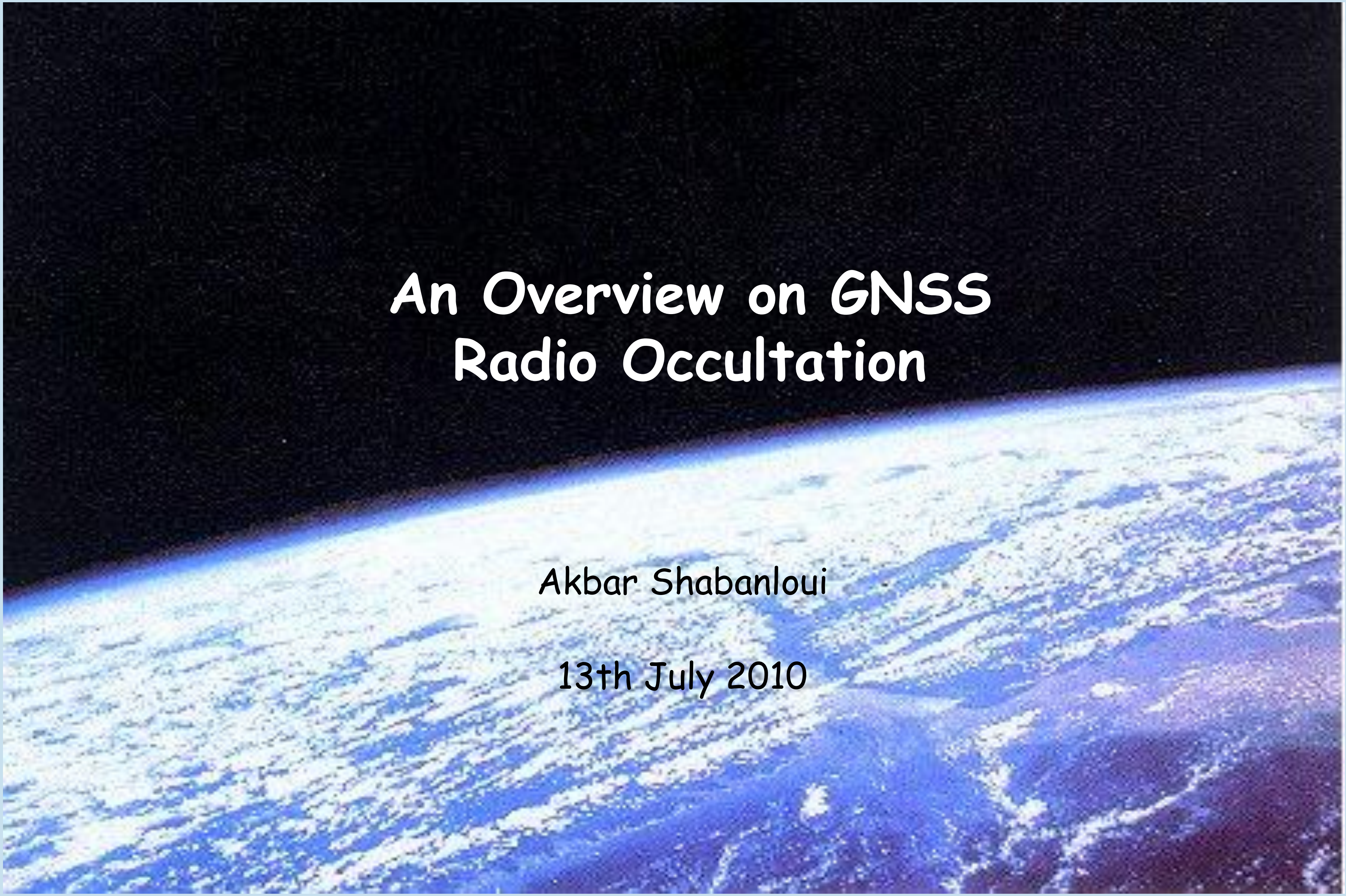


An Overview on GNSS Radio Occultation

Akbar Shabanloui

13th July 2010

Outline

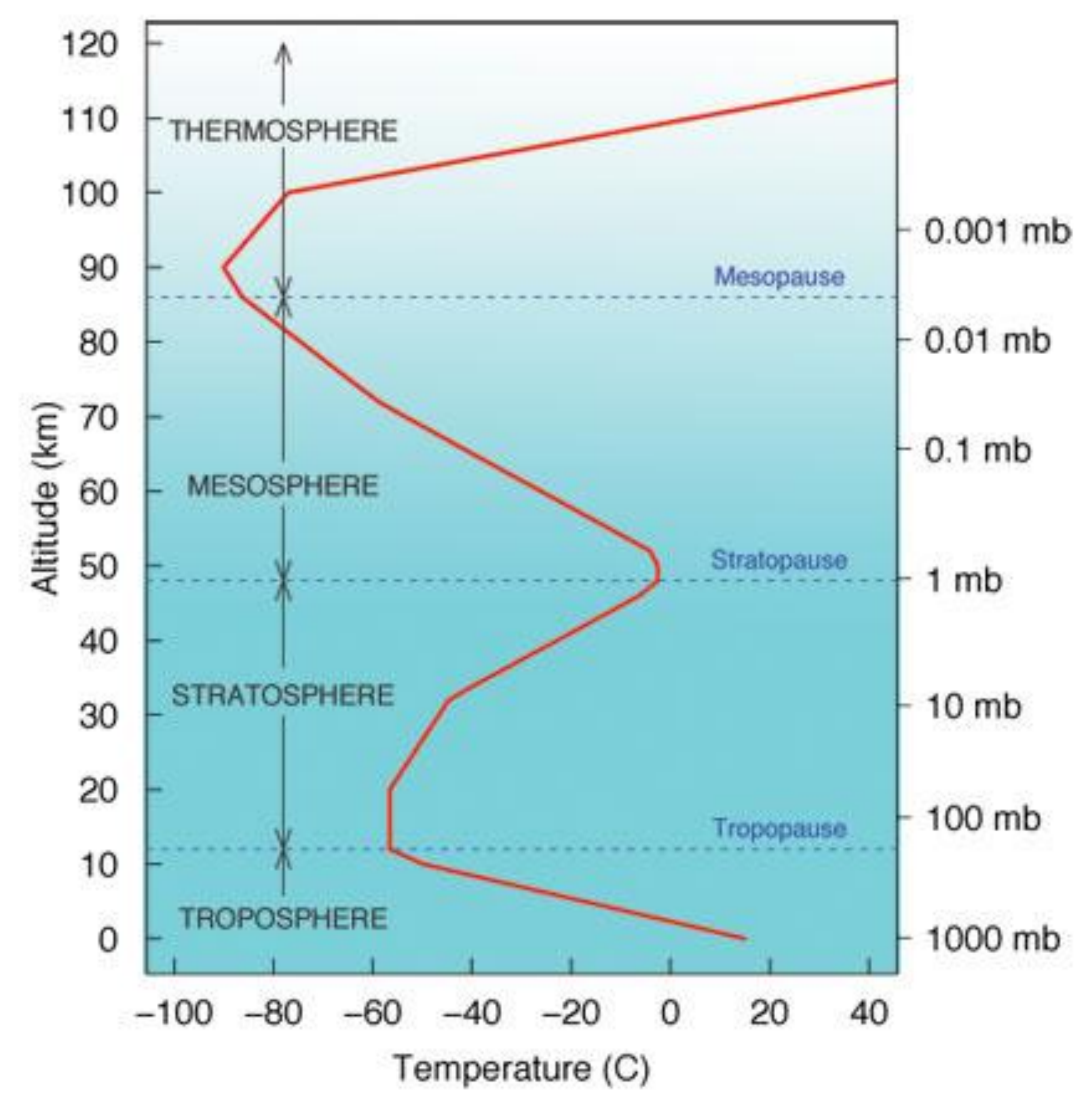
- Basic concepts
- Physic of atmosphere
- Ground-based GNSS atmospher sounding (measurements)
- GNSS Radio Occultation (GNSS-RO) measurement geometry
- Classical GNSS-RO retrieval method
- Results
- Data Assimilation (DA)
- Summary

Atmosphere

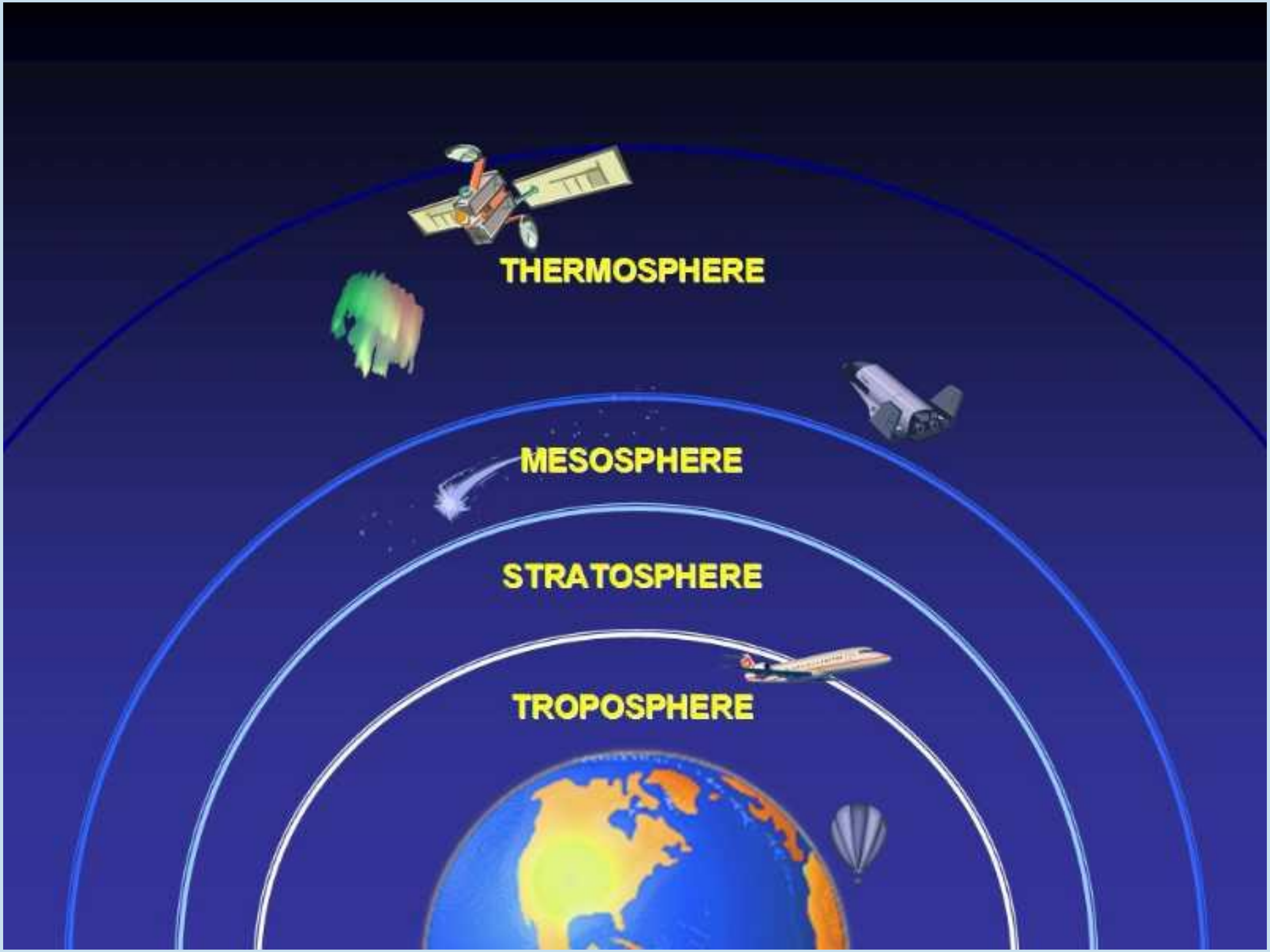
Parameterization

- Temperatur
- Pressure
- Water Vapour Pressure
- Density
- ….

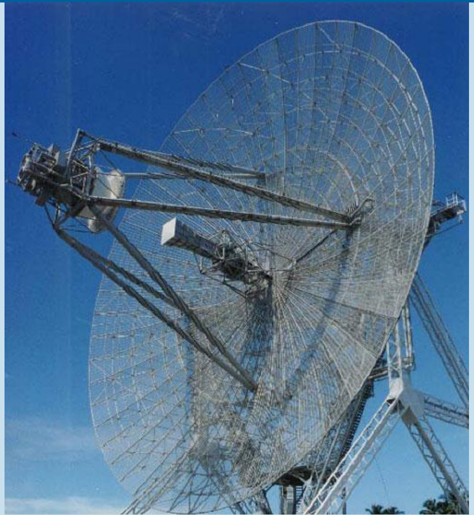
Atmosphere structure



Atmosphere



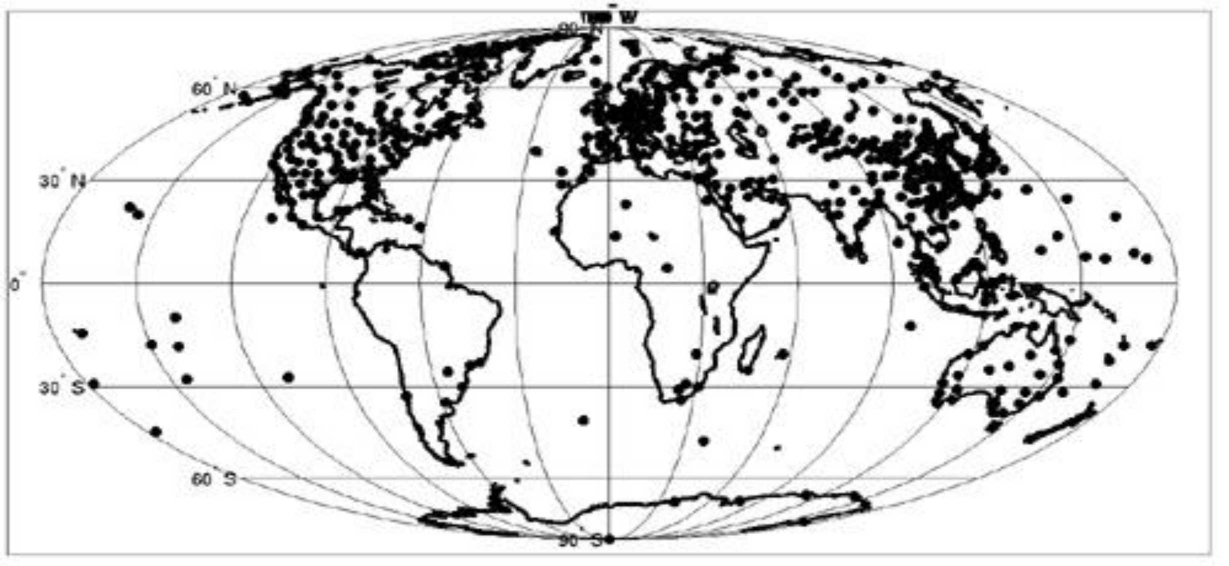
Atmosphere Sounding methods



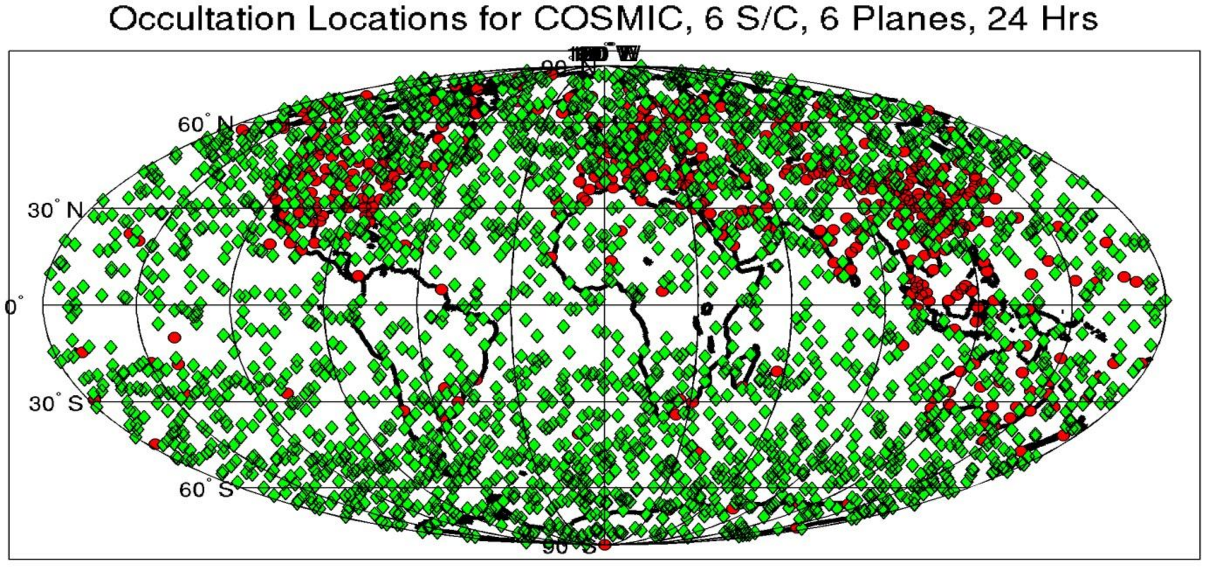
- RADAR (RAdio Detection And Ranging)
  - expensive,
  - poor coverage
- SODAR (Sound Detection And Ranging)
  - Based on sound system
  - expensive
  - Poor coverage
- Radiosound
  - Ballons with sensors
  - expensive
  - poor coverage
- Remote sensing (active or passive) - Image Processing
- GNSS based
  - Ground based
  - Space based

Atmosphere Sounding methods (Coverage)

Radiosound



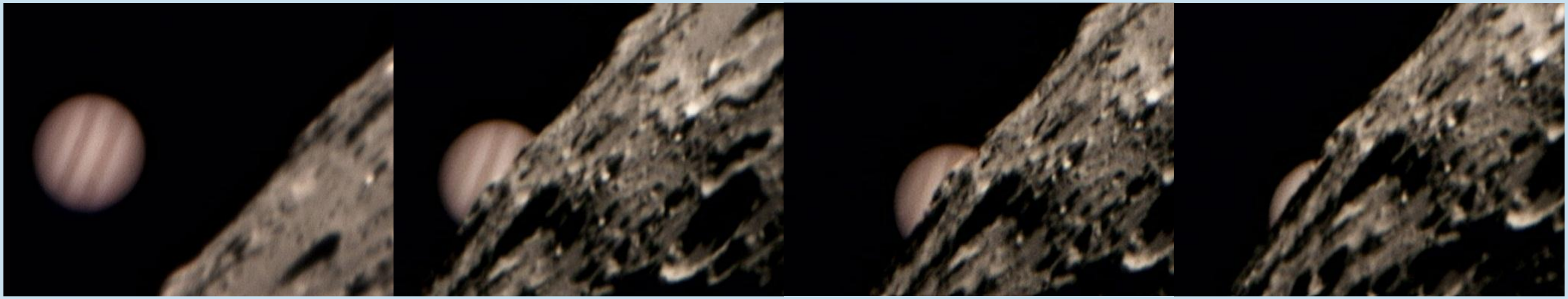
Radiosound+
COSMIC


Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

Definition

- RADIO
  - The signal frequency is less than 10 GHz.

- Occultation (Optical)
  - An occultation occurs when one object is hidden by another object that passes between it and observer!



Jupiter & Moon occultation. Dec. 7, 2004 - Pub in S&T, April 2005

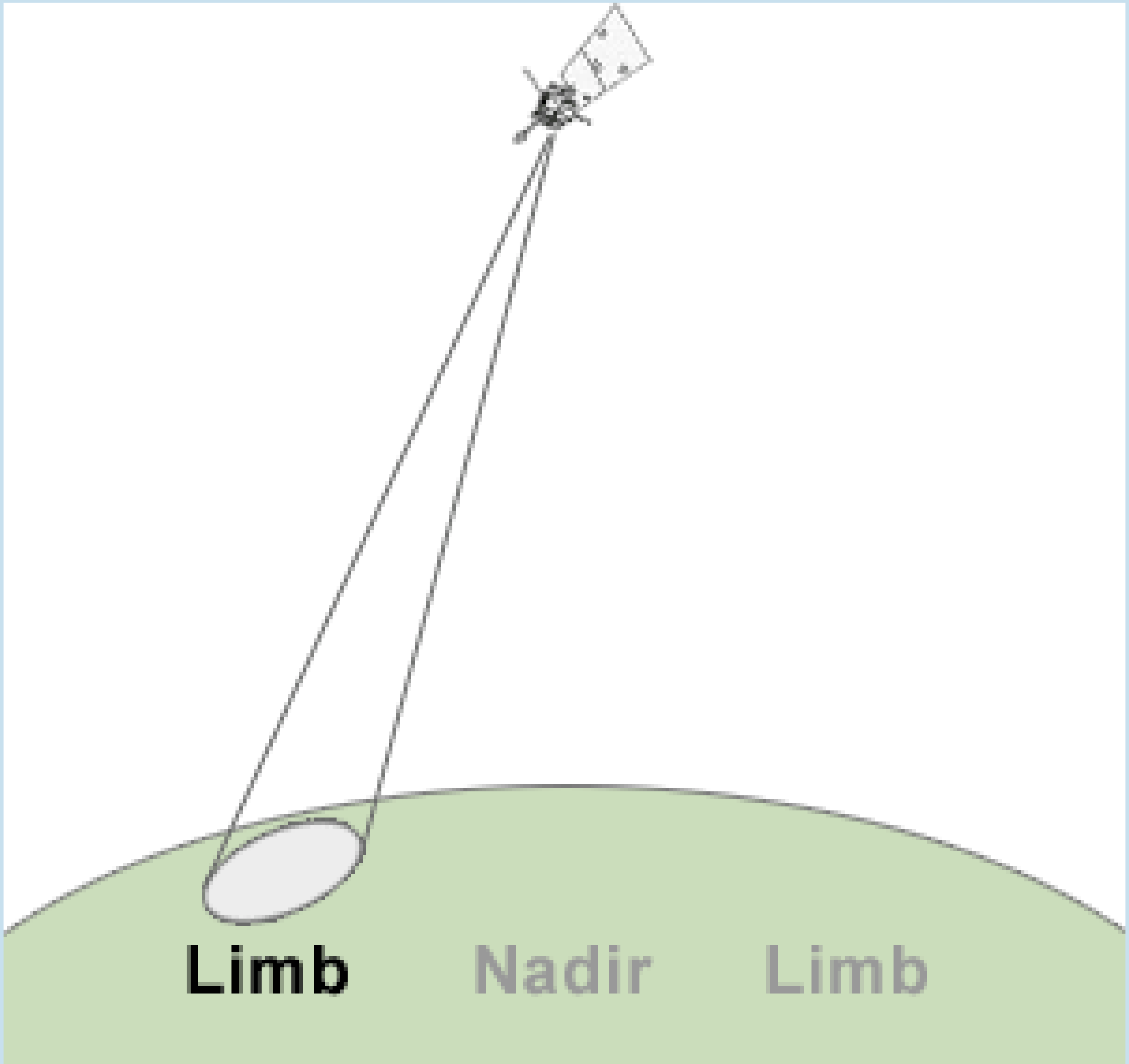
Occultation (Special case: GNSS-RO)

An occultation occurs when one object (GNSS) is hidden by another object (Earth) that passes between it and observer (LEO)!

