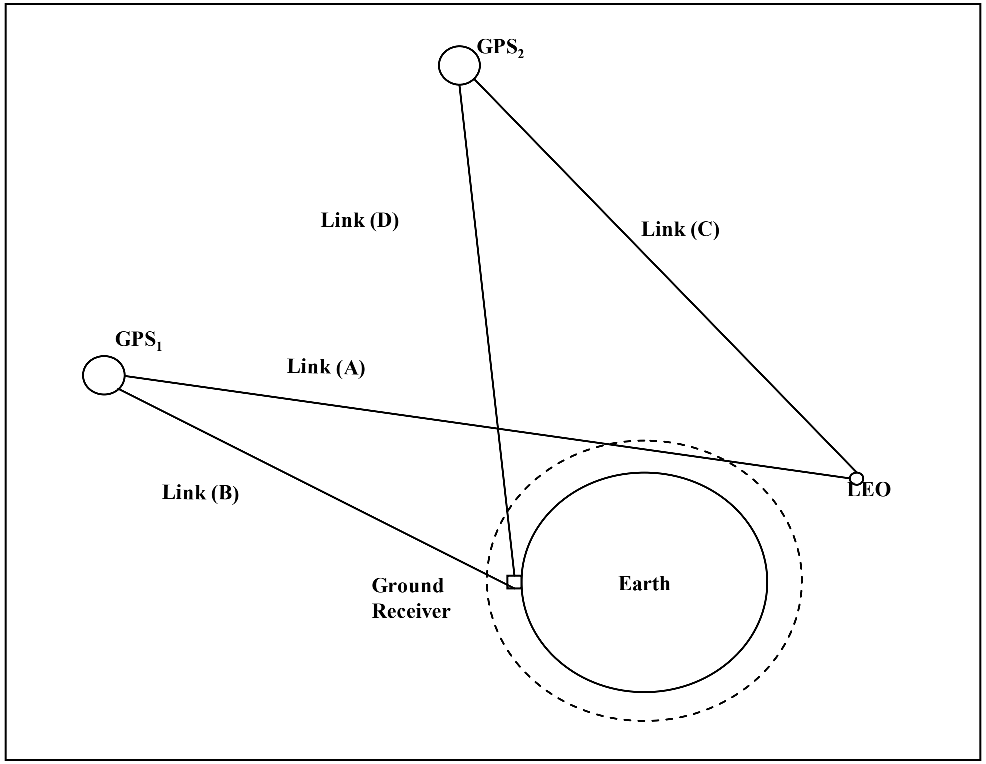
- Relative motion of GPS-LEO
- Clock Drift
- Atmospheric refraction

To single atmospheric refractivity we need:

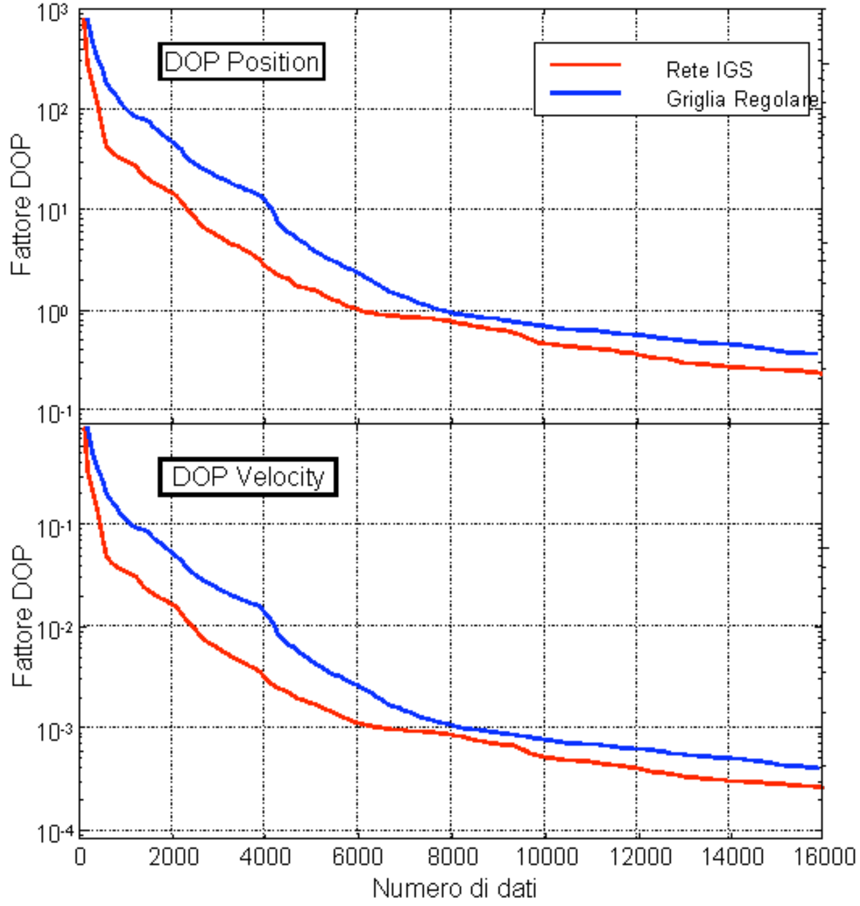
- Have GPS and LEO precise orbits
- Cancel out clock drifts

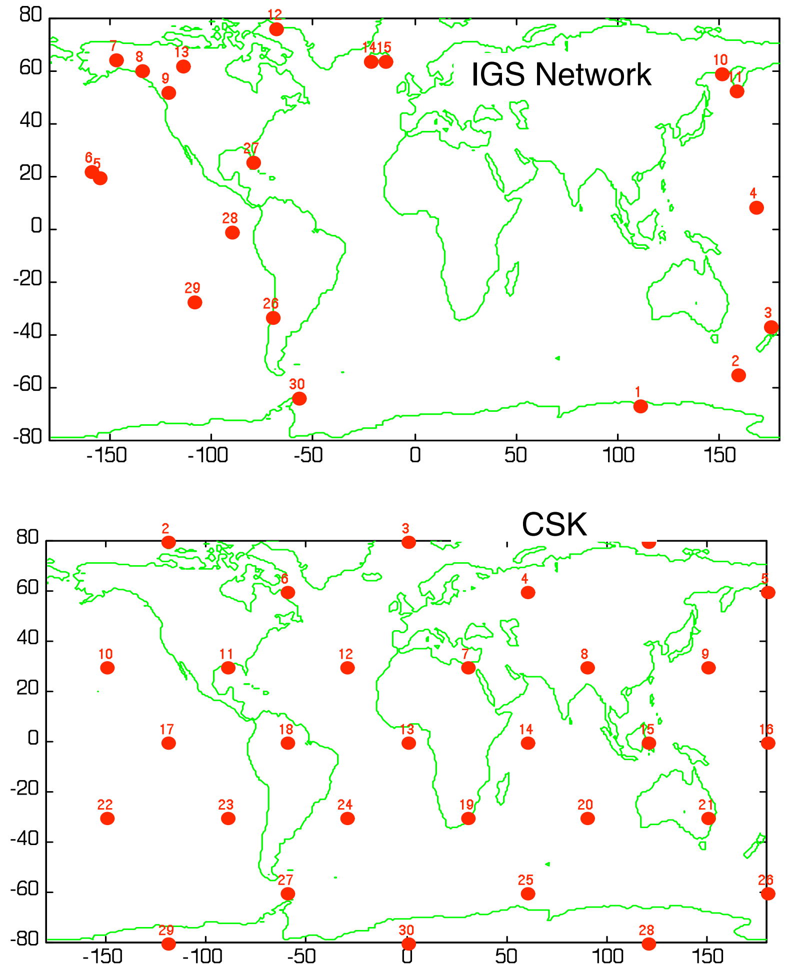
We do need Double Differences!!

Unless….we have good clocks



DOP Analysis





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Shift Doppler Excess Δf

ray-tracing equations

Bending angle $\alpha(a)$

Abel Inversion

Refractivity $n(r)$

Termodinamic Relationships

$P(r)$, $T(r)$, P_w

Innovation:

CT/FSI -Holography

BPV$_\alpha$

BPV$_n$

Integration with Ground GNSS Observations

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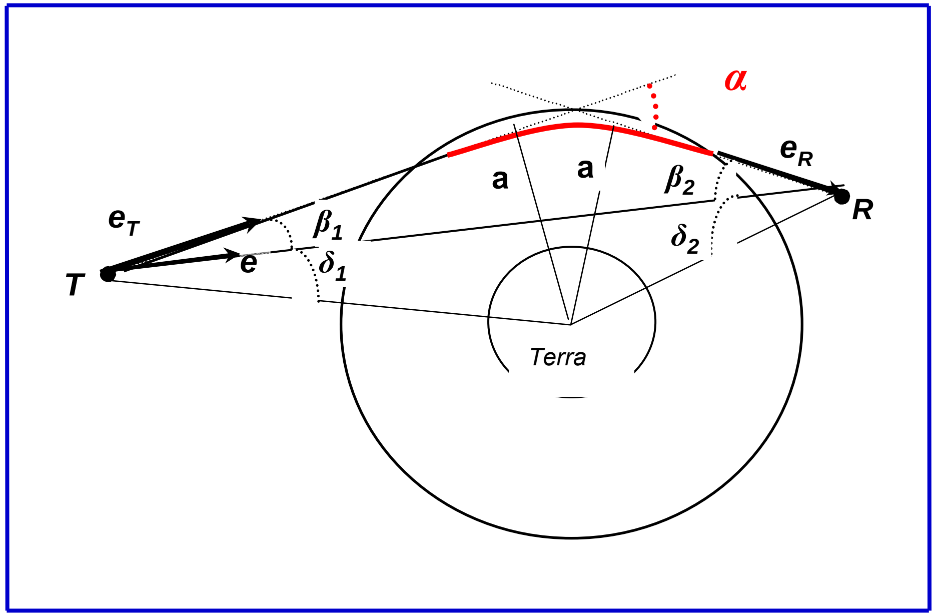
a) The Geometry of RO and the computation of the Bending Angles from Δf

The effect of the atmospheric refractivity on a travelling radiowave signal can be measured in terms of an **excess shift Doppler**

$$D_0 = \frac{f}{c}\left(\overline{v_T}\cdot\bar{e} - \overline{v_R}\cdot\bar{e}\right)$$

$$D_1 = \frac{f}{c}\left(\overline{v_T}\cdot\overline{e_T} - \overline{v_R}\cdot\overline{e_R}\right)$$

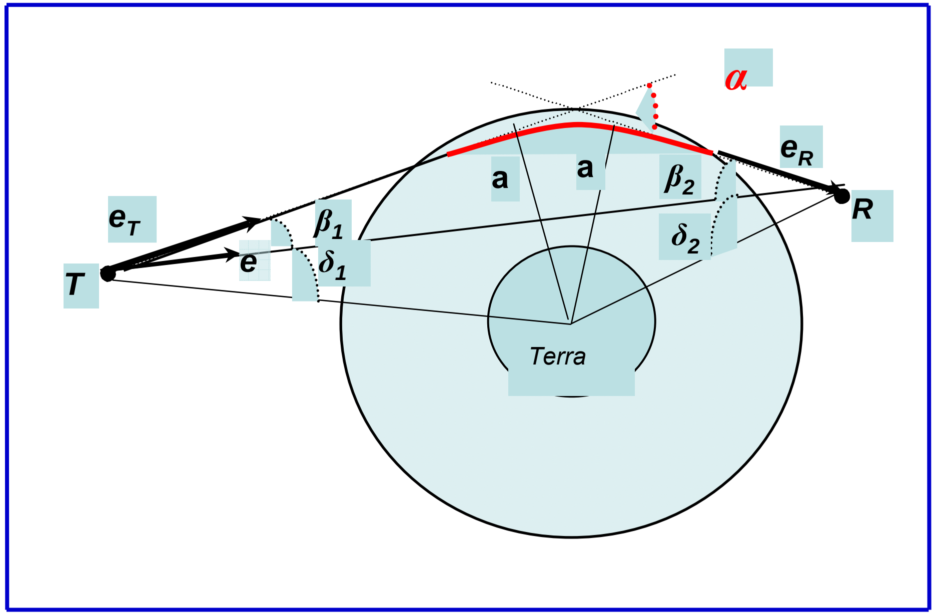
$\bar{v}_T, \bar{v}_R$: GPS and LEO velocity



1)

$$\Delta f = D_1 - D_0 = \frac{f}{c}\left[\left(\overline{v_T}\cdot\overline{e_T} - \overline{v_T}\cdot\bar{e}\right) - \left(\overline{v_R}\cdot\overline{e_R} - \overline{v_R}\cdot\bar{e}\right)\right]$$

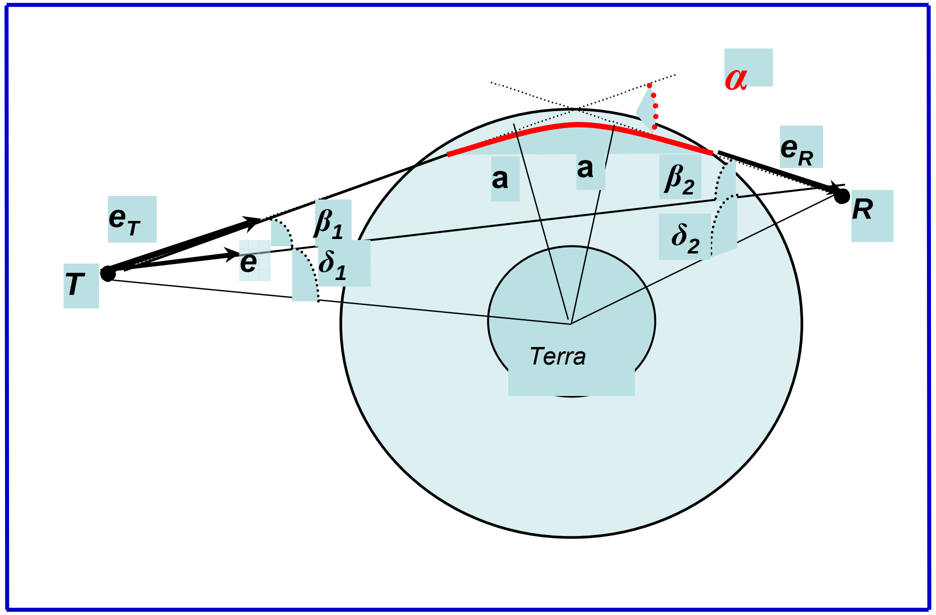
The Geometry of RO and the computation of the Bending Angles



2) $$r_T \sin(\beta_1 + \delta_1) = r_R \sin(\beta_2 + \delta_2) = a$$ → ***a*** is the Impact Parameter

3) $$\alpha = \beta_1 + \beta_2$$ → **α** is the ***bending angle***

The Geometry of RO and the computation of the Bending Angles: Iono Free Combination



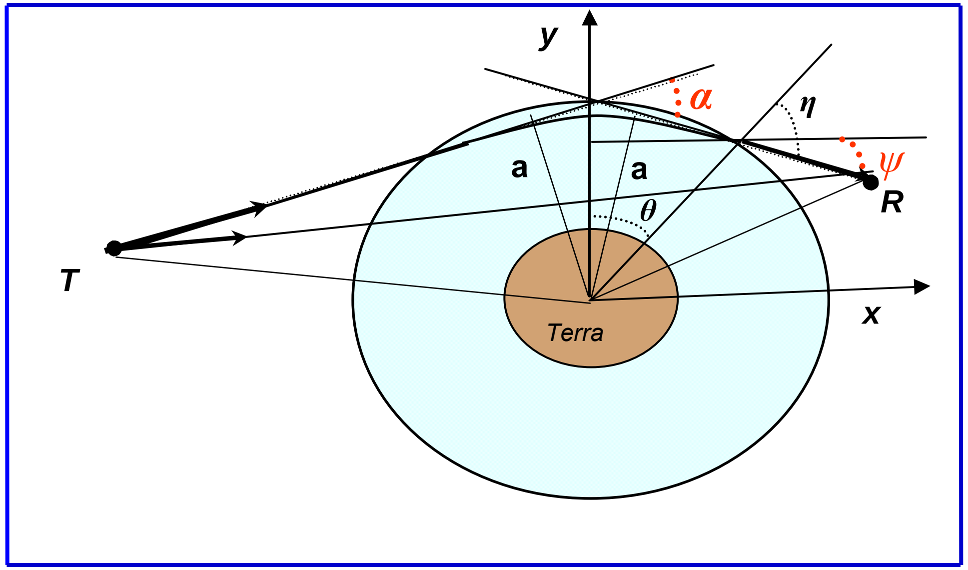
$$\alpha_{neut}(a_0) = \frac{f_1^2}{(f_1^2 - f_2^2)}\alpha_1(a_0) - \frac{f_2^2}{(f_1^2 - f_2^2)}\alpha_2(a_0)$$

Vorob'ev e Krasil'nikova, 1994

b)

RAY-TRACING: α → n(r)

- *n(r)* is a continuous function
- *n(r)·r* changes slowly and is increasing monotonic
- The horizontal gradient of *n(r)* is negligible in every layer.



$$\tan\eta = \frac{r\,d\theta}{dr}$$

$$n(r)r\sin\eta = n(r_0)r_0\sin\eta(r_0) = a$$

$$\psi = \eta + \theta - \frac{\pi}{2}$$

$$d\psi = -\frac{a}{\sqrt{n^2(r)r^2 - a^2}}\left(\frac{d\log n(r)}{dr}dr\right)$$

$$\alpha(a) = 2\int_{r_{min}}^{r_0}\frac{a}{\sqrt{n^2(r)r^2 - a^2}}\frac{d\log n(r)}{dr}dr$$

The Abel Inversion: $\alpha \rightarrow n(r)$

Volterra Equation Solution

$$\frac{1}{\Gamma(\alpha)}\int_a^x (x-t)^{\alpha-1} u(t)\,dt = f(x), \qquad a < x < b$$

$$u(x) = \frac{1}{\Gamma(1-\alpha)}\frac{d}{dx}\int_a^x (x-t)^{-\alpha} f(t)\,dt, \qquad a < x < b$$

The Abel Inversion: $\alpha \rightarrow n(r)$

$$\alpha(a) = 2a \int_{x=a}^{x=\infty} \frac{dn}{ndx} \frac{dx}{\left[x^2 - a^2\right]^{\frac{1}{2}}}$$

x = n·r

Abel Integral Equation for Refraction

$$n(r_1) = \exp\left[\frac{1}{\pi} \int_{\alpha=\alpha(a_1)}^{\alpha=\alpha(\infty)=0} \ln\left\{\frac{a(\alpha)}{a_1} + \left[\left(\frac{a(\alpha)}{a_1}\right)^2 - 1\right]^{\frac{1}{2}}\right\} d\alpha\right]$$

$$n(r_1) = \exp\left[\frac{1}{\pi} \int_{a=a_1}^{a=\infty} \ln\left\{\frac{a}{a_1} + \left[\left(\frac{a}{a_1}\right)^2 - 1\right]^{\frac{1}{2}}\right\} \frac{d\alpha}{da} da\right]$$

n(r) profile **obtained with Abel inversion. r_1 Is the tangent point.**

The Abel Inversion: $\alpha \rightarrow$ n(r)

The Volterra equations have ill-conditioned solutions….small errors can induce "unstable" behaviour of the integral solution.
Thus it is very important the selection of reliable initial conditions..

