



Global Positioning System (GPS) Radio Occultation

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Topics covered during this talk

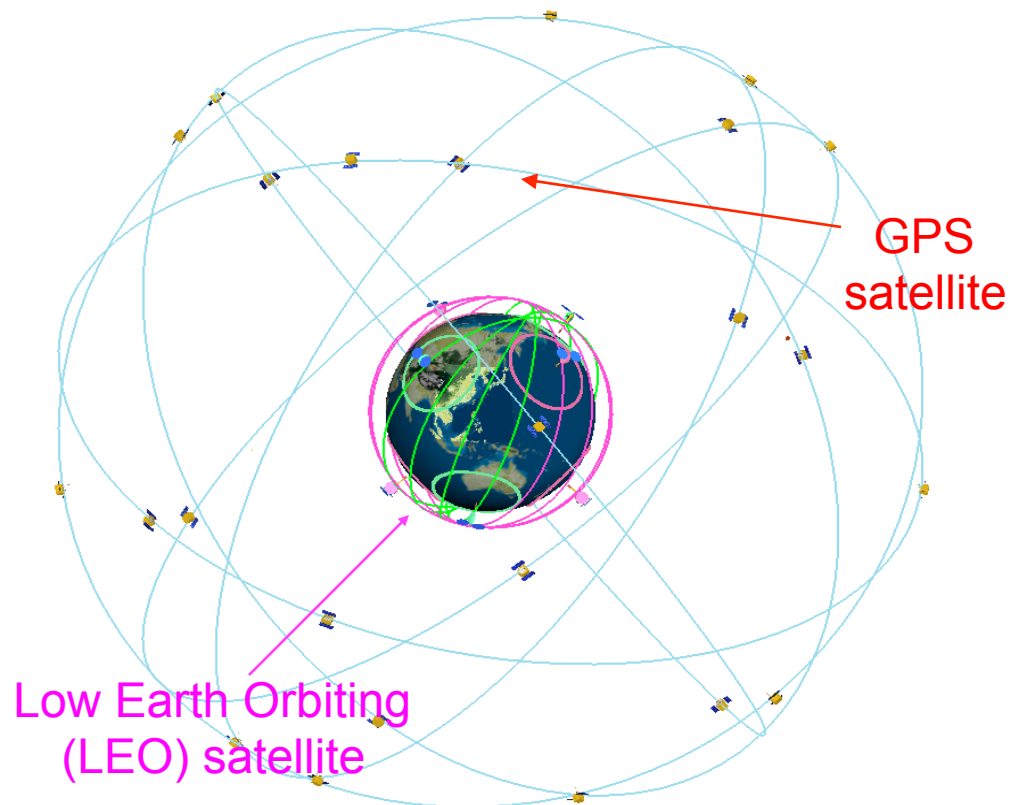
- GPS (GNSS) Radio Occultation concept
- Processing of the data - from raw measurements to retrieved atmospheric products
- Calibration, instrument drift
- Precision, accuracy, resolution
- Assimilation of Radio Occultation products in numerical weather prediction
- Summary and outlook



Characteristics of the GPS RO technique

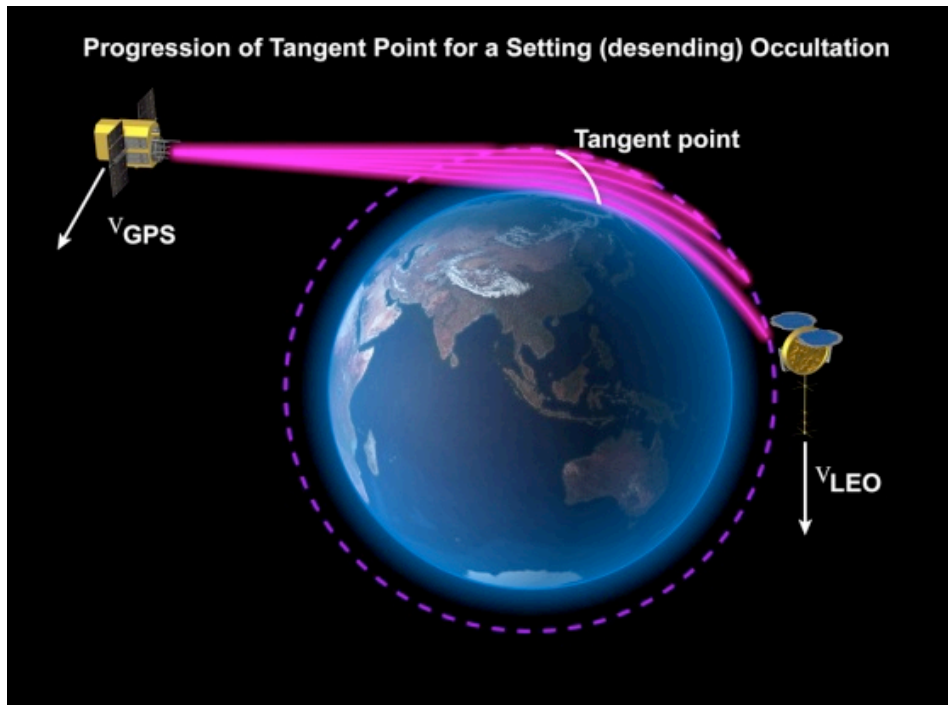
Global Positioning System (GPS)

- The 29 GPS satellites are distributed roughly in six circular orbital planes at $\sim 55^\circ$ inclination, 20,200 km altitude and ~ 12 hour periods.
- Each GPS satellite continuously transmits signals at two L-band frequencies, L1 at 1.57542 GHz (~ 19 cm) and L2 at 1.227 GHz (~ 24.4 cm).



Radio Occultation concept

- An occultation occurs when a GNSS satellite rises or sets across the limb wrt to a LEO satellite.
- A ray passing through the atmosphere is refracted due to the vertical gradient of refractivity (density and moisture).
- During an occultation ($\sim 3\text{min}$) the ray path slices through the atmosphere



Raw measurement: change of the delay (phase) of the signal path between the GNSS and LEO during the occultation. (It includes the effect of the neutral atmosphere and the ionosphere).

GPS transmits at two different frequencies: $\sim 1.6\text{ GHz}$ (L1) and $\sim 1.3\text{ GHz}$ (L2).