GNSS-RO principal

Source: Saint Exupery 1986

GNSS-RO principal

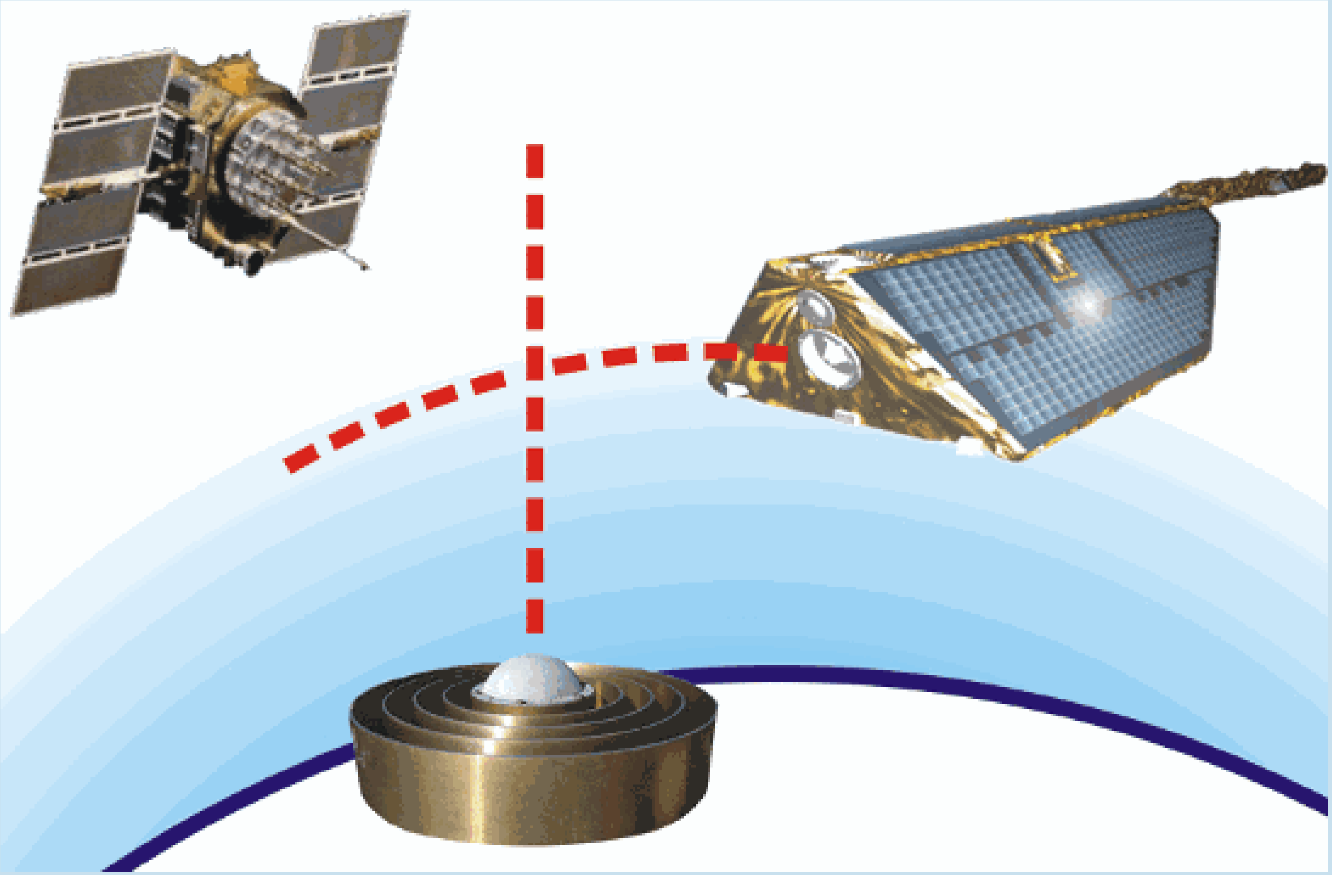


Source:
COSMIC

Concepts (Refraction)

GNSS Based Meteorology

- Ground based GNSS (Nadir direction, Column Integrated Water Vapour)
- Space based GNSS (Limb Sounding, Profile Information)



Source: GFZ

Concepts

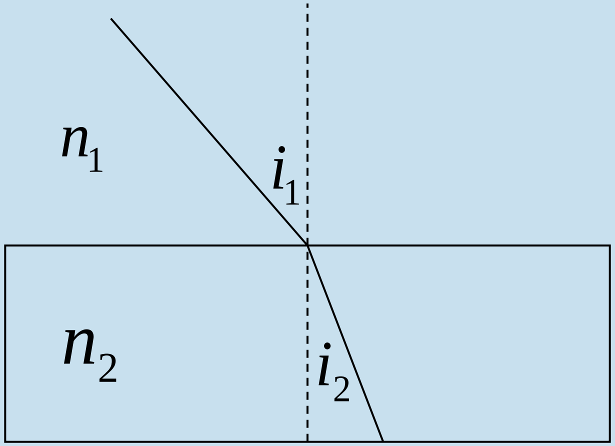
- Refractive index: Speed of an electromagnetic wave in a vacuum divided by the speed through a medium.

$$n = \frac{c}{v} \Longrightarrow N = (n-1) \times 10^6$$

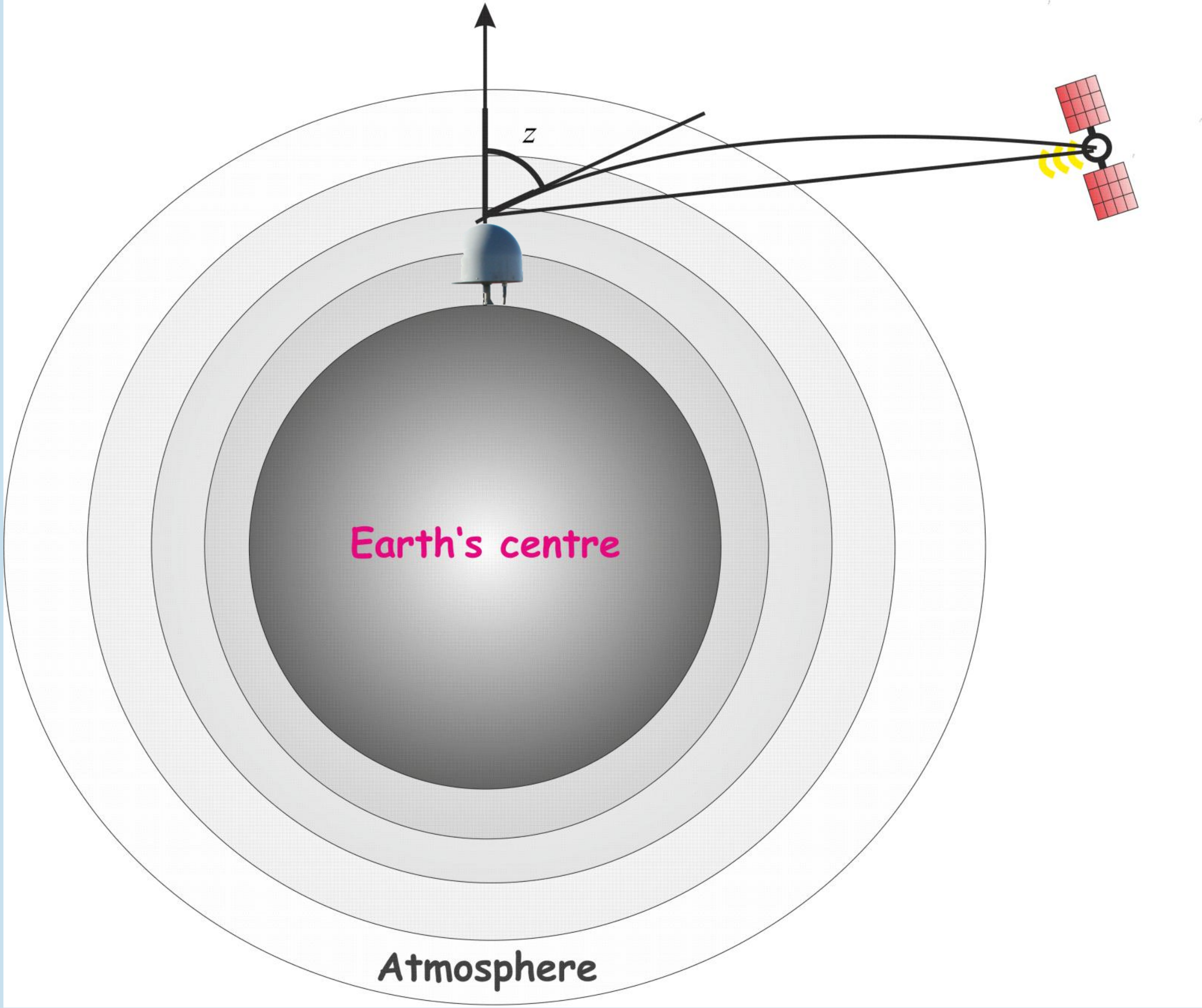
Refractivity index!

- Snell's law of refraction

$$n_1 \sin i_1 = n_2 \sin i_2$$



Ground base GNSS Atmosphere Sounding



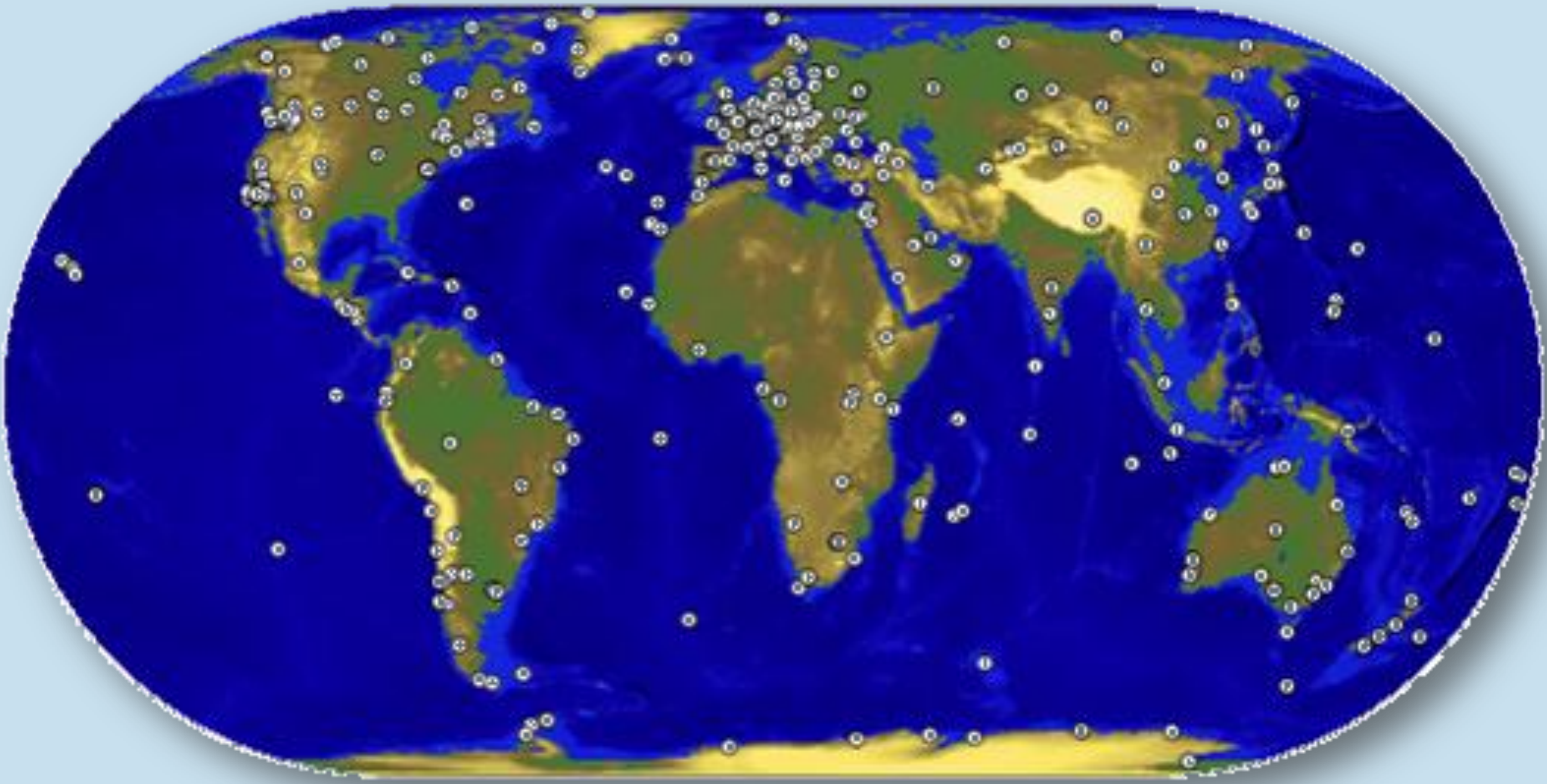
Ground base GNSS Atmosphere Sounding

- ECMWF (European Centre for Medium-Range Weather Forecast) currently monitors ground based GNSS zenith total delay (ZTD) measurements in operations.
- Ignoring bending, the excess slant delay caused by the atmosphere is

$$\Delta\phi = \int_{G}^{R} n(s)ds - S = \left(n(s) - 1\right)10^{6} \Longrightarrow ZTD(T, P, P_{w})$$

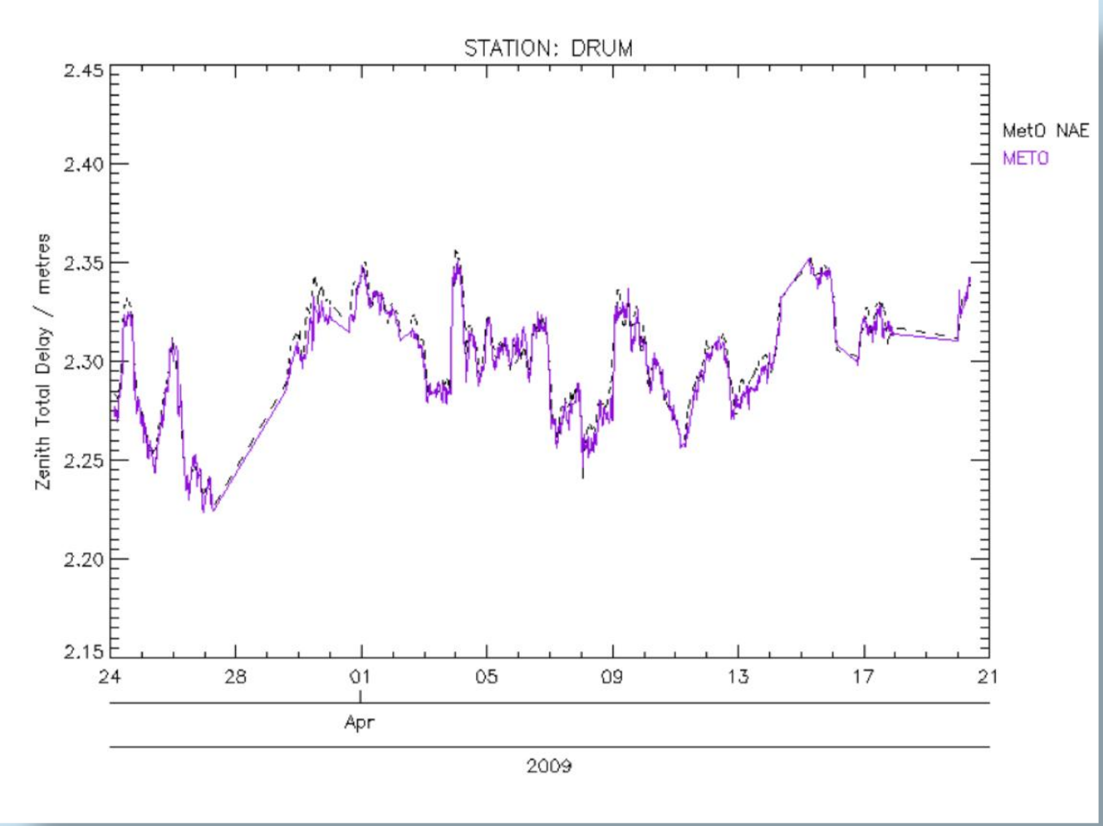
- The slant delays are mapped to a zenith delays using mapping functions (Neil mapping function or Hopfield etc…).

IGS network

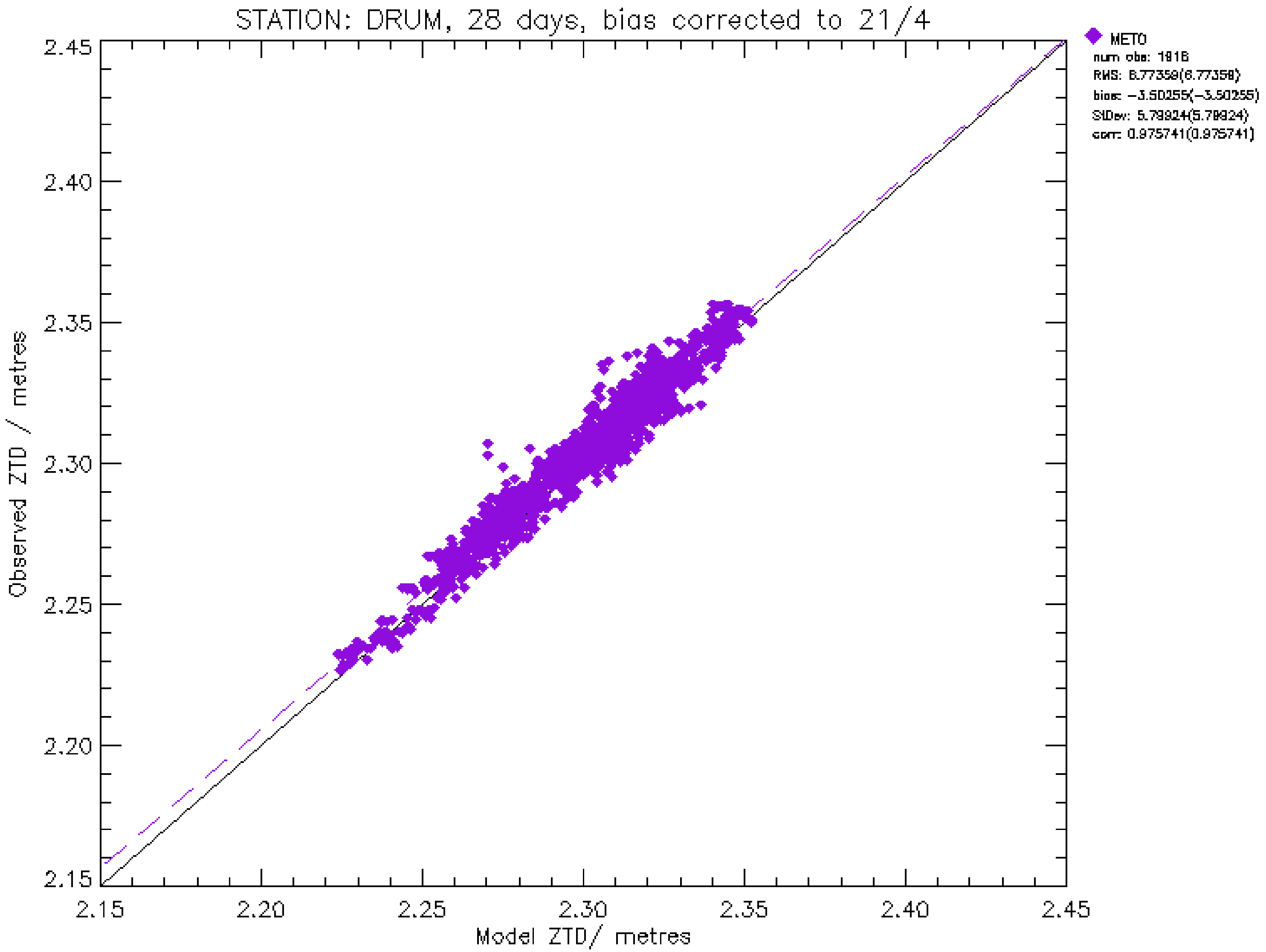


ECMWF monitors zenith total delay

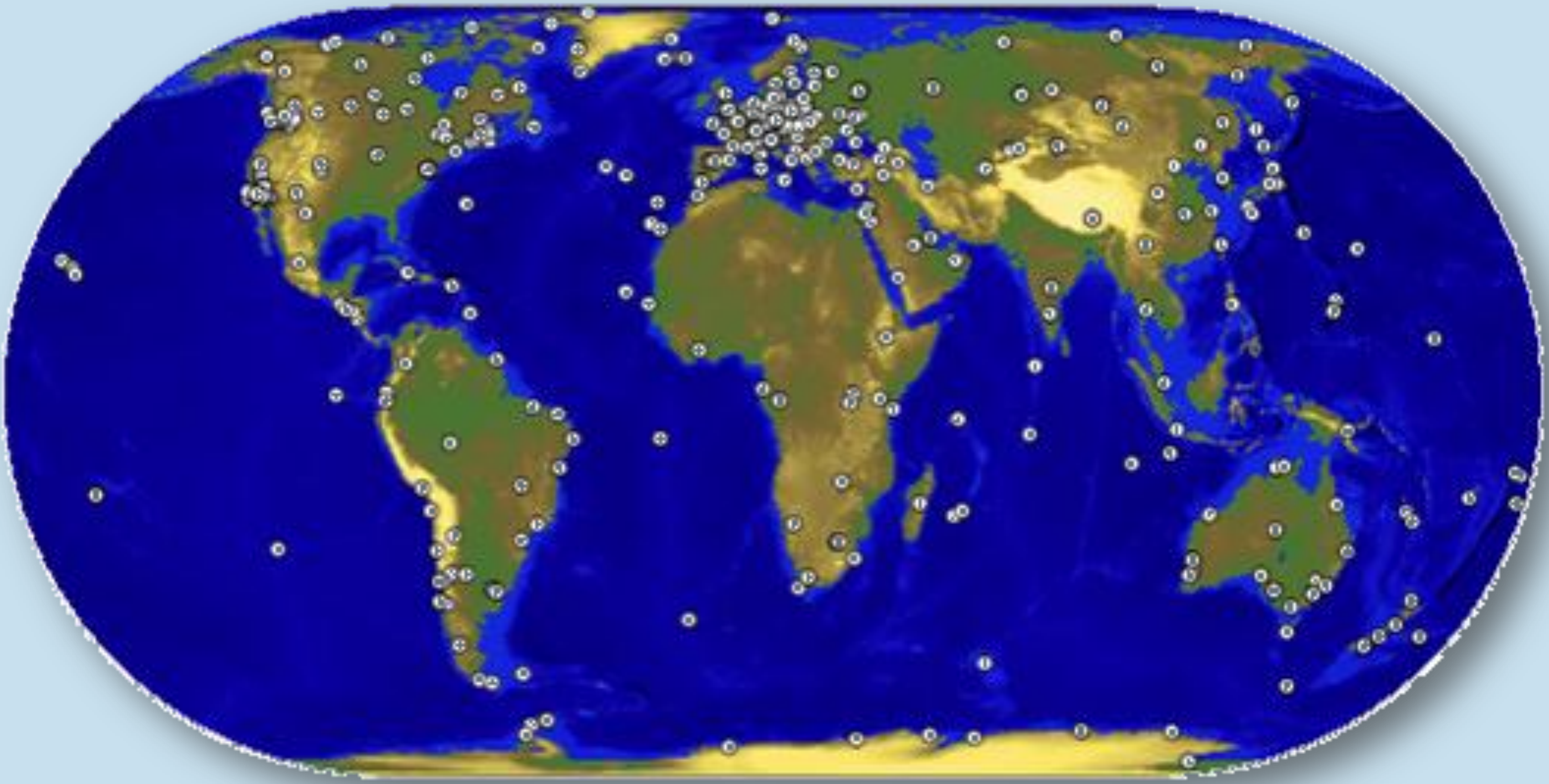
- Information content: The "hydrostatic delay" is large (90% of total), but it is only really sensitive to the surface pressure value at the receiver.
- The "wet delay" is smaller, but more variable. The wet delay is related to the vertical integral of the water vapour density.