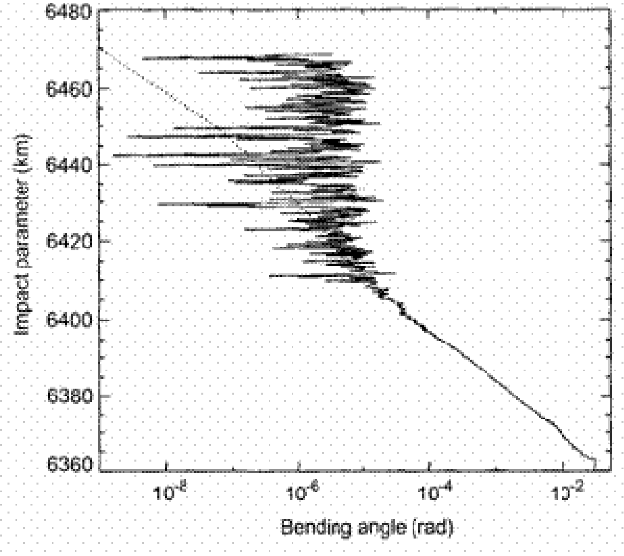
Particularly challanging in the upper Atmosphere because:

- Small $\alpha_{\mathbf{neut}}$
- **Big relative errors due to:**
  - GPS clocks
  - Orbit uncertainties
  - Thermic error of the receiver
  - Ionospheric corrections o($\frac{k}{f^2}$) not negligible anymore

The Abel Inversion: $\alpha \rightarrow n(r)$

Thus it is introduced the statistical optimization:

Sokolovskiy, S., and D. Hunt, Statistical optimization approach for GPS/MET data inversions, URSI GPS/MET Workshop, Tucson, Arizona, 1996.



$$\sigma_{noise} = \alpha - \alpha_m$$

$\alpha_m =$ the bending angle given by the model (MSISE90)

$\alpha =$ the bending angle really measured with GPS RO

$$\alpha_{new} = \alpha_m + C\sigma_{noise}$$

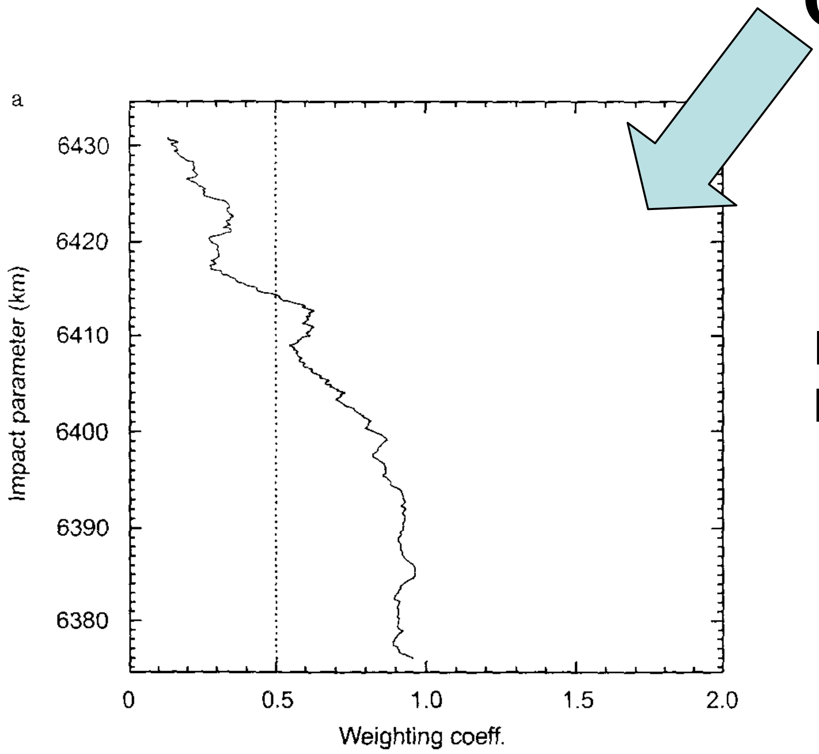
Where:

$$C = \frac{1}{1 + \left|\frac{\sigma_{noise}}{\sigma_{signal}}\right|} \qquad \sigma_{signal} = 20\%\, \alpha_m$$

Where C is the weighting coefficient

The Abel Inversion: $\alpha \rightarrow$ n(r)

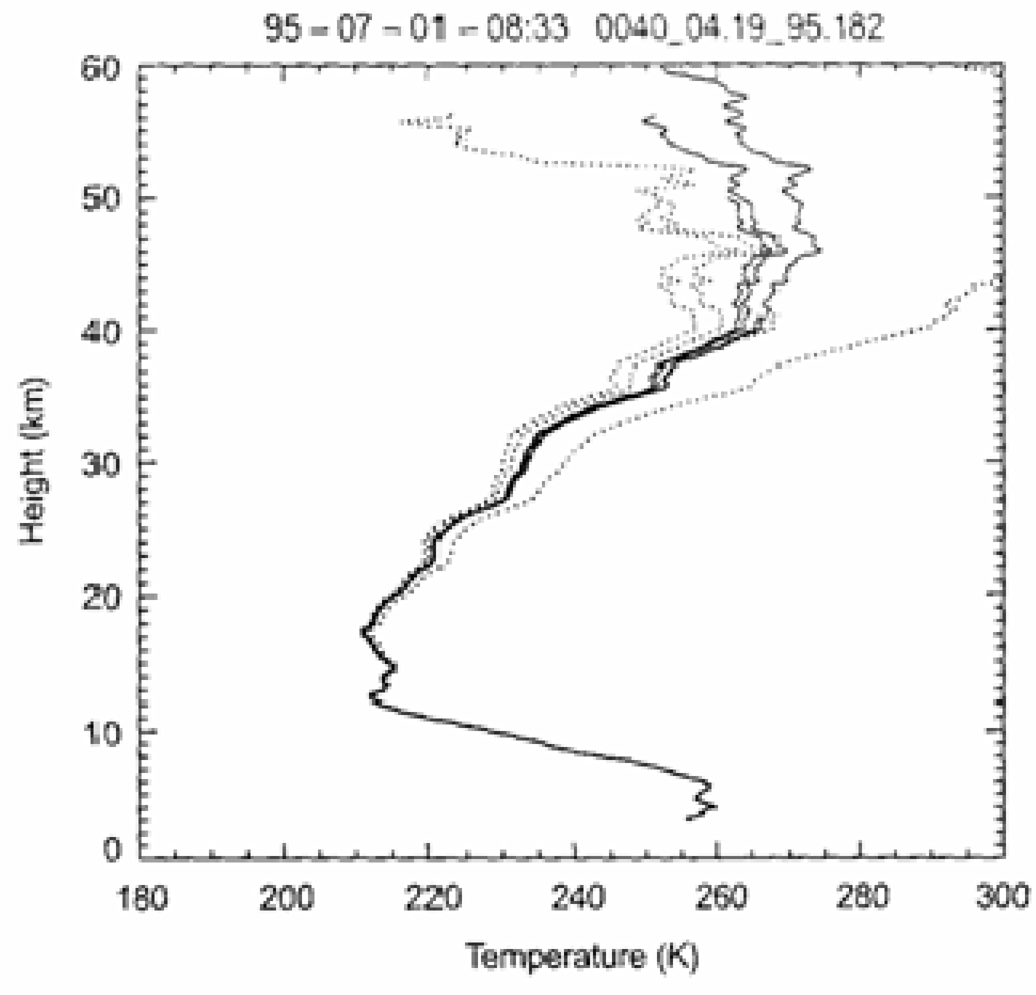
$$C = \frac{1}{1 + \left| \frac{\sigma_{noise}}{\sigma_{signal}} \right|}$$



If C→1 the observations weight more than the Model (lower atmosphere)

If C→0 the model weights more than the Observations (higher atmosphere)

The Abel Inversion: $\alpha \rightarrow n(r)$



C)

from N(α)→P,T,W

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} \qquad (1)$$

To solve for P_d, T and P_w it is used :

- **THE HYDROSTATIC EQUILIBRIUM LAW** ⇒

$$\frac{dP}{dh} = -g\,\rho \qquad (2)$$

- **THE IDEAL GAS LAW** ⇒ $PV = RT \Rightarrow \rho = \frac{mP}{TR}$

$$\rho = \rho_d + \rho_w = \frac{m_d P}{TR} + \frac{(m_w - m_d)P_w}{TR} \qquad (3)$$

Solving (1) for $\frac{P}{T}$ and combining (2) and (3) ⇒

$$\frac{dP}{dh} = -\frac{g m_d}{a_1 R} N + \frac{a_2 g m_d}{a_1 R}\frac{P_w}{T^2} + \frac{g(m_d - m_w)}{R}\frac{P_w}{T} \qquad (4)$$

So, we have the two equations: (1) and (4) in three unknowns: P_d, T and P_w

We consider two different cases:

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C)

from N(α)→P,T,W

DRY AIR

- P_w can be ignored in the upper atmosphere (for heights where T<250 °K ($h_{250°K}$)
- Given N, both T and $P = P_d$ can be solved from (1) and (4)

WET AIR

When in the middle and low troposphere P_w is not negligible. Thus we have a **Rank Deficiency** it is necessary to have an independent knowledge of one of the three parameters (***T*, *P*, P_w**) in order to solve for the other two: the method proposed for the integration are:

- Take the values of P and T from ECMWF or NCEP at certain bounday layers and use them for an iterative solution of the equations (Kursinski & al. 1997);
- Apply the Optimal Estimation Approach (Merging of RO and ECMWF models)
- Add new observations as those of GPS ground permanent stations (challanging…)
- BPV method (challanging)

from N(α)→P,T,W

Gorbunov, M.E., Sokolovskiy, S.V., 1993, Remote Sensing of Refractivity from Space for Global Observations of Atmospheric Parameters, *Report 119, Max Planck Institute for Meteorology*.
***Kursinski, E. R., Hajj,* G. A., 2001, A comparison of water vapor derived from GPS occultations and global weather analyses, *J. Geophys. Res.*,106, 1113-1138.**

WET AIR

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} \qquad (1)$$

$$\frac{dP}{dh} = -\frac{g m_d}{a_1 R} N + \frac{a_2 g m_d}{a_1 R} \frac{P_w}{T^2} + \frac{g(m_d - m_w)}{R} \frac{P_w}{T} \qquad (4)$$

1. Assume $P_w(h) = 0$ for a first guess;
2. Integrate (4) to obtain $P(h)$;
3. Use $P(h)$ and $T(h)$ in (1) to update $P_w(h)$;
4. Repeat step 2. And 3. until convergence.

from N(α)→P,T,W
Optimal Estimation

Assuming all Errors as Gaussian, the penalty function is built as follows:

$$\xi(x) = (y_{obs} - y(x))^T S_y^{-1} (y_{obs} - y(x)) + (x - x_a)^T S_a^{-1} (x - x_a)$$

Where:

y_{obs}=vector of measurements

y(x)=simulated vector of measurements based on the solution state vector ***x*** (rapresents a profile of temperature and water vapor+ a surface pressure,

x_a= the apriori state vector from an analysis

S_a and S_y are, in turn, the analysis error covariance and measurement error covariance plus the covariance forward model which relates the state vector to the observation

The Solution is:

$$x_{n+1} = x_n - [H_x \xi(x)]^{-1} \nabla_x \xi(x_n)$$

H_x and ∇_x are the Hessian and the gradient applied to the penalty function

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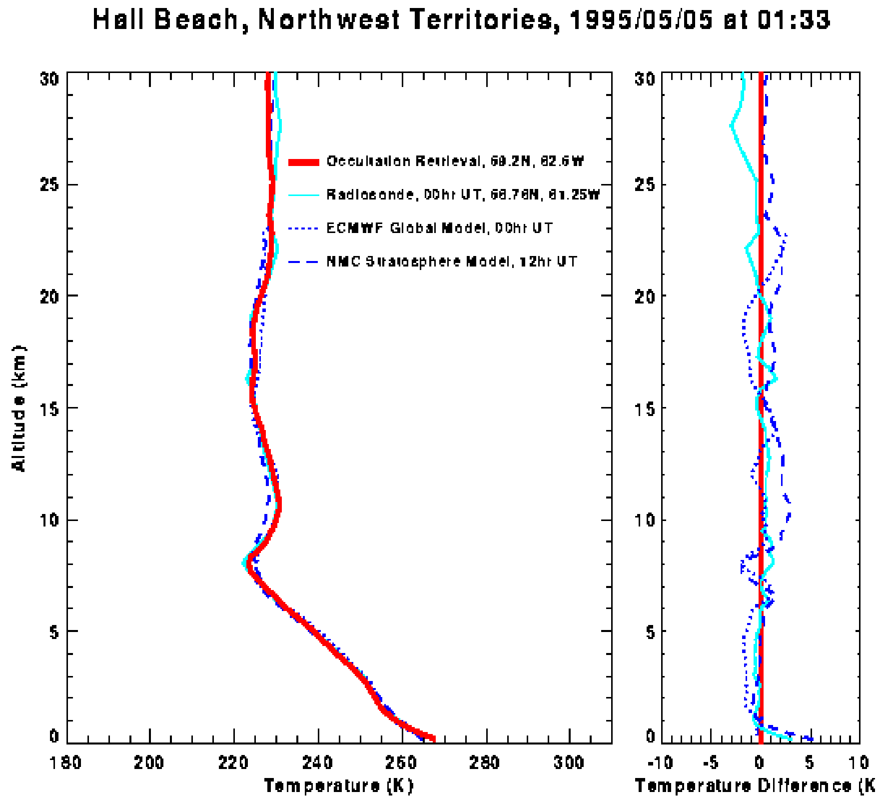
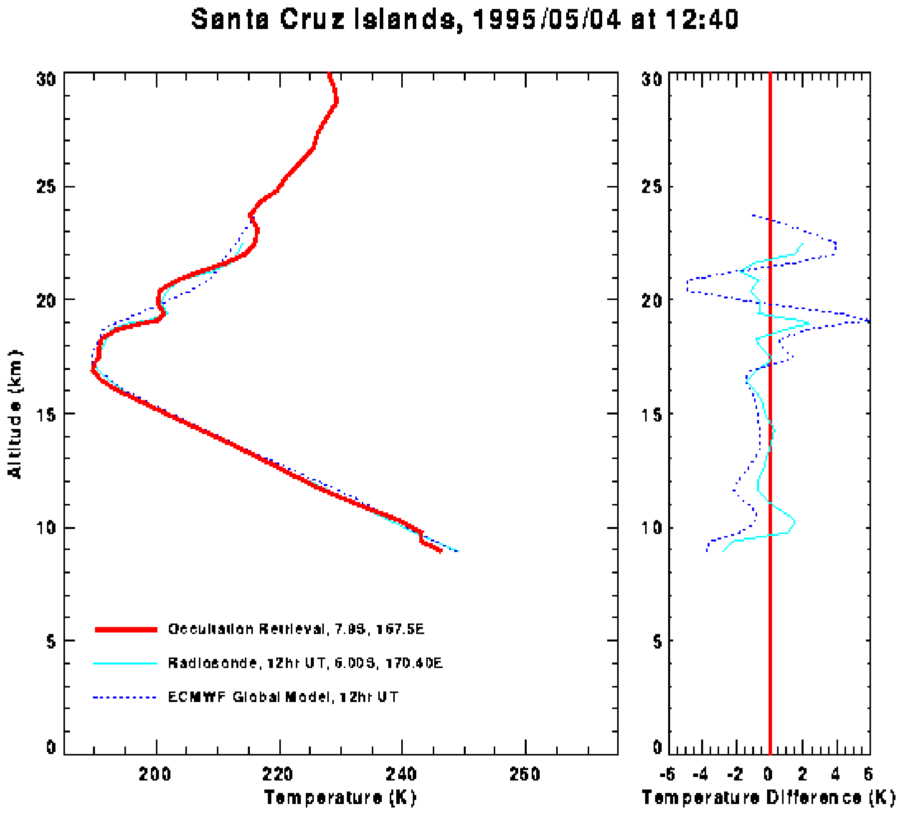
D)

PROFILES



Cold and Dry Areas

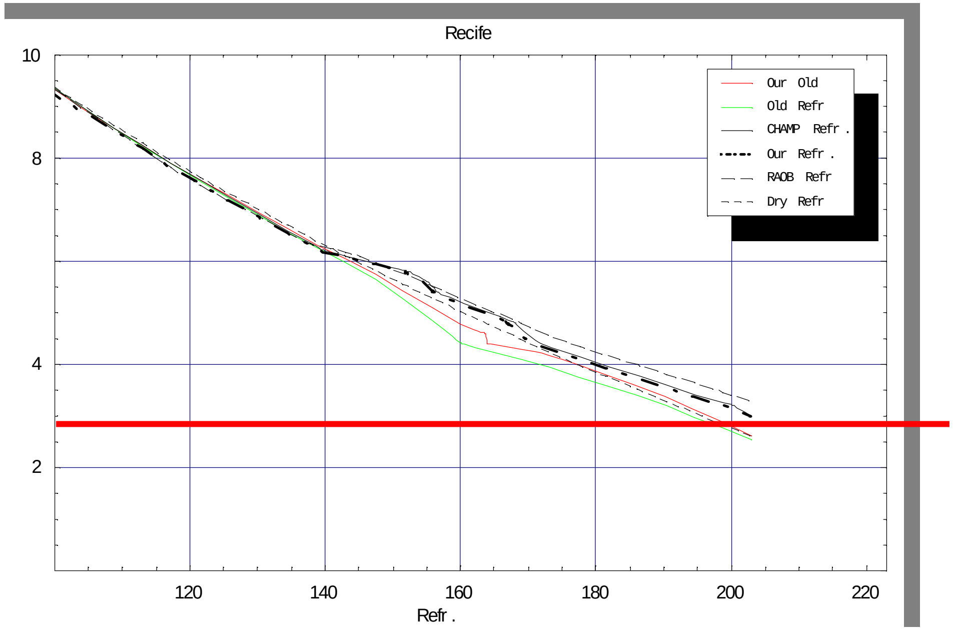


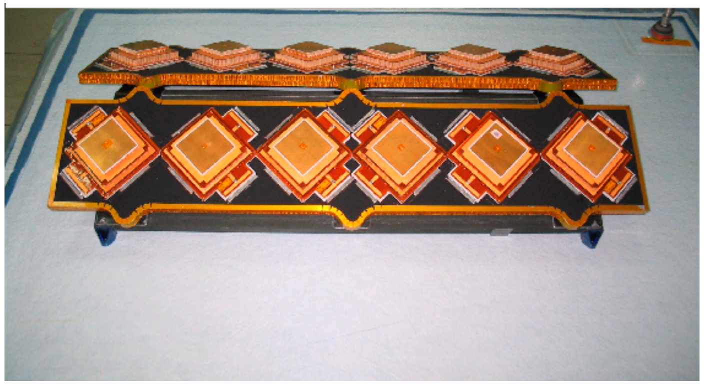
Wet and Hot Areas

❑Presentation Outline

- ❑The Origin…
- ❑ Description of the Radio Occultation Technique
- ❑ *Challenging Tasks*
- ❑ NRT x LEO-POD
- ❑Mission Analysis ROSA on OCEANSAT_2
- ❑GPS & GALILEO
- ❑Conclusions

Extinction





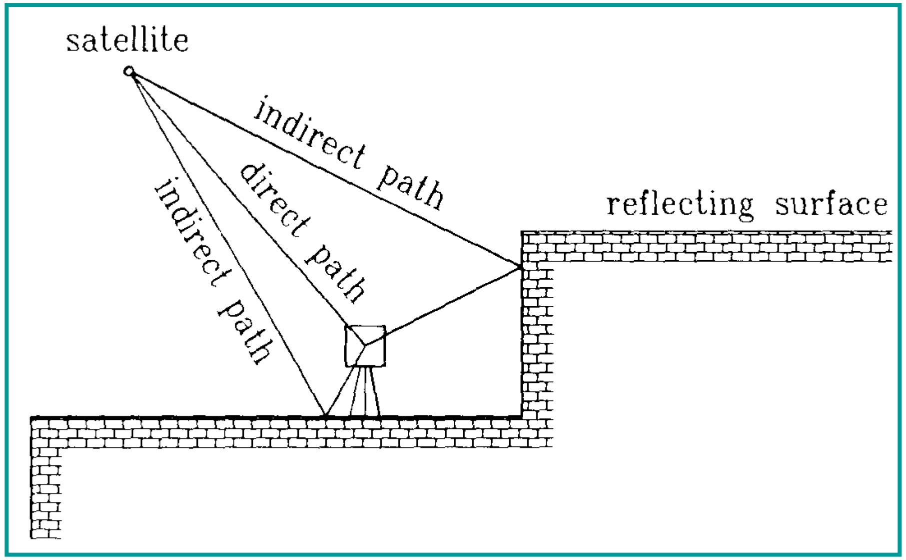
ROSA

Seldom RO is unable to retrieve profiles down to the ground

Solutions:

- **High gain antenna 12 dbm**
- **Open Loop Approach……**

MULTIPATH:



***multipath*:** The signal suffers reflections before arriving to the antenna

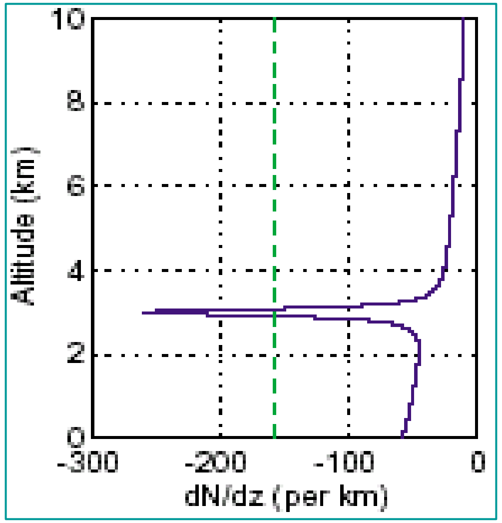
Geometrical Optics principles are not applicable anymore

Multipath is due to irregularities and inversion of refractivity through the atmosphere:

It can be solved with applying canonical transform (CT) or Radio holography technique and using good quality GPS receivers

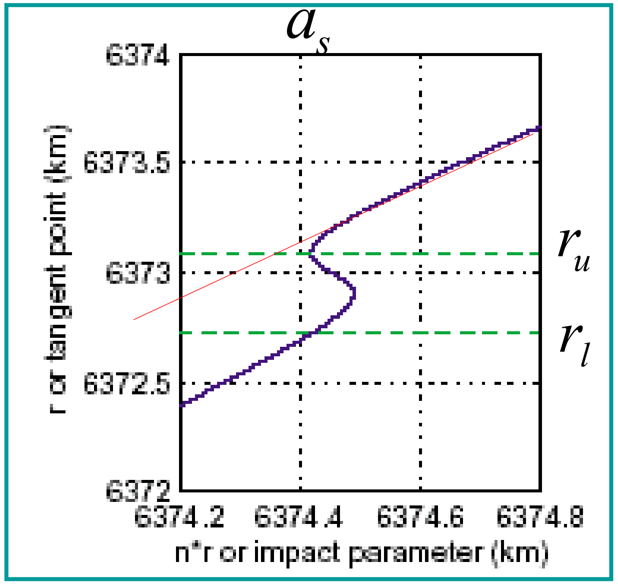
Drawback of Abel Inversion

- ***n(r) is not continuous. Sudden and unexpected variation of refractivity occur***
- ***It induces refractivity negative bias most of all in the equatorial bulge***
- **Increase of ∇ (*n(r).r)*** close to the ground.
- **<u>super-rifractivity</u>**: due to a sudden drop of humidity at upper PBL



$$\frac{d(n(r)\cdot r)}{dr} < 0$$

$$\frac{dN}{dr} < -10^6 \frac{n}{R_E} \approx -157 km^{-1}$$



The relationship: $n(r_{min})\cdot r_{min} = a$ is not fullfilled anymore in a monotone fashion.

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The CT and FIO as solution of the multipath

$$\left(-D_x^2 - D_y^2 + 1\right)u = 0 \longrightarrow -D_x u = H\left(y, D_y\right) \equiv \left(-\sqrt{1 - D_y^2}\right)u$$

Helmholtz Equation (valid for back-propagation approach)

Asymptotic short wavelength solution

$$A_x\left(y\right)\exp\left(ik\,\Psi_x\left(y\right)\right)$$

Geometric optical solution **(GO)**

Initial spatial coordinates of ray path

$$\left(y, \eta\right)$$

Canonical Transform

New coordinates: a spatial one and the impulse

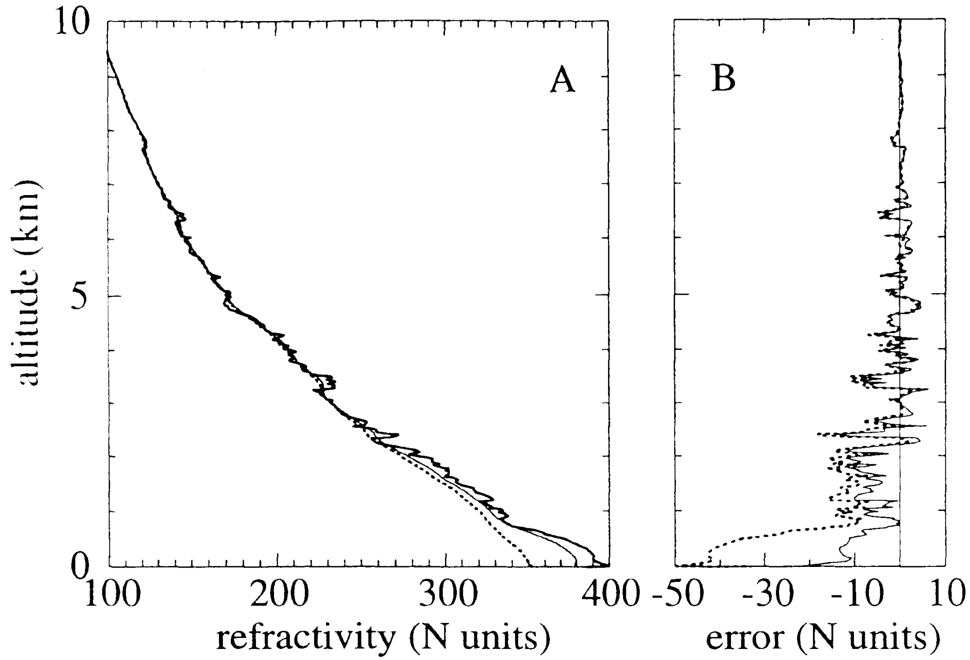
$$\left(z, \xi\right)$$

2 undistinguished signals (multipath) can now be separated in phase space (have different impulse!)

Integral Fourier Operator indeed distinguishes one and one only ray path

$$\hat{\Phi}_x v_x\left(\Delta p\right) = \frac{k}{2\pi}\int\left(1-\eta^2\right)^{-1/4} e^{1k\left[\Delta p \arcsin\eta - x\sqrt{1-\eta^2} + a\left(\arcsin\eta - \eta\right)\right]}\,\tilde{v}_x\left(\eta\right)d\eta$$

The CT and FIO as solution of the multipath



•***Gorbunov ME*** (2002) Canonical transform method for processing radio occultation data in the lower troposphere, Radio Sci, 37, 5, 1076-1085

•**Hocke K, Pavelyev AG, Yakovliev OI, Barthes L., Jakowski** (1999) Radio occultation data analysis by the radioholography method. I. Atmos. Terr. Phys., 61, 1169-1177

•**Sokolovskiy SV** (2001) Modeling and inverting radio occultation signals in the moist troposphere. Radio Science, Vol.36, nr. 3,441-458. May/June

Rank Deficiency

- We have 3 unknown (P,T, P_w) with 2 Eqs.

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} \qquad (1)$$

$$\frac{dP}{dh} = -\frac{g m_d}{a_1 R} N + \frac{a_2 g m_d}{a_1 R} \frac{P_w}{T^2} + \frac{g(m_d - m_w)}{R} \frac{P_w}{T} \qquad (2)$$

- You need external information: ECMWF models or NCEP re-analisis temperatures

The RO is not a stand alone technique!!

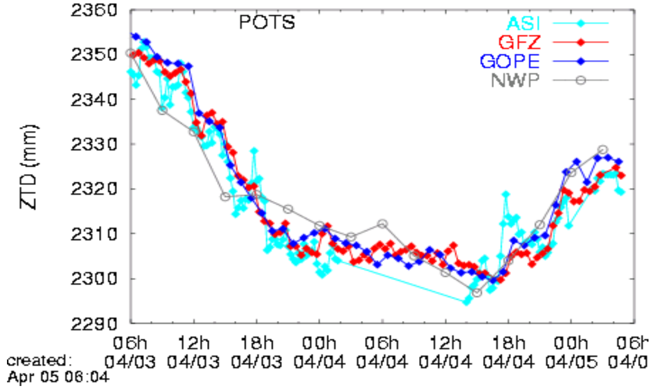
Solutions ?

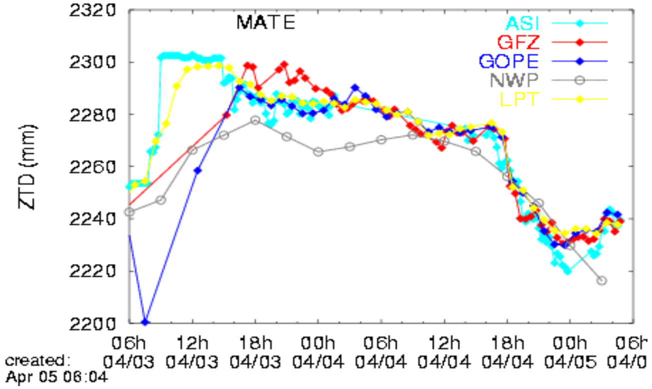
Integration of RO + Ground GPS Data

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} \qquad (1)$$

$$\frac{dP}{dh} = -\frac{g m_d}{a_1 R} N + \frac{a_2 g m_d}{a_1 R} \frac{P_w}{T^2} + \frac{g(m_d - m_w)}{R} \frac{P_w}{T} \qquad (4)$$

$$ZTD = 10^{-6} \int_{ground-GPS}^{\infty} \left(a_1 \frac{P(h)}{T(h)} + a_2 \frac{P_w(h)}{T(h)^2} \right) dh$$





Trieste 07,04,2010

Solutions ? (cont.)

- Use surface temperature information when available
  - *D.B. O' Sullivan, B.M. Herman, D. E. Feng, D. E. Flittner, D.M. Ward, "Retrieval of Water Vapor Profiles from GPS/MET Rdio Occultations", Bull. of the Amer. Meteor. Soc., Vol. 81, 1031-1040, No 5, May 2000.*
- Use an exponential model of refractivity under the assumption of constant value of the humidity…:
  - *M. de la Torre Juàrez, M. Nilsson, "On the Detection of Water Vapor Profiles and Thin Moisture Layers from Atmospheric Radio Occultations", J.Geophys. Res., in press, February 2003*

Solutions ? (cont.)

- *The BPV model (proposed at ASI/CGS Matera):*
  - *Vespe F., Benedetto C., Pacione R., "GNSS Radio Occultation: from the bending angles to the atmospheric profiles", ESA book, Proc. URSI symposium Atmospheric Remote Sensing by using GNSS systems, Matera 13-15 Oct., 2003.*
  - *Vespe F., Wickert J., Benedetto C., Pacione R.; "Derivation of the Water Vapor Content from the Radio Occultation Observations"; In Earth Observation with CHAMP: Results from Three Years in Orbit, Reigber et al. Eds, pp. 537-543, 2004*
  - *Vespe F., Persia T.: "Derivation of the Water Vapor Content from the GNSS Radio Occultations Observations," Journal of Atmospheric and Oceanic Technology, Vol. 23, No. 7, pages 936–943, 2006*

The Current Status

Upper Layers (>50 Km) : Too noise $\frac{S}{N} > 1$

The Iono, Clock and Orbit uncertainties overwhelm the tiny effects of refractivity through the outer stratosphere

S/N ratio is good. The atmosphere has no wet content. The inversion is fully reliable (no horizontal gradient). The system of 2 equations: hydrostatic equilibrium and refractivity can be heasily solved.

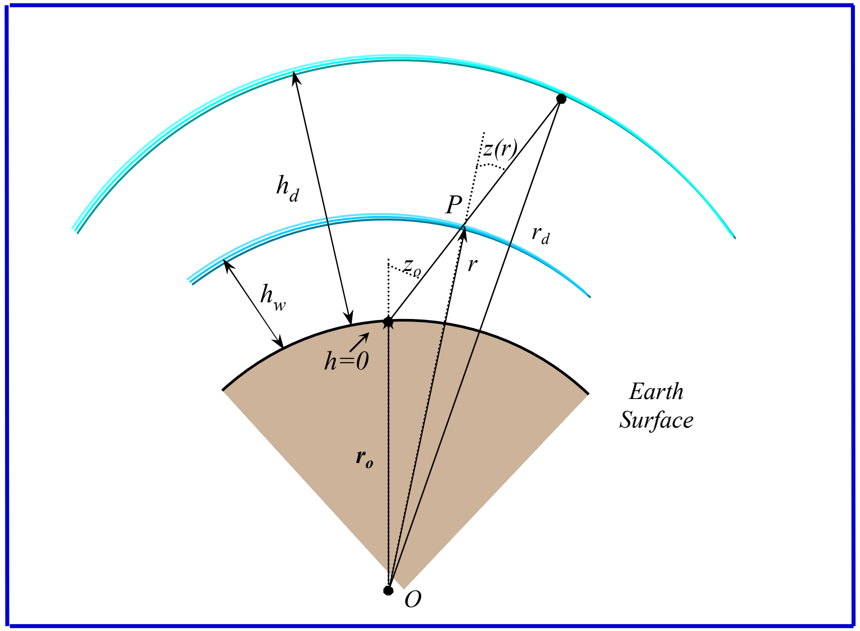
Stratopause

The atmosphere has a no negligible wet content. The inversion is not fully reliable (horizontal gradient…). The system of 2 equations: hydrostatic equilibrium and refractivity suffers of rank deficiency (3 unknows) .

$h=h_{250K}$

Ground Level

The Hopfield Model



$$N^{trop} = N_d^{trop} + N_w^{trop}$$

$$N_{w,o}^{trop} = \bar{c}_2 \frac{e}{T} + \bar{c}_3 \frac{e}{T^2} \qquad N_{d,o}^{trop} = \bar{c}_1 \frac{p}{T}$$

$$N_d^{trop}(h) = N_{d,o}^{trop} \left[\frac{h_d - h}{h_d} \right]^4$$

$$r = r_o + h \qquad r_d = r_o + h_d$$

$$h_w = 11000 \text{ m}$$

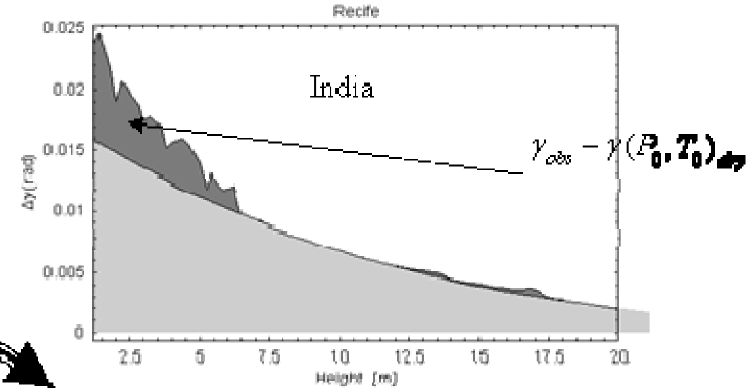
$$h_d = 40136 + 148.72 (T - 273.16)$$

$$N_d^{trop}(r) = N_{d,o}^{trop} \left[\frac{r_d - r}{r_d - r_o} \right]^4, \quad N_w^{trop}(r) = N_{w,o}^{trop} \left[\frac{r_w - r}{r_w - r_o} \right]^4$$

BPV Approach to Retrieve N and WV

1. **Fit bending angles from stratopause down to $h_{T\le240}$, using atmo dry (Hopfield) model:**

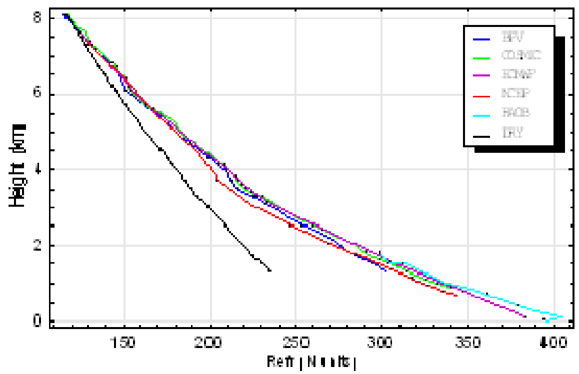
$$\mathrm{Min}\left[\left|\gamma(a)+2\int_{r_t+h_1}^{r_t+h_{max}}\frac{d}{dr}\left[\ln\left[n_{dry}(r,P_0,T_0)\right]\right]\frac{a}{\sqrt{n^2(r,P_0,T_0)r^2-a^2}}\,dr\right|^2\right]$$

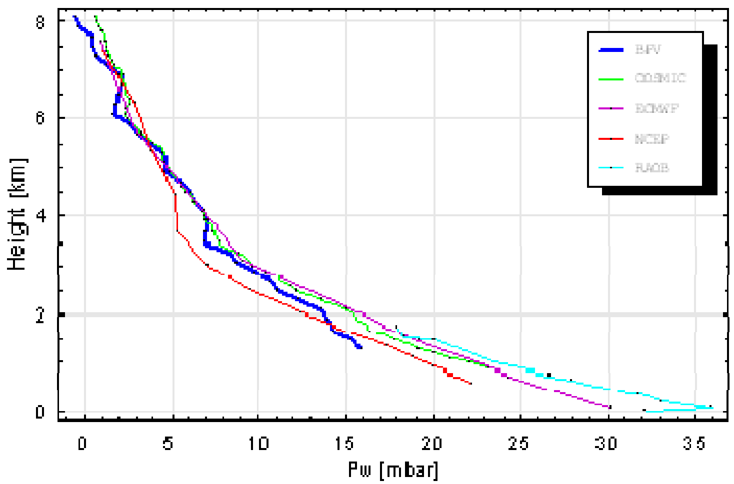


2. **The BA excess for lower layers is due to humidity. So from ndry by an iterative LS method we estimate Δn(r) needed to fit the obs. BA in the lower layers as well**
3. **With the assumption that $\Delta N(r) = N_{wet}(r)$**

$$P_v = a_1 \frac{N_{wet}T^2}{a_2 T + a_3}$$

a1 = 77.6;
a2 = 70.4;
a3 = 3.739 * 10^5





With COSMIC we have a huge amount of RO down to h<1 Km: So it is possible to validate the BPV approach!!

Step 1

Siti	Data	Recife	Guam	Brest	Mangalore
Press. BPVα [mbar]	GO	1012.56	1016.57	1017.45	1003.48
	CT	1012.50	1027.95	1043.70	1000.19
Press. BPVn [mbar]	GO	1024.80	1028.57	1028.57	1019.30
	CT	1026.50	1041.15	1041.15	1017.48
Press. RAOB [mbar]		1013	1005	1005	1007.00
Temp. BPVα [K]	GO	297.96	299.1	283.272	300.93
	CT	299.20	294.71	286.026	300.688
Temp. BPVn [K]	GO	297.70	299.01	286.98	299.36
	CT	299.1	294.77	283.379	298.91
Temp. RAOB [K]		300.14	303.75	285.95	303.30

❑Presentation Outline

- ❑The Origin…
- ❑ Description of the Radio Occultation Technique
- ❑ Challenging Tasks
- ❑ *NRT x LEO-POD*
- ❑Mission Analysis ROSA on OCEANSAT_2
- ❑GPS & GALILEO
- ❑Conclusions

Phase Measurement Cleaning
(Double Differencing, Clock Estimation, Iono free combination)

Precise Orbital Determination

(Pre-processing)

Shift Doppler Excess Δf

ray-tracing equations

Bending angle $\alpha(a)$

Abel Inversion

Refractivity $n(r)$

Termodinamic Relationships

$P(r), T(r), P_w$

Users:

- *Meteorology ?*
- *Climatology*
- *Space Weather*
- *Ionosphere Tomography (?)*
- *Space Geodesy*
- *Geophysics*

Why Near Real Time ?