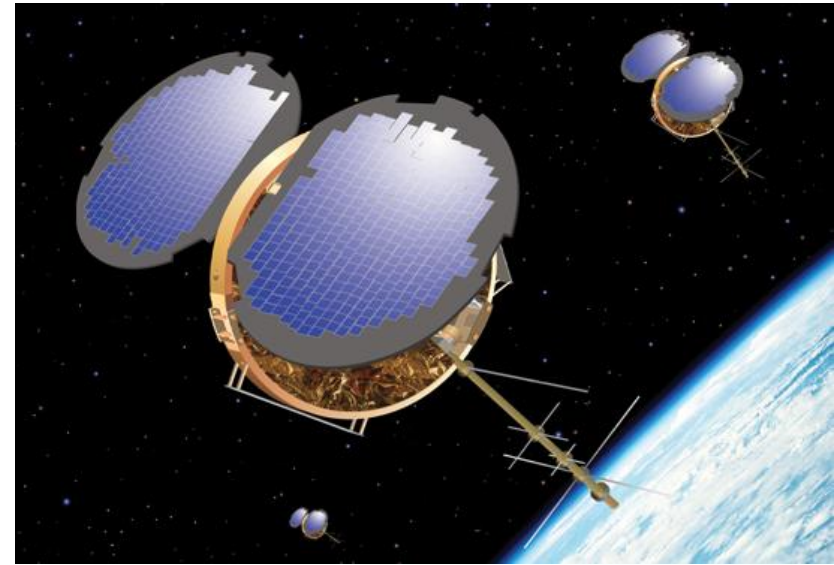


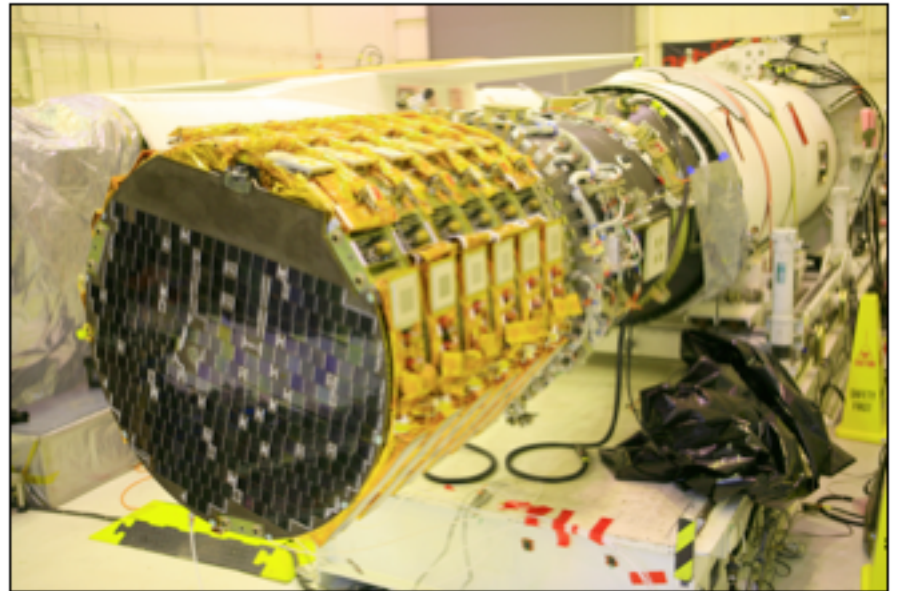
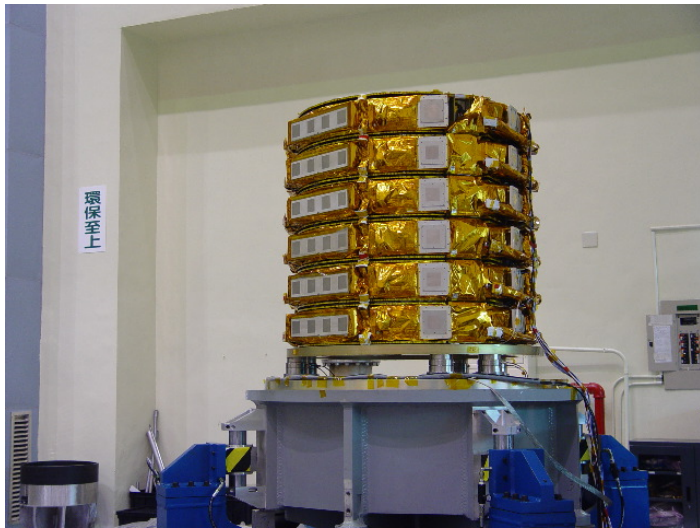
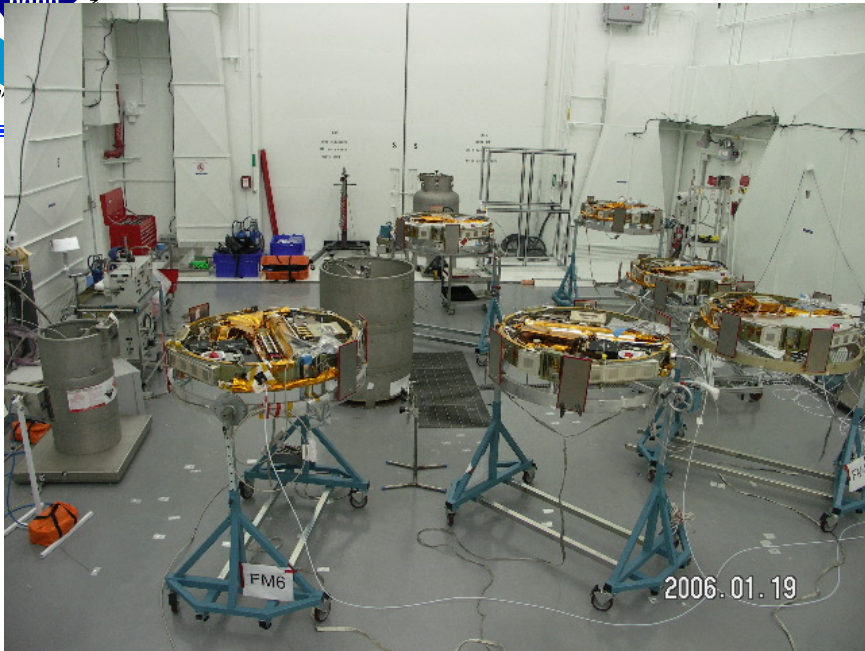
A few additional words

- The RO occultation technique has four decades of history as a part of NASA's planetary exploration missions (e.g. Fjeldbo and Eshleman, 1969; Fjeldbo et al., 1971; Tyler, 1987; Lindal et al., 1990; Lindal, 1992) (Mariner IV at Mars, July 1965; Mariner V at Venus, October 1967)
- Applying the technique to the Earth's atmosphere using the GPS signal was conceived two decades ago (Yunck et al., 1988; Gurvich and Krasil'nikova, 1990) and demonstrated for the first time with the GPS/MET experiment in 1995 (Ware et al., 1996)
- The promises of the technique generated a lot of interest from several disciplines including meteorology, climatology and ionospheric physics

COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate)

- Joint US-Taiwan mission
- 6 LEO satellites launched in 15 April 2006
- Three instruments:
GPS receiver, TIP, Tri-band beacon
- Demonstrate “operational” use of GPS limb sounding with global coverage in near-real time
- web page: www.cosmic.ucar.edu







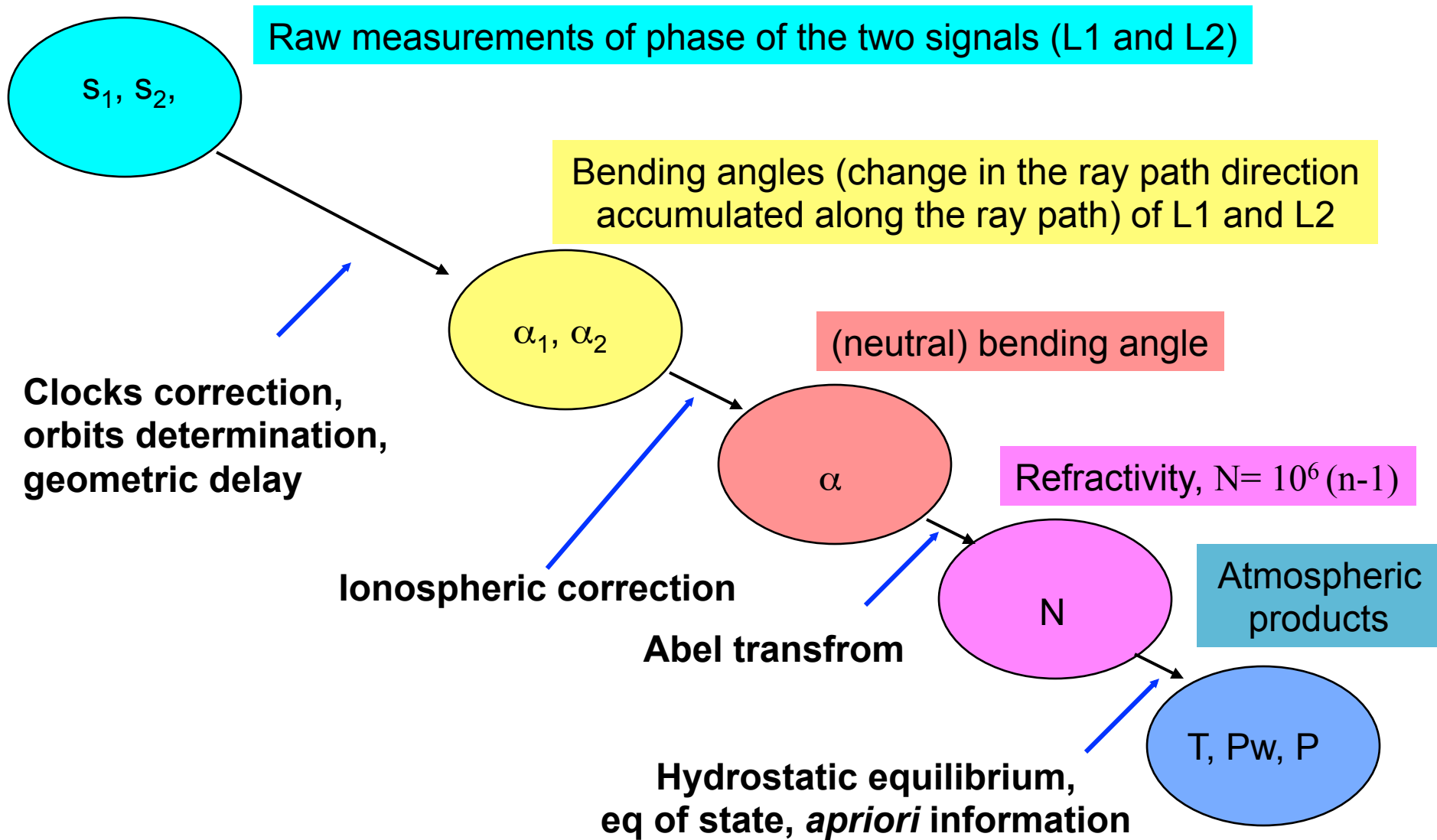
COSMIC Launch picture provided by Orbital Sciences Corporation





Processing the data

RO processing steps





Bending angle

- Correction of the clocks errors and relativistic effects on the phase measurements (time corrections).
- Compute the Doppler shift (change of phase in time during the occultation).
- Remove the expected Doppler shift for a straight line signal path to get the atmospheric contribution (ionosphere + neutral atmosphere). [The first-order relativistic contributions to the Doppler cancel out].
- The atmospheric Doppler shift is related to the known position and velocity of the transmitter and receiver (orbit determination).
- However, there is an infinite number of atmospheres that would produce the same atmospheric Doppler. (The system is undetermined).
- Certain assumption needs to be made on the shape of the atmosphere: ‘local’ spherical symmetry of the index of refraction of the atmosphere.

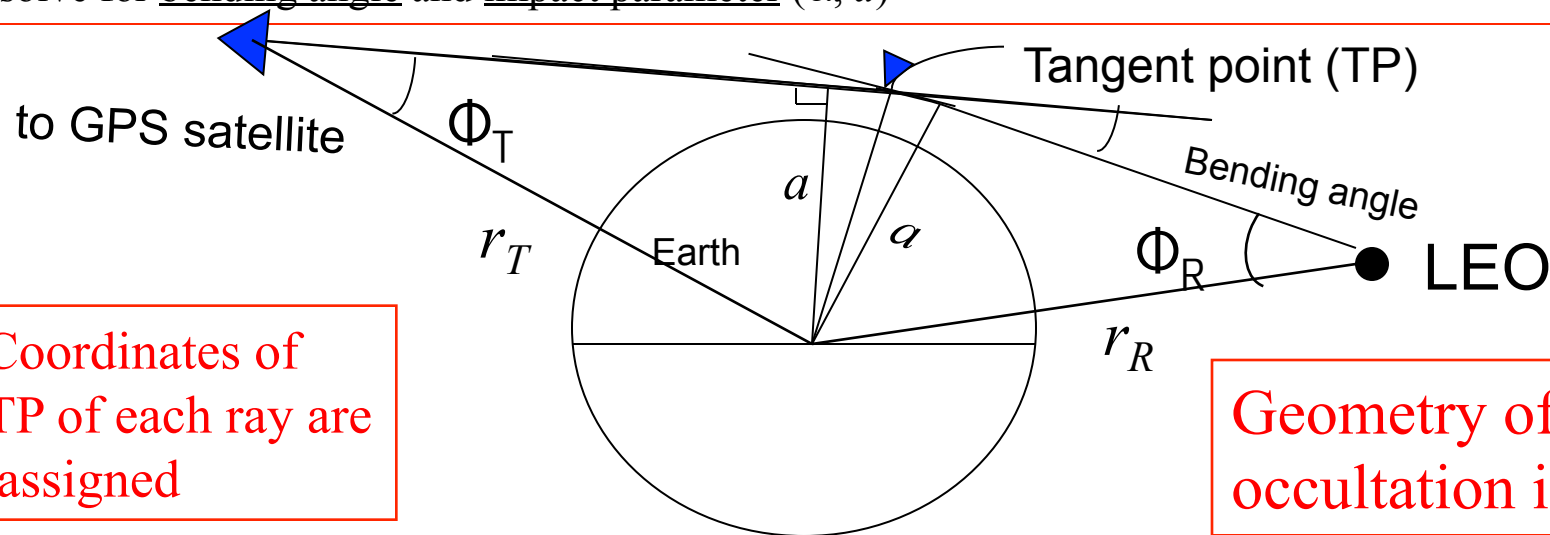
Bending angle (cont' d)