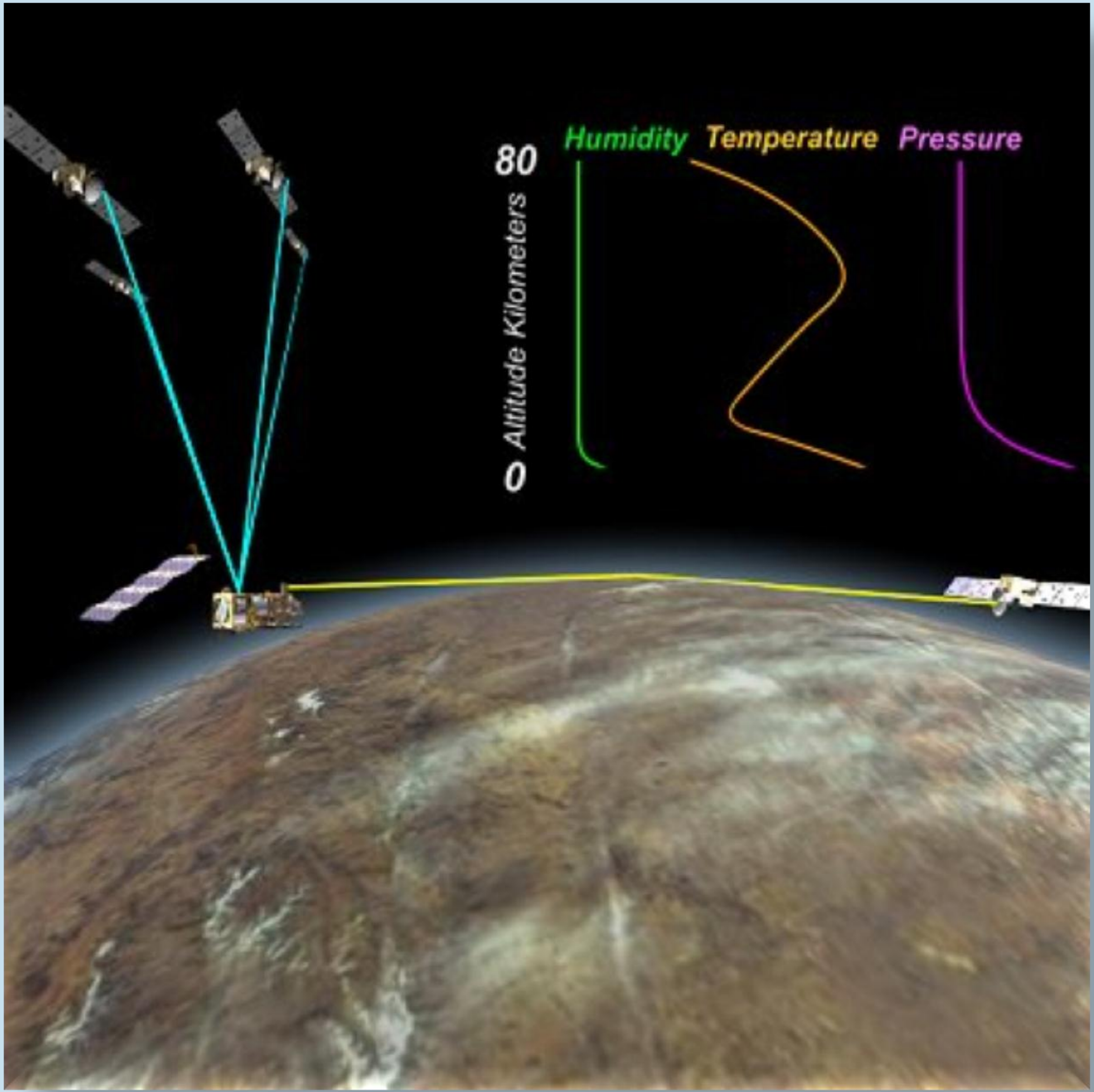
IGS ZTD correlation



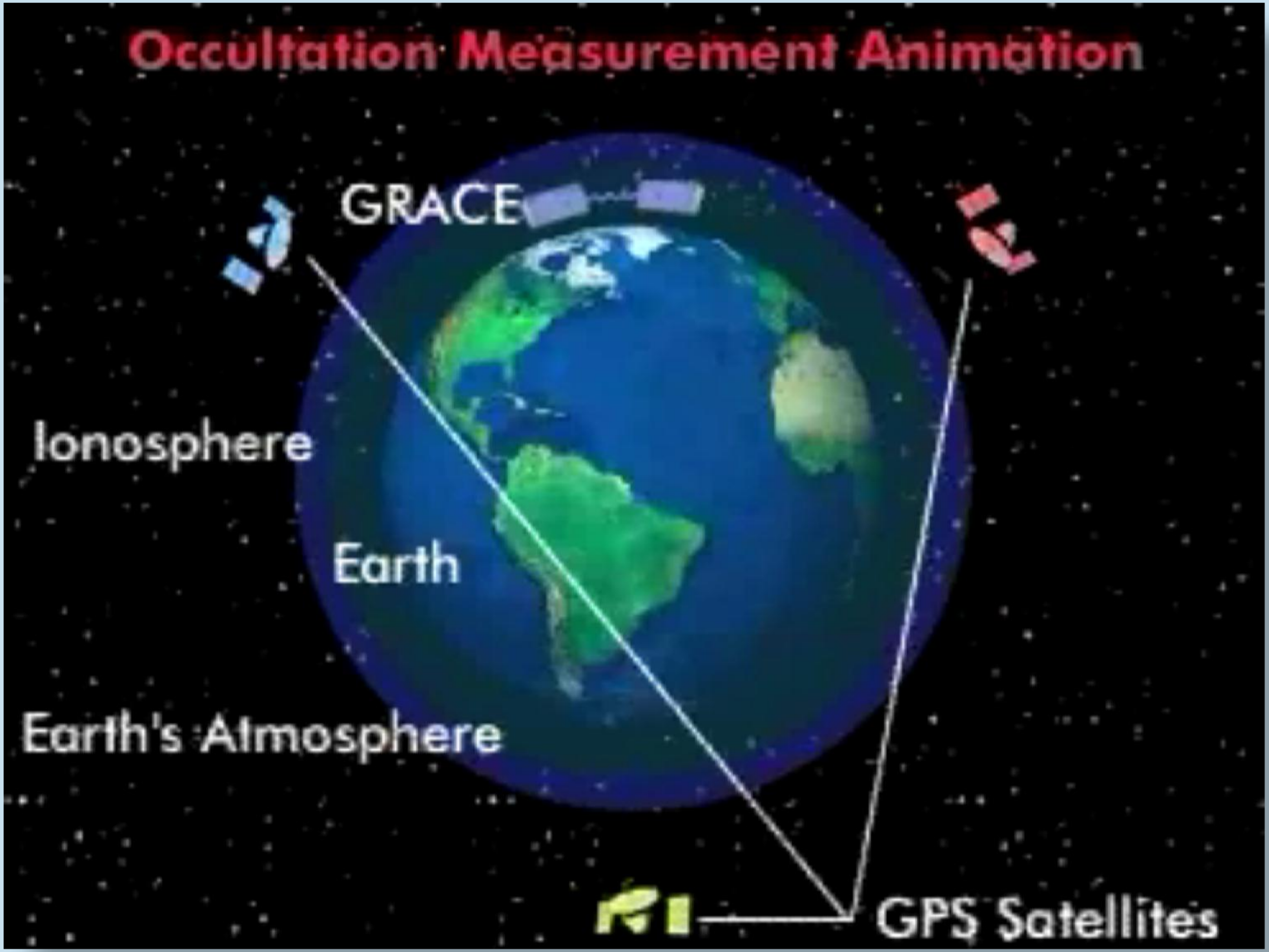
Why GNSS-RO (Space based)?



GNSS Radio Occultation (GNSS-RO)

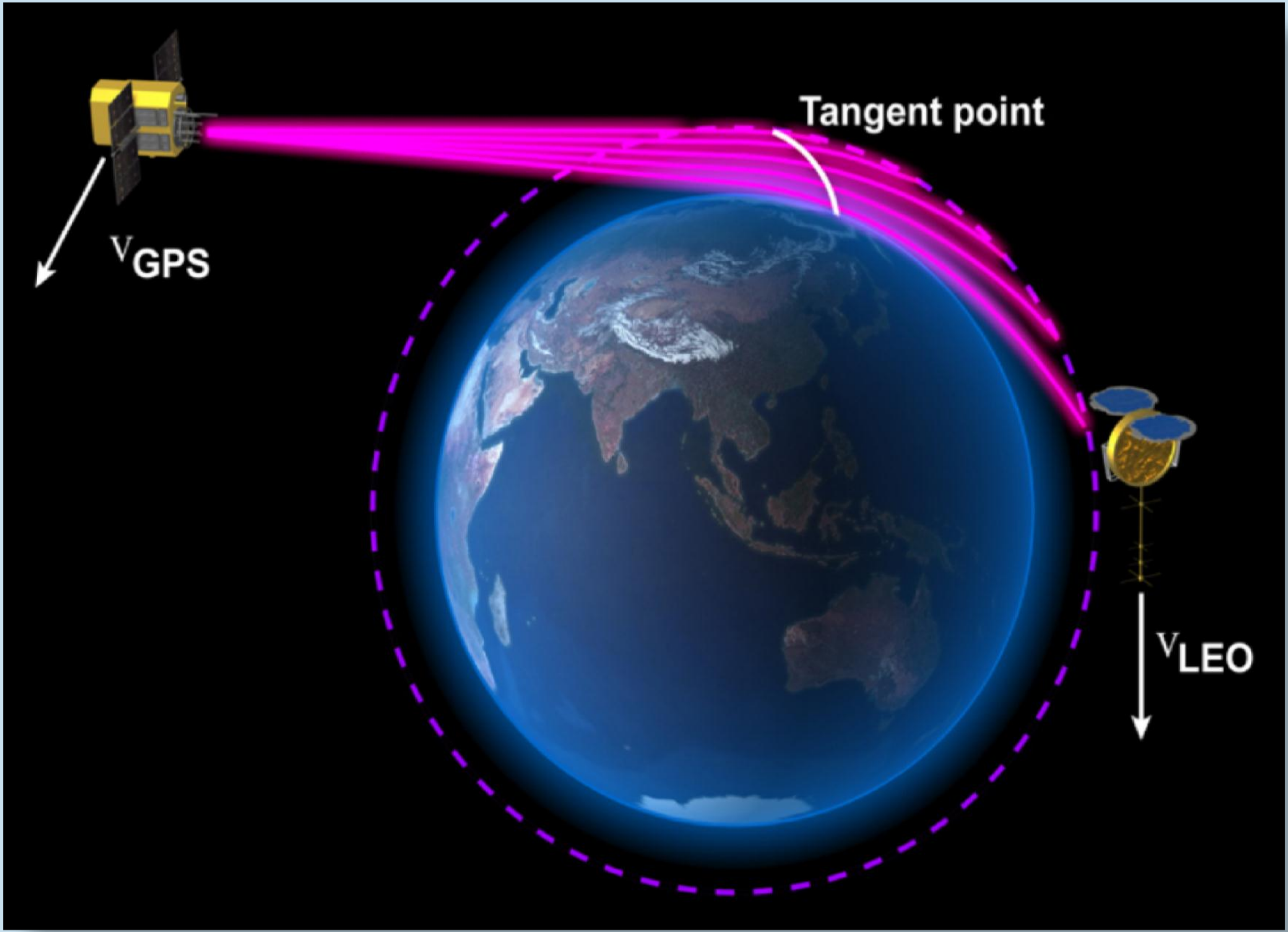


GNSS Radio Occultation (GNSS-RO)

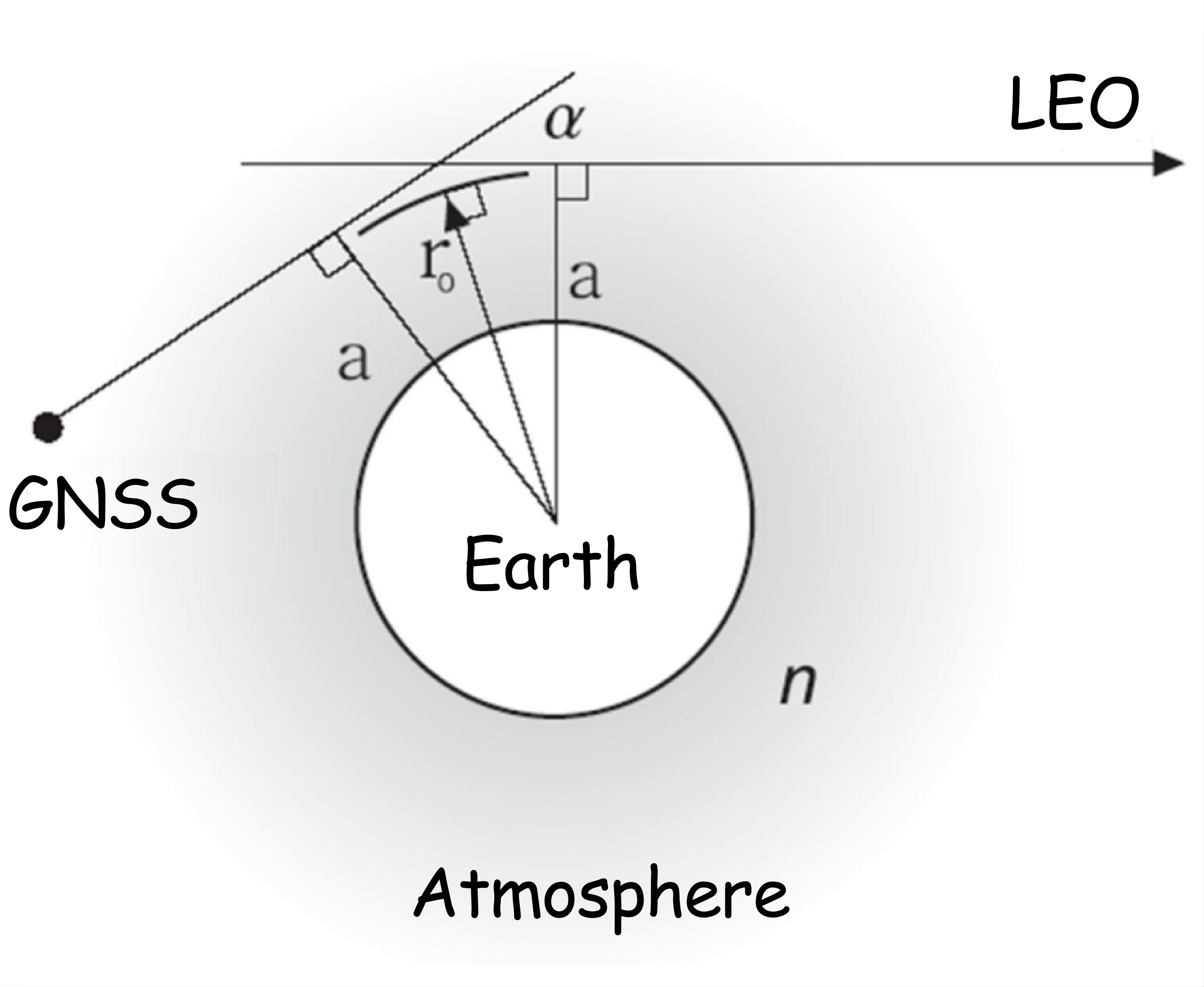


Source: CSR

Processing of GNSS-RO observations



GNSS Radio Occultation Geometry



Radio Occultation Background

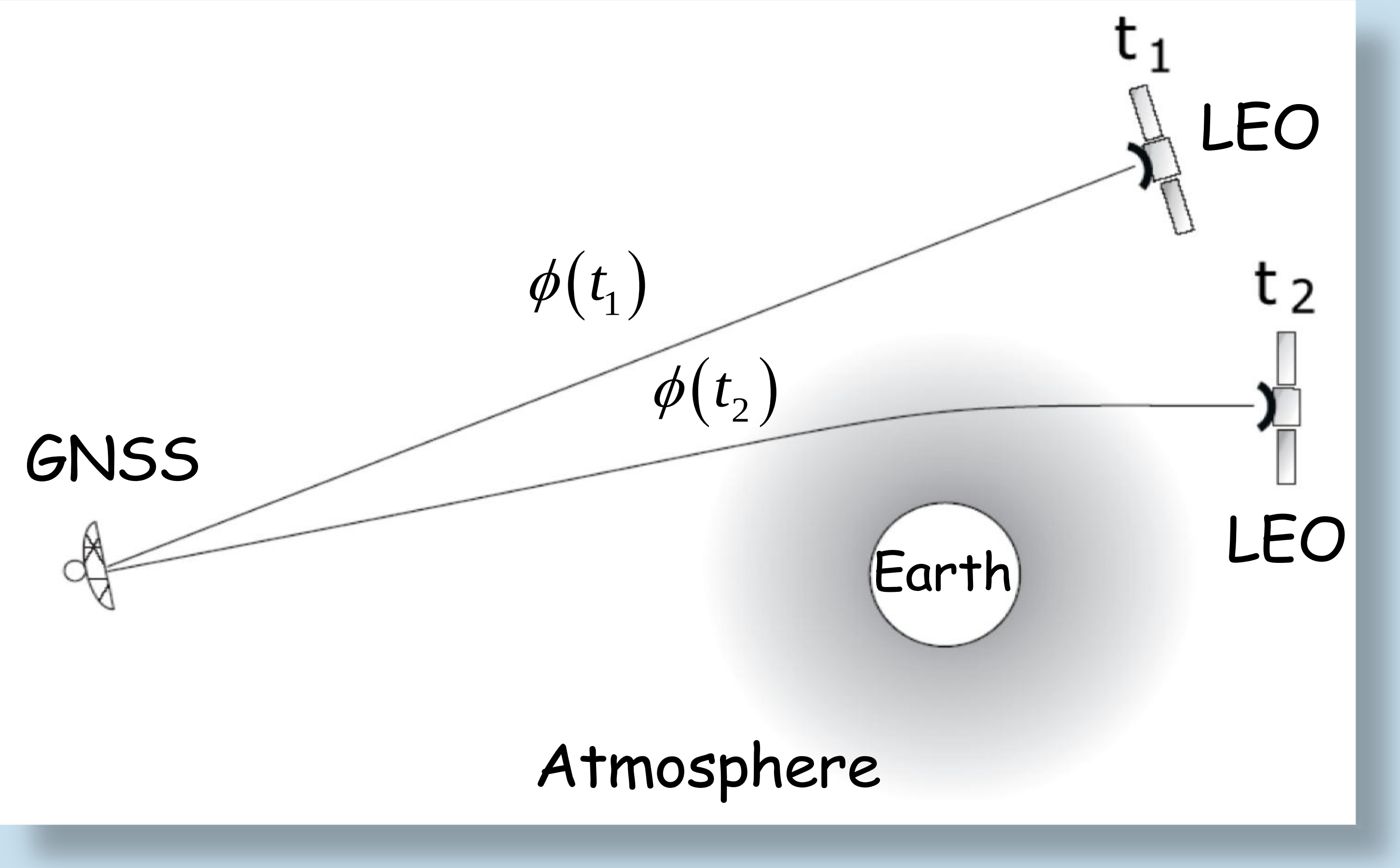
- Radio occultation (RO) measurements have been used to study planetary atmospheres, such as Mars and Venus, since the 1960's. Its an active technique. We simply look at how the paths of radio signals are bent by refractive index gradients in the atmosphere (Optical and Radio).
- The use of RO measurements in the Earth's atmosphere was originally proposed in 1965, but required the advent of the GPS constellation of satellites to provide a suitable source of radio signals.
- The GPS satellites are primarily a tool for positioning and navigation. These satellites emit radio signals at L1= 1.57542 GHz and L2=1.2276GHz (~20 cm wavelength, Radio wavelength).
- In 1996 the proof of concept "GPS/MET" experiment demonstrated useful temperature information could be derived from the GPS RO measurements.

Radio Occultation Background

- The GNSS signal velocity is modified in the ionosphere and neutral atmosphere because the refractive index is not unity, the path is bent because of gradients in the refractive index.
- GNSS-RO is based on analysing the bending caused by the neutral atmosphere along ray paths between a GNSS satellite and a receiver placed on a LEO.

Processing of GNSS-RO observations

- GNSS receivers do not measure bending angle directly!
- The GPS receiver on the LEO satellite measures a time series of phase-delays $\phi(i),\phi(i+1),...$ at the two GPS frequencies,

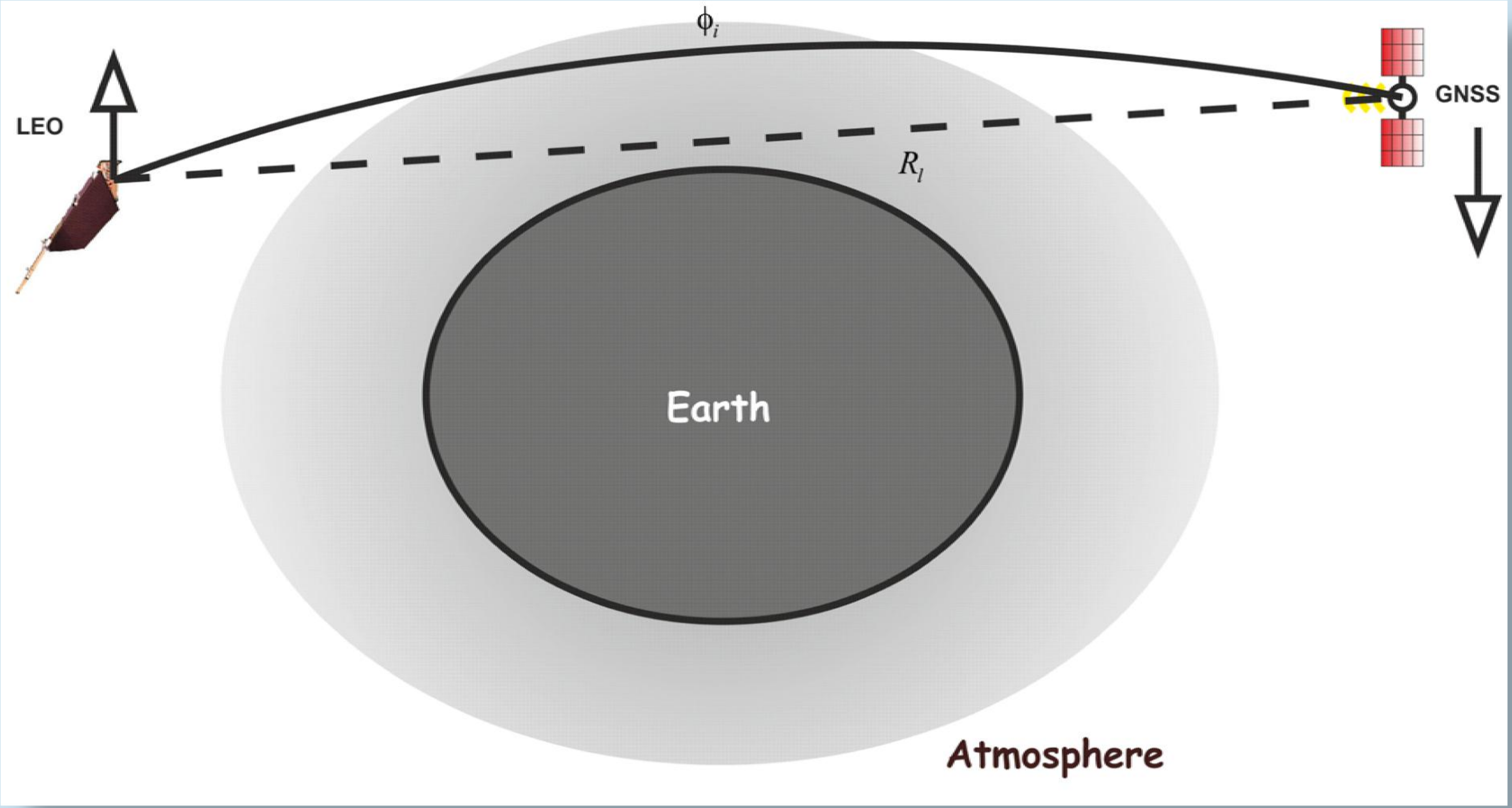


Processing of GNSS-RO observations

- The phase delays are "calibrated"
  - Removing special and general relativistic effects
  - Removing GNSS and LEO clock offsets (POD problem):
    - GNSS precise orbits in Zero Difference (ZD) concept
    - Single Difference (SD) between GNSS satellites to remove LEO clock offset
    - Double Difference (DD) between GNSS satellites, LEO satellite and GNSS ground station.

Processing of GNSS-RO observations

- Calculate Excess Phase Delays: remove straight line path delay $\Delta\phi(i)$

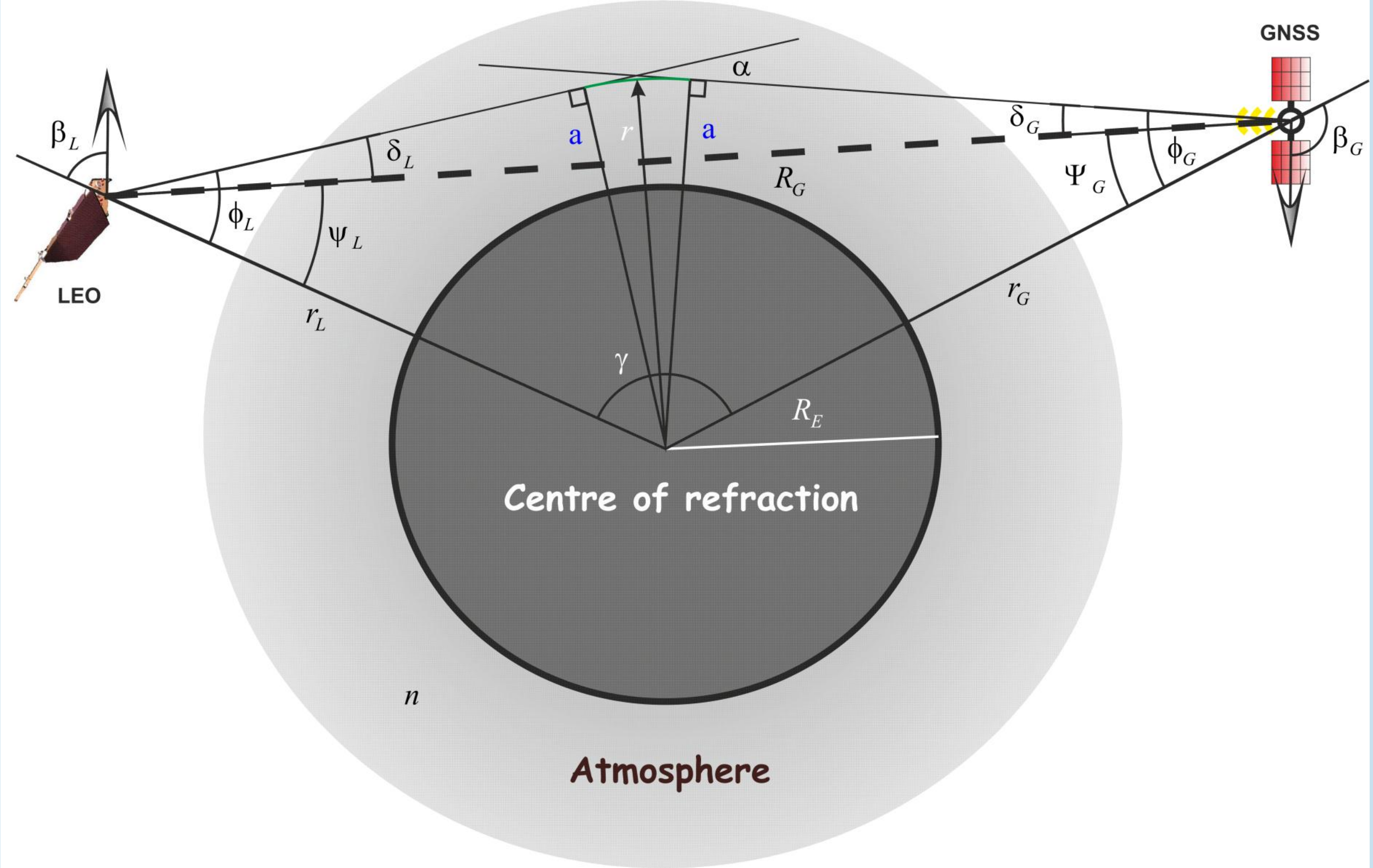


- A time series of excess Doppler shifts at L1 and L2 are calculated by differentiating the excess phase delays with respect to time.