❑ Numerical Weather Prediction Requirements:

- ❑ RO & LEO-POD data within 45' (2 download/orbit at least) must be available
- ❑ *Within 1h.30' the Precise Ephemeris of the LEO Satellite (σ<50 cm) must be available*
- ❑ Within 1h 45' the RO products to assimilate (level 2-3) must be available;
- ❑ Within 3h must be issued the NWP

THE ITALIAN ROSA PROJECT AND ITS BENEFITS FROM COSMIC MISSION

F. Vespe[1], G. Perona[2], M. Molinaro[2], V. De Cosmo[3], A. Zin[8], S. Landenna[8], R. Notarpietro[4], B. Nava[9], S. Radicella[9], C. Benedetto[1] , M. Amoroso[11], P. Sacco[11] , I. Bordi[5], M. Materassi, P. Spalla[6], N. Tartaglione[7], S. Casotto[10],

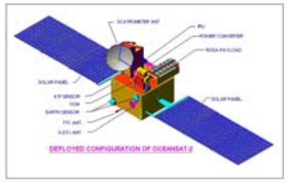
(1) Italian Space Agency, Centro di Geodesia Spaziale, Matera, IT;
(2) Istituto Superiore M. Boella, Italy (IT);
(3) Italian Space Agency, Roma, IT
(4) Politecnico di Torino , Torino, IT
(5) Università La Sapienza, Roma, IT
(6) Istituto dei Sistemi Complessi (ISC/CNR), Firenze, Italy
(7) CINFAI, Camerino, IT
(8) THALES-Alenia Spazio, Milano, Italy
(9) ICTP, Trieste, IT
(10) CISAS, Padova, IT;
(11) INNOVA, Matera, IT

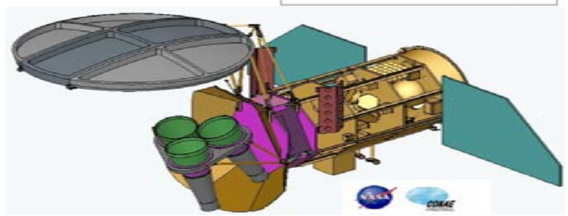
Trieste 07,04,2010

II Workshop on Satellite Navigation Science and Technology for Africa

ASI strategy

- We have developed a GPS receiver devoted to Radio Occultation: **R**adio **O**ccultation **S**ounder for **A**tmosphere studies
- We are developing the processing chain from data to profiles
- We don't have a space mission devoted to RO
- We try to embark ROSA on available national and/or international Earth space missions:
  - OCEANSAT_2 (Currently Flying)
  - SAC-D (2010)
  - MEGHA-TROPIQUES ?





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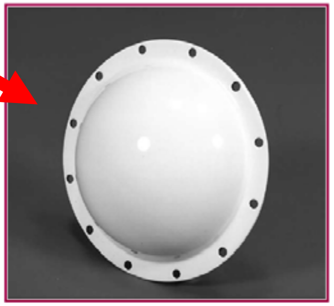
ROSA Instrument

ROSA main blocks

Receiver

2 high gain RO antenna (up to 12 dB) (1x 0.6 m)

Navigation antenna



ROSA Instrument Description

Receiver Type:	Space-borne (LEO), geodetic-class GPS receiver for atmospheric sounding. Developed by TAS-I under ASI contract.
Channels:	48 single frequency channels configured in order to have 16 L1CA/L1P/L2P dual-frequency channels
Frequency Bands:	GPS L1: 1575.42 MHz GPS L2: 1227.60 MHz
Observables:	L1 C/A, L1P(Y) & L2P(Y) Code phase L1 C/A & L2P(Y) Carrier phase Raw sampling (I/Q) at high frequency (100 Hz) Instantaneous Doppler Time measurements, determined from the GPS system SNR, Amplitude and Noise measurements

- ✓ *Real-Time Navigation Solution*, determined using GPS L1 C/A code phase and navigation messages (through SPS and Extended Kalman Filter)
- ✓ *On-board atmospheric model* for excess doppler prediction of occultation signals (based on Cira86aQ_UoG climatological Model)
- ✓ Rising and setting occultation capabilities (depending on instrument configuration)

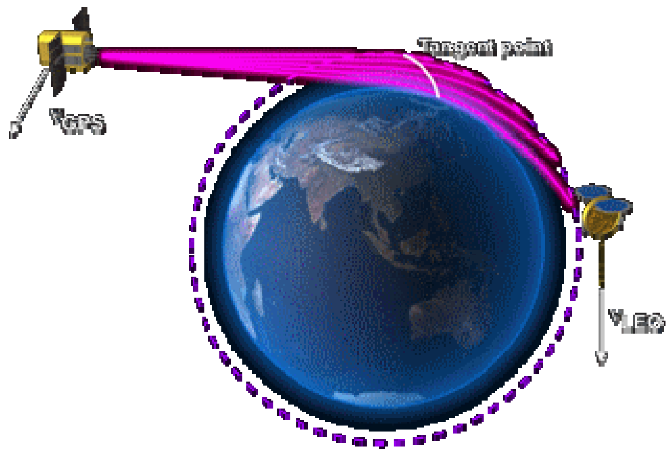
Radio Occultation – Processing Chain

(Pre-Processing)

•**Phase Measurement Cleaning**

(Double Differencing, Clock Estimation, Iono free combination)

•**Precise Orbital Determination**



Shift Doppler Excess Δf

Ray-tracing equations

Bending angle $\alpha(a)$

Abel Inversion

Refractivity $n(r)$

Termodinamic Relationships

$P(r)$, $T(r)$, Pw

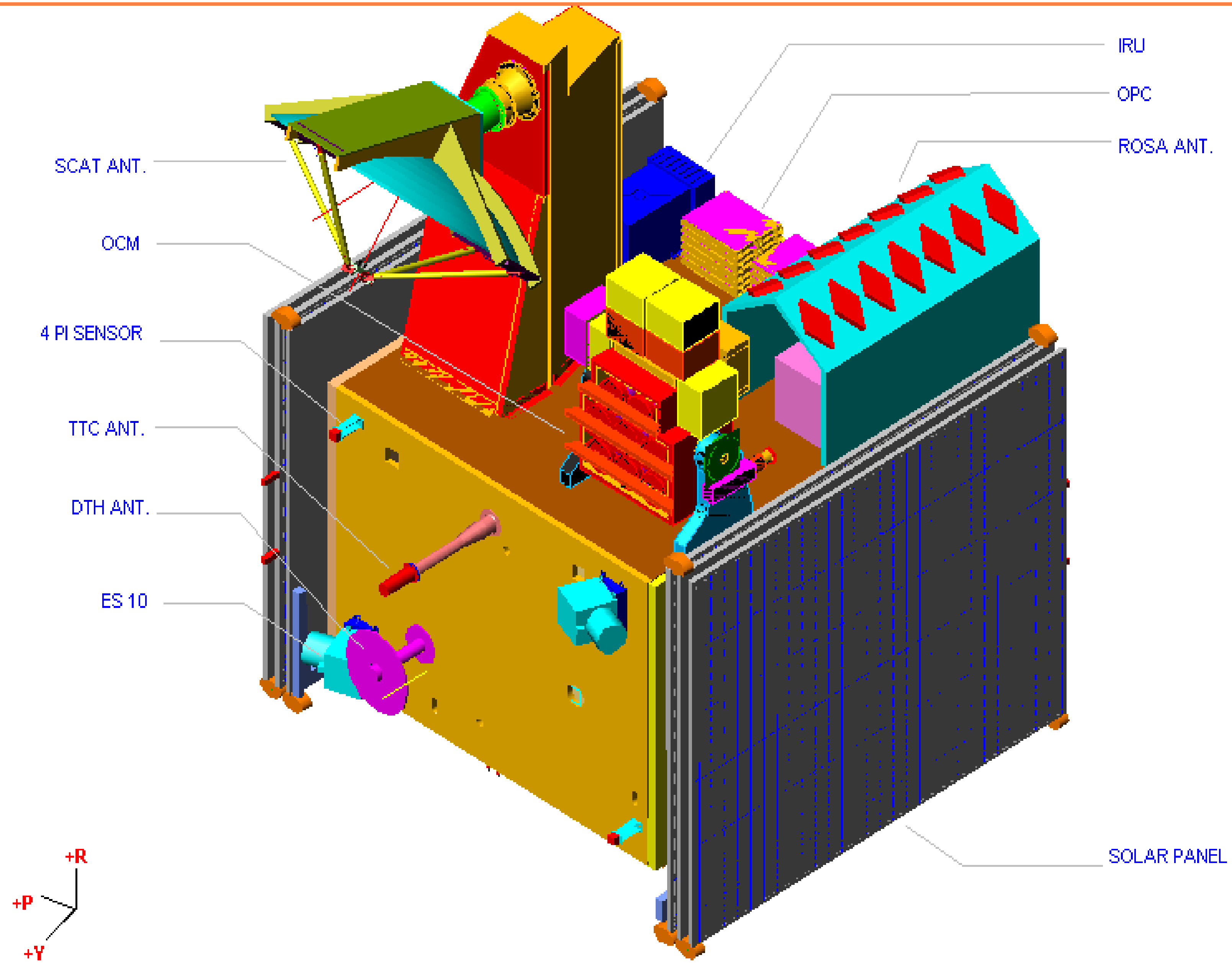
Users:

- **Meteorology**
- **Climatology**
- **Space Geodesy**
- **Ionosphere**
- **Space Weather**
- **Geophysics**

ROSA DATA LEVELS

LEVEL 3 - Final Output

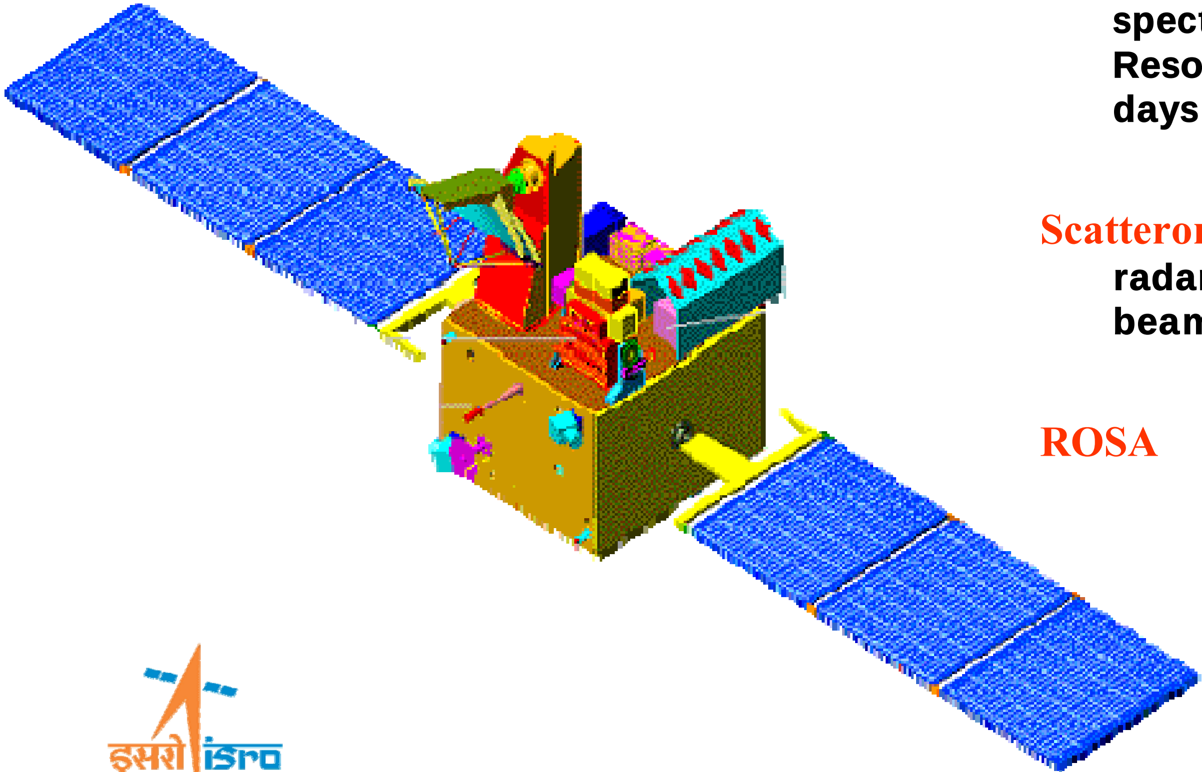
	Basic	Final
a. L_1 and L_2 Bendings vs Impact Parameters profiles	Geom. Opt. methods	CT, FSI (Wave Optics)
b. Iono-free Bendings vs Impact Parameters profile	Std techn. needed both L_1 and L_2	Tomography and use of OL data
c. Stratospheric initialization of Iono-free Bendings vs Impact Parameters profile	Through Global Climatol.	Through Local Climatol.
d. N, P and T Profiles	Abel	Numerical (BPV_α)
e. Water Vapour vertical profiles	Through Climatol. models	**NWP -IDVAR or SA (BPV_n),**
f. Electron Density vertical profiles	Onion Peeling	Tomography



OCEANSAT-2 STOWED CONFIGURATION

VIEWED FROM +YAW SIDE (19.07.05)

ROSA on OCEANSAT-2



OCM-2: 8-narrow Band multi-spectral camera, 360 m Resolution, 1420 Kms Swath, 2 days repetevity

Scatterometer: Ku-band (13.515GHz) radar, V & H polarisation, two-beam conical scanning

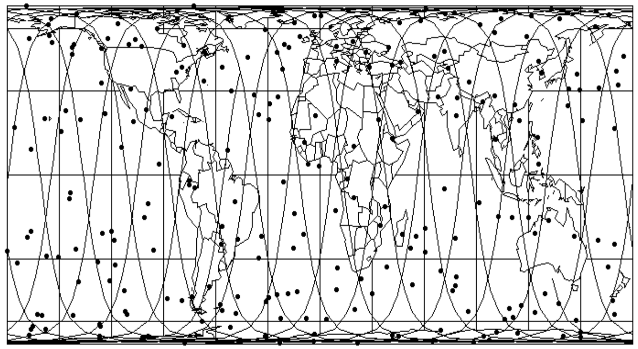
ROSA

Launched : 23 Sept. 2009!!

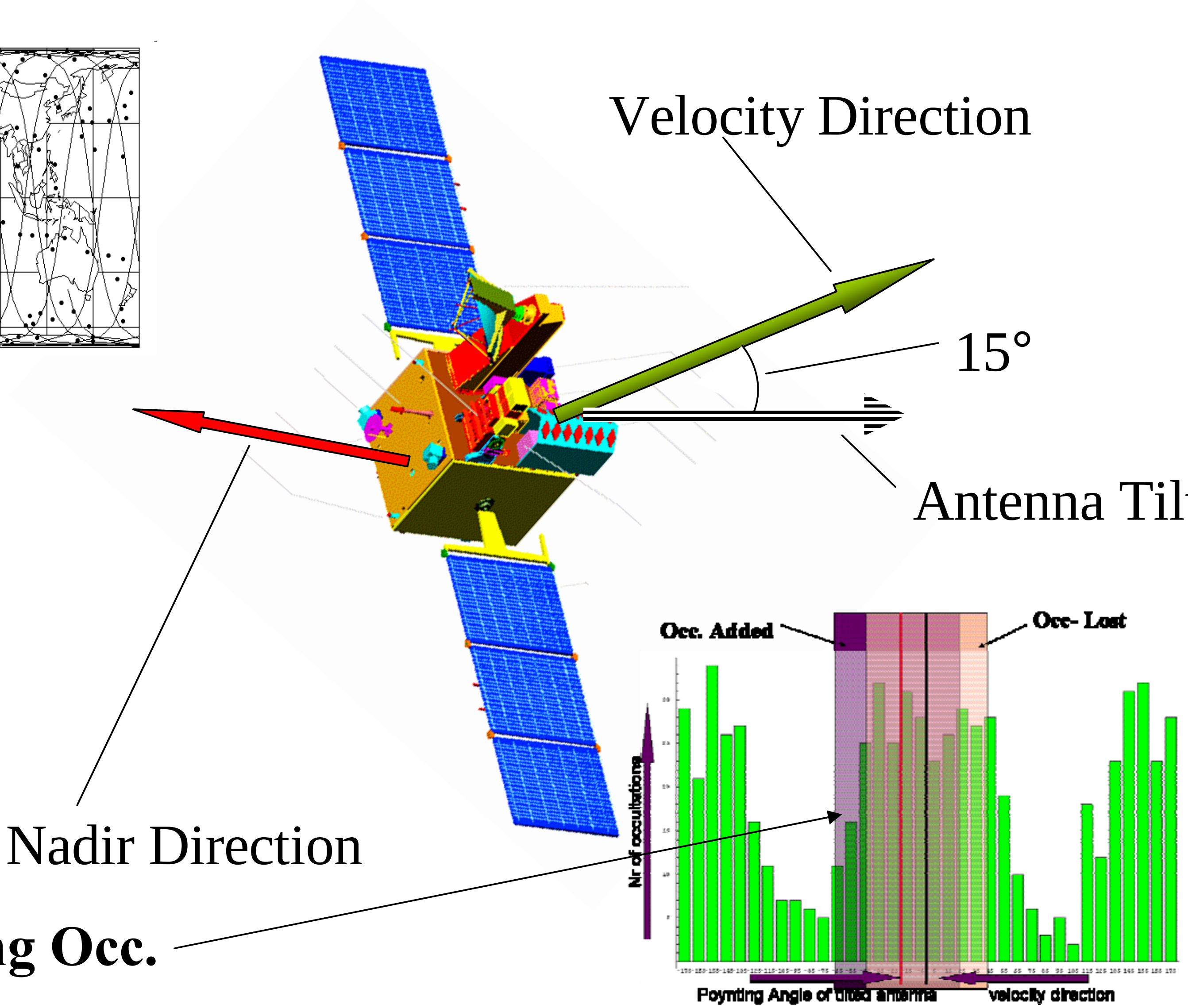
ROSA on OCEANSAT-2

Type	-	Near polar sun-synchronous
Altitude	-	720 km
Inclination	-	98.28°
Period	-	99.31 min.
Local time of pass	-	12 noon $\pm$ 10 min.
Repetevity cycle	-	2 days
Distance between adjacent traces	-	1382 km
Distance between successive ground tracks	-	2764 km
Average ground trace velocity	-	6.781 km/s

Problems of Accomodation



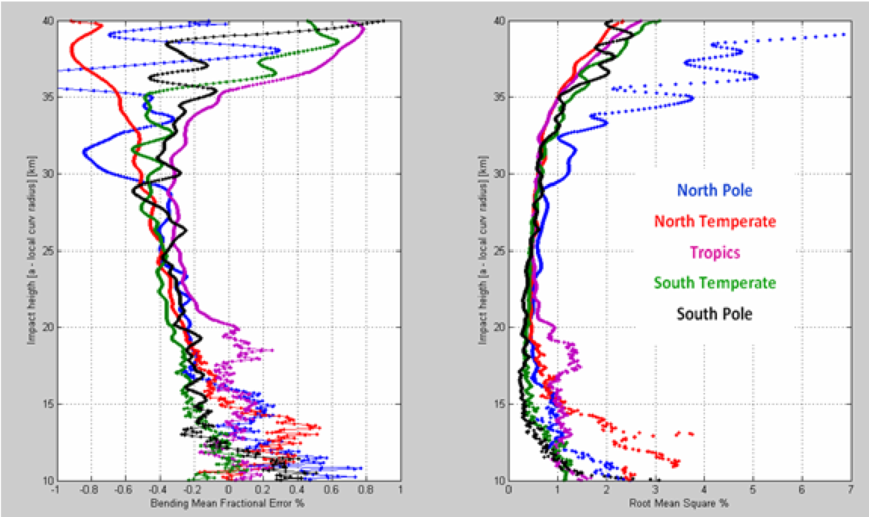
~270 Occ./day



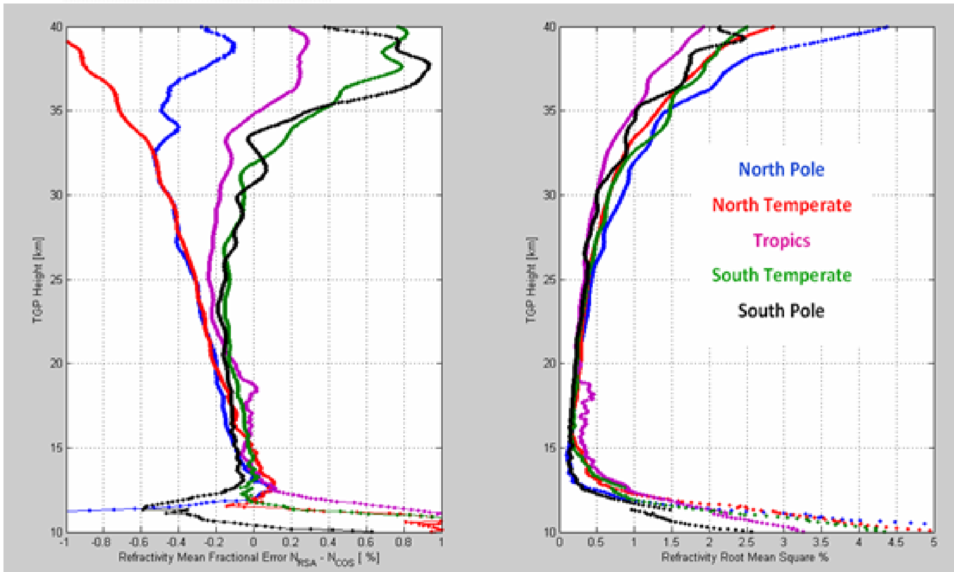
Side looking Occ.