Global Spherical symmetry: $n=n(r) \rightarrow r n \sin(\Phi) = \text{const} = a$ along the ray path, where n is the index of refraction (c/v), r is the radial direction, Φ is the angle between the ray path and the radial direction, and a is the impact parameter (Bouguer's rule). (Note that at the tangent point TP, $n_{TP} r_{TP} = a$)

Local Spherical symmetry: condition required only at the receiver and transmitter locations

$$n_T r_T \sin(\Phi_T) = n_R r_R \sin(\Phi_R) = a$$

With this assumption, the knowledge of the satellites positions & velocities, and the local center of curvature (which varies with location on the Earth and orientation of the occultation plane), we solve for bending angle and impact parameter (α, a)



Coordinates of TP of each ray are assigned

Geometry of the occultation is defined



(neutral) Bending angle

- We compute bending angle and impact parameter for each GPS frequency (α_1, a_1) and (α_2, a_2) . [The two rays travel slightly different paths because the ionosphere is dispersive].
- For neutral atmospheric retrievals, we compute linear combination of α_1 and α_2 to remove the first-order ionospheric bending ($\sim 1/f^2$) and get the ‘neutral’ bending angle $\alpha(a)$
 - The correction should not be continued above ~ 50 - 60 km because the signature of the neutral atmosphere might be comparable to the residual ionospheric effects.
 - Errors introduced by deviations from spherical symmetry of the ionosphere ($O(1/f^3)$ or higher, comparable to the correction residual errors).
 - Small-scale variations in plasma structure do not cancel completely
 - Scintillation effects
- Retrieval: **profile of $\alpha(a)$** during an occultation ($\sim 3,000$ rays!)

Refractivity

- Under (global) spherical symmetry, a profile of $\alpha(a)$ can be inverted (through an Abel inversion) to recover the index of refraction at the tangent point (ie. we reconstruct the atmospheric refractivity)

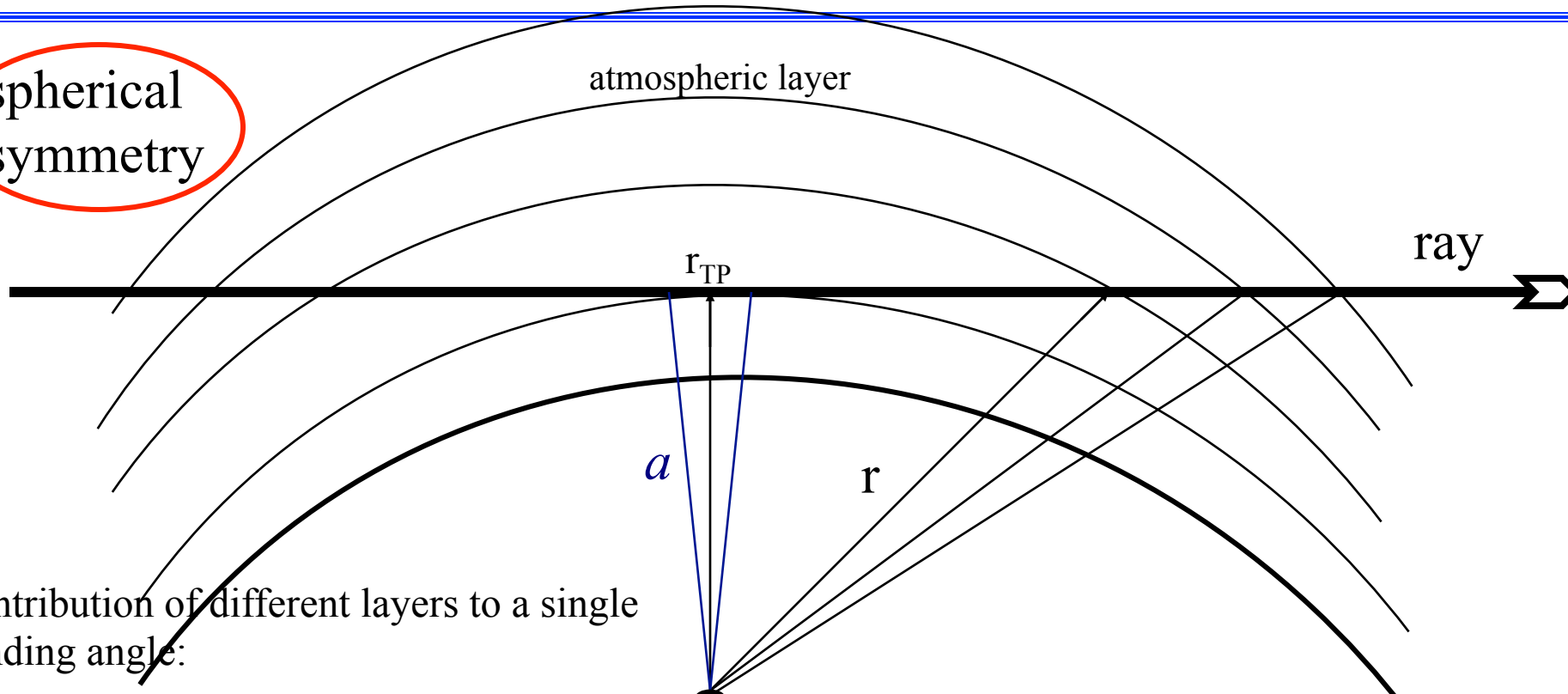
$$n(r_{TP}) = \exp \left[1/\Pi \int_{a_1}^{\infty} \frac{\alpha(a)}{(a^2 - a_1^2)^{1/2}} da \right]$$

$$nr_{TP} = a_1$$

- Profile of $\alpha(a)$ is extrapolated above ~ 60 km (up to ~ 150 km) using climatology information (through statistical optimization) to solve the integral. (The effects of climatology on the retrieved profile are negligible below ~ 30 km).
- Tangent point radius are converted to geometric heights z (ie. heights above mean-sea level geoid).
- Index of refraction is converted to refractivity: $N = 10^6 (n - 1)$
- Retrieval: **profile of $N(z)$** during an occultation ($\sim 3,000$ rays)

Rationale for Abel inversion

spherical symmetry



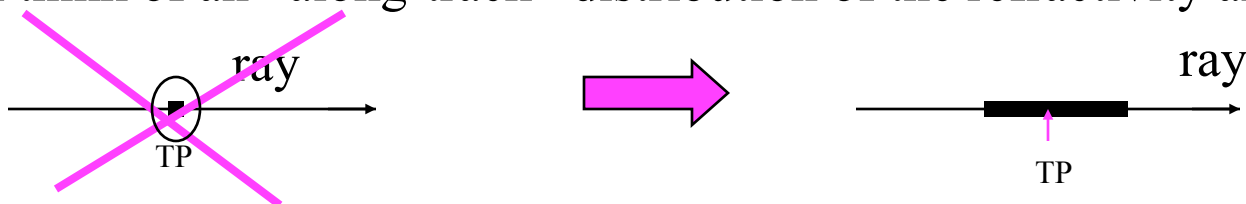
Contribution of different layers to a single bending angle:

$$\alpha(a) = 2a \int_{r_{TP}}^{\infty} \frac{d \ln n / dr}{(n^2 r^2 - a^2)^{1/2}} dr \quad \longrightarrow \quad \left\{ \begin{array}{l} n(r_{TP}) = \exp \left[1/\Pi \int_{a_1}^{\infty} \frac{\alpha(a)}{(a^2 - a_1^2)^{1/2}} da \right] \\ nr_{TP} = a_1 \end{array} \right\}$$

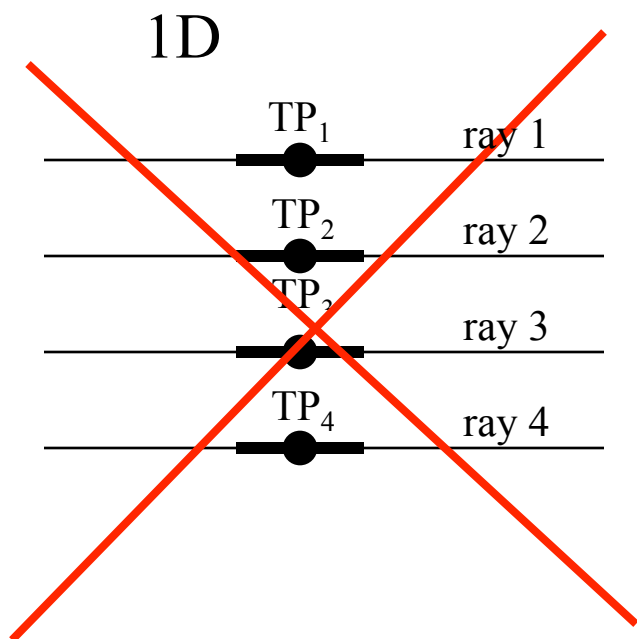
Larger contribution when larger gradient and closer to r_{TP} -> integral peaks at r_{TP}

Real world....