Processing of GNSS-RO observations

- The ray bending caused by gradients in the atmosphere and ionosphere modify the L1 and L2 Doppler values, but deriving the bending angles, from the Doppler values is an ill-posed problem?.

ill posed problem



Bending angle

$$\alpha = \phi_L + \phi_G + \gamma - \pi$$

Snell's law

$$a = n_L r_L \sin\left(\phi_L\right) = n_R r_R \sin\left(\phi_R\right) = const.$$

Processing of GNSS-RO observations

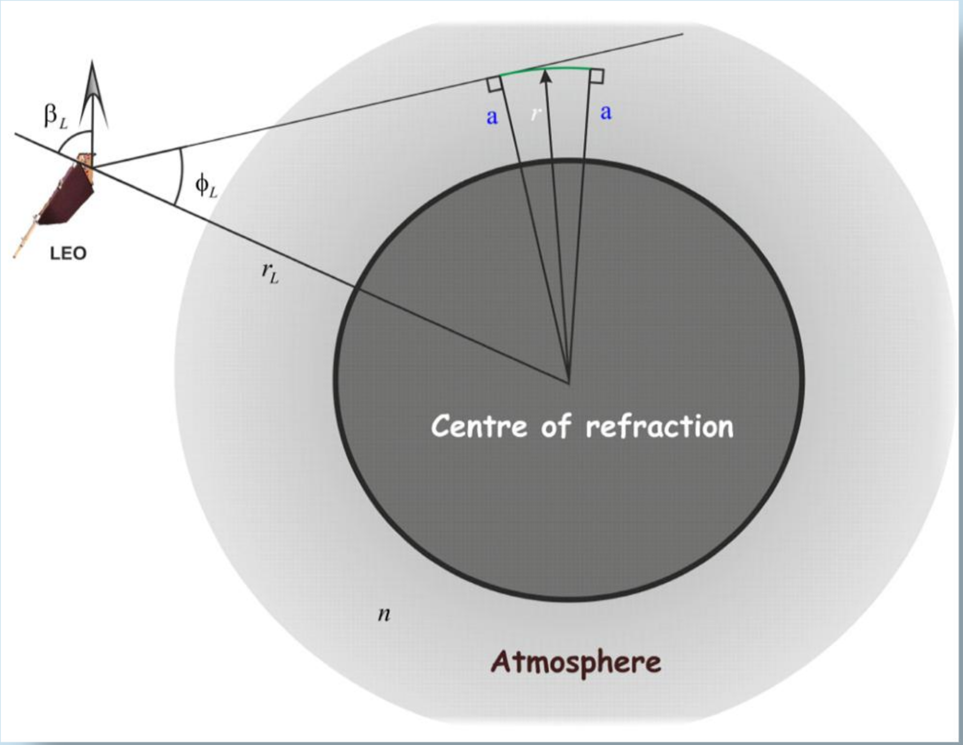
- The ray bending caused by gradients in the atmosphere and ionosphere modify the L1 and L2 Doppler values, but deriving the bending angles, from the Doppler values is an ill-posed problem.
- The problem made well posed by assuming the impact parameter, given by (spherical symmetry) has the same value at both the satellites.

- Snell's rule:

$$a = n_L r_L \sin(\phi_L) =$$
$$= n_R r_R \sin(\phi_R) = const.$$

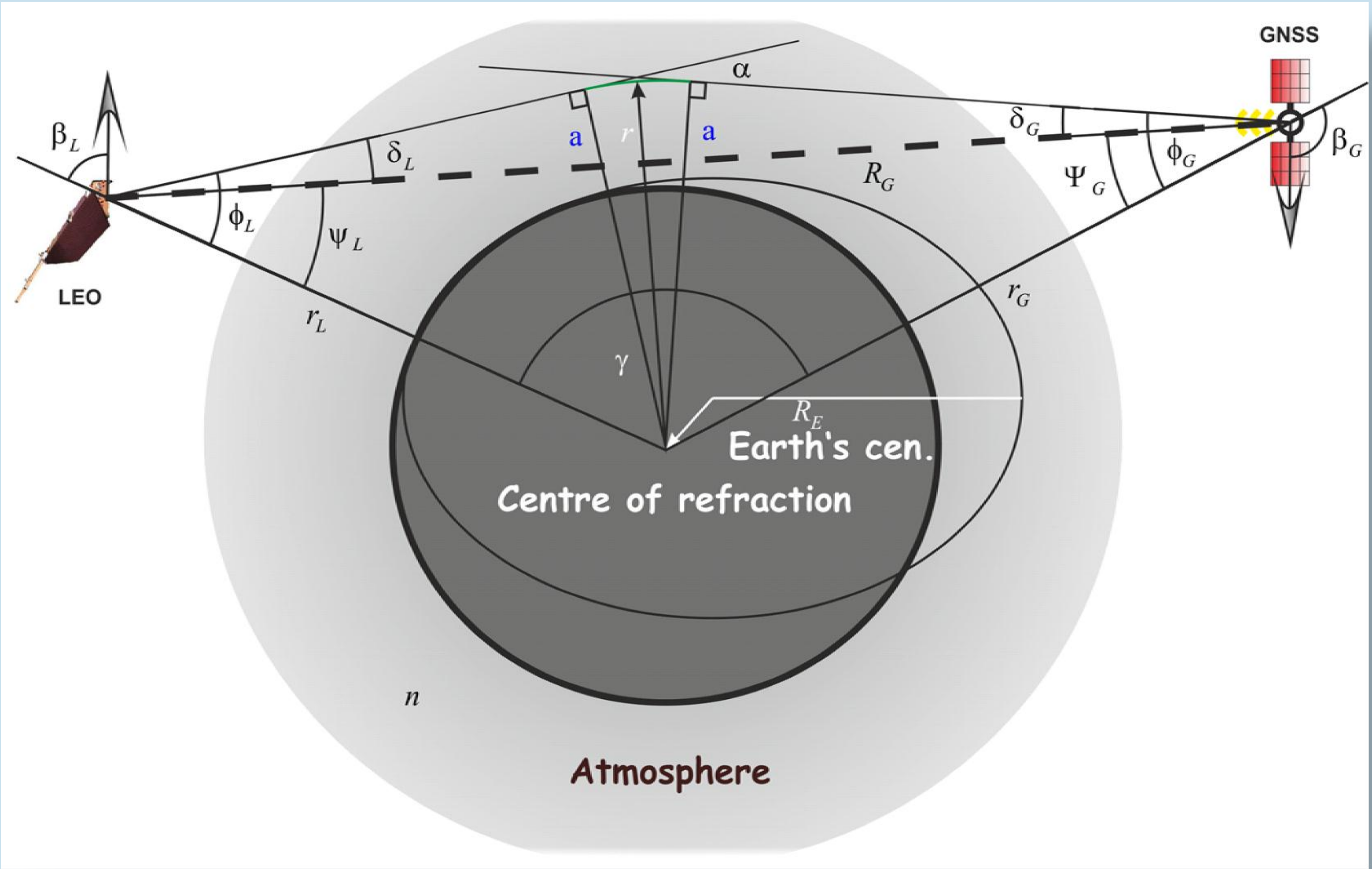
- At the tangent point (TP):

$$a = n_L r_L = n_R r_R$$



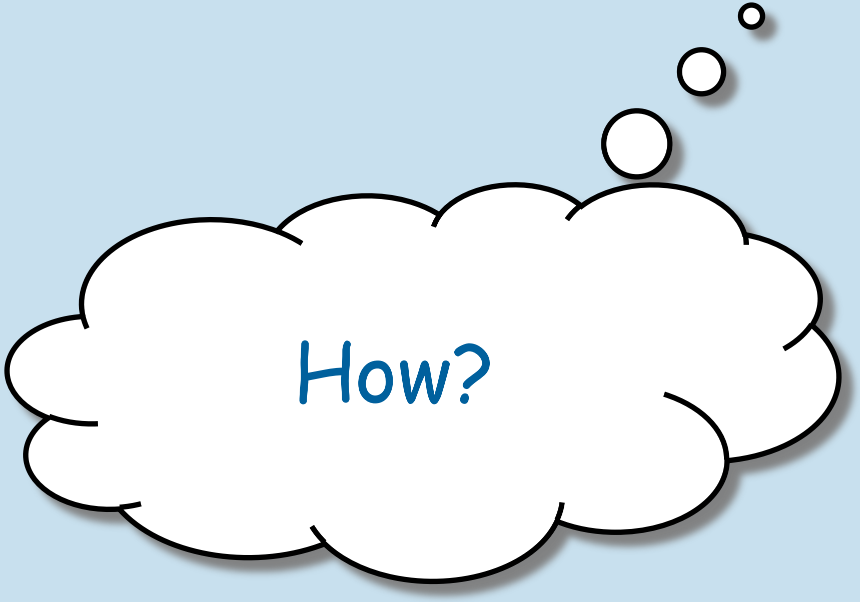
Ellipsoidal correction

- Correction of the LEO and GNSS satellite positions w.r.t the centre of refraction and deriving the bending angle and impact parameter for the spherical case (see Syndergaard, 1998).



Processing of GNSS-RO observations

- Given accurate position and velocity estimates for the LEO and GNSS satellites (after applying ellipsoidal corrections), and making the impact parameter assumption (spherical symmetry), the bending angle and impact parameter value can be derived s a pair simultaneously from the Doppler.



Processing of GNSS-RO observations

- Calculate Excess Doppler shift $\left(f_D \right)$ by 3rd order polynomial fit differentiation of the L1 and L2 phase paths

$$\frac{\left(f_D \right)_i}{f_i} = \frac{1}{c}\frac{d\Delta\phi_i}{dt}, \quad i = 1, 2$$

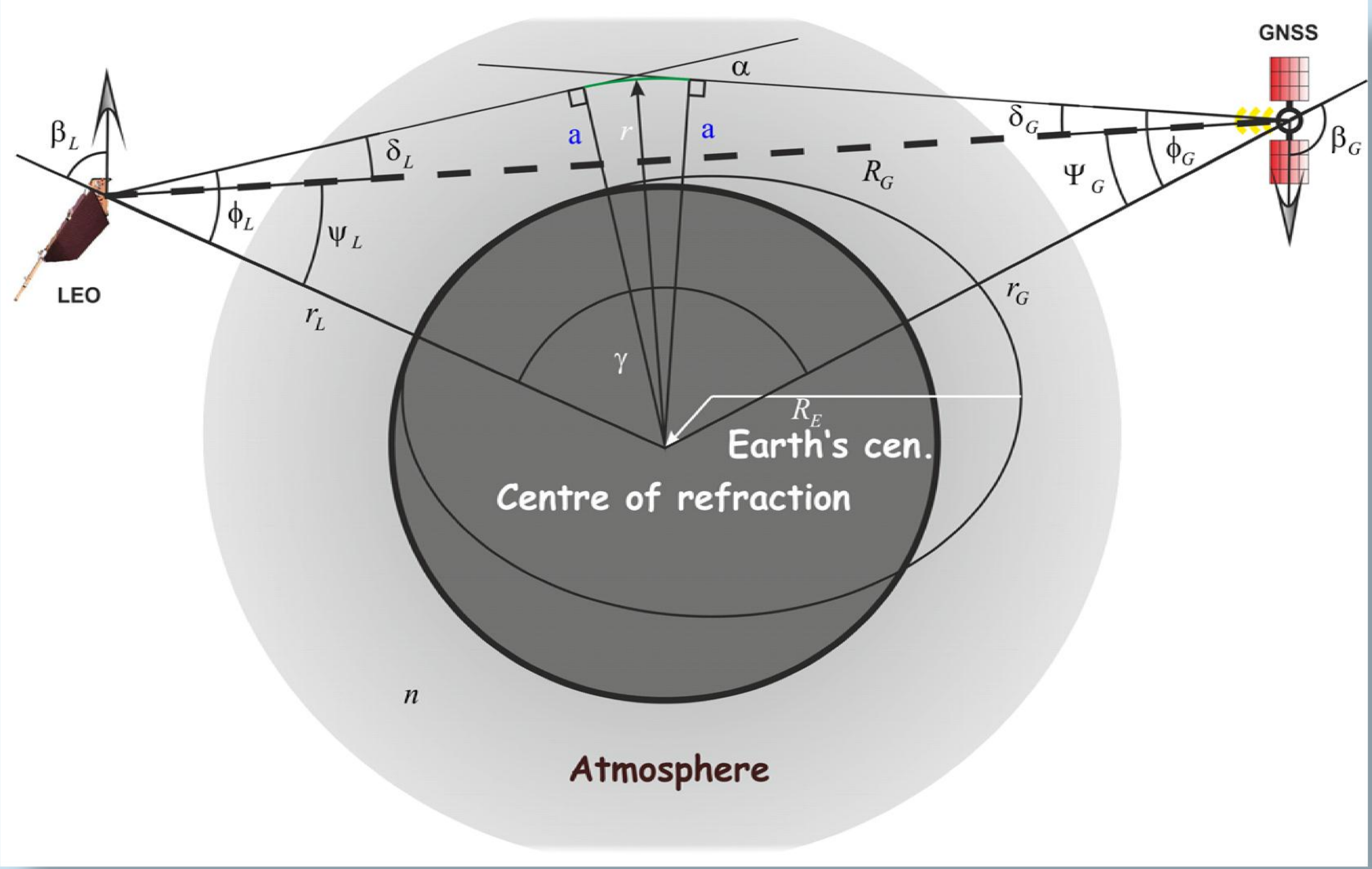
- Calculate zenith angle ϕ_G

  - The Doppler shift at the LEO can be expressed as the difference in the projected velocities of two moving satellites on the ray path tangent :

$$v_{L\_t} - v_{G\_t} = \frac{d\Delta\phi_i}{dt} + v_{L\_s} - v_{L\_s}$$

$$-v_L \cos\left(\phi_L - \beta_L\right) - v_G \cos\left(\phi_G + \beta_G\right) = \frac{d\Delta\phi_i}{dt} - v_L \cos\left(\psi_L - \beta_L\right) - v_G \cos\left(\psi_G + \beta_G\right)$$

Processing of GNSS-RO observations



Processing of GNSS-RO observations

$$\phi_G = \arcsin\left(\frac{\dfrac{d\Delta\phi_i}{dt} - v_L\cos\left(\phi_L - \beta_L\right) - v_G\cos\left(\phi_G + \beta_G\right)}{v_G\left(\sin\beta_G - \dfrac{\cos\beta_G}{\tan\phi_G}\right) - v_L\dfrac{r_G}{r_L}\left(\sin\beta_L + \dfrac{\cos\beta_L}{\tan\phi_L}\right)} \right)$$

- Some elements (e.g. positions and velocities) are derived from measurements (POD or OD problem) and some of them (e.g. angles) are derived from geometrical relations!

- The zenith angles are derived in an iteration process using circular orbits as start value!

- The same process can be applied to the LEO satellite zenith angle.

Processing of GNSS-RO observations

- Calculate refraction angles for both satellites

$$\delta_G = \phi_G - \psi_G \qquad \delta_L = \phi_L - \psi_L$$

- Calculate bending angles and impact parameter as a pair at two frequencies $(\alpha_i, a_i), \quad i = 1,2$

$$\alpha_i = \delta_{G,i} + \delta_{L,i}, \quad i = 1,2$$

$$a_i = r_L \sin \phi_{L,i}, \quad i = 1,2$$

Neutral atmosphere (Ionosphere corrections)

- We have to isolate the atmospheric component of the bending angle. The ionosphere is dispersive and so we can take a linear combination of the L1 and L2 bending angles to obtain the "corrected" bending angle. (Vorob'ev and Krasil'nikov, 1994)

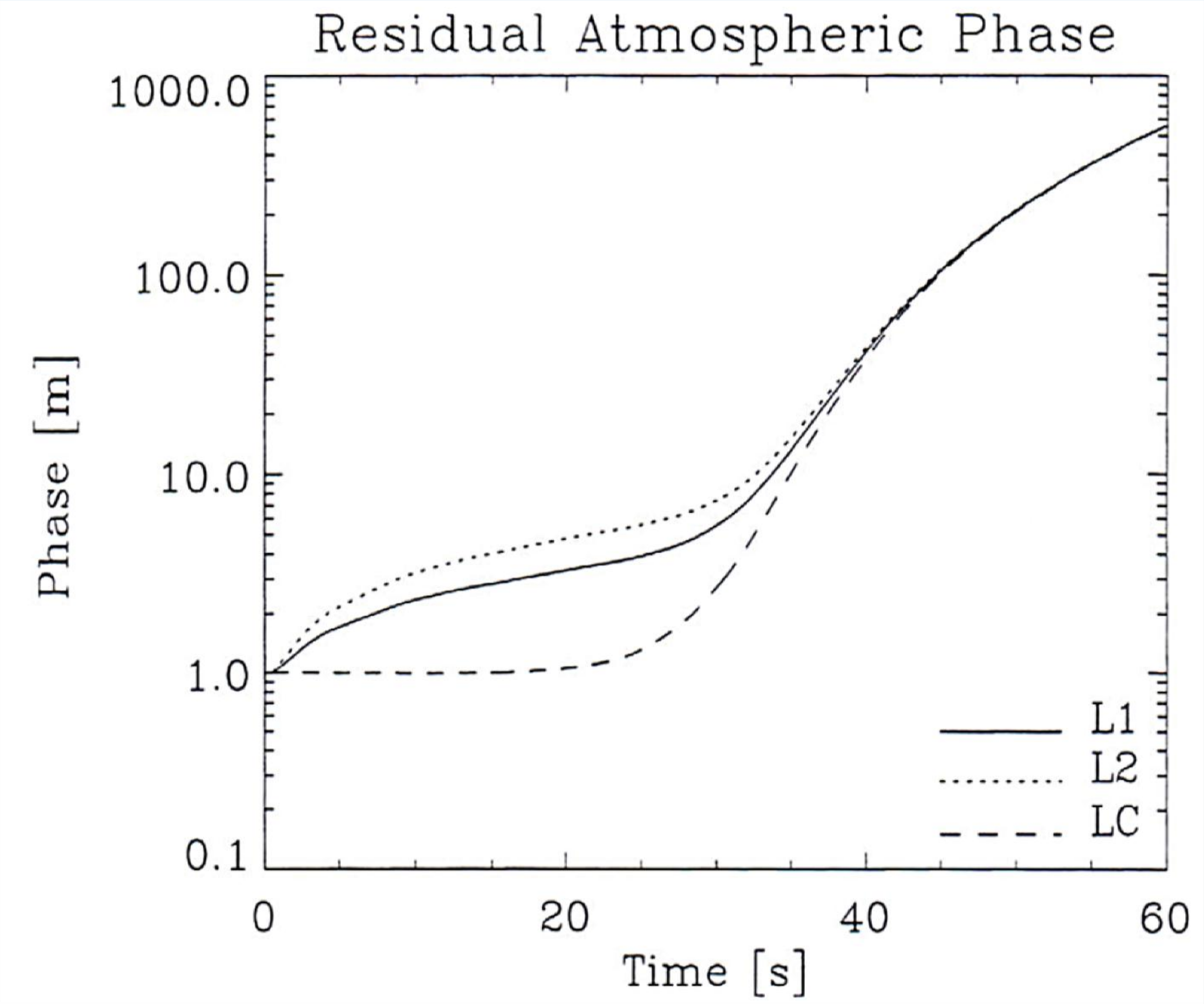
- Calculate Ionosphere free bending angle:
  - Linear Ionosphere free combination of L1 and L2 at the observation level (at the same time t)

$$\boxed{\phi_3(t) = \frac{f_1^2 \phi_1(t) - f_2^2 \phi_2(t)}{f_1^2 - f_2^2}}$$

  - Linear Ionosphere free combination of bending angles at two frequencies L1 and L2 (at the same impact factor a)

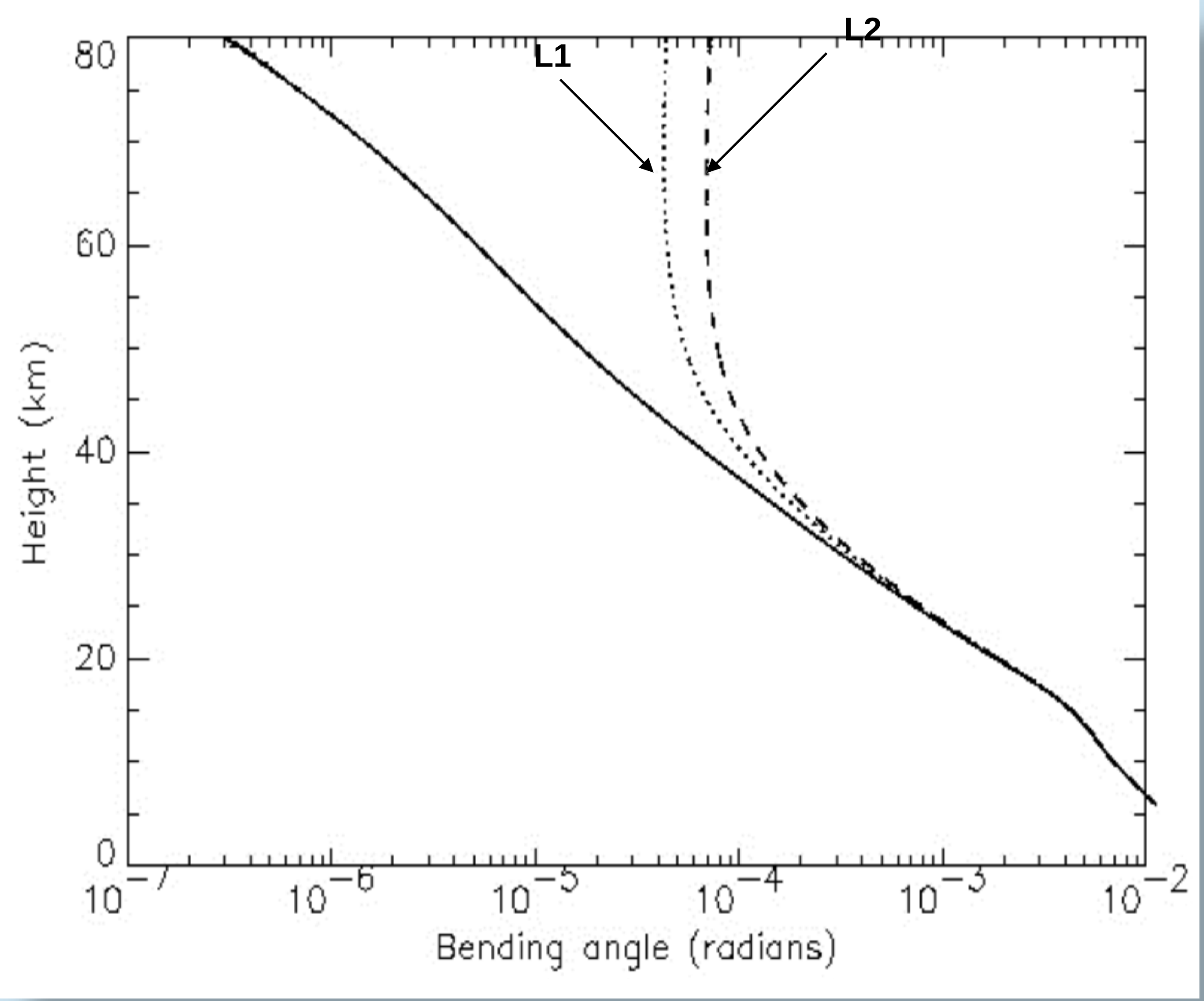
$$\boxed{\alpha_3(t) = \frac{f_1^2 \alpha_1(a) - f_2^2 \alpha_2(a)}{f_1^2 - f_2^2}}$$

Ionosphere correction



Source:
Dr. Steiner (Uni-Graz

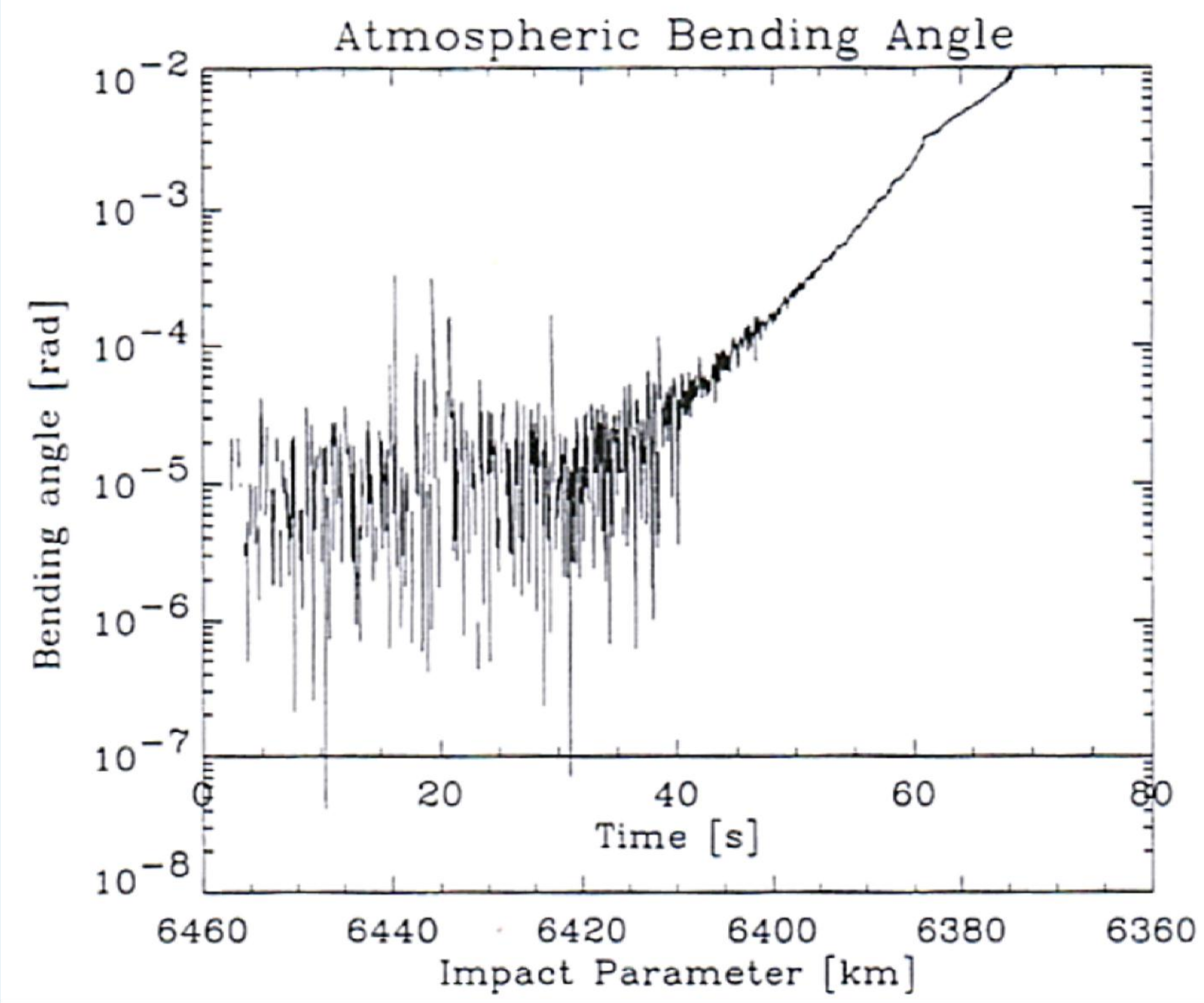
Ionosphere correction (simulated case)



Corr. is very big!