COMPARISON OF RESULTS WITH OUR SW vs COSMIC (COSMIC DATASET 31-12-2007)

R O S A Radio Occultation Sounder for Atmosphere - ROSSA BENDING



R O S A Radio Occultation Sounder for Atmosphere - ROSSA REFRACTIVITY



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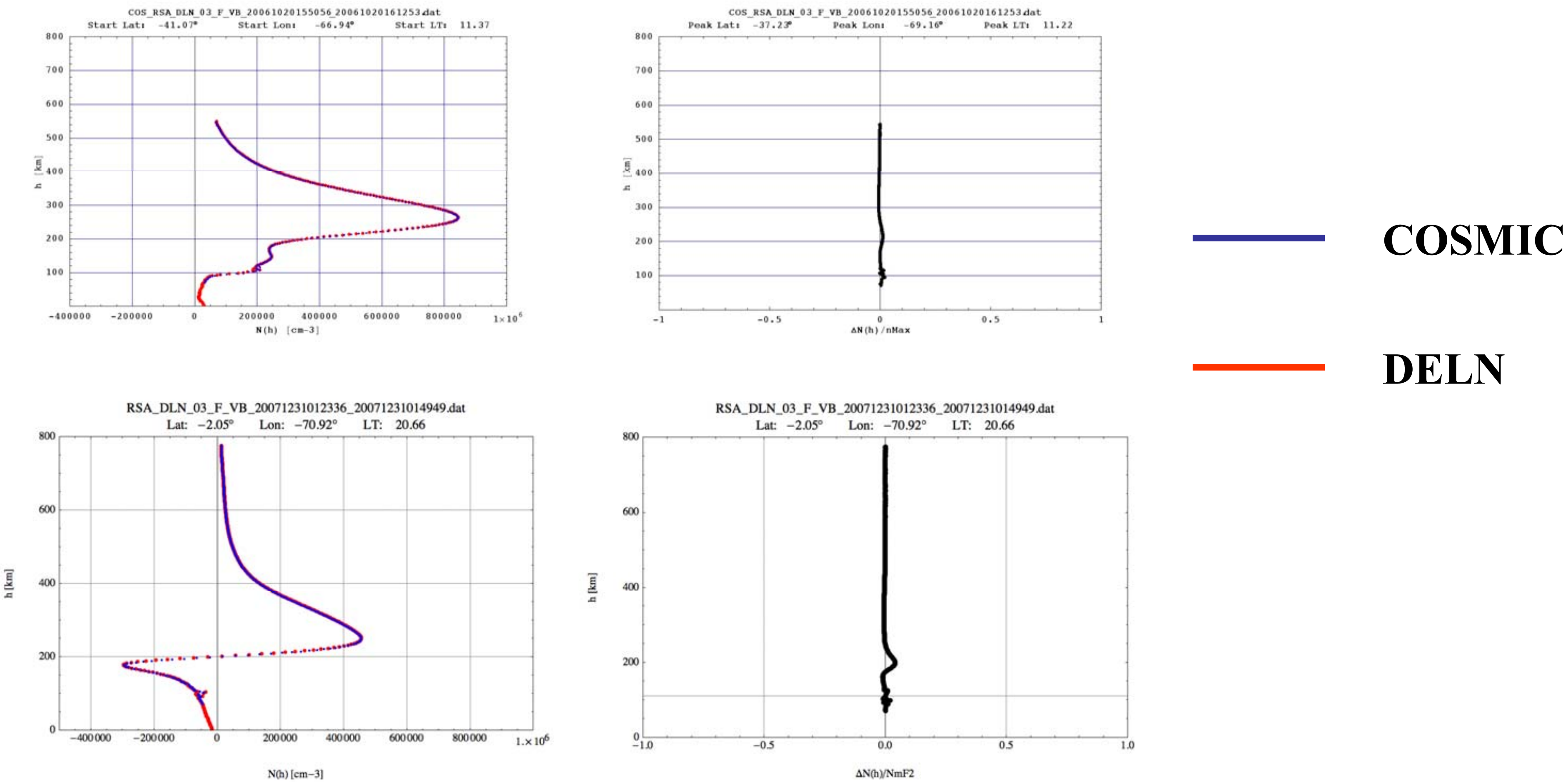
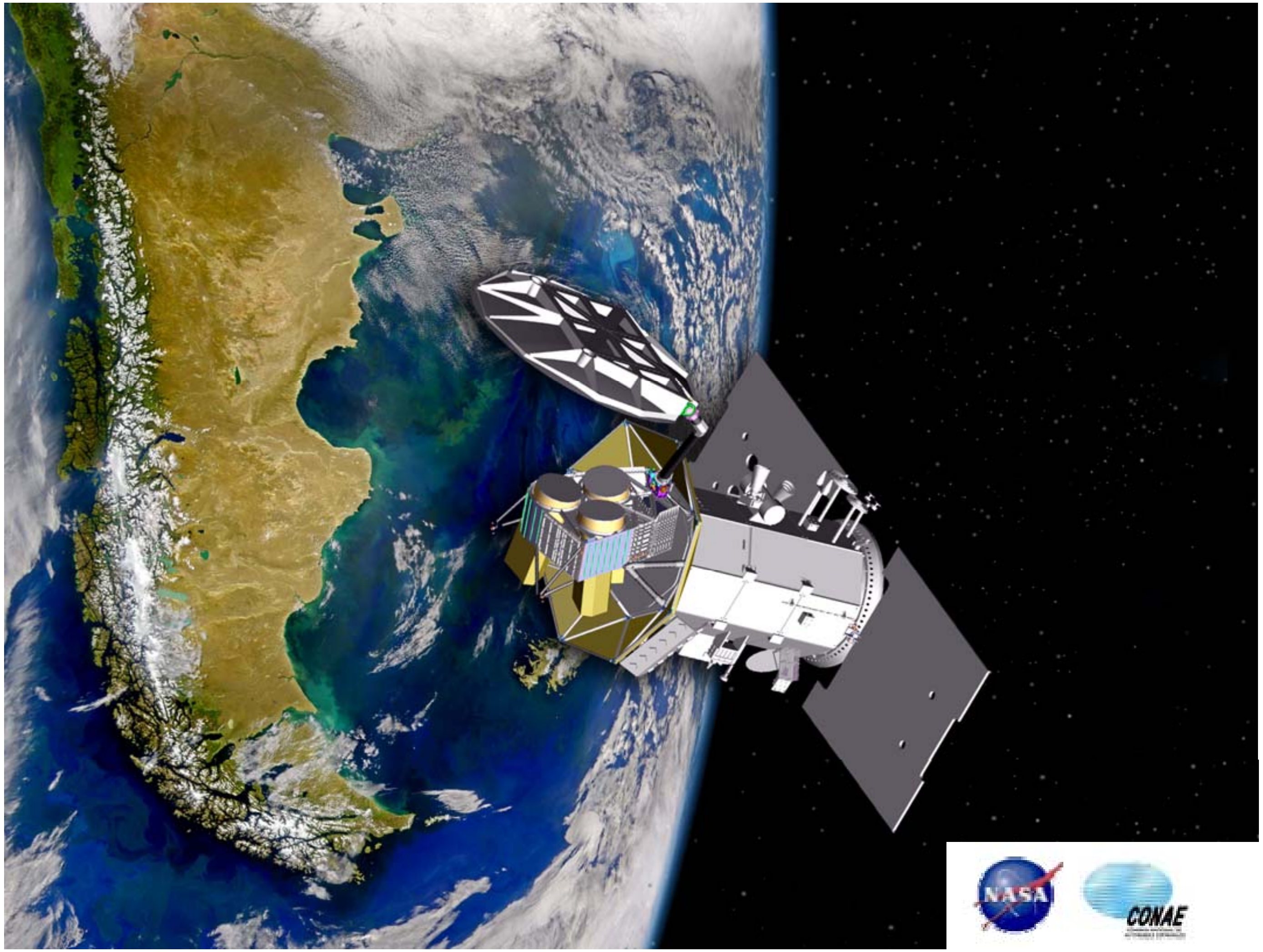
Ionosphere Profiles…. (ICTP)



ROSA on Aquarius/SAC-D



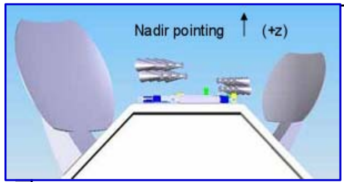
Trieste 07,04,2010

II Workshop on Satellite Navigation Science and Technology for Africa

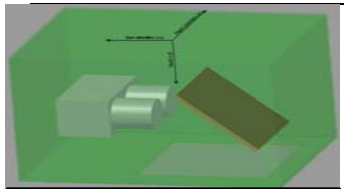
ROSA on *Aquarius*/SAC-D

Type	-	Near polar sun-synchronous exact repeat orbit. Earth viewing &
Nadir		pointing instruments
Altitude	-	657 km
Inclination	-	98. °
Local time of pass	-	6 pm ascending node
Repetevity cycle	-	7 days

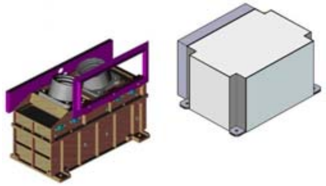
ROSA on Aquarius/SAC-D



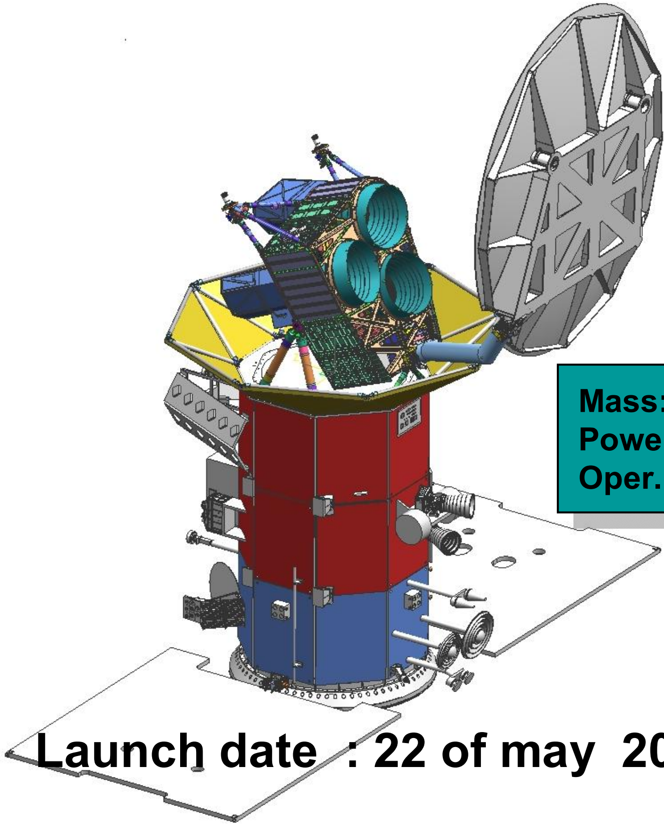
Microwave Radiometer
MWR



New InfraRed Sensor Technology
NIRST

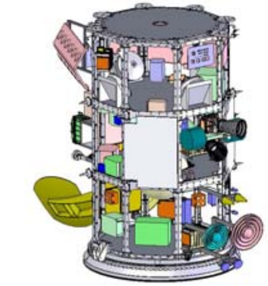


High Sensitivity Camera
HSC

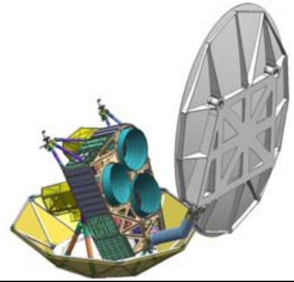


Launch date : 22 of may 2010

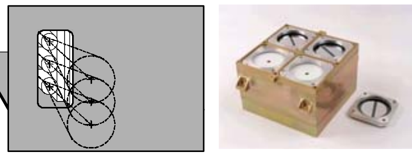
Mass: 1675 Kg
Power:1443 W
Oper. Life: 5 yrs



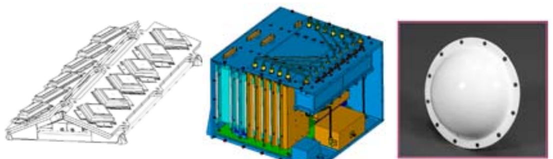
Satélite de Aplicaciones Científicas-D
Service Platform **SAC-D S/P**



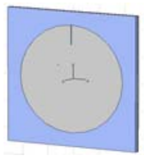
Aquarius
(primary instrument)



CARMEN-1
(ICARE-NG & SODAD)



Radio Occultation Sounder for the Atmosphere
ROSA

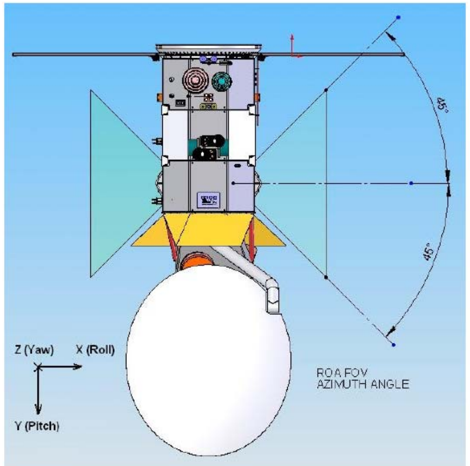


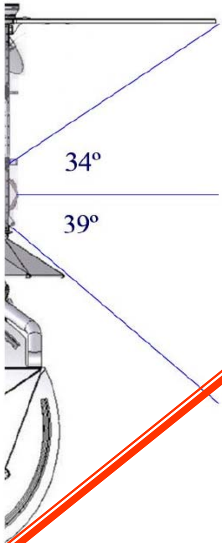
Data Collection System
DCS

Technology Demonstration Package
TDP

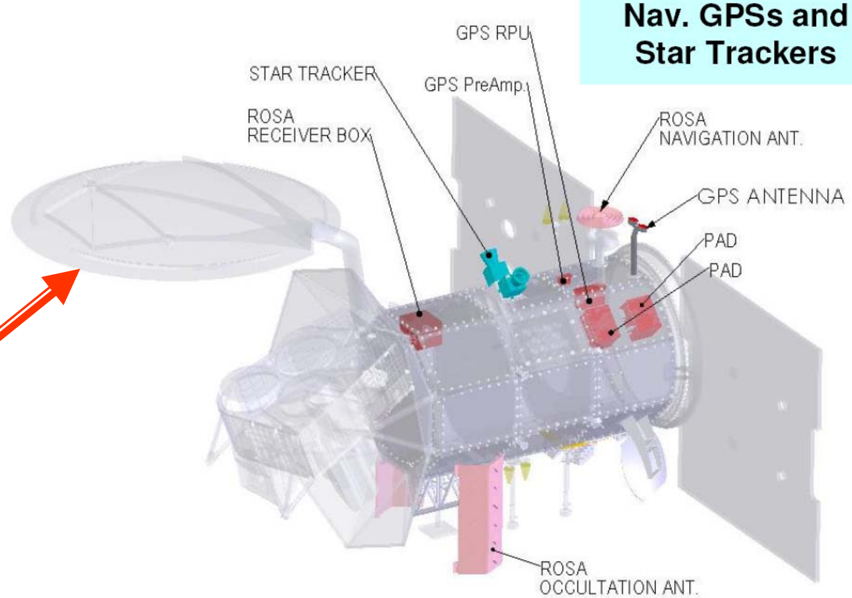
SAC-D

ROSA antennae FOV





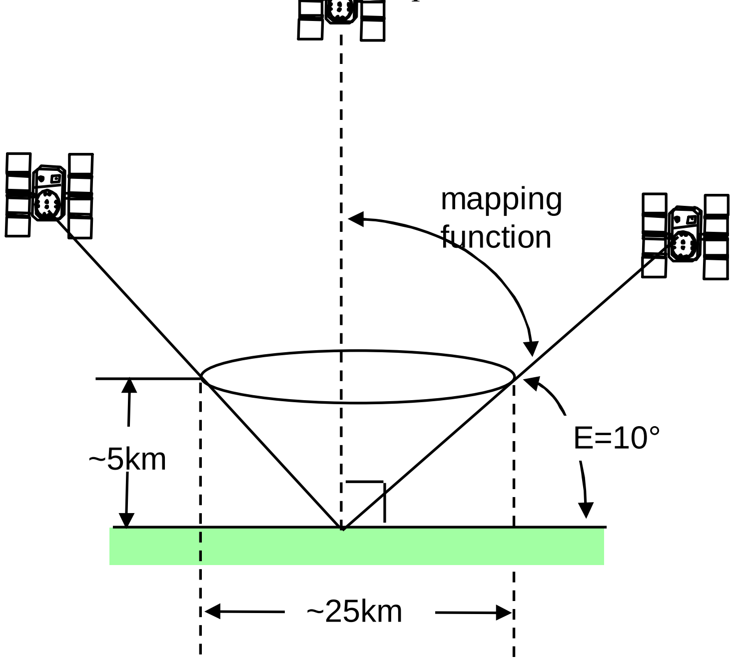
Location of ROSA, Nav. GPSs and Star Trackers

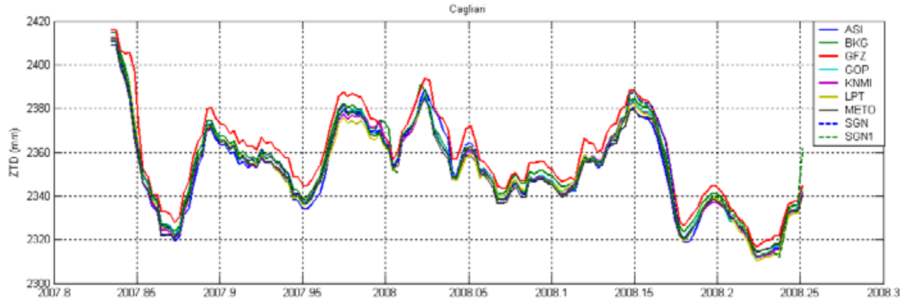


Problems: Aquarius is an active antenna which emits signal 400 W strong just close to L2 frequency. ROSA receiver was modified (new filtering system applied) to prevent interferences

Ground-Based GPS Meteorology

$$\Delta_{trop} = ZTD \cdot M(E)$$





Fundamental Measurement

$$L_S = 10^{-6}\int N(s)ds$$

$$N = k_1 \cdot \left(\frac{P_d}{T}\right) + k_2 \cdot \left(\frac{e}{T}\right) + k_3 \cdot \left(\frac{e}{T^2}\right)$$

A mapping function is applied to determine how the signal delay changes with elevation angle.
The results are averaged over all the satellites to give the ZTD.