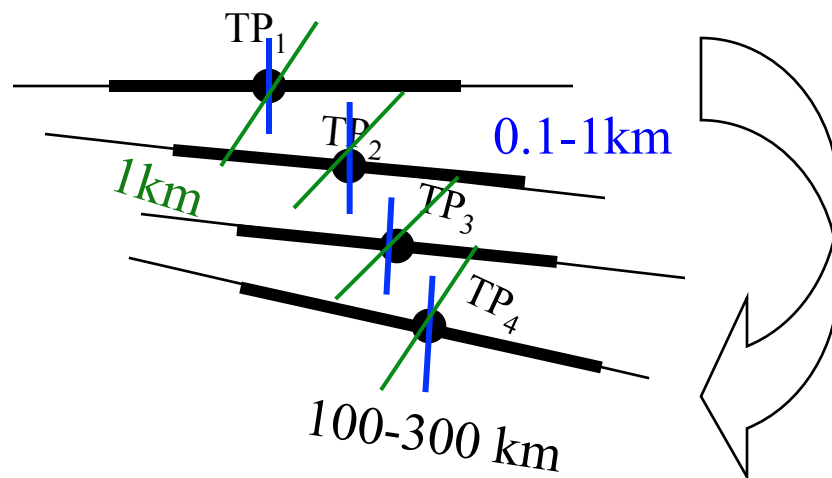
- If the spherical symmetry assumption was exactly true (ie. no horizontal gradients of refractivity, refractivity only dependent on radial direction)
 - we would not have a job on this business (no weather!)
 - Abel transform would exactly account for and unravel the contributions of the different layers in the atmosphere to a single bending angle.
- However, there is a 3D distribution of refractivity (or 2D) that contributes to a single bending angle and only 1D bending angle (undetermined problem). [Different from the usual nadir-viewing soundings].
- There is contribution from the horizontal gradients of refractivity to a single bending angle. (This can be significant in LT).
- Abel inversion does not account for these contributions along the ray path so there is some residual mapping of non-spherical horizontal structure into the refractivity profile
- We can think of an “along-track” distribution of the refractivity around the TP.



Spatial resolution of a RO



We need to think in 3D



3,000 rays!!!!

An occultation is not just a vertical profile. The relative motion of the satellites involves an inclination away from the vertical of the surface swept out by the occulting rays (a surface, moreover, that is not in general even a plane)

Atmospheric variables

At microwave wavelengths (GPS), the dependence of N on atmospheric variables can be expressed as:

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{P_w}{T^2} - 40.3 \times 10^6 \frac{n_e}{f^2} + O\left(\frac{1}{f^3}\right) + 1.4 \times W_w + 0.6 \times W_i$$

Hydrostatic balance

P is the total pressure (mb)
 T is the temperature (K)

Moisture

P_w is the water vapor pressure (mb)

- important in the troposphere for $T > 240K$
- can contribute up to 30% of the total N in the tropical LT.
- can dominate the bending in the LT.

Ionosphere

f is the frequency (Hz)
 n_e electron density (m^{-3})

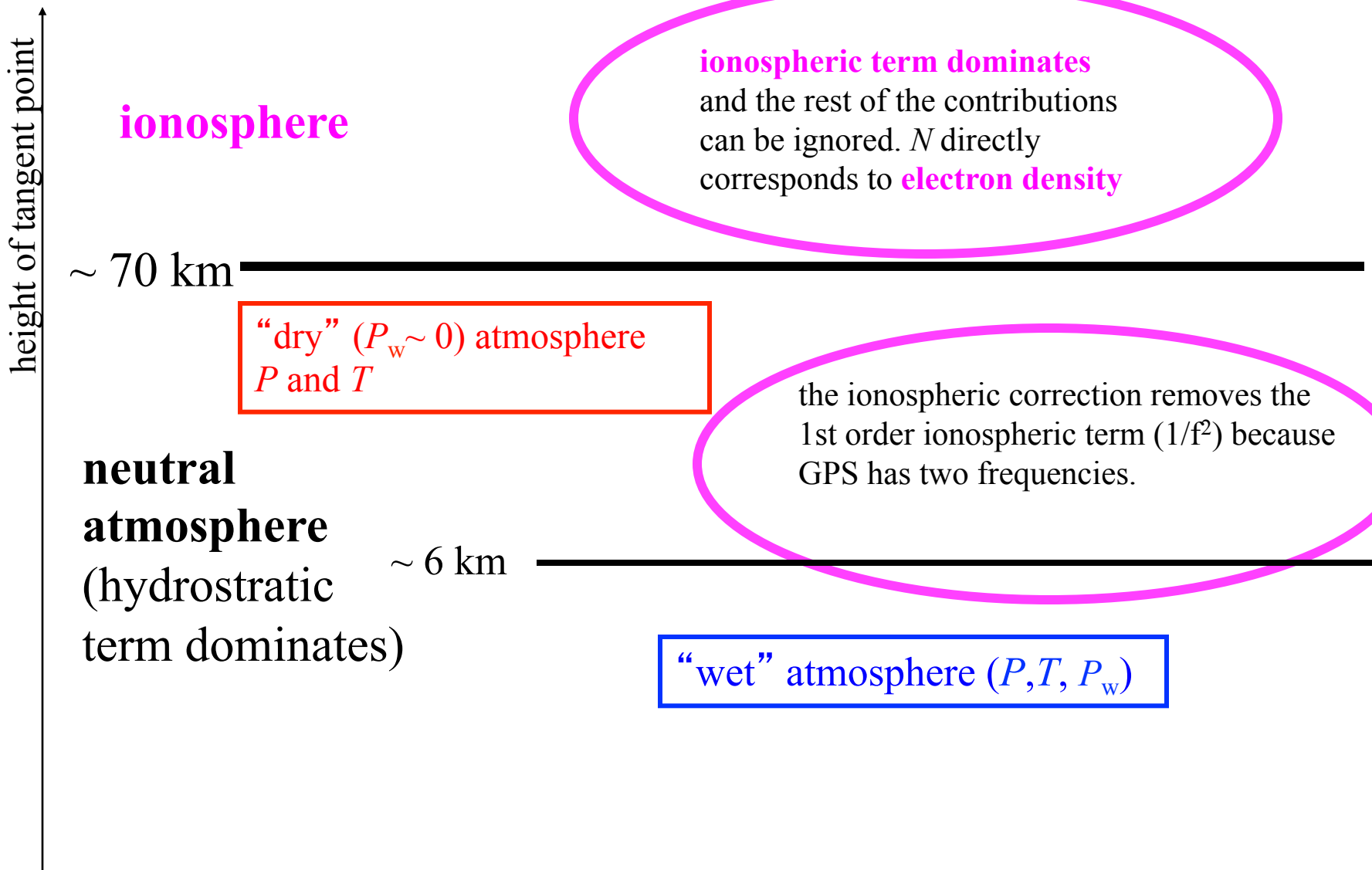
Scattering terms

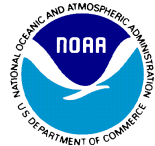
W_w and W_i are the liquid water and ice content (gr/m^3)

Contributions from liquid water & ice to N are very small and the scattering terms can be neglected
RO technology is almost insensitive to clouds.



Atmospheric variables





“Dry” atmosphere: P and T

- Where the contribution of the water vapor to the refractivity can be neglected ($T < 240\text{K}$) the expression for N gets reduced to pure density (and $P = P_d$),

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

- + equation of state: $\rho(z) = \frac{N(z)m}{77.6R}$ with $\begin{cases} m = \text{mean molecular mass of dry air} \\ R = \text{gas constant} \end{cases}$

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

- Given a boundary condition (e.g., $P=0$ at 150 km), one can derive
 - Profiles of pressure
 - Profiles of temperature (from pressure and density)
 - Profiles of geopotential heights from the geometric heights (RO provides independent values of pressure and height).

“Dry” atmosphere: P and T (cont’ d)

- When there is no moisture in the atmosphere, the profiles of P and T retrieved from N correspond to the real atmospheric values.

- But when there is moisture in the atmosphere, the expression

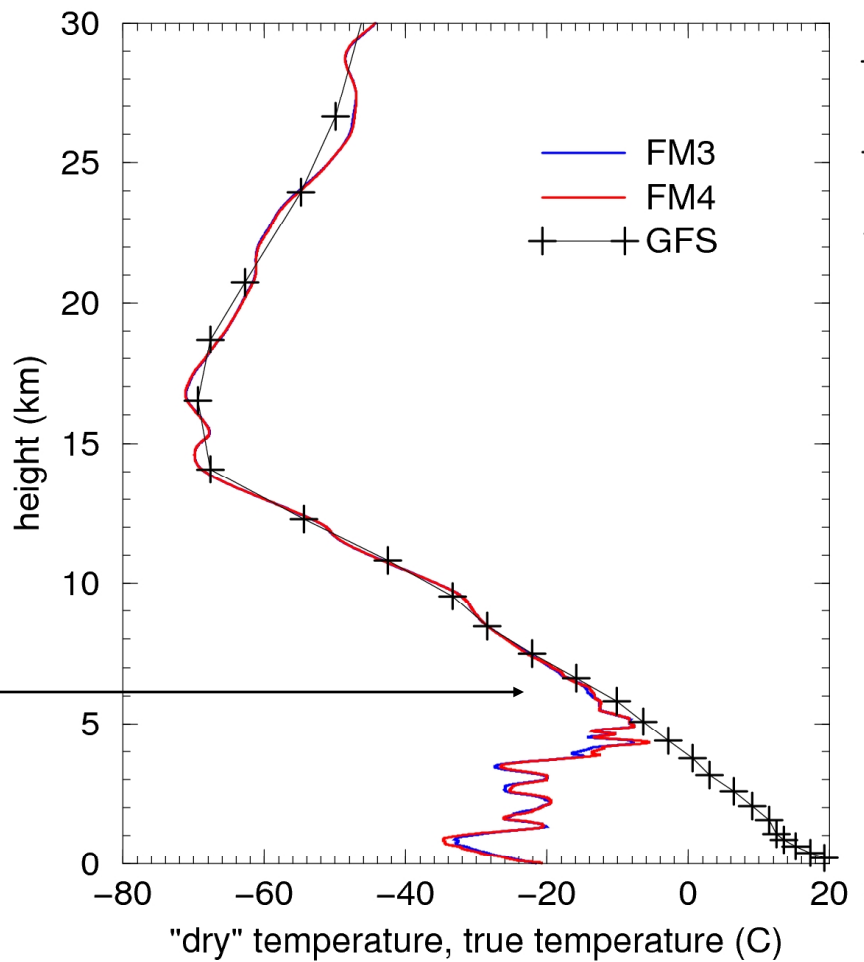
$$N = 77.6 \frac{P}{T}$$

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

- In other words, all the water vapor in the real atmosphere is replaced by dry molecules that collectively would produce the same amount of N .
- As a consequence, the retrieved temperature will be lower (cooler) than the real temperature of the atmosphere
- Within the GPS RO community, these profiles are usually referred to “dry temperature” profiles.
- This is confusing and misleading...
- I agree!!!