Source: Dr. Hardy

Atmospheric bending angle (Ionosphere free)



Source:

Dr. Steiner (Uni-Graz

Neutral bending angle (Ionosphere free)

- How good is the correction? Does it introduce time varying biases?

- The correction should not be continued above ~50-90 km, because the signature of the neutral atmosphere might be comparable to the residual ionospheric effects!

- For ionospheric retrievals, the bending angle from each frequency is used above 60 km.

Atmosphere

Bending angle → Refractivity →

- Temperatur
- Pressure
- Water Vapour
- Density
- ….

Deriving the refractive index profiles

- Assuming spherical symmetry the ionosphere corrected bending angle can be written as (Bouger's Law):

$$\alpha(a) = -2a\int_a^\infty \frac{d\ln n / dx}{\sqrt{x^2 - a^2}}\,dx$$

Corrected Bending angle as a function of impact parameter

Convenient variable (x=nr)
(refractive index * radius)

✓ Deriving the refractive index from bending angle is an inverse problem!

Deriving the refractive index profiles

- There are two methods to derive the refractive index profile from the bending angle (solving inverse problem)
  - Abel transform

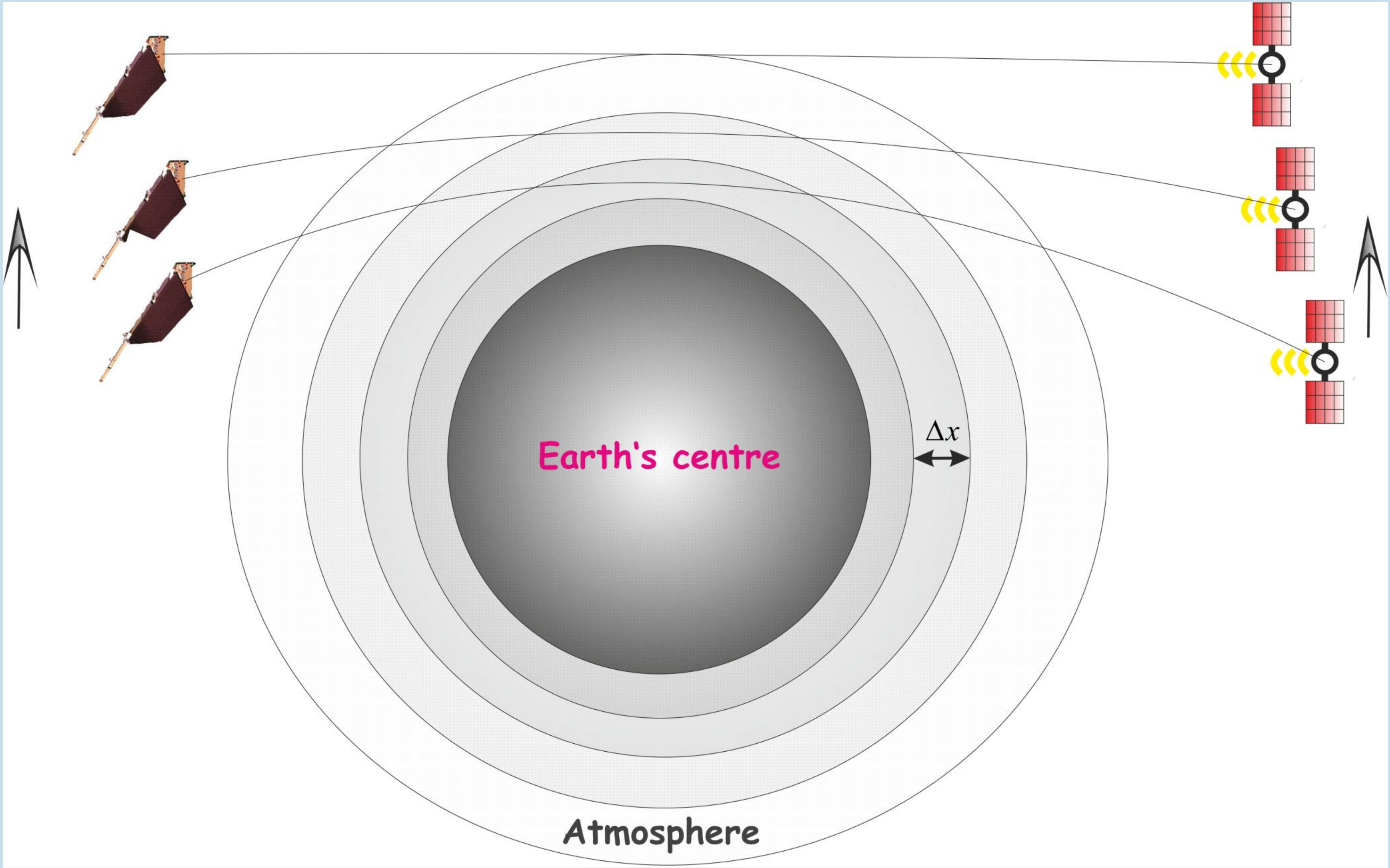
$$n(x) = \exp\left(\frac{1}{\pi}\int_a^\infty \frac{\alpha(a)}{\sqrt{a^2 - x^2}}\,da\right)$$

Note the upper-limit of the integral! A priori needed!

  - Matrix inversion of bending angles (see Steiner, 1999)

$$\alpha(a) = -2a\int_a^\infty \frac{d\ln n \big/ dx}{\sqrt{x^2 - a^2}}\,dx$$

Deriving the refractive index profiles (onion)



Deriving the refractive index profiles

$$\frac{\alpha_i(a)}{2a_i} = -\int_a^{\infty} \frac{d\ln n \big/ dx}{\sqrt{x^2 - a^2}}\,dx \quad \Rightarrow \quad \frac{\alpha_i(a)}{2a_i} \cong -\sum_{k=1}^{i} \nabla n_k \frac{\Delta x_k}{\sqrt{x_k^2 - a_i^2}}$$

$$\begin{pmatrix} \dfrac{\alpha_1}{2a_1} \\ \vdots \\ \dfrac{\alpha_i}{2a_i} \end{pmatrix} \cong \begin{pmatrix} A_{11} & & & \\ \vdots & \vdots & & \\ \vdots & \vdots & & \\ A_{i1} & A_{i2} & \cdots & A_{ik} \end{pmatrix} \begin{pmatrix} \nabla n_1 \\ \vdots \\ \vdots \\ \nabla n_k \end{pmatrix}$$

$$A_{ik} = \frac{\Delta x_k}{\sqrt{x_k^2 - a_i^2}} = \ln\left| x_{k-1} + \sqrt{x_{k-1}^2 - x_i^2} \right| - \ln\left| x_k + \sqrt{x_k^2 - x_i^2} \right|$$

Deriving the refractive index profiles

$$\mathbf{l} = \mathbf{A}\nabla\mathbf{n} \quad \Rightarrow \quad \nabla\mathbf{n} = \mathbf{A}^{-1}\mathbf{l} \quad \Rightarrow \quad n = ?$$

Refractive index gradients have to be multiplied with their respective atmospheric layer thickness to derive the vector which contains the constant refractive indices for each layer,

$$n = \nabla\mathbf{n}.\Delta\mathbf{x}$$

An initial value for the refractivity is taken from the atmospheric model (e.g. MSISE-90) model, then the refractive index profile is derived by adding the refractivity for each layer

$$N_i\left(h_i\right) = N_0 + \sum_{i=1}^{k} n_i.10^6, \quad h_i = \frac{a_i}{n(a_i)} - r_c = r - r_c$$

h_i is the geometrical height, r denotes the radius at the perigee of the ray and r_c is the Earth's radius of the curvature in the occultation plane at the occultation location.

Atmosphere

Bending angle → Refractivity →

- Temperatur
- Pressure
- Water Vapour
- Density
- ….

Retrieval of atmospheric key parameters

At microwave wavelengths (e.g. GNSS), the dependence of refractivity index (N) on atmospheric variables can be expressed:

$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{P_w}{T^2} - 40.3\times10^{6}\frac{n_e}{f^2} + O\left(\frac{1}{f^3}\right) + 1.4\times$$

Hydrostatic balance,
P : is the total pressure (mbar)
T : is the temperature (Kelvin)

Ionospheric term,
f is frequency (Hz) and
n_e is the total electron content m^{-3}

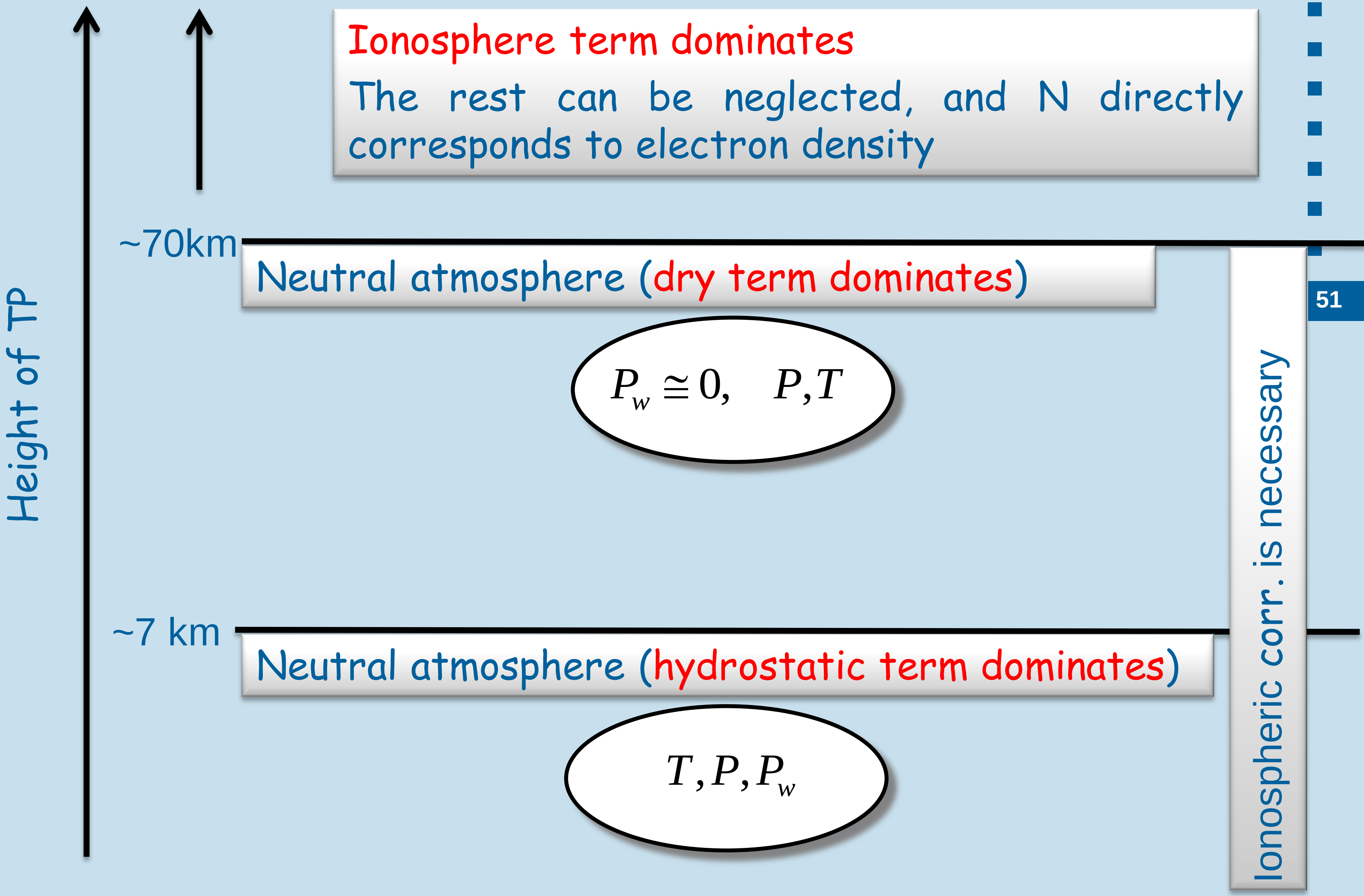
Moisture term,
P_w is the water vapour pressure (mbar)

- Important in the troposphere for T>240K
- Can contribute up to 30% of the total N in the tropical lower troposphere (LT)
- Can dominate the total bending angle in the LT

Scattering term,
W_w, W_i are the liquid water and ice content $gr.m^{-3}$

Contributions are very small and can be neglected.
RO is almost insensitive to clouds

Deriving the refractive index profiles



Height of TP

Ionosphere term dominates

The rest can be neglected, and N directly corresponds to electron density

~70km

Neutral atmosphere (dry term dominates)

$$P_w \cong 0, \quad P, T$$

~7 km

Neutral atmosphere (hydrostatic term dominates)

$$T, P, P_w$$

Ionospheric corr. is necessary

“Dry” atmosphere: P and T (UT and S)

- Where the contribution of the water vapour to the refractivity index can be neglected (T<240 K), the N gets reduced to pure density,

$$N(z) = 77.6\frac{P(z)}{T(z)}$$

- + equation of state:

$$\rho(z) = \frac{N(z)m}{77.6R}$$

M: mean molecular mass

R: gas constant

- + hydrostatic equilibrium:

$$\frac{\partial P}{\partial z} = -g(z)\rho(z)$$

boundary conditions (e.g. P=0 at 150 km)

With neglecting the water vapour pressure e.g. for middle and upper troposphere (MT and UT),

$$N(z) = 77.6\frac{P(z)}{T(z)} = 77.6R\rho(z)$$

Vertical profile of density is derived!

Retrieval of atmospheric key parameters

We can derive the pressure by integrating the hydrostatic equation:

$$P(z) = P(z_u) - \frac{1}{77.6R} \int_{z}^{z_u} N(z) g(z) dz$$

The temperature profile can then be derived with the ideal gas law:

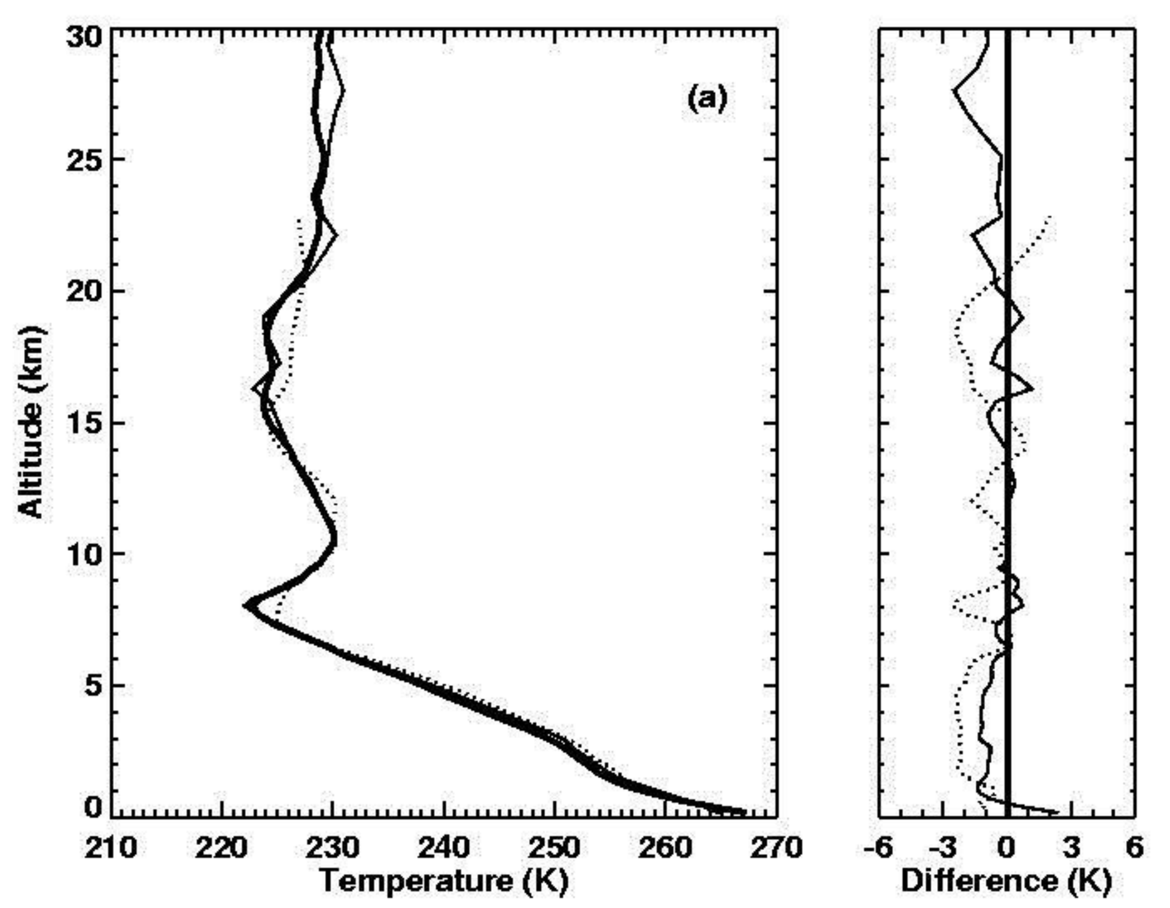
$$T(z) = 77.6 \frac{P(z)}{N(z)}$$

- Then we have the profiles of :
  - pressure
  - temperature
  - geopotential height from the geometrical height (GNSS-RO provides independent values of P and h)

GPS/MET experiment (1996): Groups from JPL and UCAR demonstrated that the retrievals agreed with co-located analyses and radiosondes to within 1K between ~5-25km.

Retrieval of atmospheric key parameters

GPS/MET Temperature Sounding



-GPS/MET - *thick solid.*

-Radiosonde – *thin solid.*

-ECMWF - *Dotted*

Occultation event:
(Location 69N, 83W.
01.33 UT, 5th May, 1995)

(Source: Kursinski et al, 1996, Science, 271, 1107-1110, Fig2a)

"Dry" atmosphere: P and T

- When there is no moisture in the atmosphere, the profile of P and T retrieved from N correspond to the real atmospheric values,
- But when there is moisture in the atmosphere, the expression:

$$N(z) = 77.6\frac{P(z)}{T(z)}$$

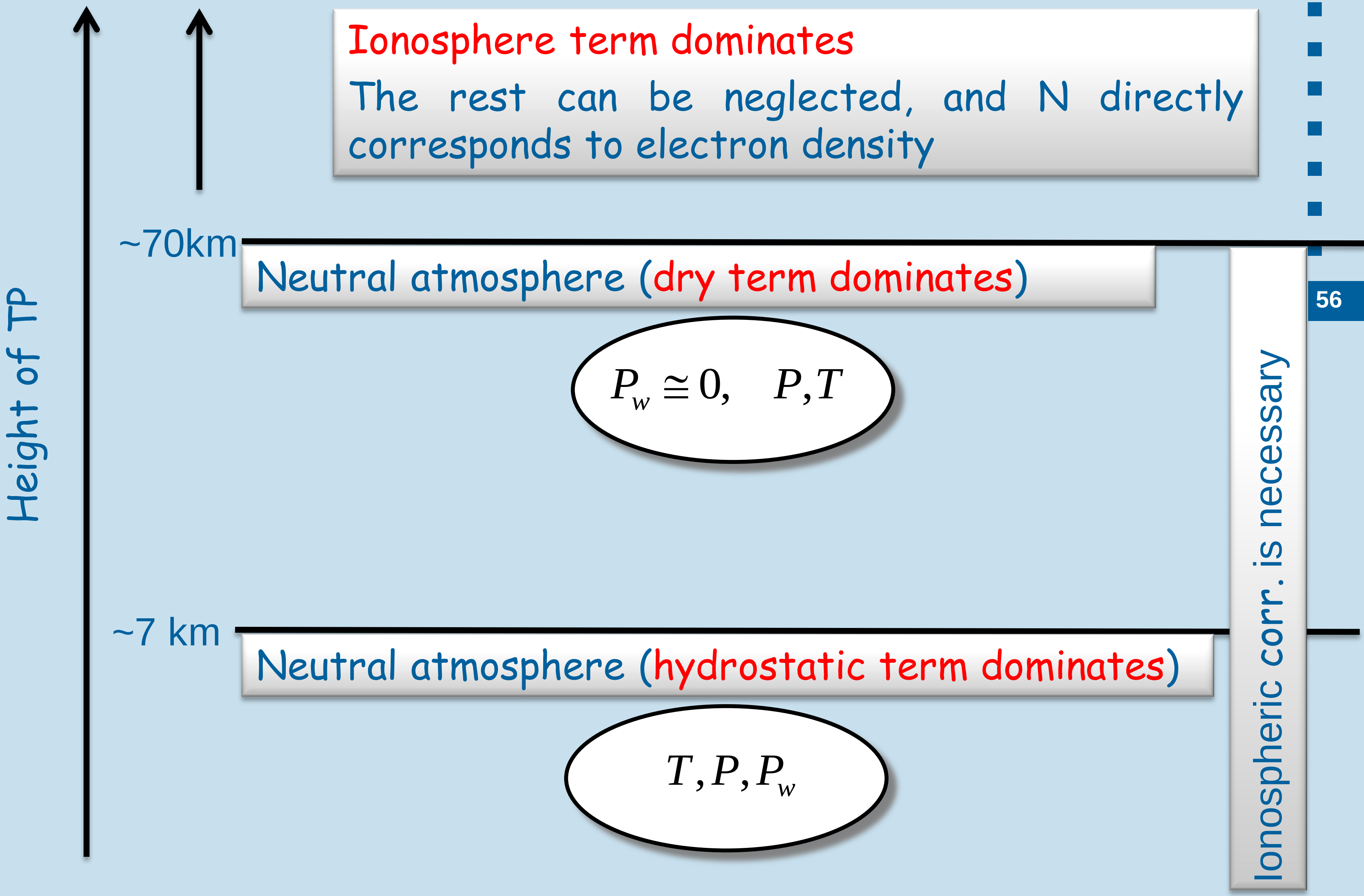
will erroneously map all the N to P and N of a dry atmosphere.

- In other words, all the water vapour in the real atmosphere is replaced by dry molecules that collectively would produce the same amount of N.

- As a consequence, the retrieval temperature will be lower (cooler) than the real temperature of the atmosphere.

- Within the GNSS-RO community, these profiles are usually referred to "dry temperature" profiles.