Mapping Function Marini-Murray-like (1972)

$$m(E) = \cfrac{1}{\sin E + \cfrac{a}{\sin E + \cfrac{b}{\sin E + \cfrac{c}{\sin E + \ldots}}}}$$

$$\Delta^{trop} = ZHD \cdot M_d(E) + ZWD \cdot M_w(E)$$

Niell (1996)

$$m(\varepsilon)=\frac{1+\dfrac{a}{1+\dfrac{b}{1+c}}}{\sin(\varepsilon)+\dfrac{a}{\sin(\varepsilon)+\dfrac{b}{\sin(\varepsilon)+c}}}+\left(\frac{1}{\sin(\varepsilon)}-\frac{1+\dfrac{a_h}{1+\dfrac{b_h}{1+c_h}}}{\sin(\varepsilon)+\dfrac{a_h}{\sin(\varepsilon)+\dfrac{b_h}{\sin(\varepsilon)+c_h}}}\right)\cdot h$$

$$a(\lambda_i,t)=a_{avg}(\lambda_i)-a_{amp}(\lambda_i)\cos\left(2\pi\frac{t-T_0}{365.25}\right)$$

An equivalent formulation is given for the wet MF but its coefficients depends on the latitude only :

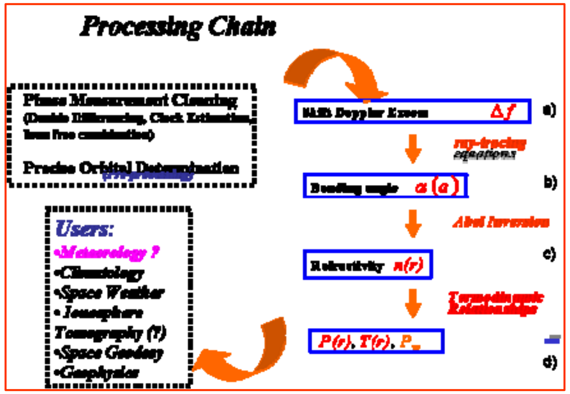
$$m_{wet}(E)=\frac{1+\dfrac{a_{wet}}{1+\dfrac{b_{wet}}{1+c_{wet}}}}{\sin(E)+\dfrac{a_{wet}}{\sin(E)+\dfrac{b_{wet}}{\sin(E)+c_{wet}}}}$$

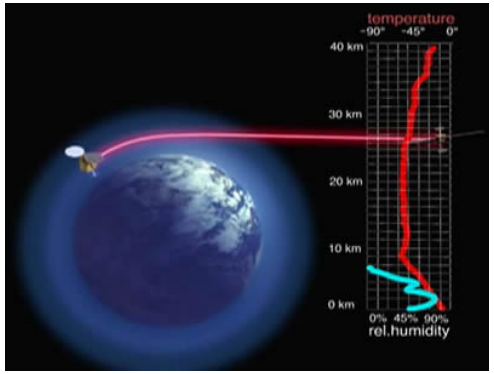
WE ARE USING JUST THE SAME FORMULATION OF NIELL BUT USING RADIO OCCULTATION DATA !!

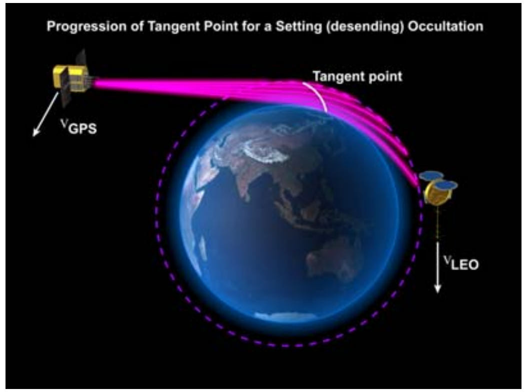
Parameters involved:
latitude “φ”
Height “*h*”
DoY “*t*”

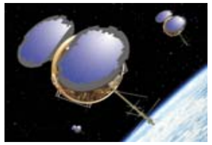
For the computation of the coefficients RAOB data were used

Radio Occultation Data suitable now to build the MF

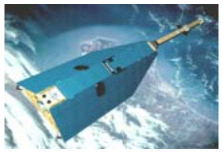








COSMIC 6 satellites in orbit since 14 April 2006 (~2000 occ/day). Still active



CHAMP launched on July 2000 (~200 occ/day). Still active

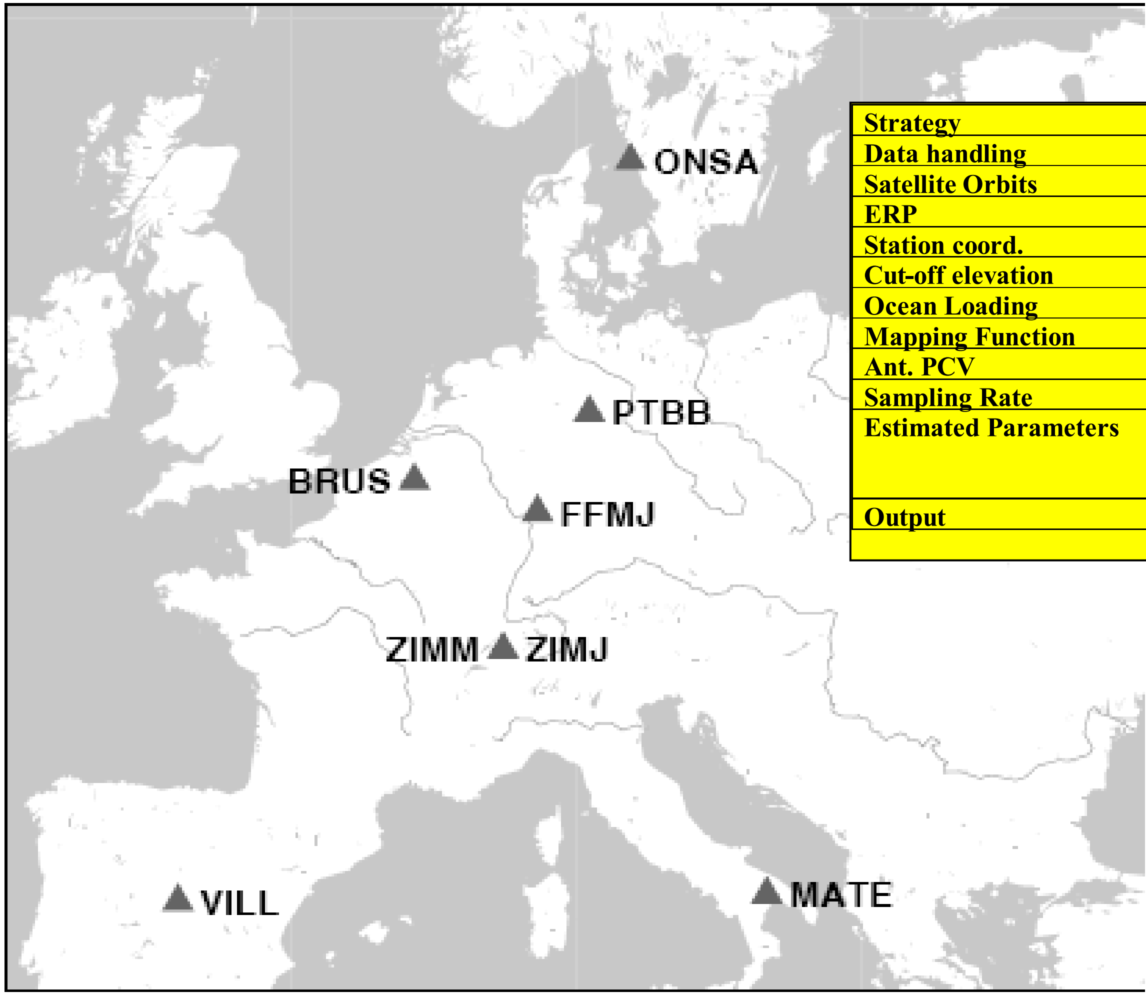
SAC-C launched on November 2000 (one year only of data)

>1,000,000 RO events selected !!

Spreaded and organized according the day of the year acquired. The selected events must provide profiles down at an height h < 1 km over the ground at least

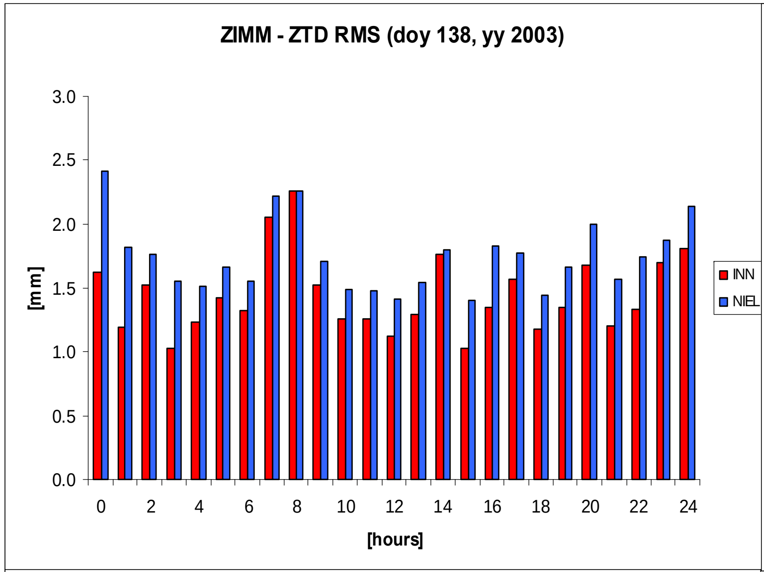
Test Site of MT_MF

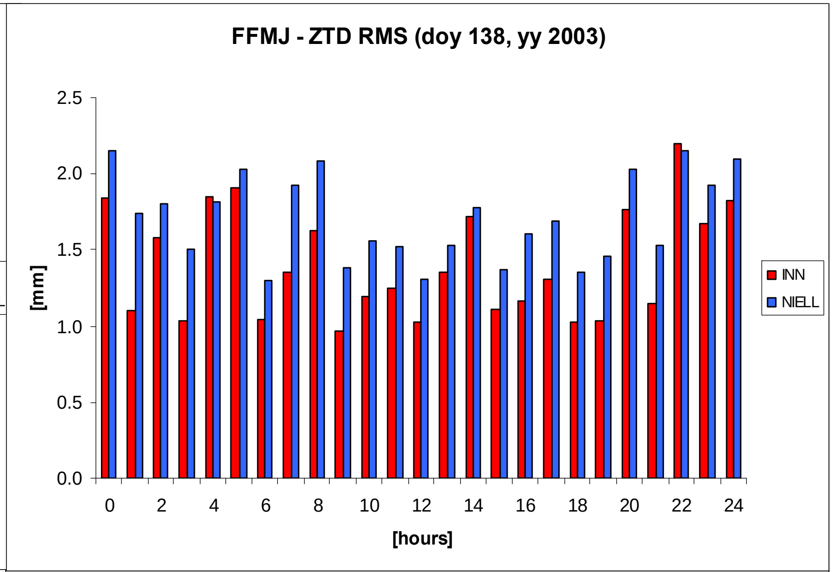
Processing Strategy (BERNESE SW used)

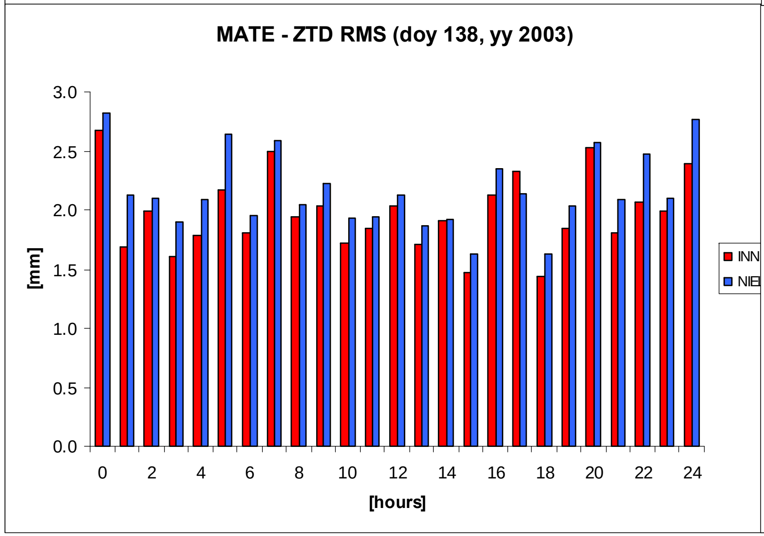


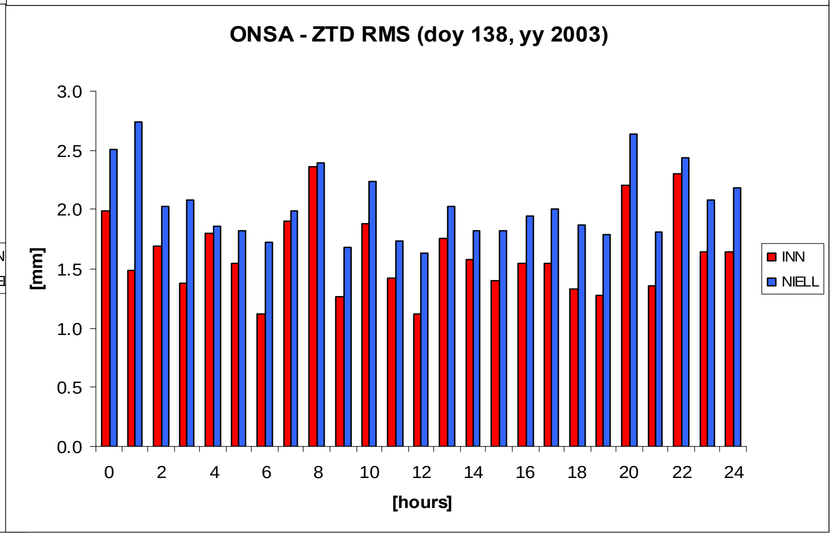
Strategy	Network Adjustment
Data handling	1 week of Data of 8 Perm. GPS Stations
Satellite Orbits	IGS Precise
ERP	IERS-IGS
Station coord.	aligned to IGS00
Cut-off elevation	5°
Ocean Loading	Applied (H.G.Scherneck)
Mapping Function	Neill (1996), INN (2008)
Ant. PCV	Relative
Sampling Rate	30”
Estimated Parameters	Coordinates, Satellite & station clocks w.r.t a reference one, Phase ambiguities (float), ZTD time resolution: everyhour
Output	Coordinates, ZTD