Retrieved vs Physical temperature



Moisture becomes significant



“Wet” atmosphere: mass and moisture

- When the moisture contribution to N is important (middle and lower troposphere), the system is undetermined (P, T, P_w).
- We need independent knowledge of temperature, pressure or water vapor pressure to estimate the other two variables.
- Usually, temperature is given by an external source (model) and we solve for pressure and moisture iteratively.
- Alternatively, we can use *apriori* information of pressure, temperature and moisture from a model along with their error characterization (background error covariance matrices) and find the optimal estimates of P , T and q (variational assimilation)



Calibration, instrument drift



**No Calibration,
No instrument drift**

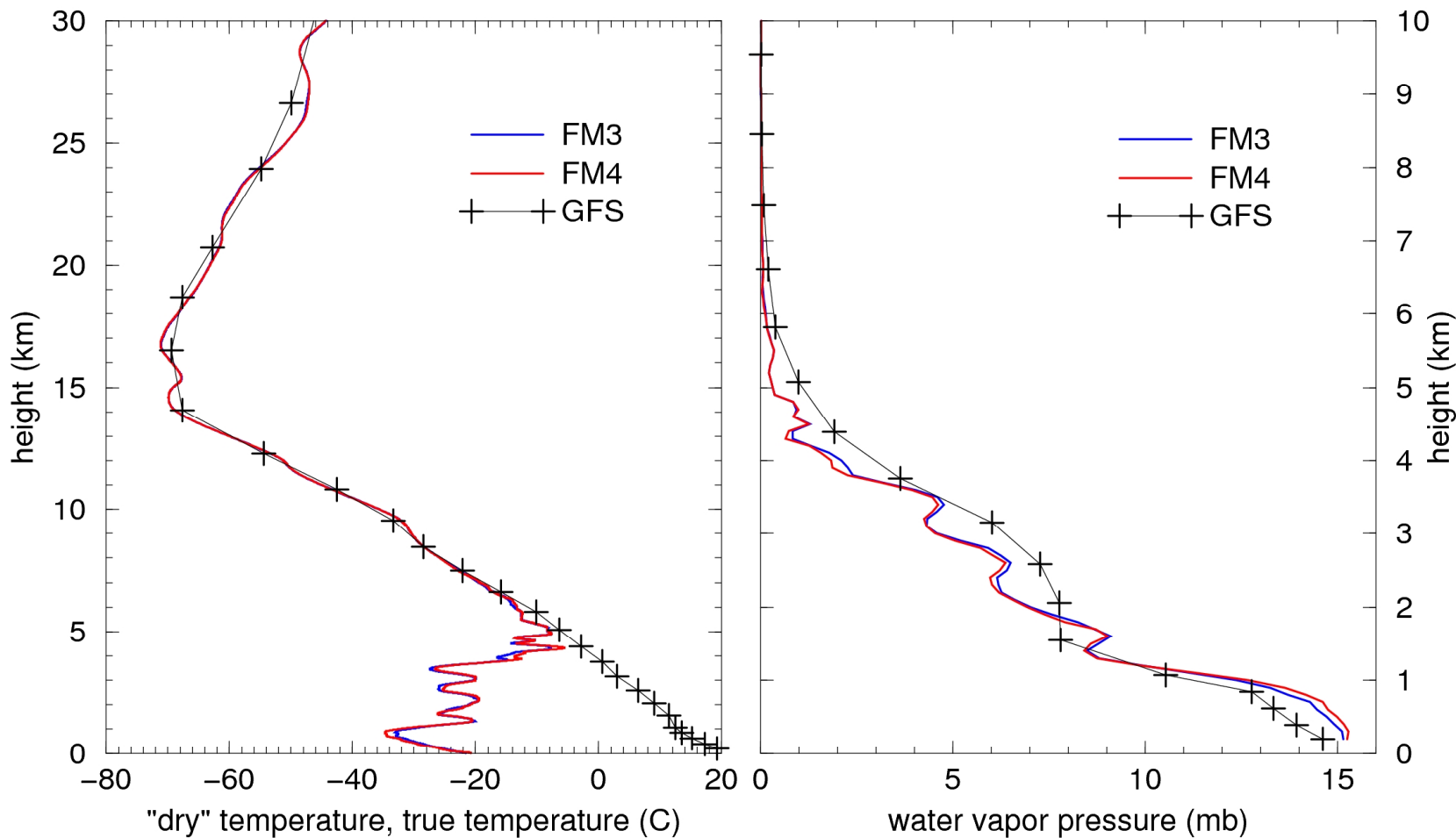


Uniqueness of RO technique

- Most measurements are based on physical devices that are not perfect and usually deteriorate with time. They usually drift and need to be calibrated.
- Radio Occultation technique is based on time delays, traceable to an absolute SI base unit.
- The raw measurement is not based on a physical device that deteriorates with time.
- There is no need for calibration
- There is no drift
- There is no instrument-to-instrument bias