Deriving the refractive index profiles



Ionosphere term dominates

The rest can be neglected, and N directly corresponds to electron density

~70km

Neutral atmosphere (dry term dominates)

$P_w \cong 0, \quad P,T$

~7 km

Neutral atmosphere (hydrostatic term dominates)

T,P,P_w

Ionospheric corr. is necessary

Retrieval of atmospheric key parameters

The refractive index (or refractivity) is related to the pressure, temperature and water vapour pressure using two experimentally determined constants (from the 1950's and 1960's!)

$$N(z)=\left(n(z)-1\right)10^{6}=77.6\frac{P(z)}{T(z)}+3.73\times10^{5}\frac{P_{w}(z)}{T^{2}(z)}$$

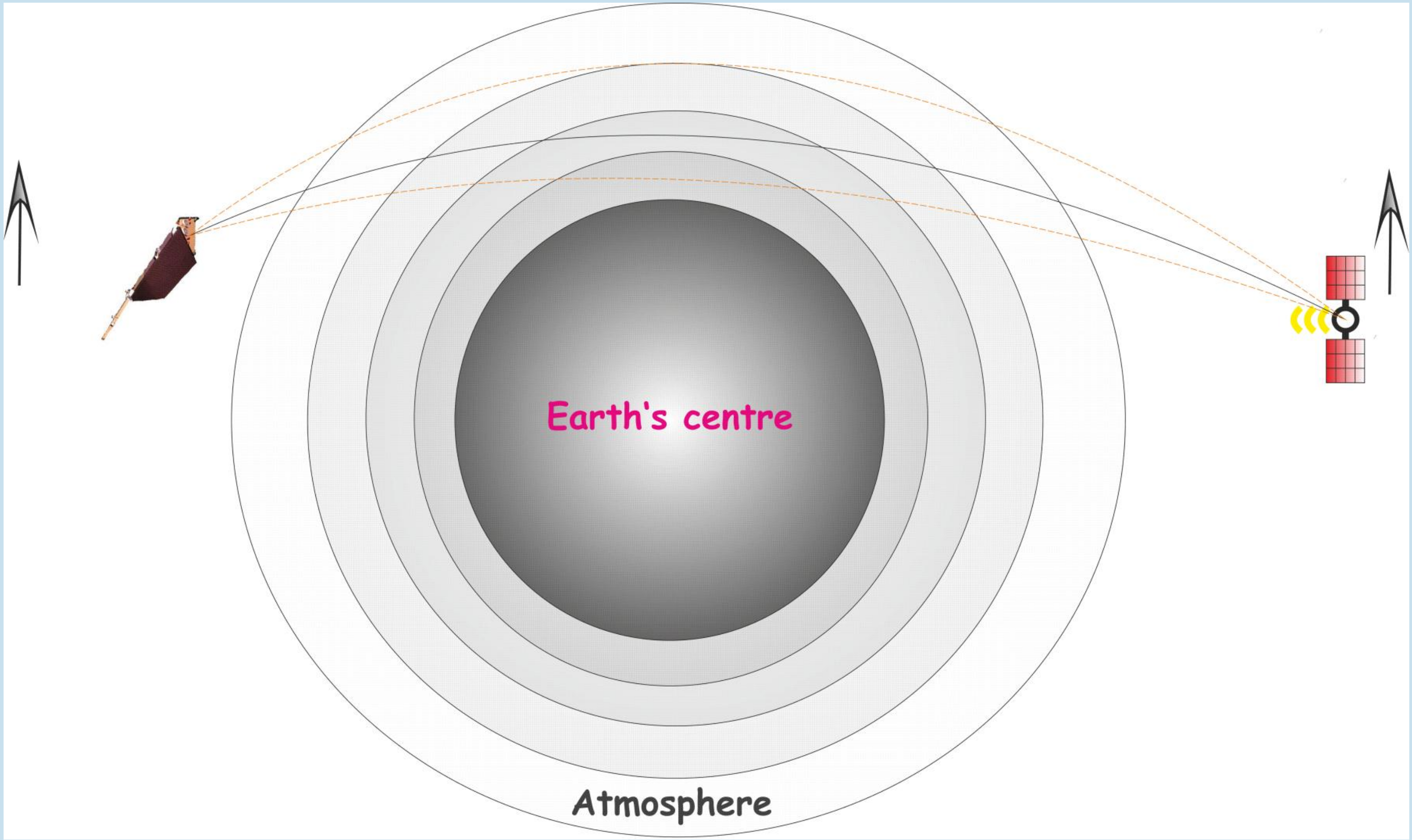
The simplest formulation, but it is widely used in GNSS-RO.

Moisture atmosphere: P, Pw and T

- Where the moisture contribution to N is important (middle and lower trop. (MT and LT)), the system is under-determined $\left(P, T, P_w \right)$
- To solve this problem, independent knowledge of temperature, pressure or water vapour is necessary to estimate the other two variables.
- Usually, temperature is given by an external source (model), then we solve for pressure and moisture iteratively.
- Alternatively, we can use a-priori information of pressure, temperature and moisture from a model along with their error characterization (background error covariance matrices) and find optimal estimates of P, T and q (variational assimilation)

GNSS-RO limitations (Lower Troposphere, LT)

Atmospheric Multipath processing – more than one ray is measured by the receiver at a given time (different rays sample different sections of the atmosphere!!!) – Solution: Radio Holographic (RH).



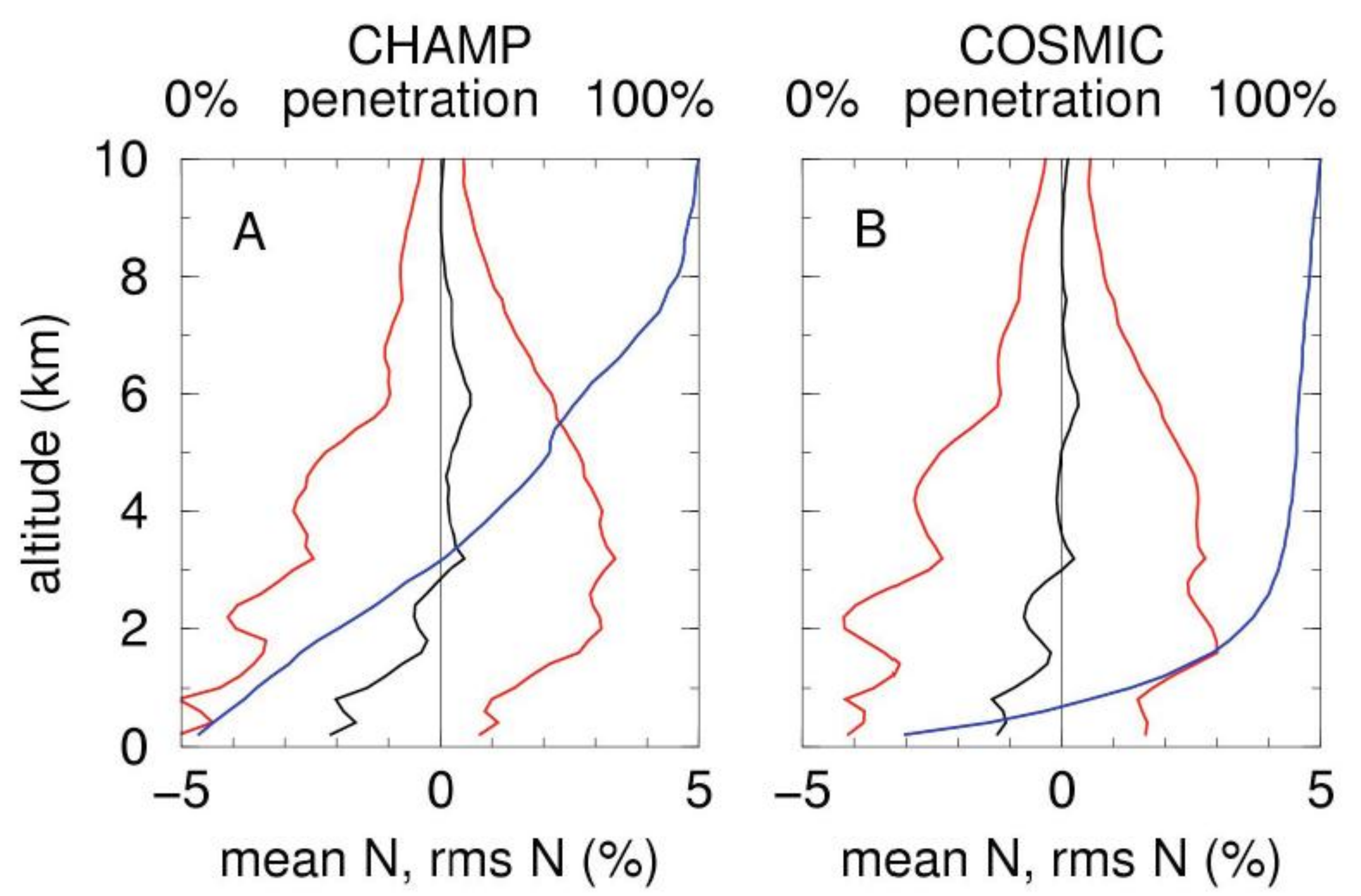
GNSS-RO limitations (Lower Troposphere, LT)

Wave optics retrievals: Full Spectral Inversion. (refer to Jensen et al. 2003, Radio Science, 38, 10.1029/2002RS002763.)

Improved GNSS receiver software: Open-loop (OL) processing instead of Phase-Locked loop processing. OL processing enable us to track down to the surface without tracking errors (COSMIC mission). OL records the spectrum!

GNSS-RO limitations (Lower Troposphere, LT)

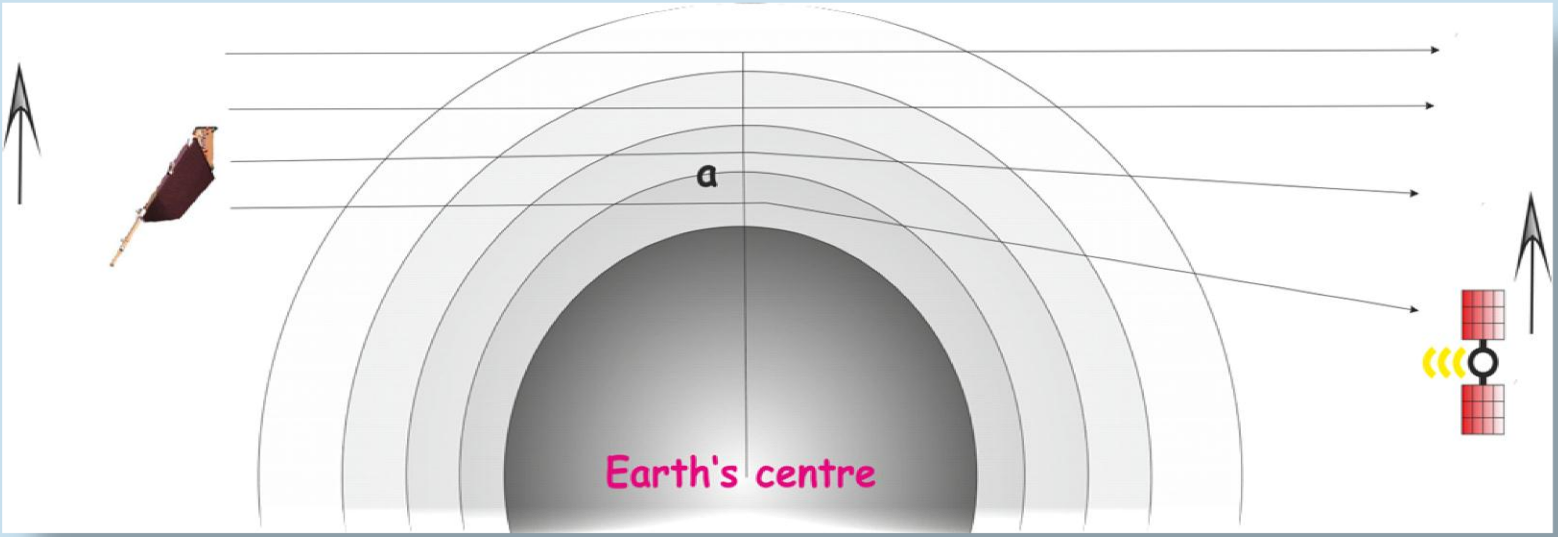
Most profiles did not make it to the ground (Now it is possible!)



Source: Dr. Lidia Cucurull (NOAA)

Physical limitations (Lower Troposphere, LT)

Atmospheric defocusing: If the bending angle changes rapidly with height, the signal reaching the receiver has less power.

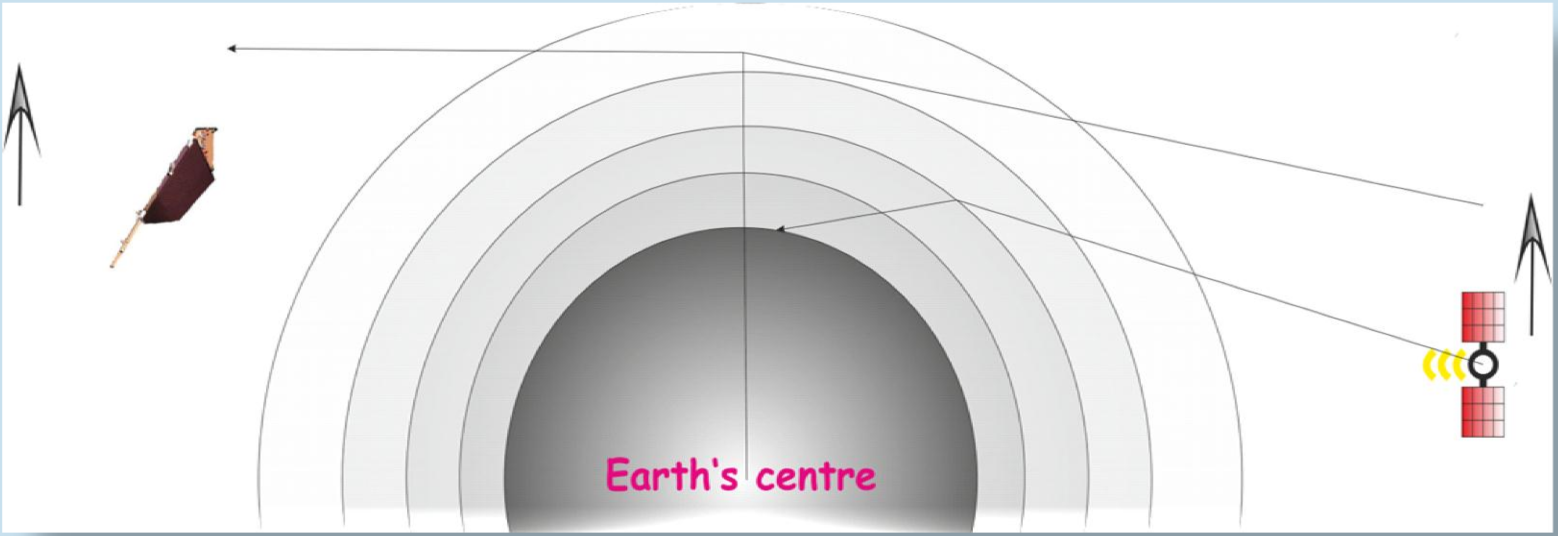


$$DF \propto \frac{1}{1 - f\left(\frac{\partial \alpha}{\partial a}\right)}$$

A tube of rays is spread out by the ray bending and the signal to noise falls.

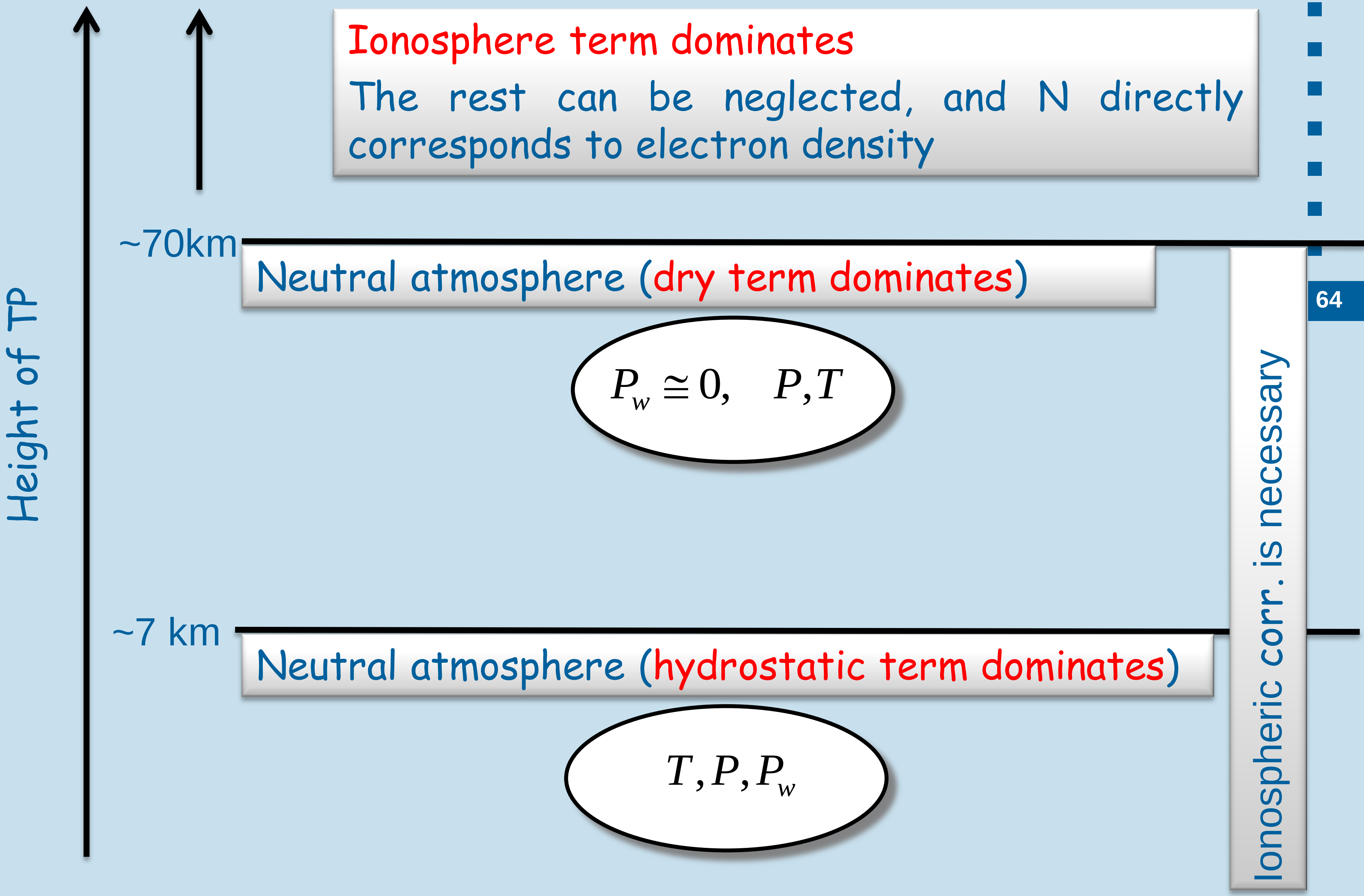
Physical limitations (Lower Troposphere, LT)

Atmospheric ducting: if the refractive index gradient exceeds a critical value the signal is lost power!



$$-{}^{dn}\!/_{dr} \geq {}^{1}\!/_{R_e}$$

Deriving the refractive index profiles



Height of TP

Ionosphere term dominates

The rest can be neglected, and N directly corresponds to electron density

~70km

Neutral atmosphere (dry term dominates)

$$P_w \cong 0, \quad P, T$$

~7 km

Neutral atmosphere (hydrostatic term dominates)

$$T, P, P_w$$

Ionospheric corr. is necessary

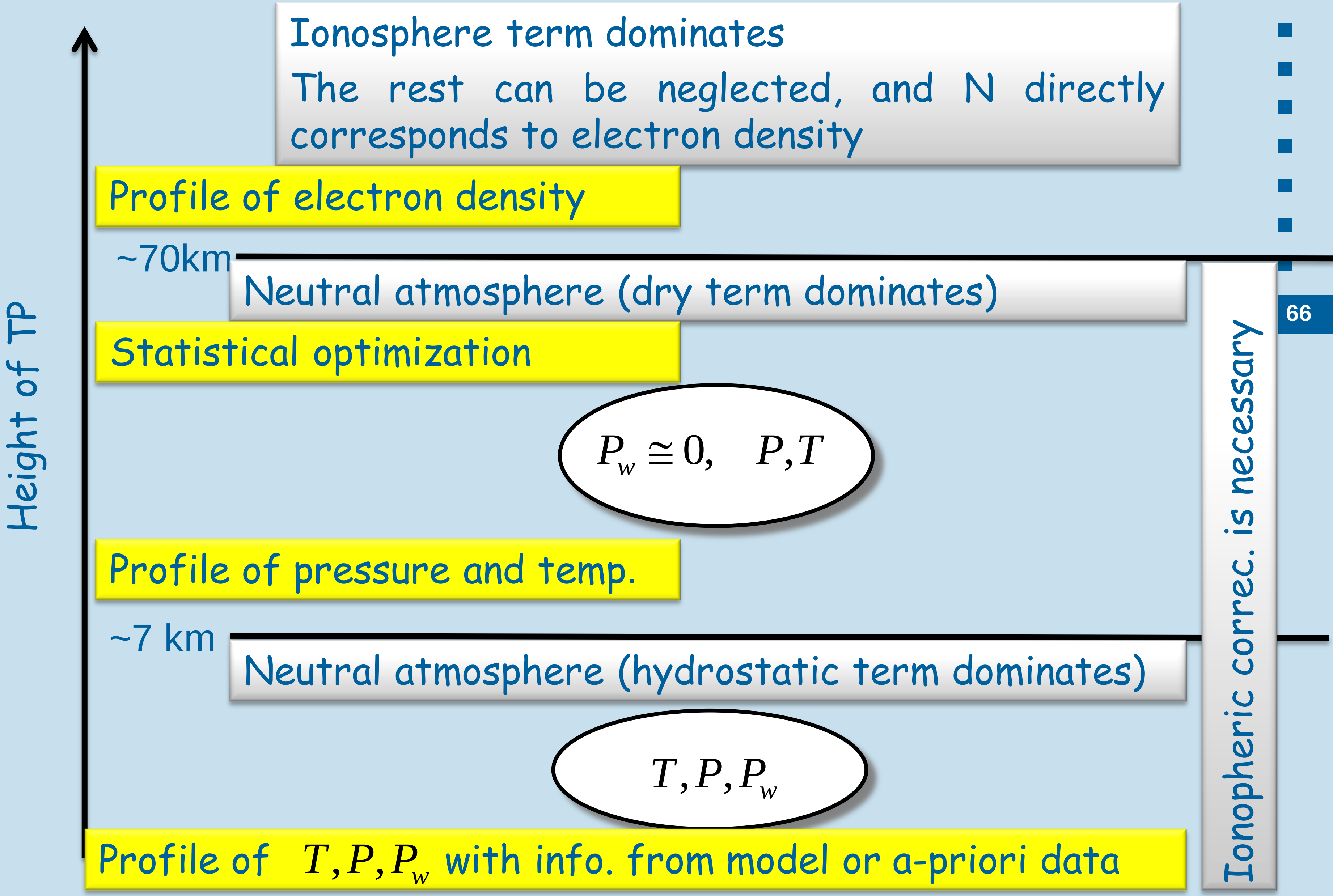
GNSS-RO limitations (Upper Stratosphere, US)

In order to derive refractivity the (noisy – e.g. residual ionospheric noise) bending angle profiles must be extrapolated to infinity – i.e., we have to introduce a-priori information. The combination of observed and simulated bending angles is called "statistical optimisation". The refractivity profiles above ~35 km are sensitive to the choice of a priori.

The temperature profiles require a-priori information to initialise the hydrostatic integration. Sometimes ECMWF temperature at 45km!

I would be sceptical about any GNSS-RO temperature profile above ~35 km, derived with the classical approach. It will be very sensitive to the a-priori!

Deriving the refractive index profiles



Height of TP

Ionosphere term dominates

The rest can be neglected, and N directly corresponds to electron density

Profile of electron density

~70km

Neutral atmosphere (dry term dominates)

Statistical optimization

$P_w \cong 0, \quad P,T$

Profile of pressure and temp.

~7 km

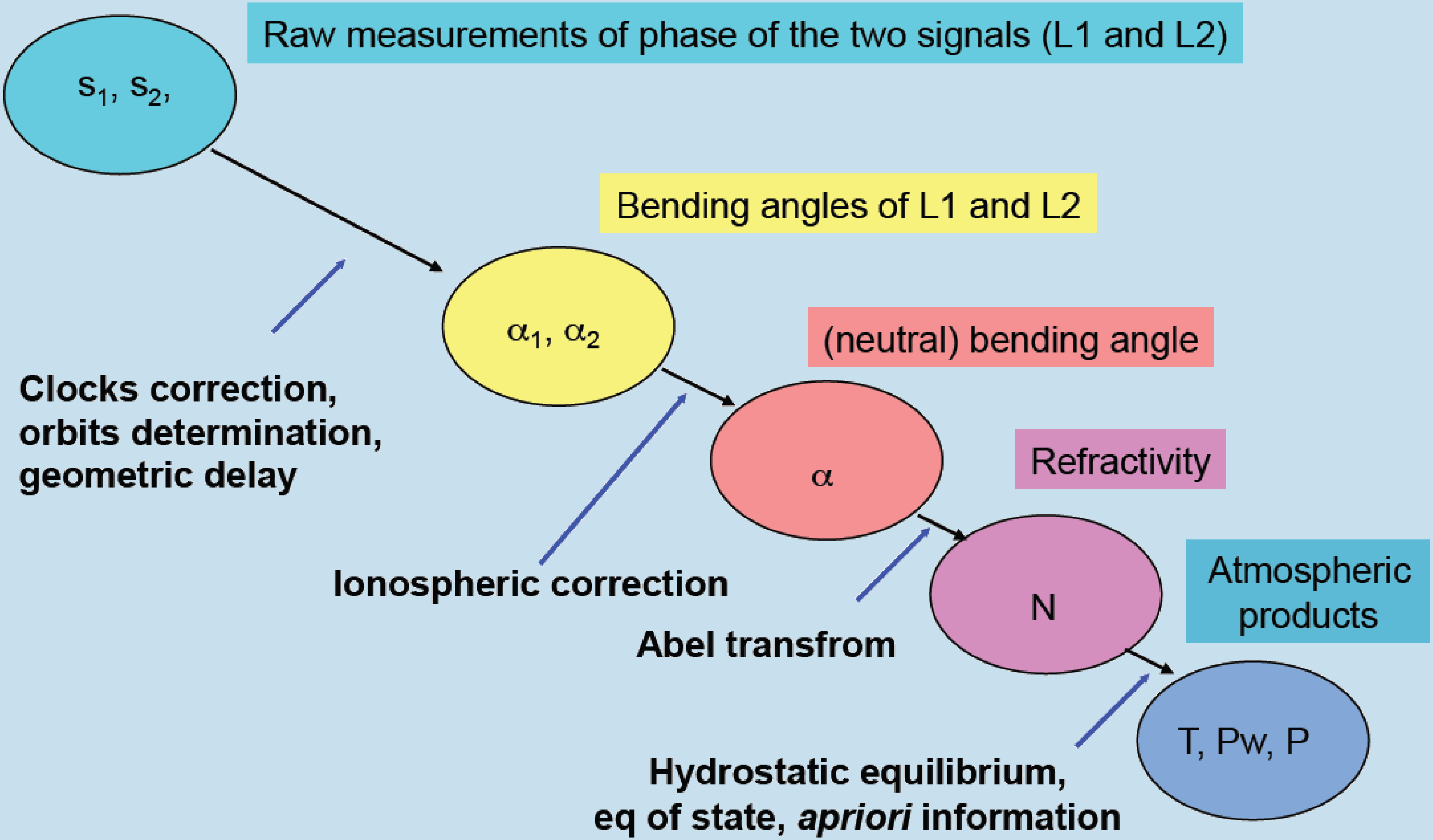
Neutral atmosphere (hydrostatic term dominates)

T,P,P_w

Profile of T,P,P_w with info. from model or a-priori data

Ionopheric correc. is necessary

GNSS-RO Data Processing



$s_1, s_2,$

Raw measurements of phase of the two signals (L1 and L2)

Clocks correction, orbits determination, geometric delay

α_1, α_2

Bending angles of L1 and L2

Ionospheric correction

α

(neutral) bending angle

Abel transfrom

N

Refractivity

T, Pw, P

Atmospheric products

Hydrostatic equilibrium, eq of state, *apriori* information

GNSS-RO missions

The GPS/MET mission "proof of concept" in 1996 was a major success. This led to a number of missions of opportunity, proposals for a constellation of LEO satellites and first dedicated operational instruments.