Results

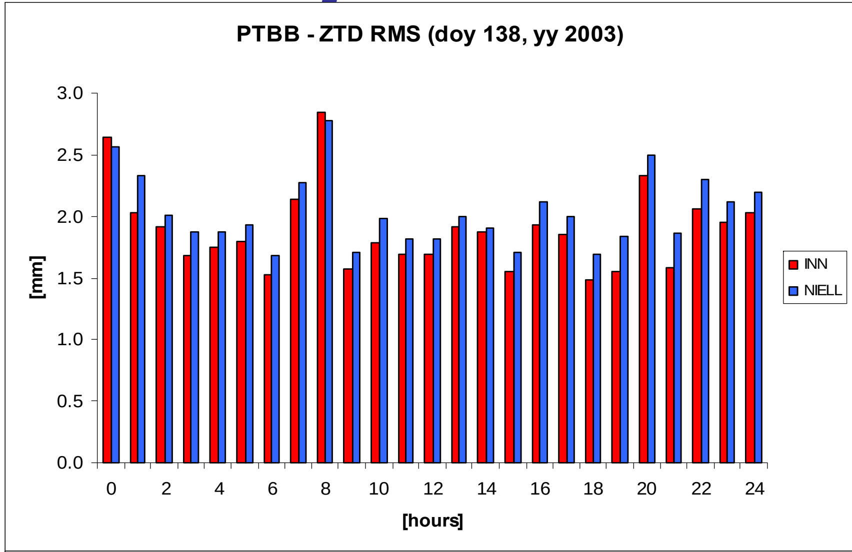

ZIMM - ZTD RMS (doy 138, yy 2003)
[mm]
[hours]
INN
NIEL

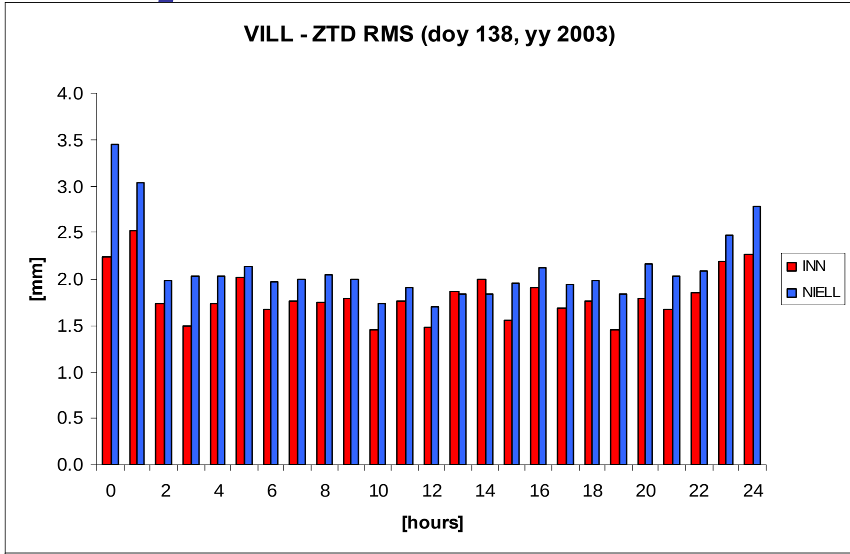

FFMJ - ZTD RMS (doy 138, yy 2003)
[mm]
[hours]
INN
NIELL

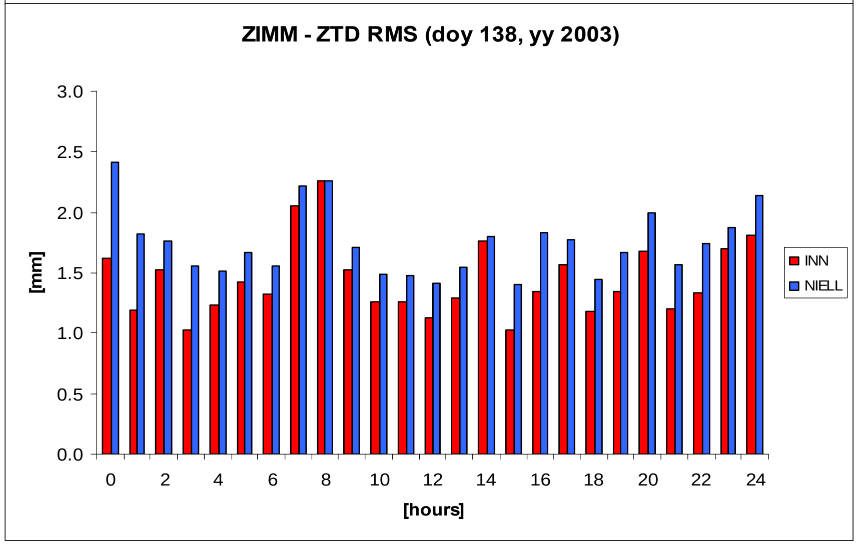

MATE - ZTD RMS (doy 138, yy 2003)
[mm]
[hours]
INN
NIE

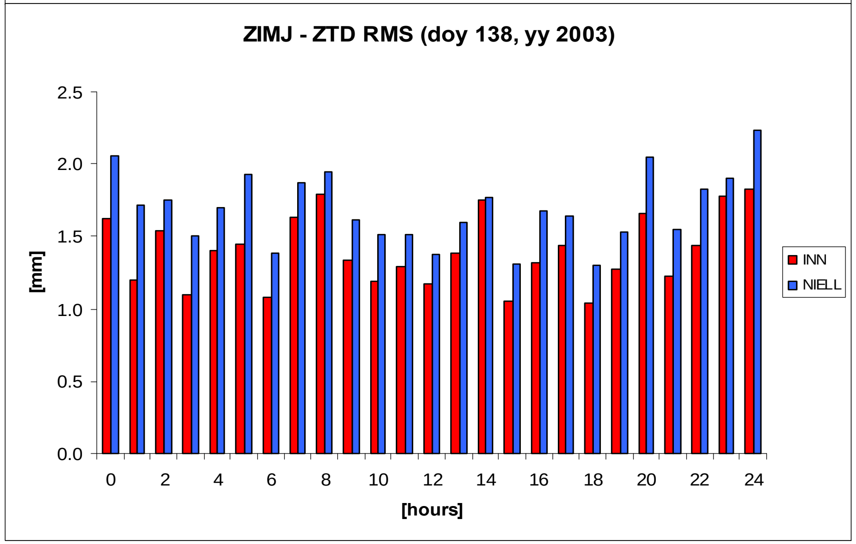

ONSA - ZTD RMS (doy 138, yy 2003)
[mm]
[hours]
INN
NIELL

Results_2
Improvements up to ~20%



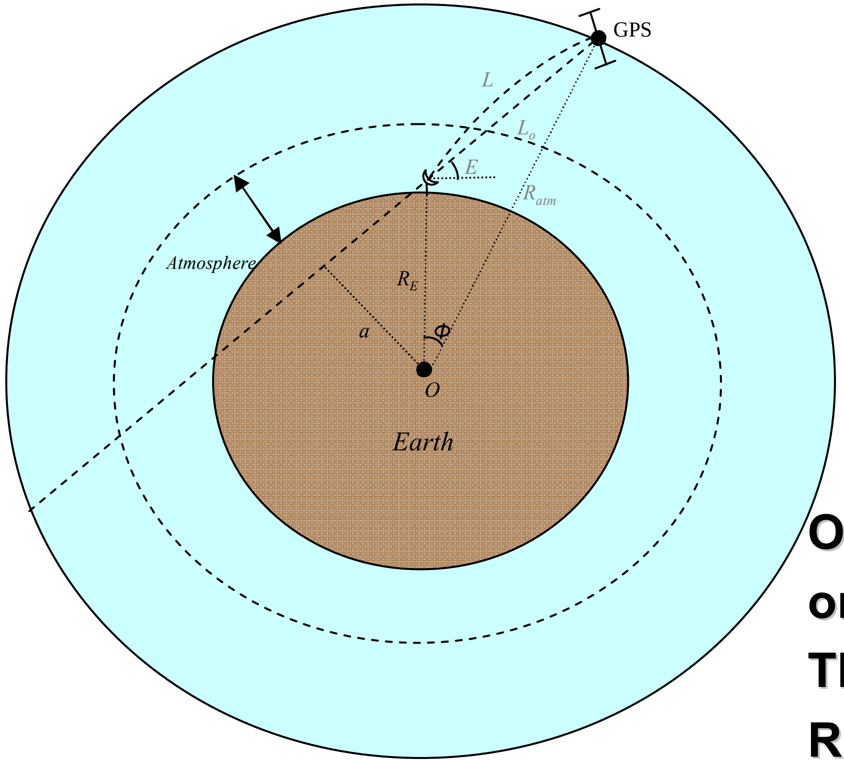






GPS TD with Ray-Tracing

The tropospheric delay TD is given by the difference between the optical path of the signal (*L*) and the geometrical distance satellite-receiver (L_0):



$$TD = \Delta L = L - L_0$$

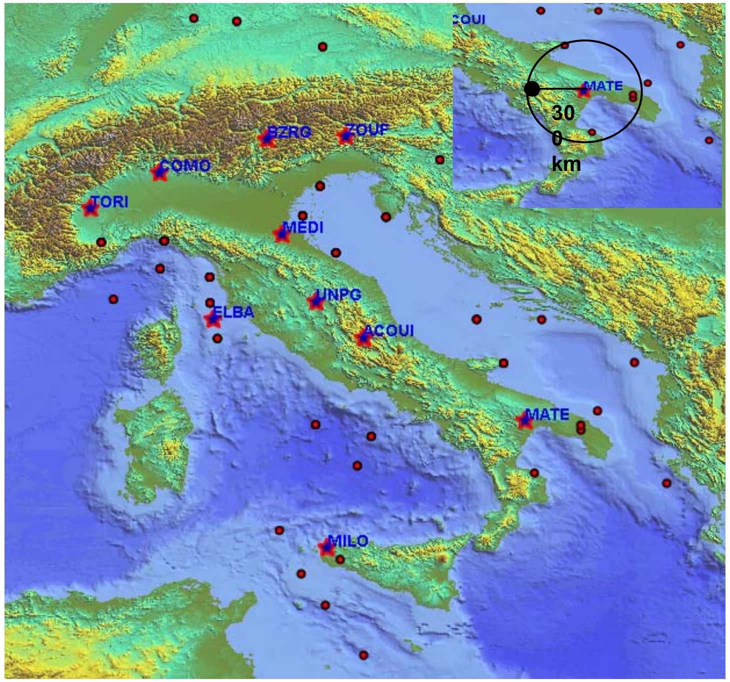
$$L = \int_{R_E+h}^{R_{atm}} \frac{n^2(r)\cdot r}{\sqrt{n^2(r)\cdot r^2 - a^2}}\,dr$$

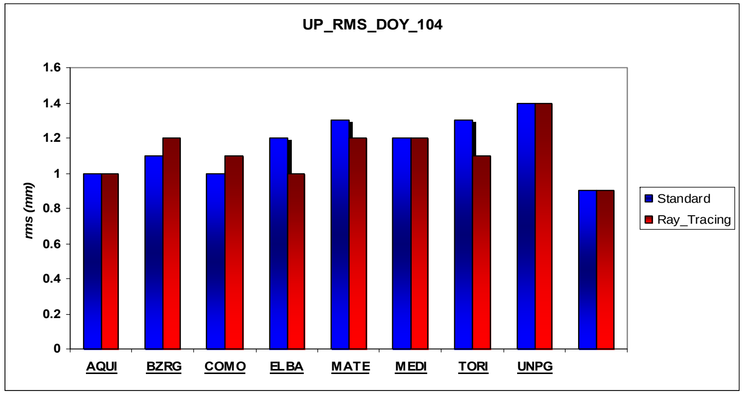
$$L_0 = \left\| \overline{r_{GPS}} - \overline{r_{st}} \right\|$$

Once computed, the *TD* is removed on both L_1 and L_2 carrier phase measurements. The correction is applied directly to RINEX files !!

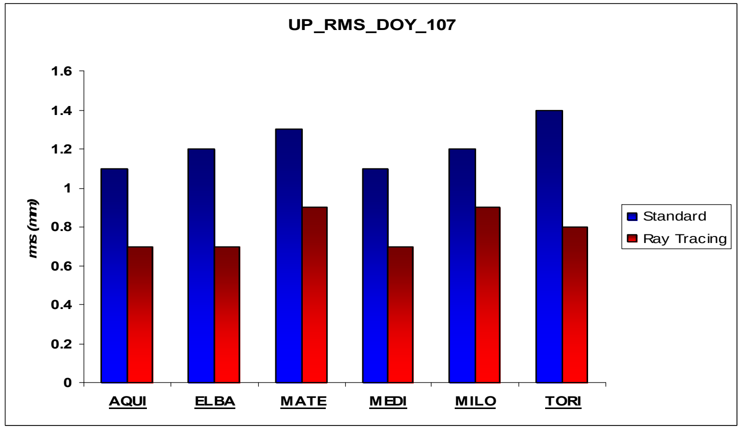
RAY-TRACING TECHNIQUE

The modified RINEX "troposphere free" files are processed by BERNESE sw in order to estimate only the coordinates of the stations (by applying network adjustment approach) <u>switching off</u> any tropospheric delay model !!





Neutral Impact on Formal Error



Positive Impact on Formal Error

GALILEO

- 30 satellites, The Orbits have a period of 14.35 hours
- 3 MEO orbits, h= 23616 km and I=56°
inclinazione rispetto al piano equatoriale di 56 gradi

- The lifetime of the satellites will be 12 ys at least, Power 1.6 kw, mass di 680 kg and dimensions: 2.7m-1.2m-1.1m

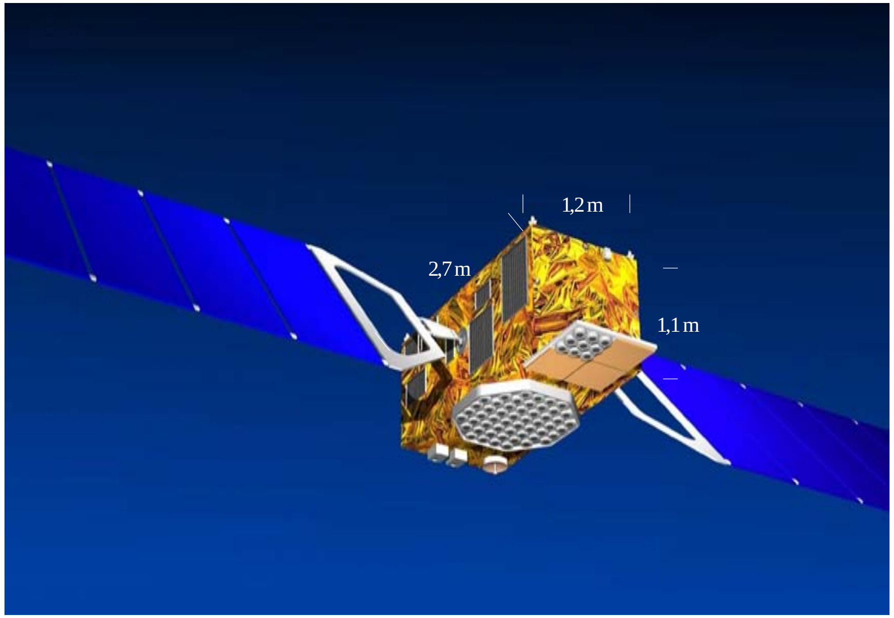
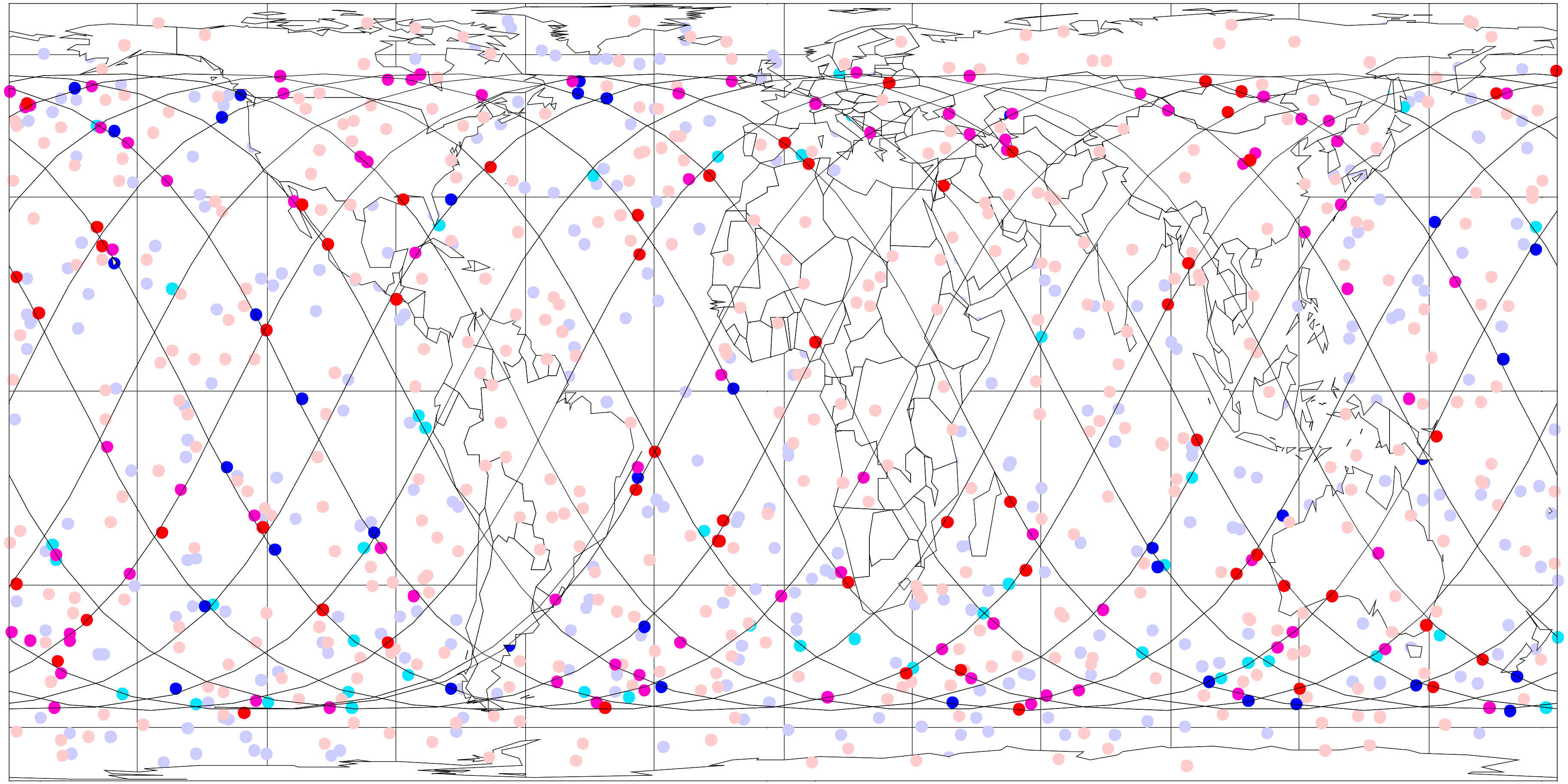


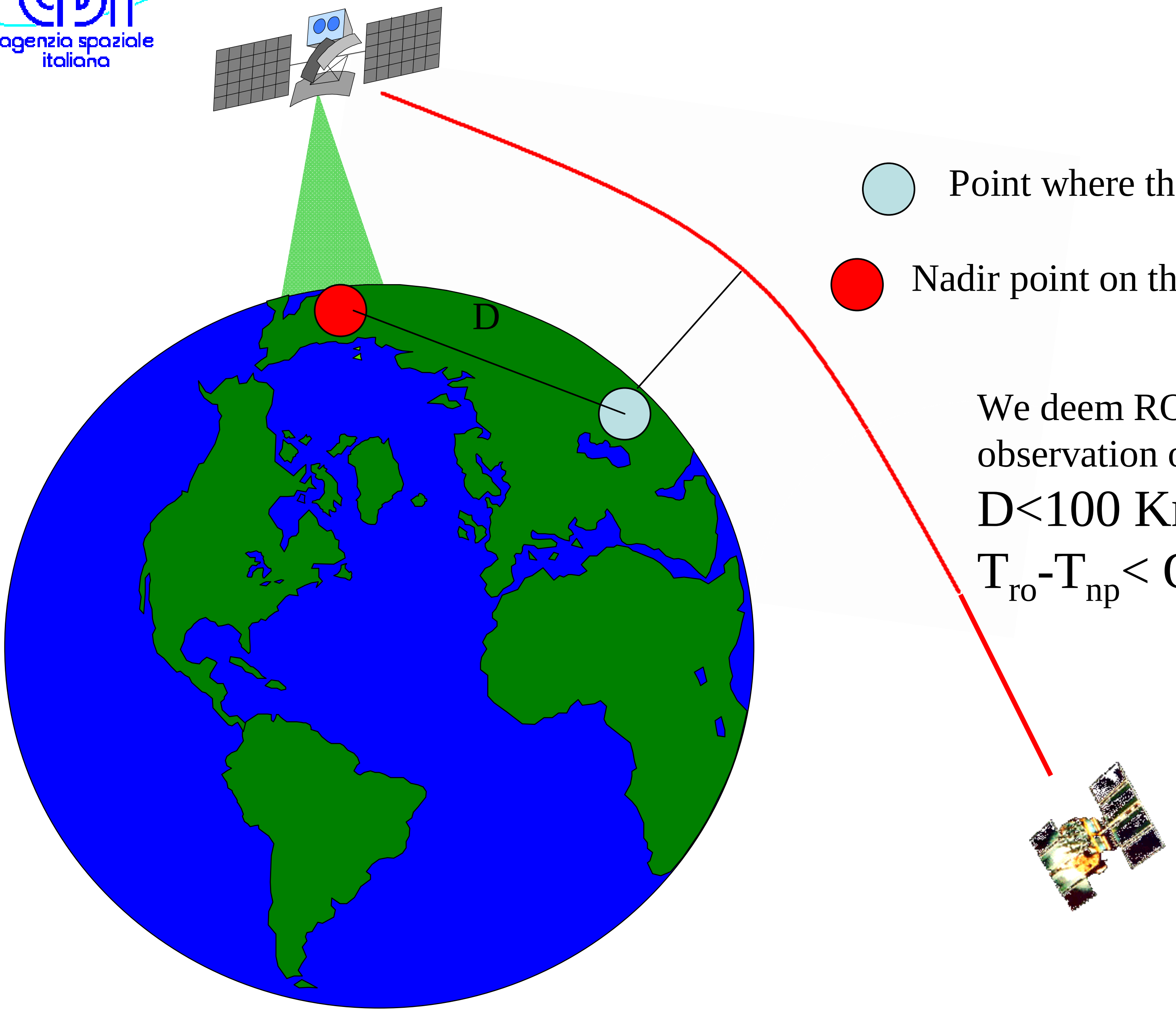
Table of Radio Occultion Events without and with GALILEO

Height: 800 km	Tot. Nr Occultation/Day			Nr. Occ./Day far <100 km from PFS Measurement			Nr. Occ./Day <100 km and Δt < Torb		
Inclination (°)	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL
5°	373	435	808	225	264	489	43	36	79
25°	418	479	897	163	165	328	41	35	76
55°	424	484	908	110	131	241	35	51	86
75°	440	498	938	110	112	222	33	34	67
98°.6	478	553	1031	125	152	277	27	44	71
125°	494	556	1050	126	163	289	44	59	103



CLimatology

- Global
- All Weather
- Relevant (refractivity, tropopause etc.)
- *Self Calibrating (could be used for "in flight" calibration of other sensors but…)*



Point where the RO occurs

Nadir point on the ground

We deem RO and Nadir pointing observation overlapped if:

$D<100$ Km;

$T_{ro}-T_{np}<$ Orbital Period

GPS+GALILEO Radio Occultation Table

Height: 800 km	Tot. Nr Occultation/Day			Nr. Occ./Day far <100 km from PFS Measurement			Nr. Occ./Day <100 km and Δt < Torb		
Inclination (°)	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL
5°	373	435	808	225	264	489	43	36	79
25°	418	479	897	163	165	328	41	35	76
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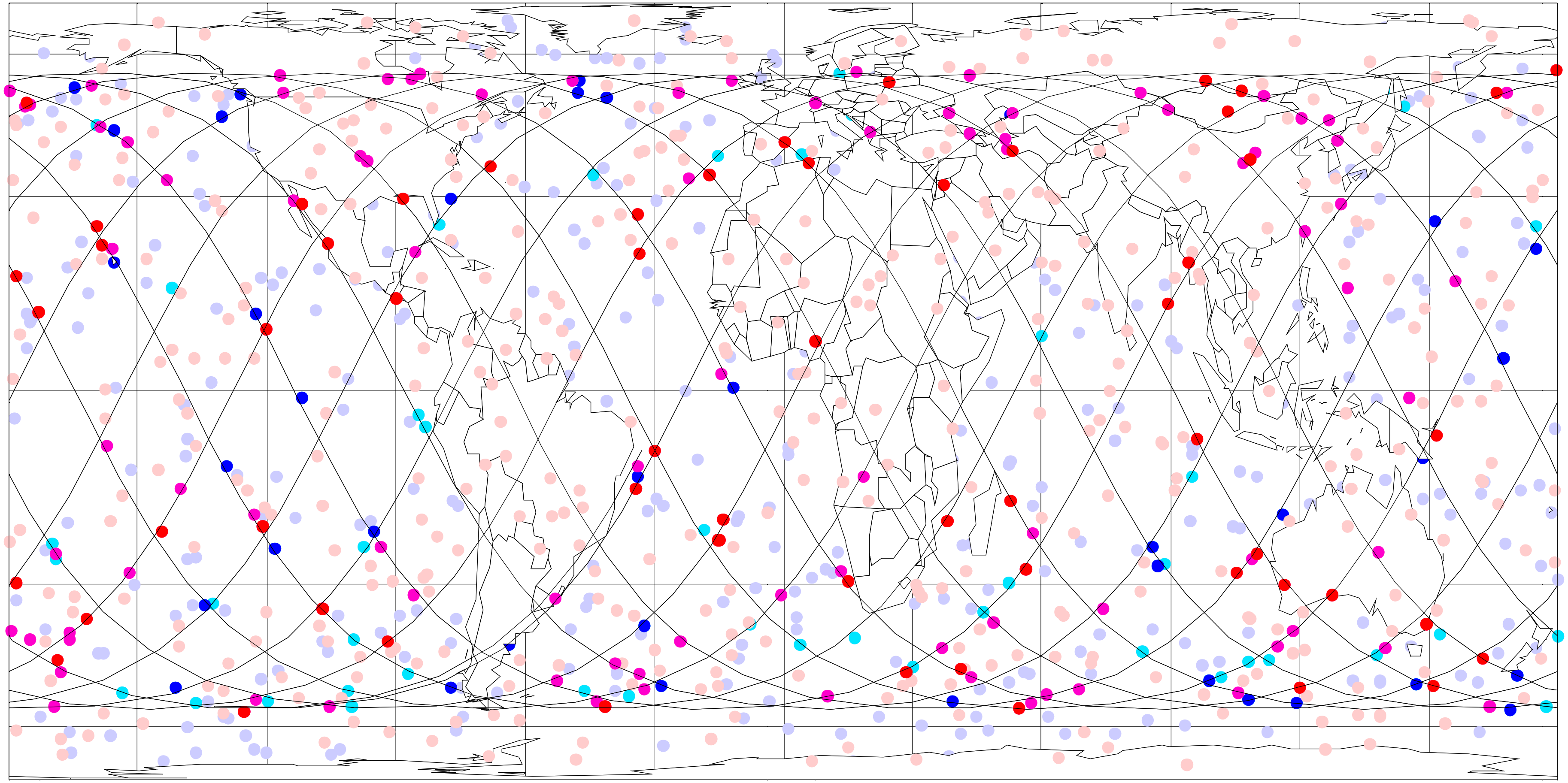

The number of points suitable for “in flight” calibration of Nadir pointing instruments with GNSS RO doubles

CLIMATE

- Refractivity can be estimated with RO with a relative accuracy of 10^{-3}. Suitable for Climate investigations
- Refractivity as a fingerprint to investigate the Climate
- Fingerprint could be formed by combining projections for about 20 different levels below 25 Km, for some 30 different locations over the globe, and for four seasons
- (Goody et al. (1998).