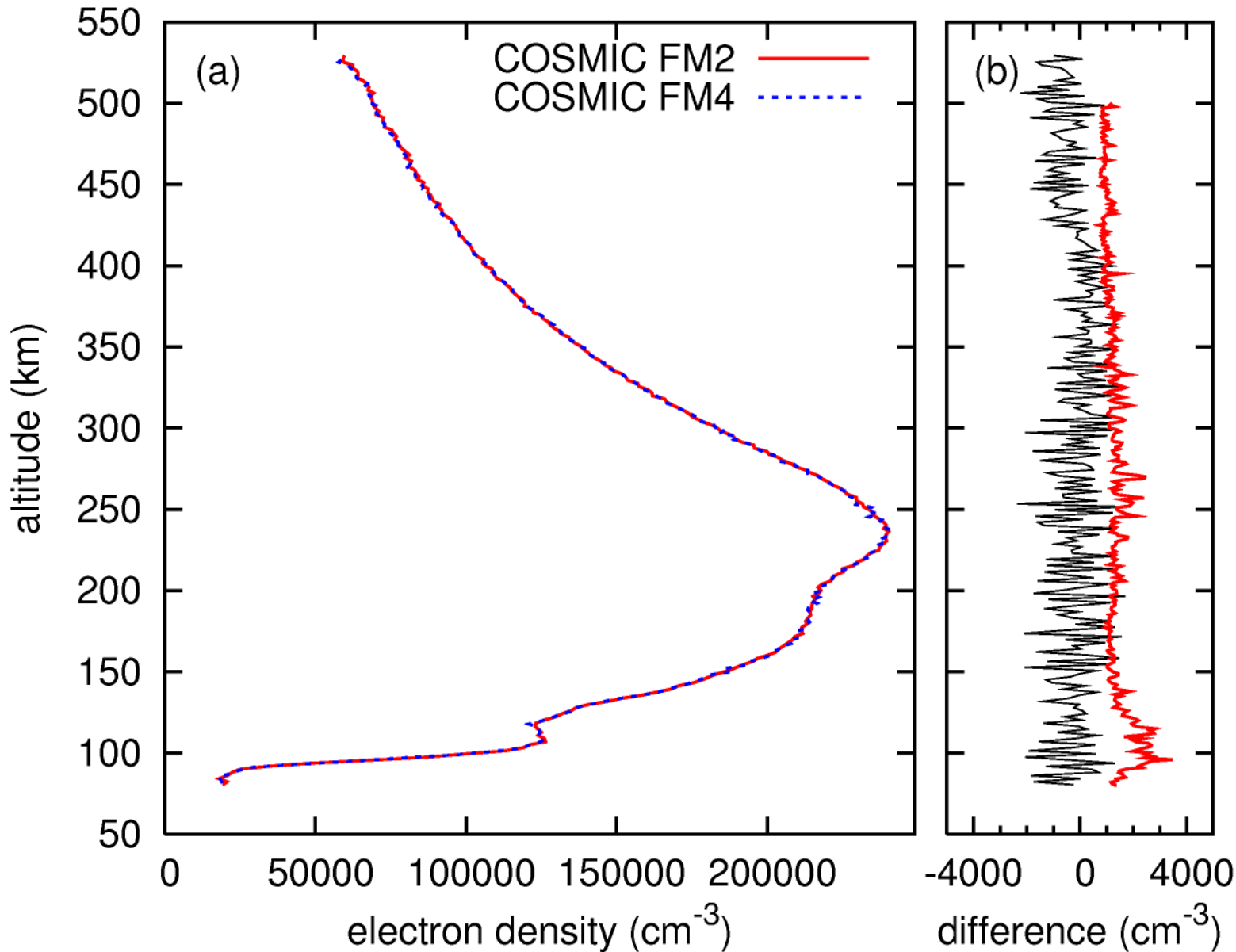
Comparison of collocated Profiles



C. Rocken (UCAR)



First collocated ionospheric profiles



From presentation by
S. Syndergaard,
UCAR/COSMIC

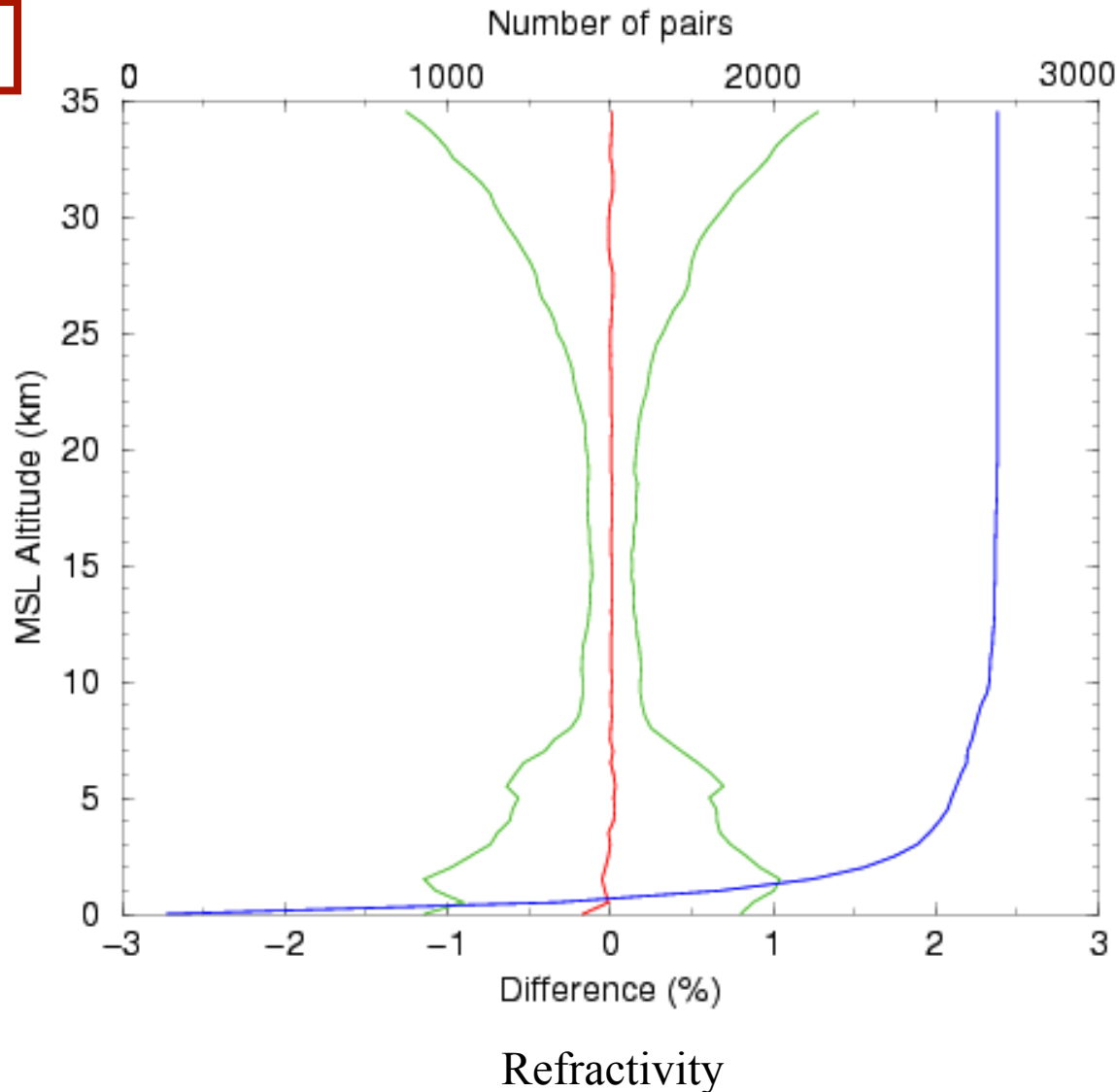


precision, accuracy,
resolution



Statistical comparison of FM3-FM4 Soundings separation < 10 km

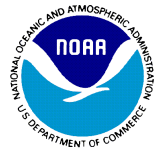
Precision



0.2% (N)
precision
between
10-20 km

~ 0.05K in
temperature!

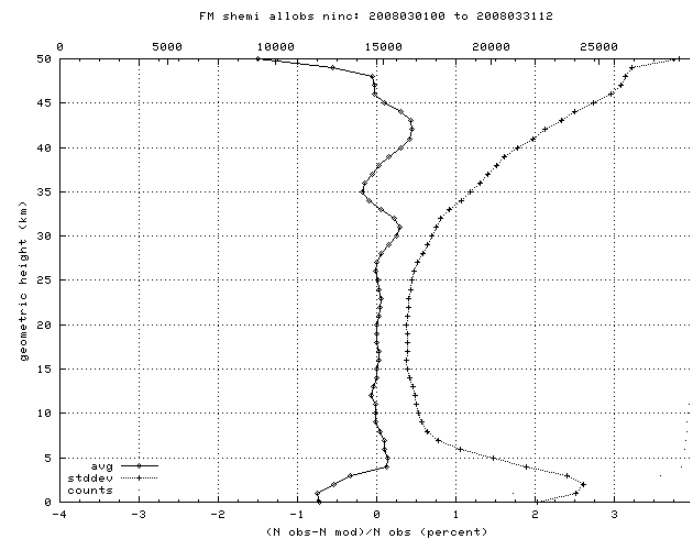
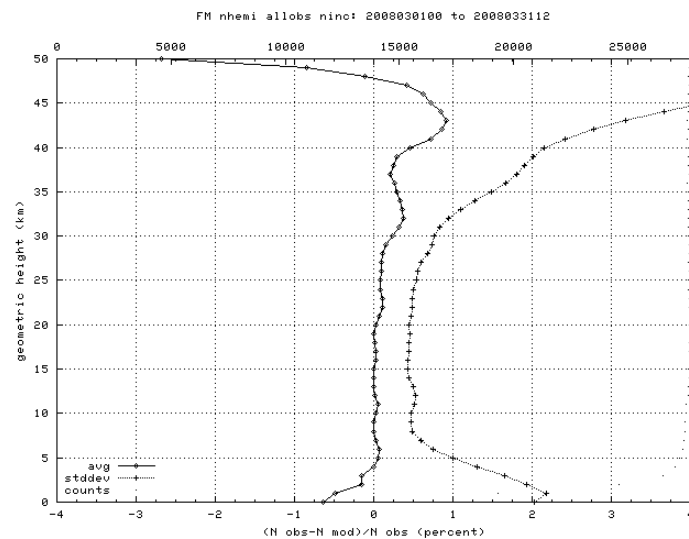
Schreiner et
al., 2007



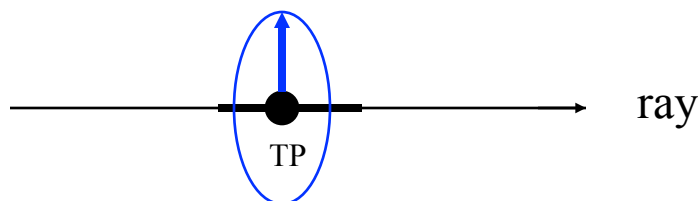
COSMIC vs GFS statistics for March 2008

Accuracy

- Accuracy is more difficult to evaluate
 - difficult to find other instruments as precise (eg. GFS performance changes with season, latitude range, atmospheric phenomena....)
 - each instrument has its own error characteristics
- Accuracy of RO is ~ 0.1 K in T between ~ 7 -25 km; better than ~ 2 mb rms error (~ 0.5 mb bias) in P_w

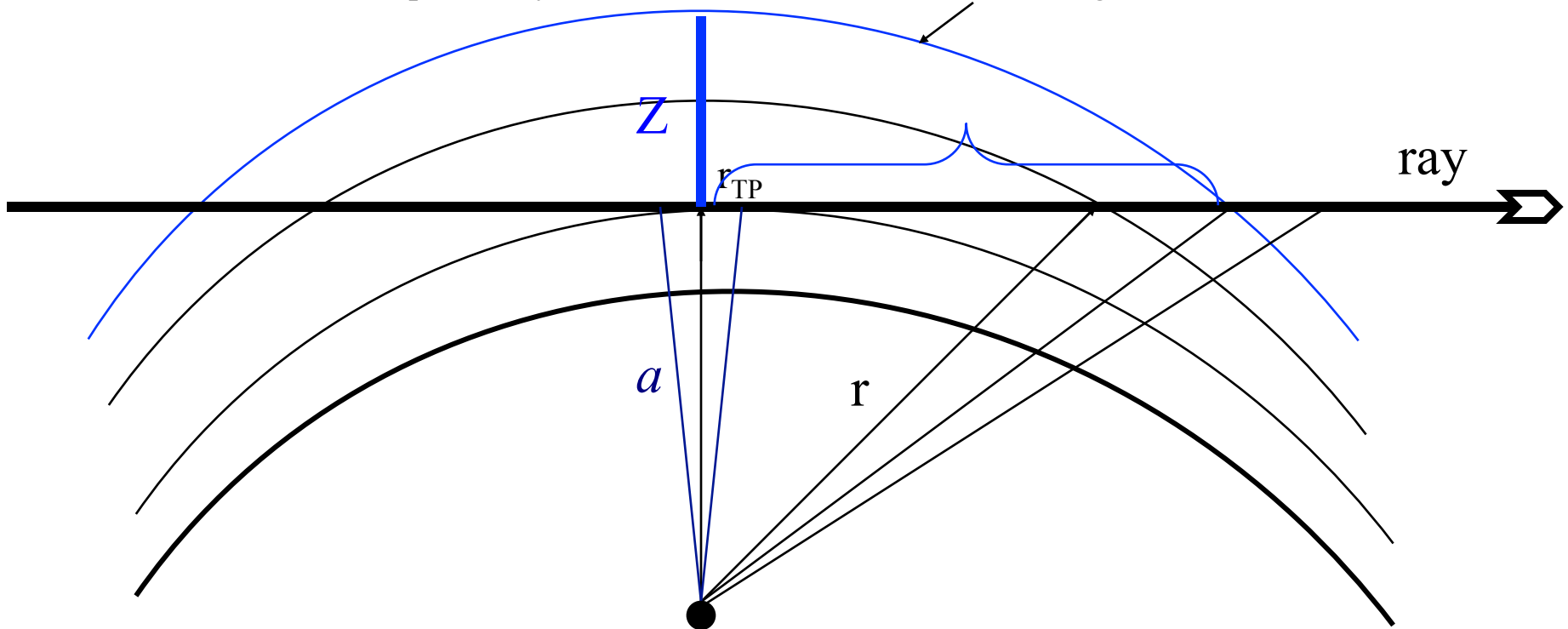


“across-track” resolution of an RO ray



- Bending angle is created by the contribution of the different atmospheric layers (vertical gradient of refractivity).
- Given a TP, the layer that contributes the most is the one at TP (closest point to the Earth surface and exponential behavior or refractivity).
- For each TP, we can compute the maximum layer interval that contributes a certain percentage to the bending.
- The vertical height above the TP that contributes 50% of the bending can be interpreted as vertical resolution of the bending of that single ray (hereafter, resolution of an RO ray).
- Remember we have 3,000 rays per RO!!

atmospheric layer that contributes 50% of the bending



Z varies typically from 1-2 km (~ 500 m when strong inversion) (Kurskinski et al., 1997). The resolution varies between the 3,000 rays because the atmospheric structure which affects the propagation of the signal changes ray to ray.