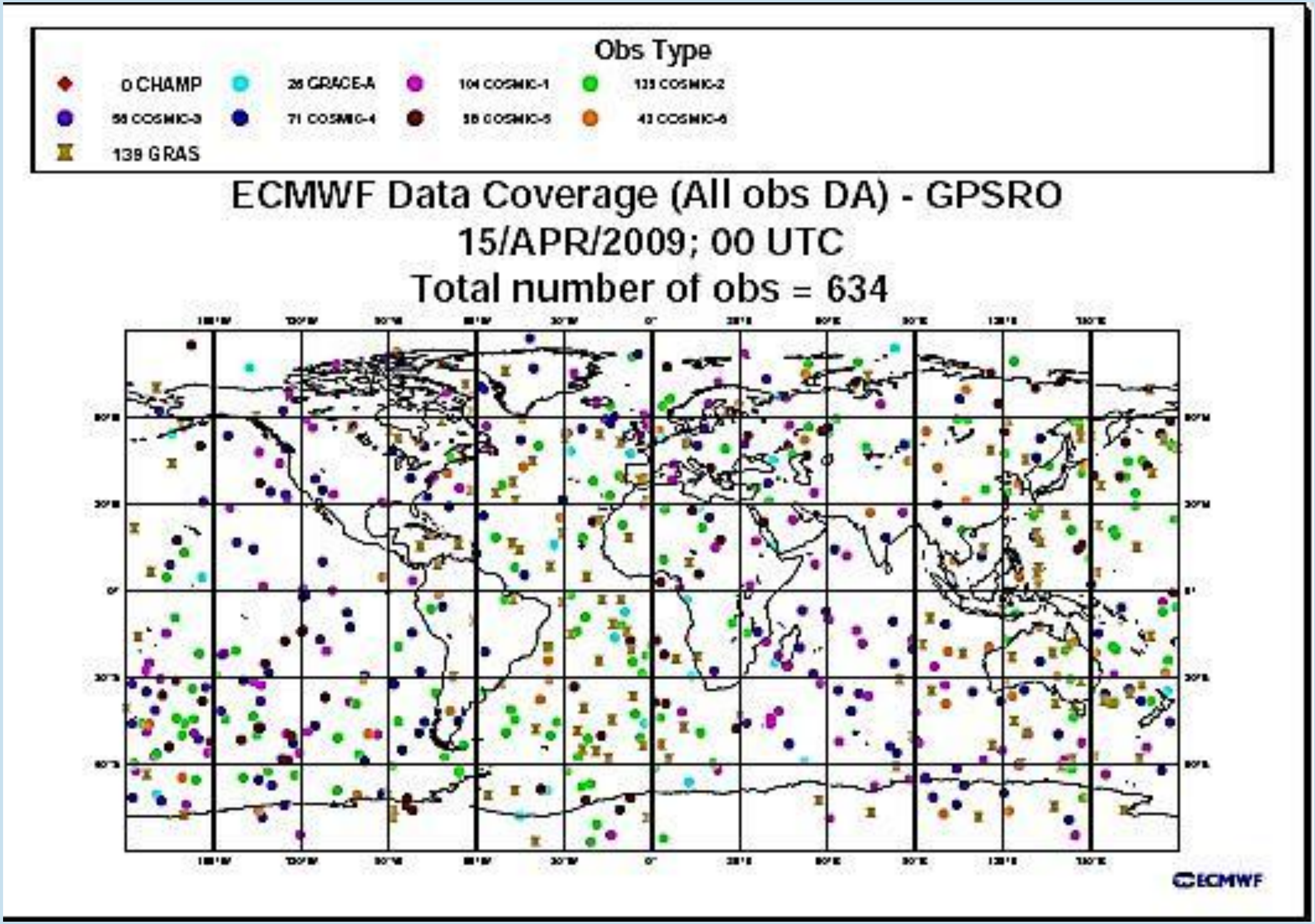
Current status:

Missions of opportunity: GRACE-A and SAC-C currently provides around 120 occultations per day. CHAMP has stopped providing data.

The COSMIC (Constelation Observing System of Meteorology Ionosphere and Climate) constellation of 6 LEOs was launched 2006. Currently providing ~1800-2000 occultations per day.

The GRAS (GNSS Receiver for Atmosphere Sounding) instrument on METOP (Meteorological Operational) provides ~650 measurements. GRAS was declared operational 17th April, 2008.

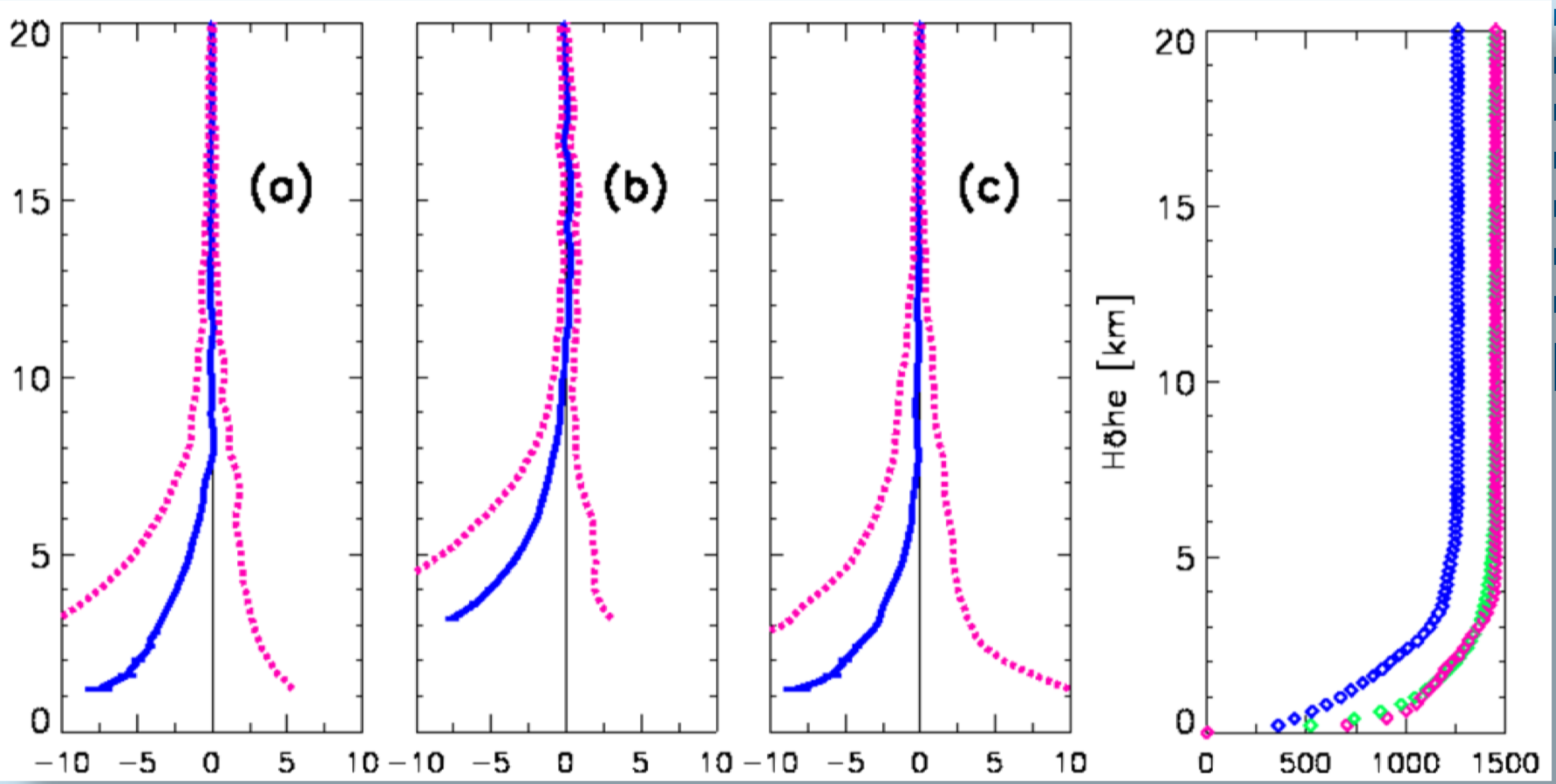
GPS-RO Data Coverage 15th April, 2009



GNSS-RO CHAMP Results

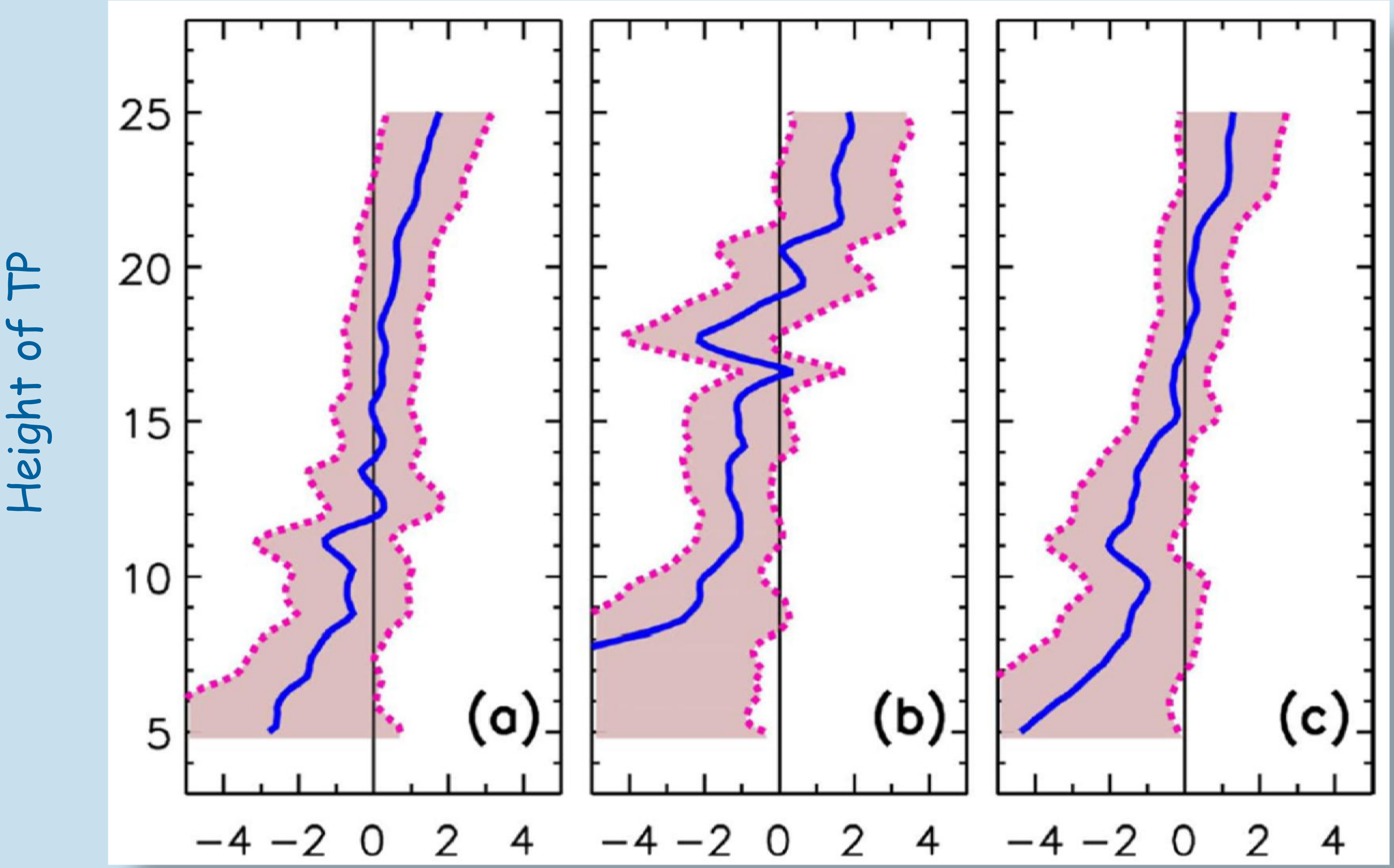
GNSS-RO CHAMP Results(refractivity N)

Height of TP



Differences between refractivity index (N) derived from CHAMP and ECMWF (a: Nord hemisphere (lat.>30N), b: Tropical (30S<lat.<30N), c: South hemisphere (lat.<30S), right panel: Number of GNSS-RO, Occ. Event: 14.05-10.06-2001), Source: GFZ

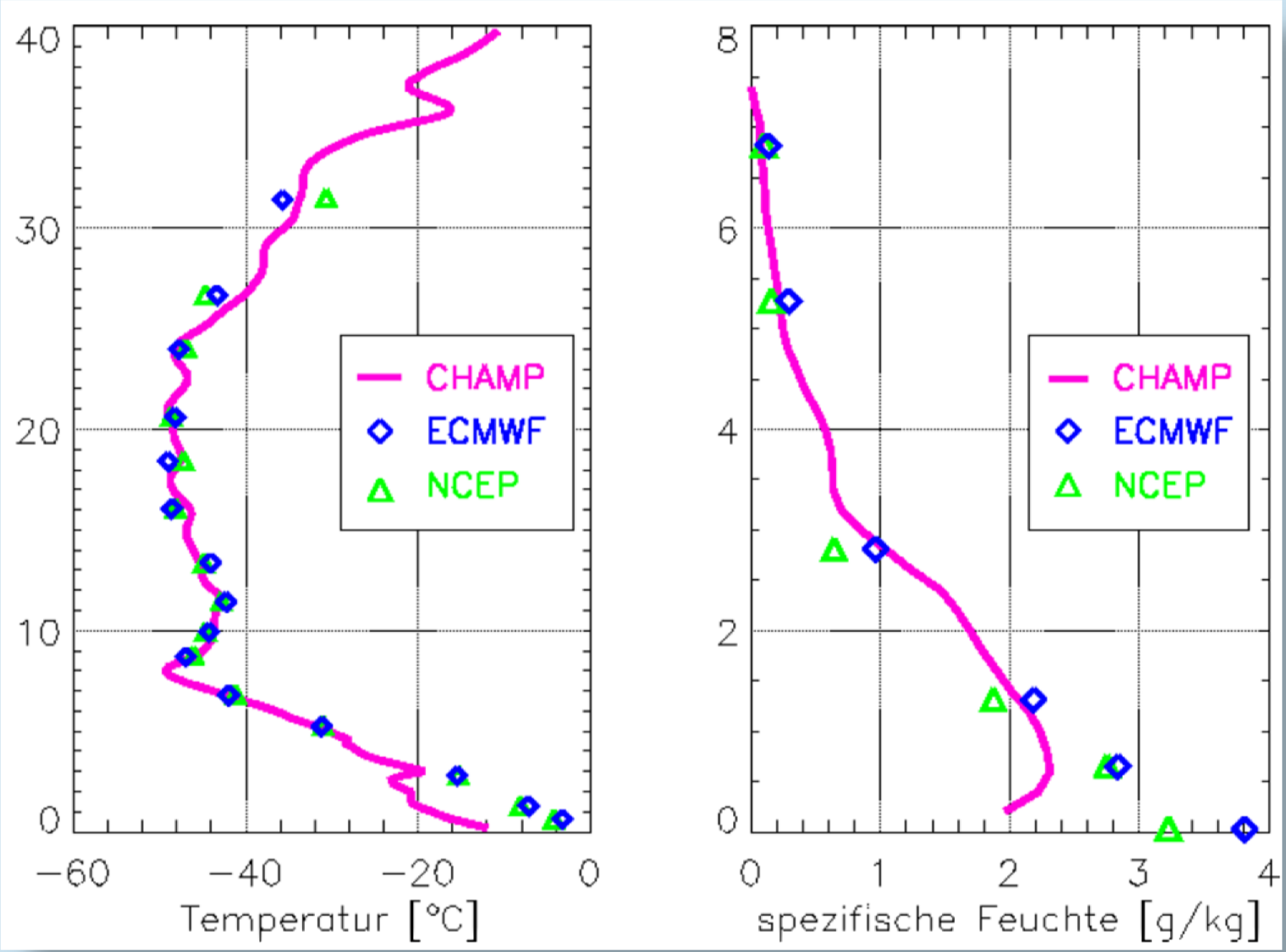
GNSS-RO CHAMP Results (temp.)



Diff. between Temperature (T) derived from CHAMP and ECMWF (a: Nord hemisphere b: Tropical, c: South hemisphere).

GNSS-RO CHAMP Results (WVP)

Height of TP



link: Dry Temperature, right: Water Vapour, Occ. events-11.02.2001, 0.5 W, 53.2 S, Time: 19:43 UTC, Source: GFZ

GNSS-RO precision

GNSS-RO precision

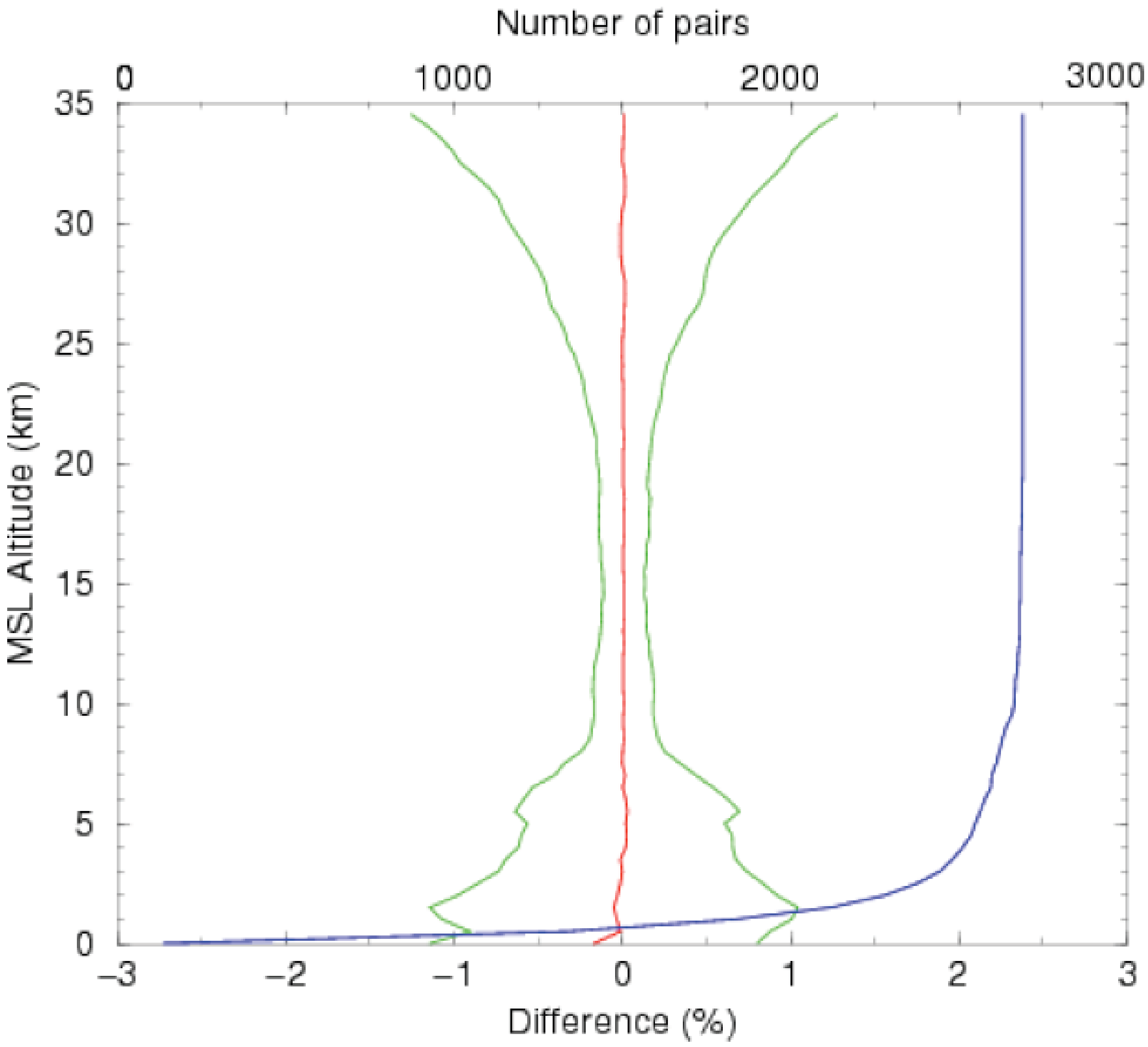
- Accuracy is more difficult to evaluate!

  -Difficult to find other precise instrument as GNSS-RO. Usual atmosphere instrument performance changes with season, latitude range and atmosphere phenomena, etc…

  -Each instrument has its own error characteristics.

- Accuracy of RO is ~0.5% in N and ~0.5 K in T between ~7-25km; better than ~2mb rms error (~0.5 mb bias) in Pw

GNSS-RO precision (comparison FM3-FM4)



Refractivity

0.2% (N) precision between 10-20 km

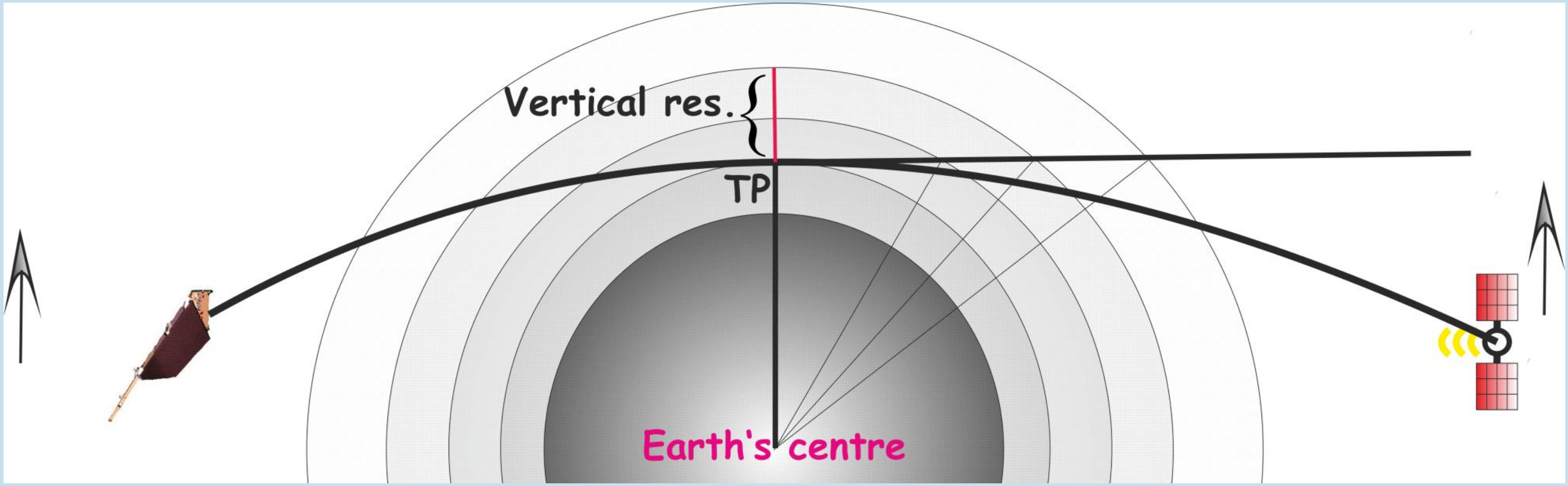
~ 0.05K in temperature!