Tables of the number of Radio Occultation with and without GALILEO

Height 800 km	Tot. Nr Occultation/Day			Nr. Occ/Day for <100 km from ISS Measurement			Nr. Occ/Day <100 km and Δz < Turb		
Inclination (°)	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL	GPS	GAL	GPS + GAL
5°	375	436	[illegible]	166	164	330	43	36	79
25°	418	409	827	169	165	330	41	35	76
55°	424	484	908	116	131	241	35	51	86
75°	440	498	938	110	113	223	33	34	67
98°.6	478	553	1031	125	153	277	37	44	71
125°	464	546	1050	126	163	289	44	59	103

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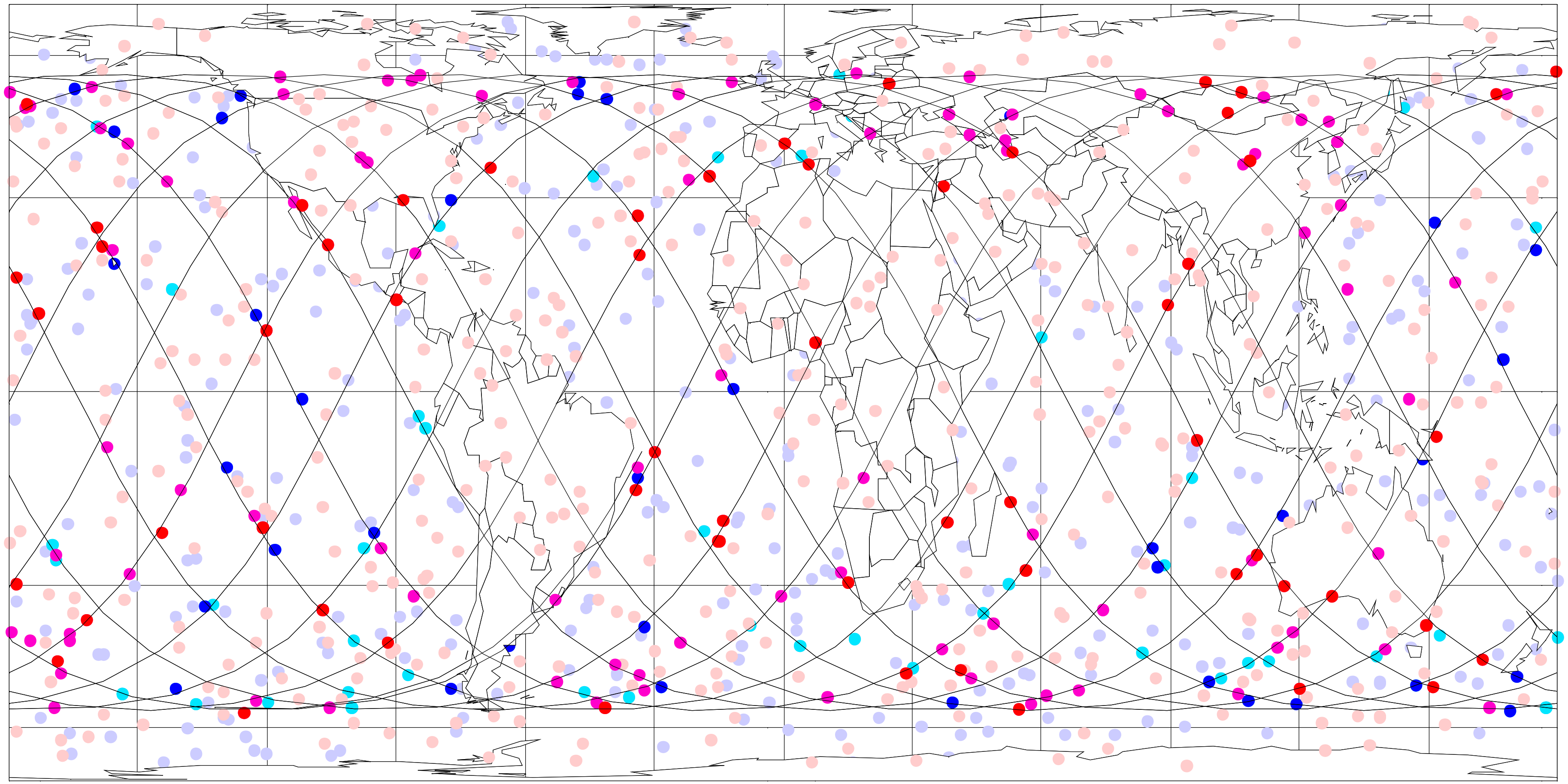
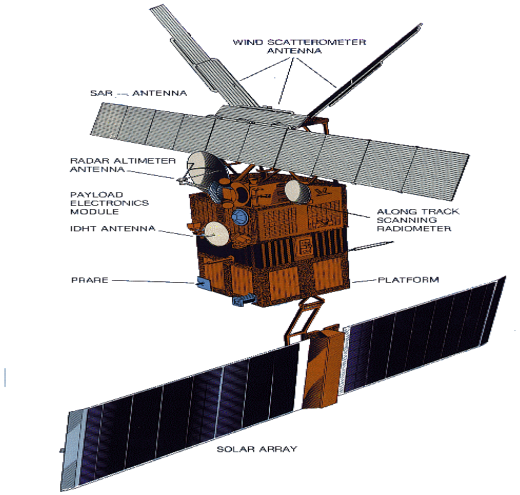


GPS for :
POD and Gravity field recovery

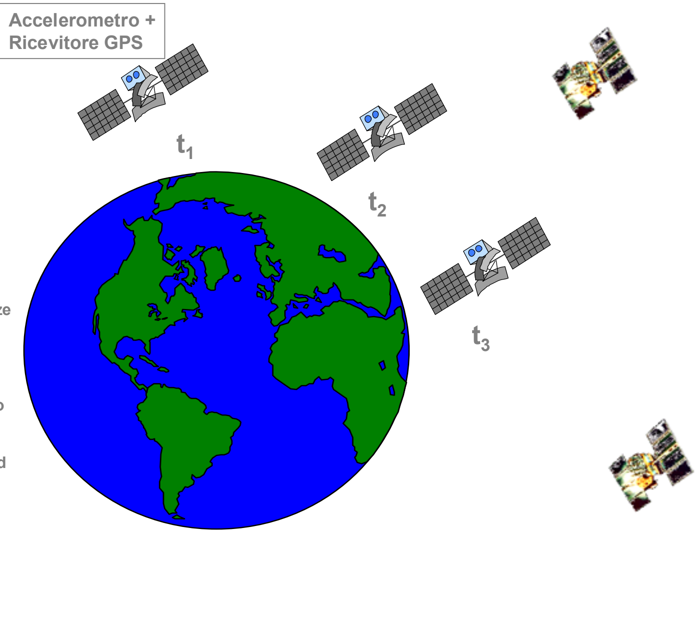


Precise Orbit Determination

$$A_{grav} = A_{gps} - A_{acc}$$

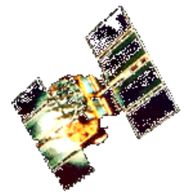
Accelerazione Totale data dalle doppie differenze nel tempo dell'osservabile GPS;

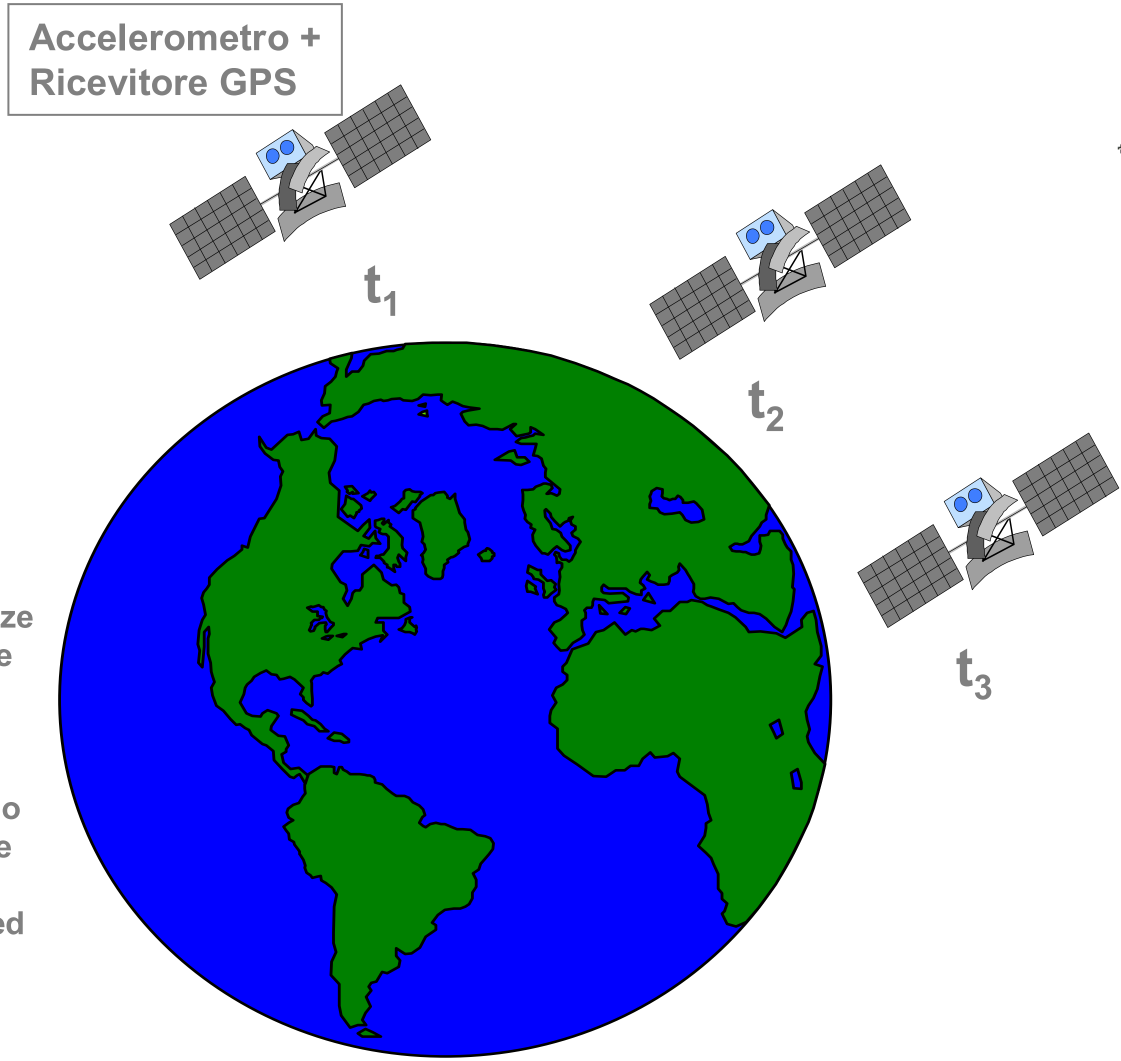
mentre l'accelerometro fornisce accelerazioni solo delle forze superficiali che agiscono sul satellite (pressione di radiazione ed atmosfera)



Trieste 07,04,2010

II Workshop on Satellite Navigation Science and Technology for Africa

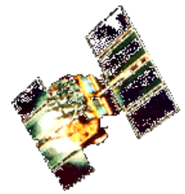


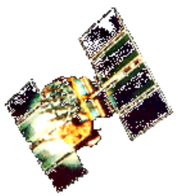


$$A_{grav} = A_{gps} - A_{acc}$$

Accelerazione Totale data dalle doppie differenze nel tempo dell'osservabile GPS;

mentre l'accelerometro fornisce accelerazioni solo delle forze superficiali che agiscono sul satellite (pressione di radiazione ed atmosfera)





What are the ASI matter in Africa ?
An ASI ground station exists in Malindi (Kenia)

Italian – Kenian Working Group for the establisment of a Regional Centre for Earth Observation was created:

Kenyan delegation: F.R.O. Eshikuta, J. Kimani (Observer), E. Waithaka ;

Italian delegation: M. Castronuovo, S. Di Ciaccio, L.Garramone;

Table of contents

- **Objectives of the Italian-Kenian task force;**
- **Feasibility study: status of completion;**
- **Main features of KCEO;**
- **Preliminary architecture;**
- ***GPS Fiducial Network;***
- **Cost identification;**
- **Activities to be done.**

Objectives of the Italian-Kenian task force

- Generation of a feasibility study for the implementation of an Earth Observation Regional Centre in the Sub Saharan Africa;
- Identification of possible available local resources and infrastructures;
- Generation of a draft Memorandum of Understanding (MOU) between Italy and Kenya;
- Organization of an International Workshop in order to present results of the feasibility study;
- Activities started on June 2008, when the task force meet in Malindi and the work plan for the activities was generated.

Main features of RCEO

- Remote sensing antenna installed in the ASI Centre at Malindi;
- Direct ingestion of the remote sensing data carried out in Malindi;
- Quality Check and transcription on permanent media in Malindi;
- Remote Sensing archives in Malindi and Nairobi;
- Transfer of data from Malindi to Nairobi via electronic link (for Near Real Time product generation and distribution);
- Transfer of huge quantities of data from Malindi to Nairobi through postal courier;
- Application processors (higher level processors) in Nairobi;
- User Interface in Nairobi.

GPS Fiducial Network

➢ From the Kenian side, a request to explore the possibility of implementing a GPS fiducial network arrived.

➢ Task force agreed on this request; as consequence, this aspect has been considered in the study.

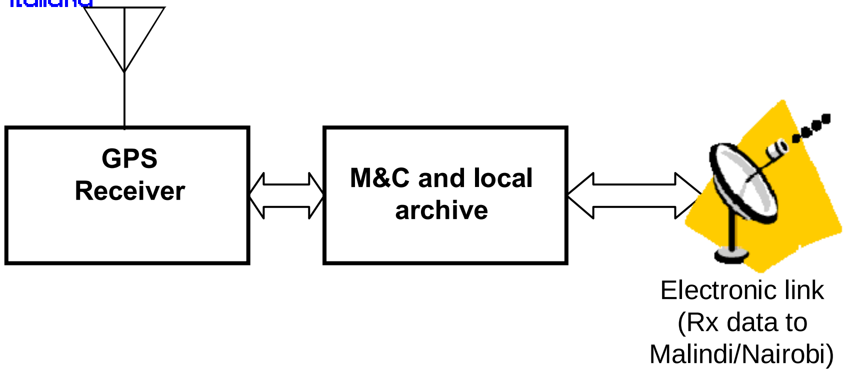
➢ A GPS fiducial network could represents an useful facility to establish a terrestrial reference frame in Kenya.

➢ In addition, the establishment of a geodetic local network in the Malindi area would represent the first step for the creation of a geodetic fundamental station at the Broglio Space Center (BSC).

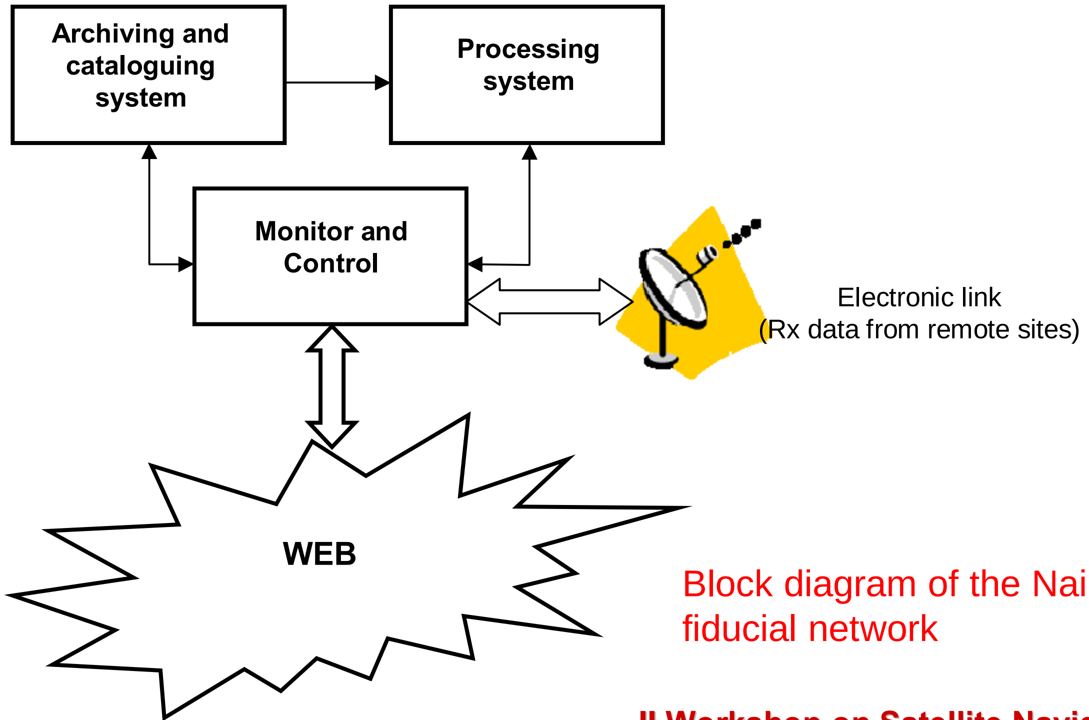
➢ A strong “request” to have a geodetic fundamental station in this region of the African Continent has been expressed at international level (ILRS, IVS).

International VLBI Network

GPS Fiducial Network



Block diagram of a Kenyan fiducial site



Block diagram of the Nairobi facility for the GPS Kenyan fiducial network

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Thank you for your kind attention!