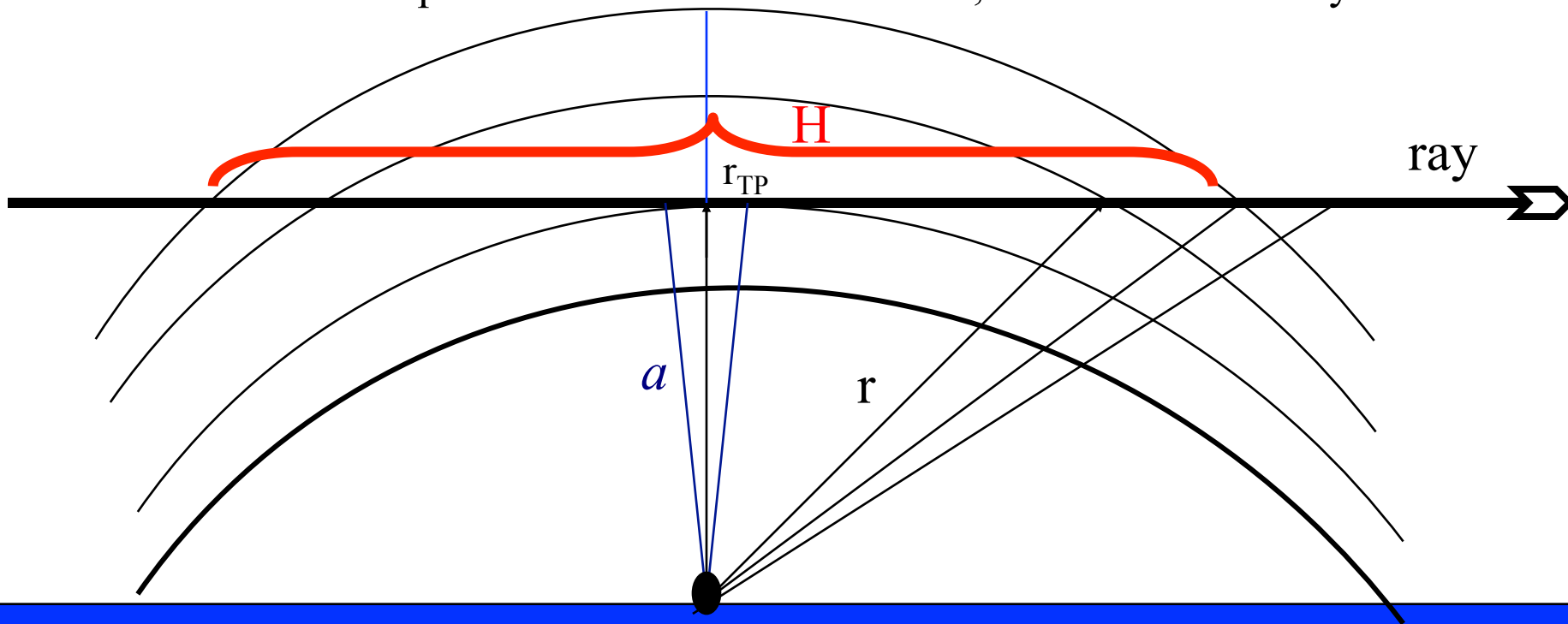
Real “across-track” RO resolution

- GPS RO samples at very high rate ($\sim 3,000$ rays in ~ 3 minutes) so the vertical resolution will be limited by diffraction (first Fresnel zone) (~ 100 m LT to ~ 1 km in stratosphere). It's the 'thickness' of GO ray.
- RH methods (diffraction correction algorithms) allow sub-Fresnel resolution at ~ 100 m in the whole vertical range.

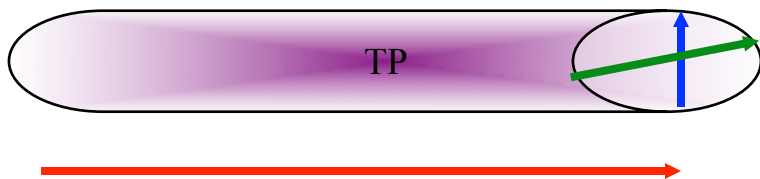


“along-track” resolution of an RO ray

- Analogously, the bending contribution of the different atmospheric layers can be written in terms of the distance along the ray path under spherical symmetry.
- Assuming that N varies exponentially and has a scale height of $\sim 6-8$ km, the bending contribution along the ray path follows a Gaussian distribution and 50% of the bending is within $\sim \pm 200$ km of TP (Melbourne et al. 1994).
- Therefore, the information content is not averaged equally along the horizontal extension of the ray path.
- This has been interpreted as horizontal resolution, but it's not entirely accurate



Spatial resolution of a single RO ray



$L \sim 100 - 300 \text{ km}$

$Z \sim 0.1 - 1 \text{ km}$

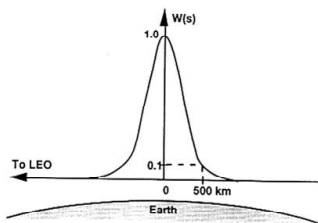
$D \sim 1 \text{ km}$

~ 4 times the volumetric resolution of an AMSU-B sounder

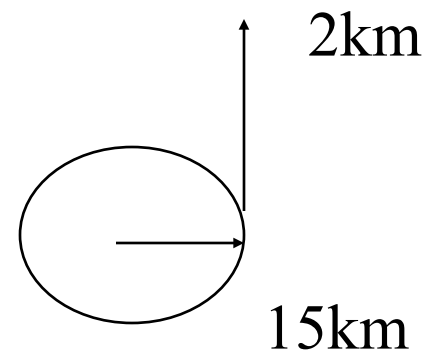
Observed Atmospheric Volume



$L \sim 300 \text{ km}$
 $Z \sim 1 \text{ km}$



Anthes et al., 2001





Real spatial RO resolution ($\sim 3,000$ rays)

- How well RO technology can resolve structures will depend on (1) spatial resolution of a single ray and (2) density or number of rays.
- GPS RO samples at very high rate ($\sim 3,000$ rays in ~ 3 minutes) so the density in the vertical direction and in the horizontal direction that the TP is moving is very high.
- Horizontal resolution can be improved by increasing the density of occultations by deploying more LEOs and/or by trading off temporal resolution versus spatial resolution.



Radio Occultation characteristics

- Limb sounding geometry complementary to ground and space nadir viewing instruments
 - High vertical resolution (~ 100 m)
 - Lower 'along-track' resolution (~ 200 km)
- All weather-minimally affected by aerosols, clouds or precipitation
- High accuracy (equivalent to ~ 0.1 Kelvin from ~ 7 - 25 km)
- Equivalent accuracy over ocean than over land
- No instrument drift, no need for calibration
- Global coverage
- No satellite-to-satellite measurement bias
- Observations can be used in NWP without a bias correction scheme
- RO is one of the top contributors in improving global operational weather forecast skill



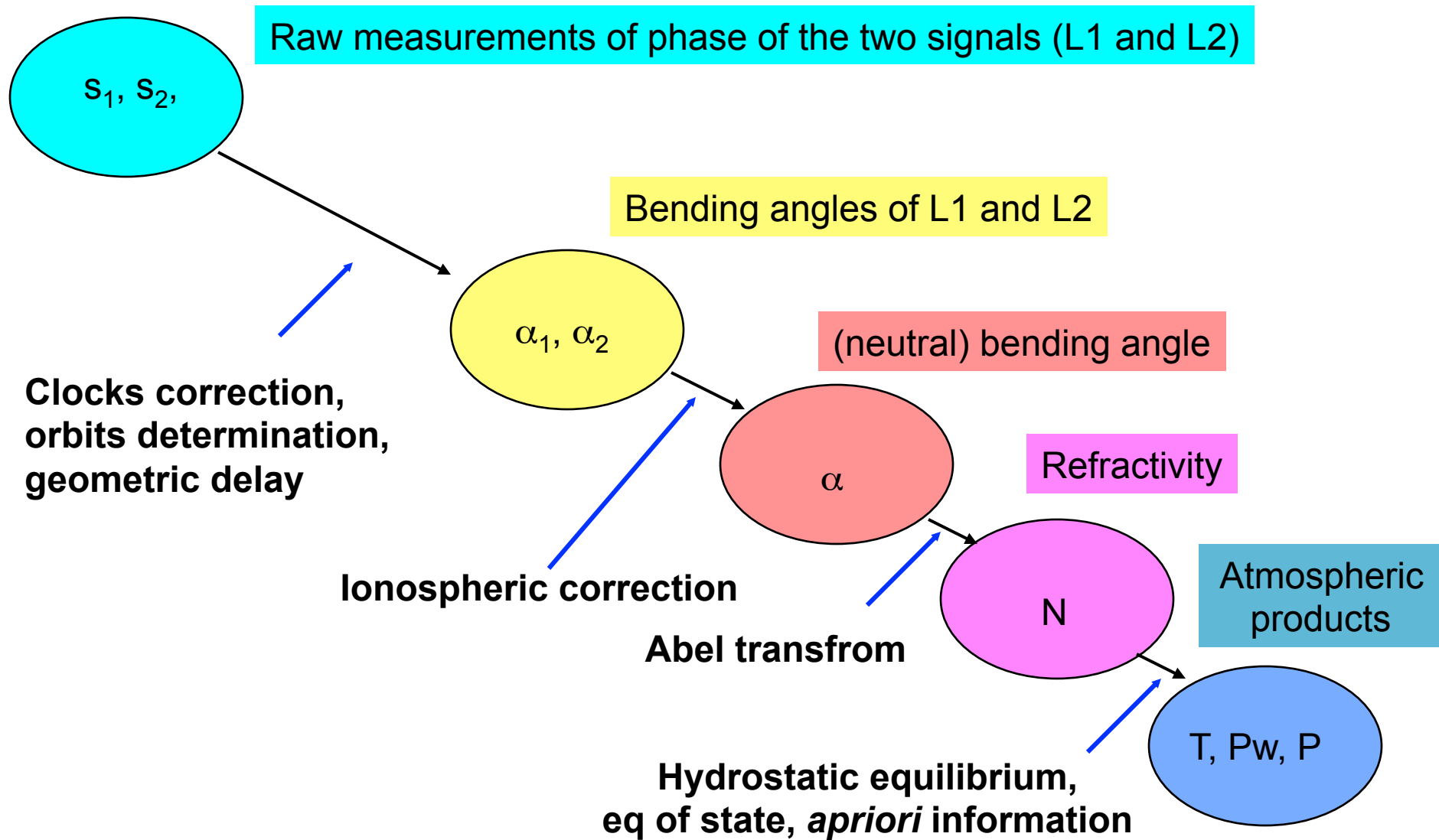
Assimilation of GPS RO observations in Operational Numerical Weather Prediction