Schreiner et al., 2007

GNSS-RO Resolution

GNSS-RO Resolution (Vertical)

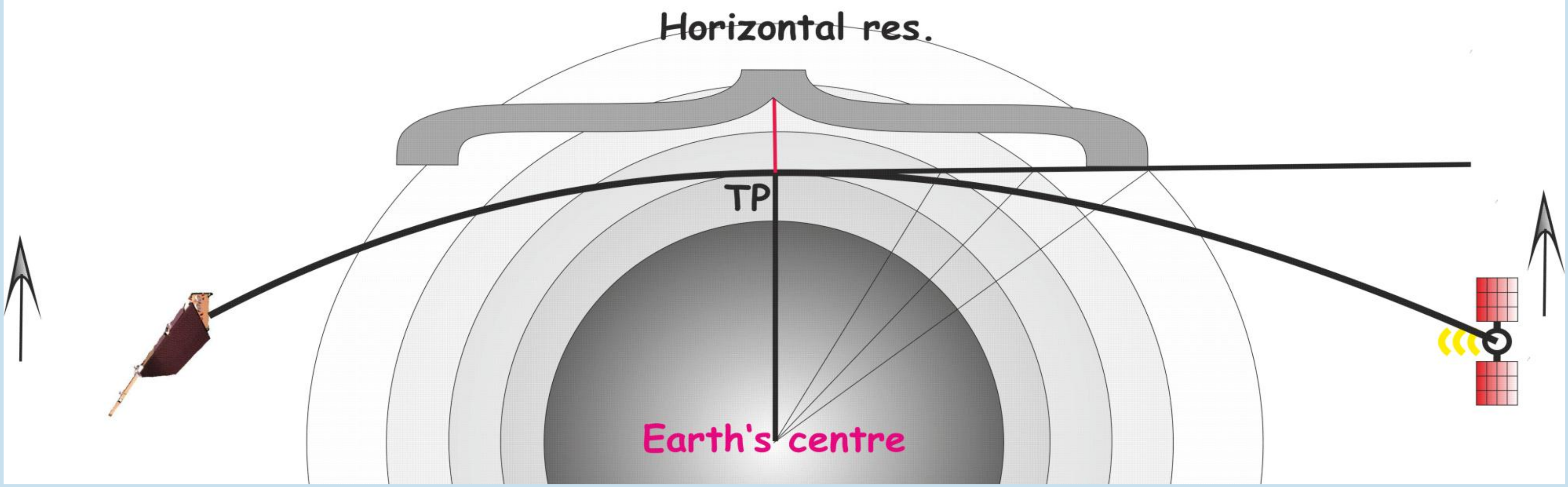
- Bending angle is creating by the contribution of different atmosphere layers (vertical gradient of refractivity).
- For each TP, the maximum layer interval which contribute a certain percentage to the bending angle can be computed
- The vertical height above the TP that contributes 50% of the bending angle can be interpreted as vertical resolution of a single RO ray. (e.g. for COSMIC we have 3000 rays per RO event (3 min.))



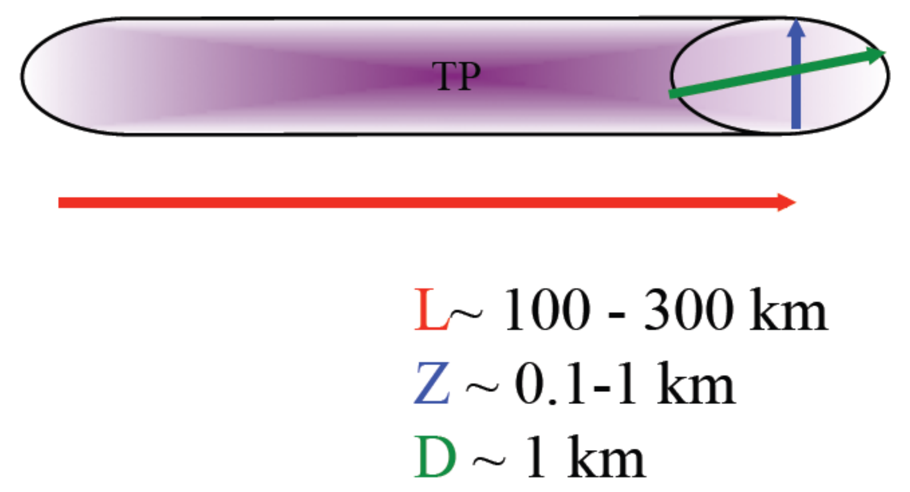
- Vertical res. varies between rays (3000) and varies from 1-2 km

GNSS-RO Resolution (Horizontal or along track)

- Analogously, the bending angle contribution of the different atmospheric layers can be considered in terms of the distance along the ray path under symmetrical symmetry!
- The bending angle contribution along ray path follows a Gaussian distribution and 50% contribution of the bending is within ~200 km from TP (see Melbourne et al. 1994). The information content is not averaged equally!
- This distance can be interpreted as horizontal resolution!



Spatial Resolution GNSS-RO



This spatial resolution is 4 times better than usual sounder (AMSU-B)

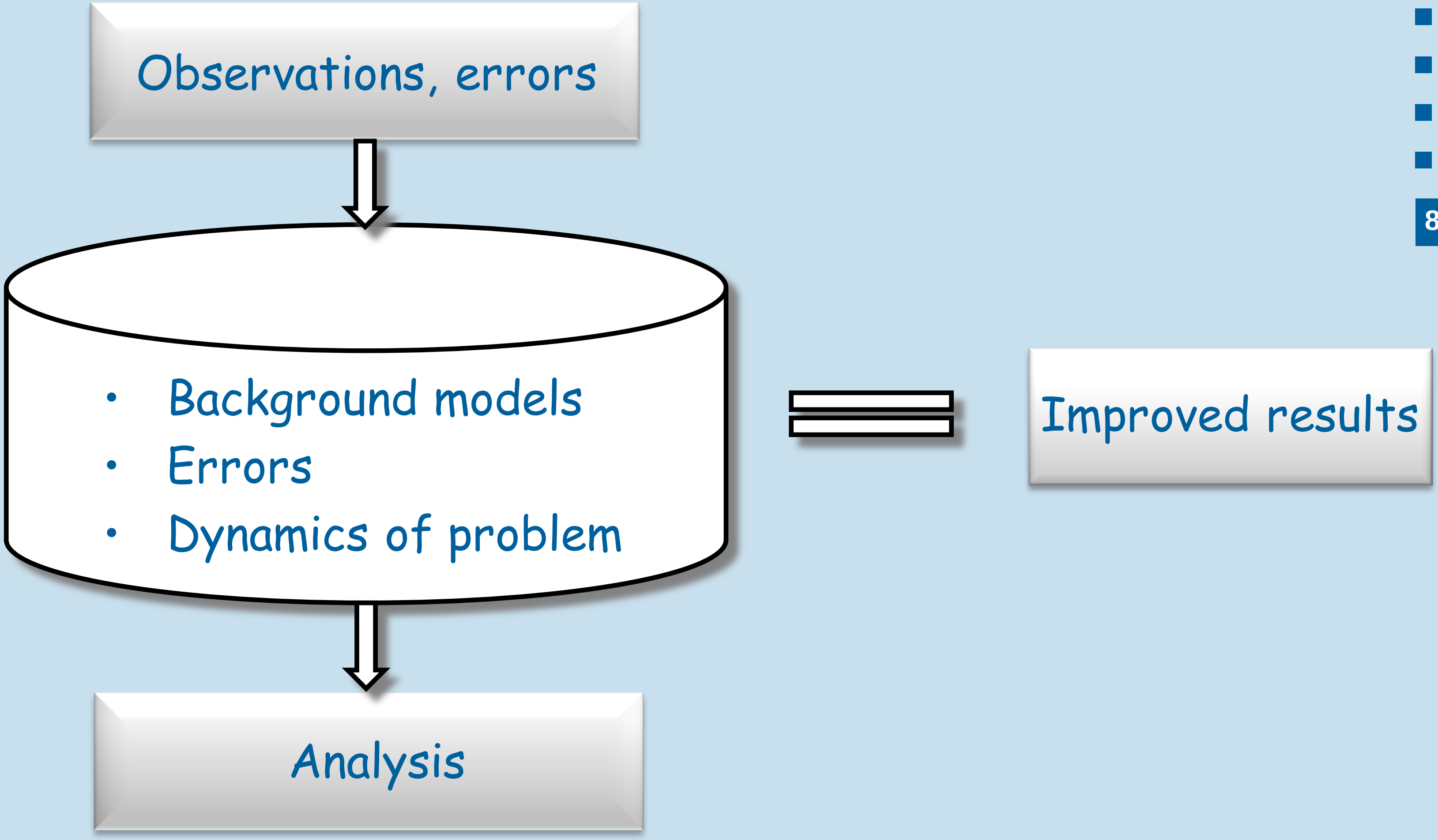
How well GNSS-RO technology resolve, will depend on

- Spatial and temporal resolution (e.g. Hori. resolution improved deploying more LEOs), trading off temp. resolution vs. spatial resolution.
- Density or number of rays (deploying more LEOs)

GNSS-RO Data Assimilation (DA) in ECMWF model

GNSS-RO Data Assimilation

- In DA, we want to minimize the cost function!



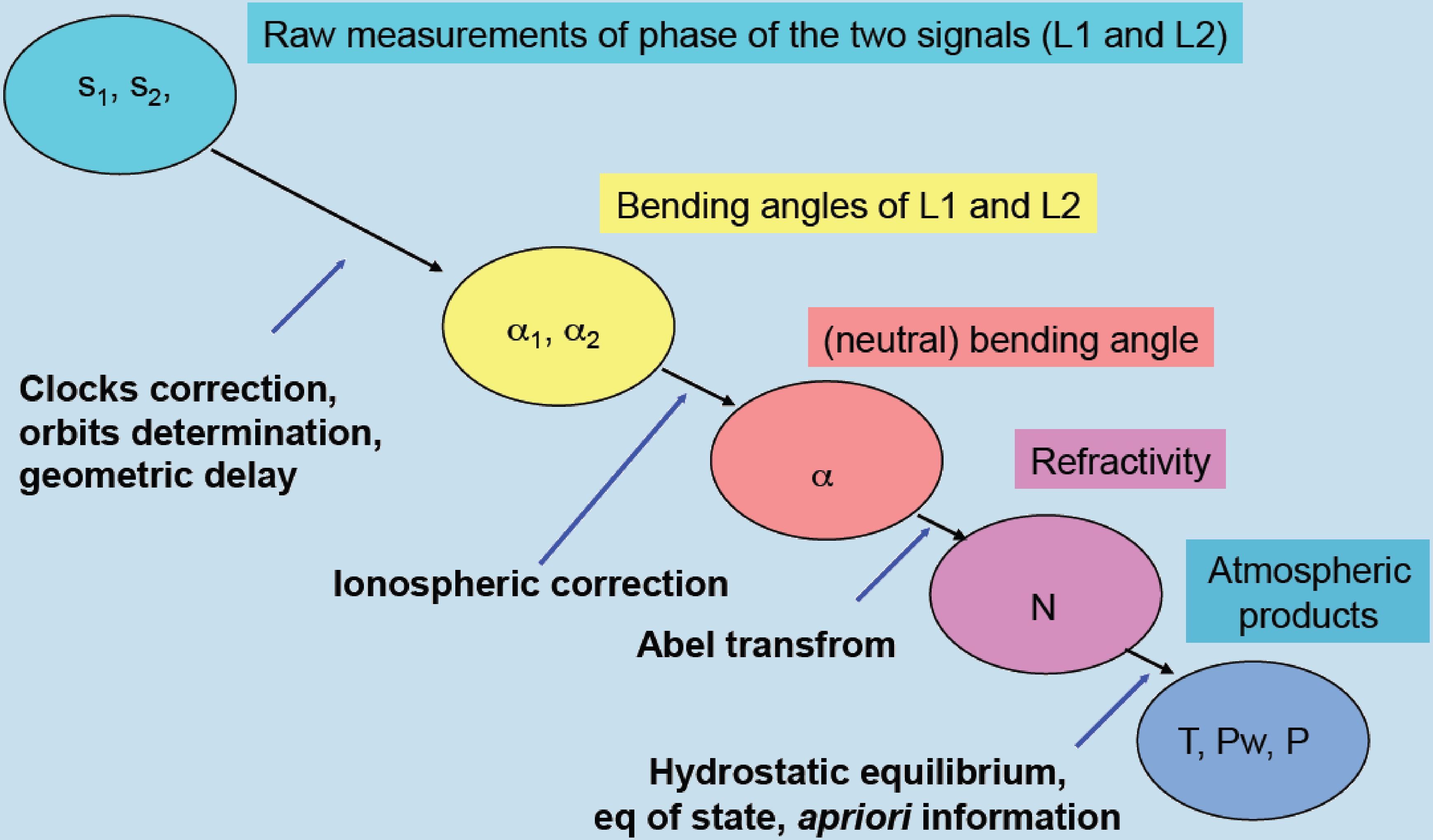
Observations, errors

- Background models
- Errors
- Dynamics of problem

Improved results

Analysis

GNSS-RO Data Assimilation (observations)



Raw measurements of phase of the two signals (L1 and L2)

$s_1, s_2,$

Clocks correction, orbits determination, geometric delay

Bending angles of L1 and L2

α_1, α_2

Ionospheric correction

(neutral) bending angle

α

Abel transfrom

Refractivity

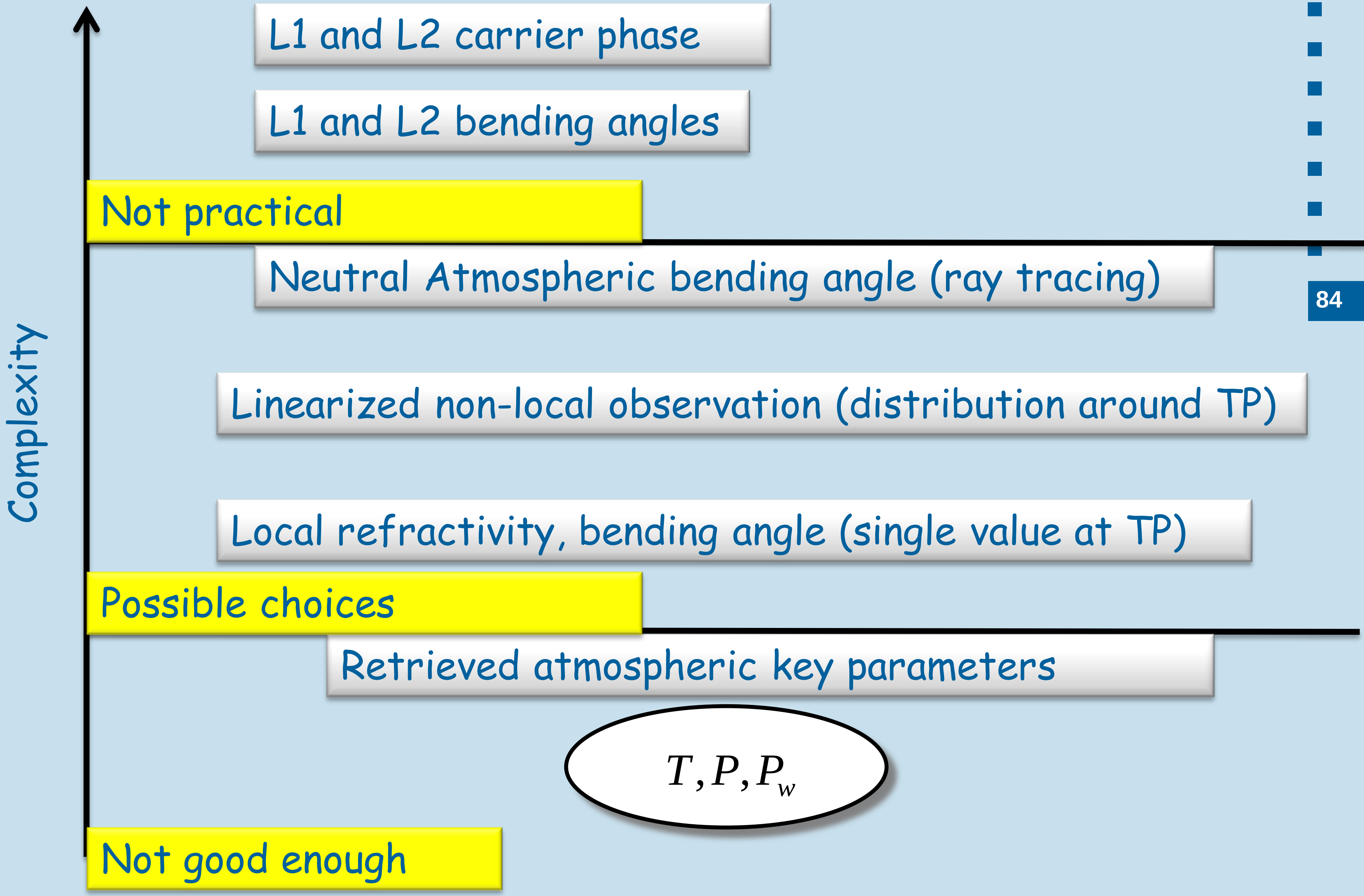
N

Atmospheric products

T, Pw, P

Hydrostatic equilibrium, eq of state, *apriori* information

Choice of observations in DA



L1 and L2 carrier phase

L1 and L2 bending angles

Not practical

Neutral Atmospheric bending angle (ray tracing)

Linearized non-local observation (distribution around TP)

Local refractivity, bending angle (single value at TP)

Possible choices

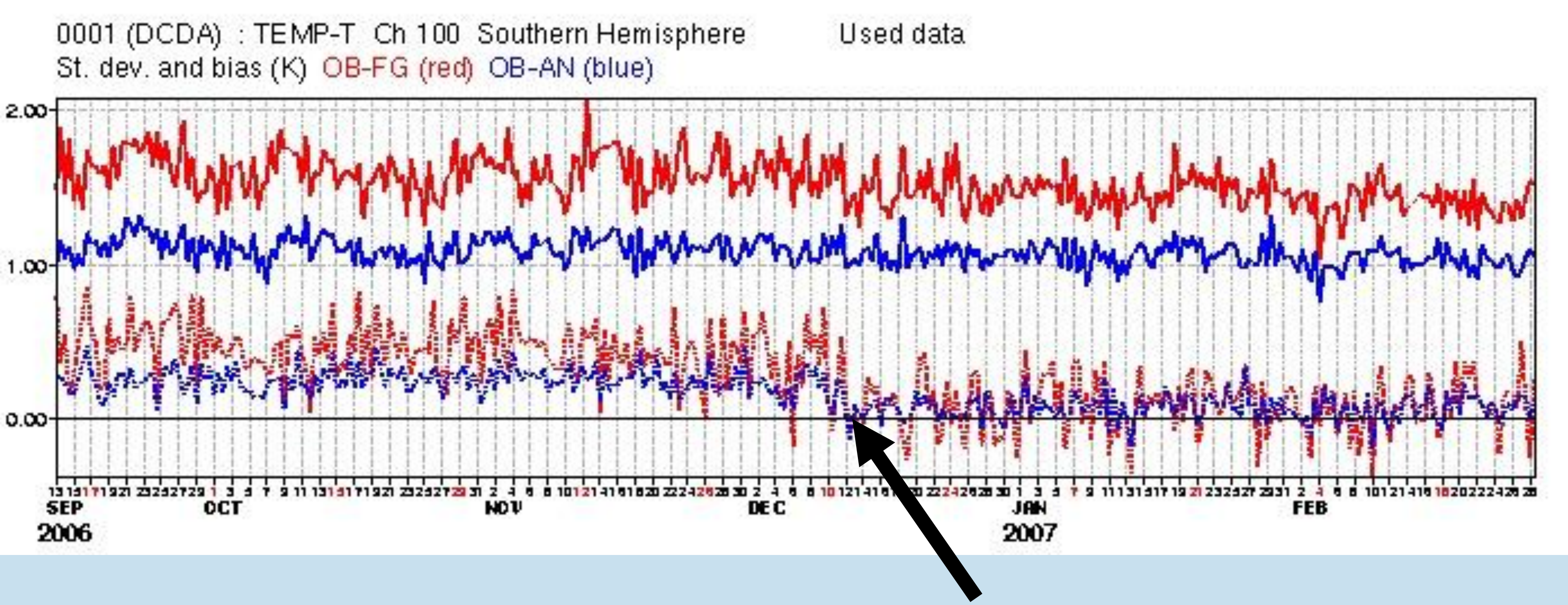
Retrieved atmospheric key parameters

T, P, P_w

Not good enough

Impact on ECMWF operational analyses

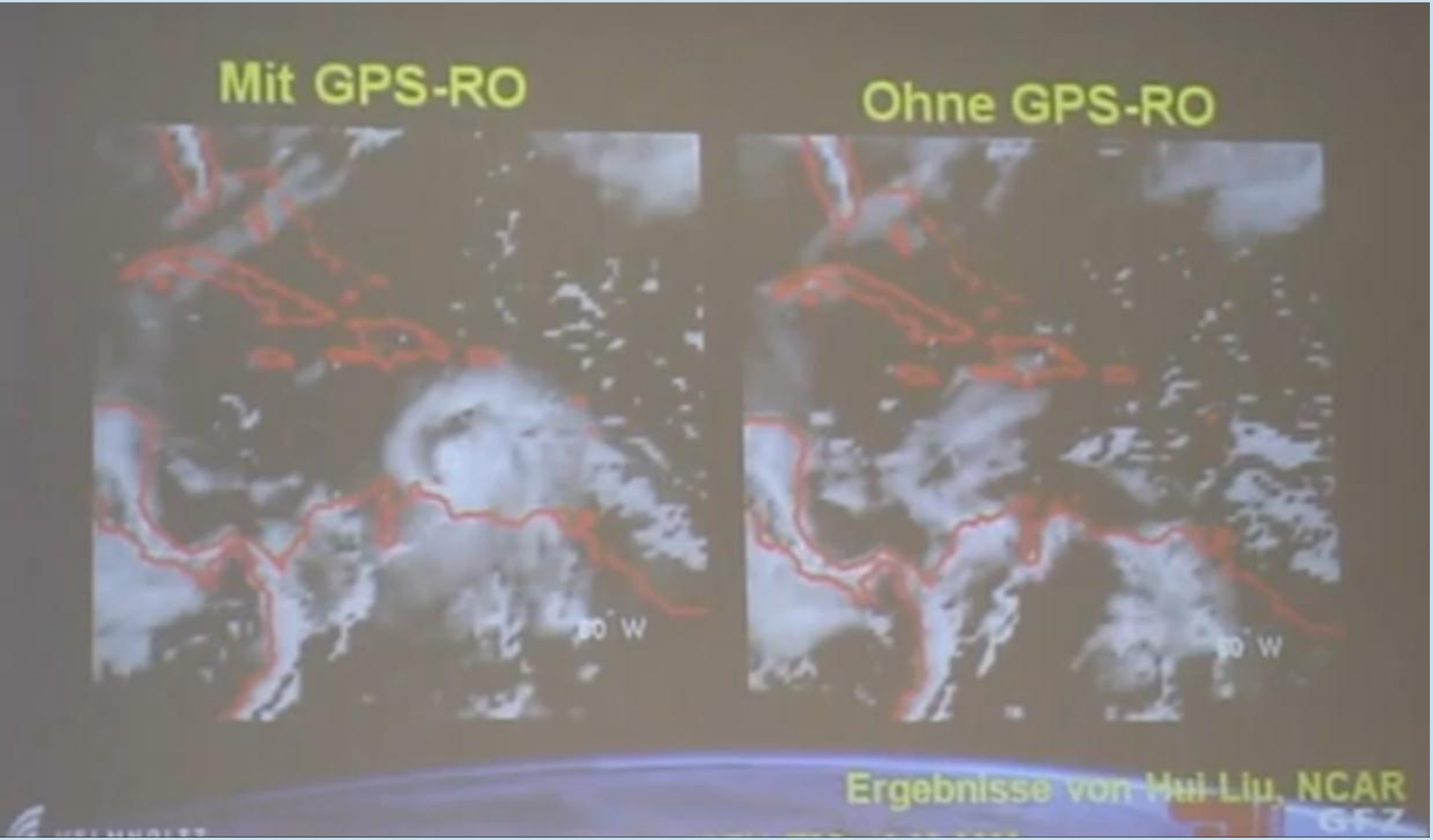
- We would expect improvements in the stratospheric temperatures. The fit to radiosonde temperatures is improved.



Source: Dr. Hardy

GNSS-RO used in operations since 12th December, 2007.

DA: Hurricane prediction in USA



Source: http://www.youtube.com/watch?v=Su3jwCG9F7Q

Summary

- ✓ GNSS-RO should provide good atmospheric key information in the upper troposphere (UT) and lower/mid stratosphere. Operational assimilation of GNSS-RO supports this.
- ✓ GNSS-RO observations are:
  - ✓ Global coverage, inexpensive,
  - ✓ All weather conditions,
  - ✓ High accuracy, high vertical resolution,
  - ✓ Very small systematic differences vs. model.
- ✓ DA of GNSS-RO can improve the atmospheric state model and predictions, e.g. weather prediction, tornado and hurricanes warning, etc…

Challenges!

- ✓ Non-spherical symmetry! (mathematical improvements)
  - ✓ Spherical symmetry is necessary to recover bending angles from excess Doppler shift and finally refractivity from bending angles!
- ✓ Horizontal (along track) gradients of refractivity will affect the retrieved bending angles (less) and refractivities (more)!
- ✓ Improvement of GNSS receiver (software and hardware) and data processing software to overcome problems!
- ✓ An occultation event is not just a vertical profile (1D -> 3D).
- ✓ Capability of DA with GNSS-RO raw data
- ✓ Future missions (e.g. new horizons in 2015)

Thank you

for your attention