Assimilation of RO data

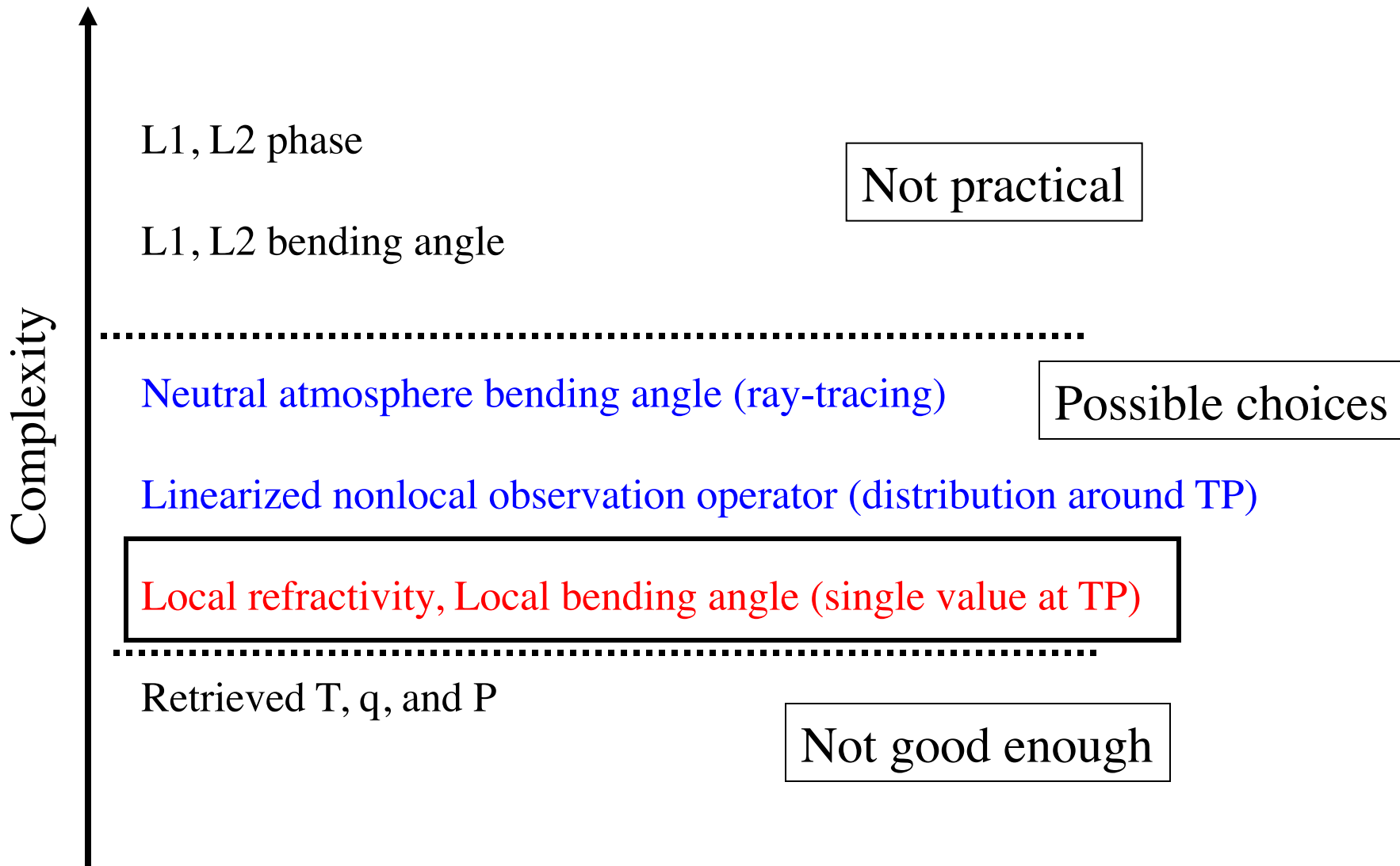
- The goal is to extract the maximum information content of the RO data, and to use this information to improve analysis of model state variables (u , v , T , q , P , ...etc) and consequent forecasts
- RO data (bending angles, refractivity, ...) are non-traditional meteorological observations (e.g., wind, temperature, moisture)
- The ray path limb-sounding characteristics are very different from the traditional meteorological measurements (e.g., radiosonde) or the nadir-viewing passive MW/IR measurements
- **Basic rule: the rawer the observation is, the better**

choice of 'observations'



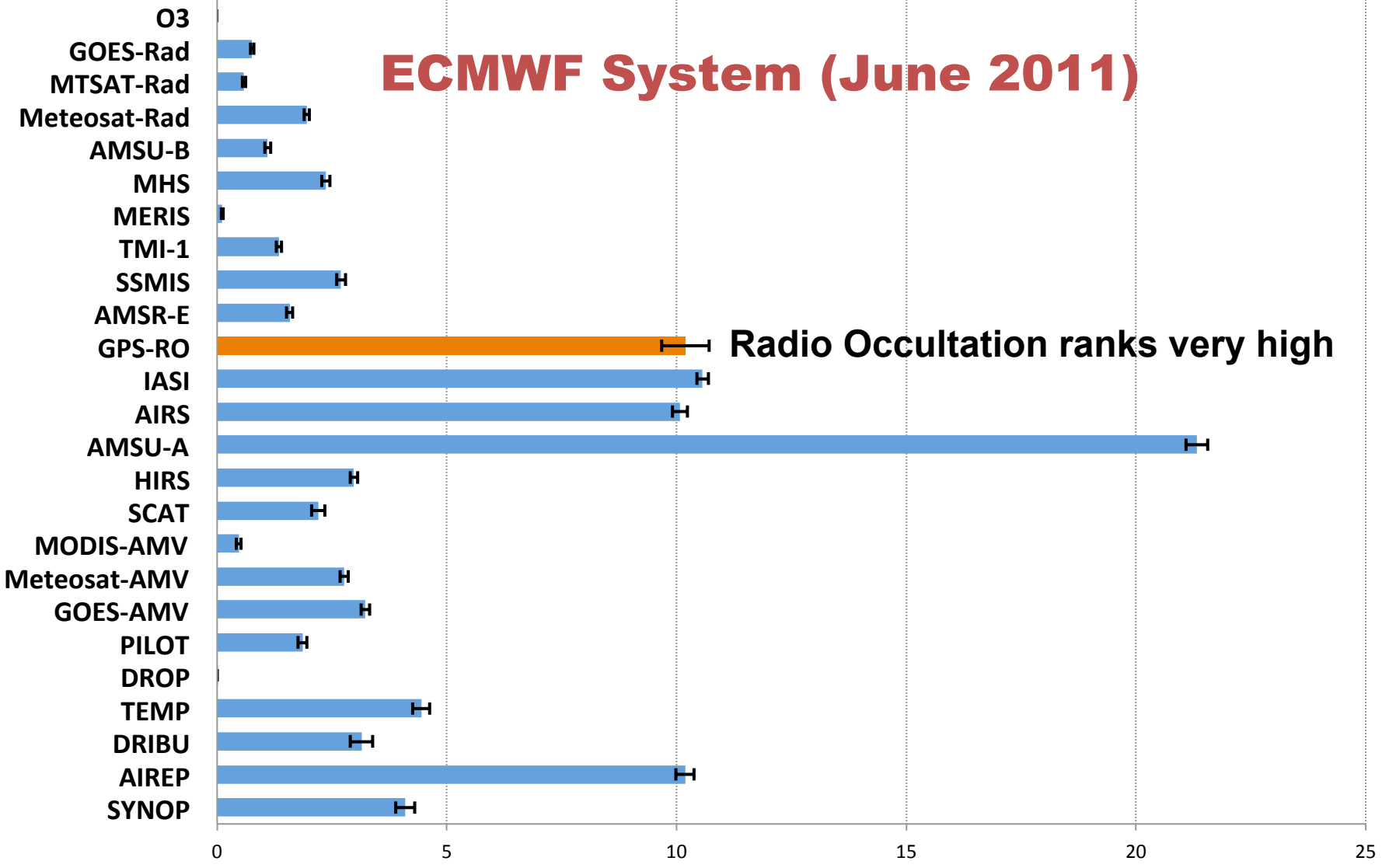


Choice of observation operators





ECMWF System (June 2011)

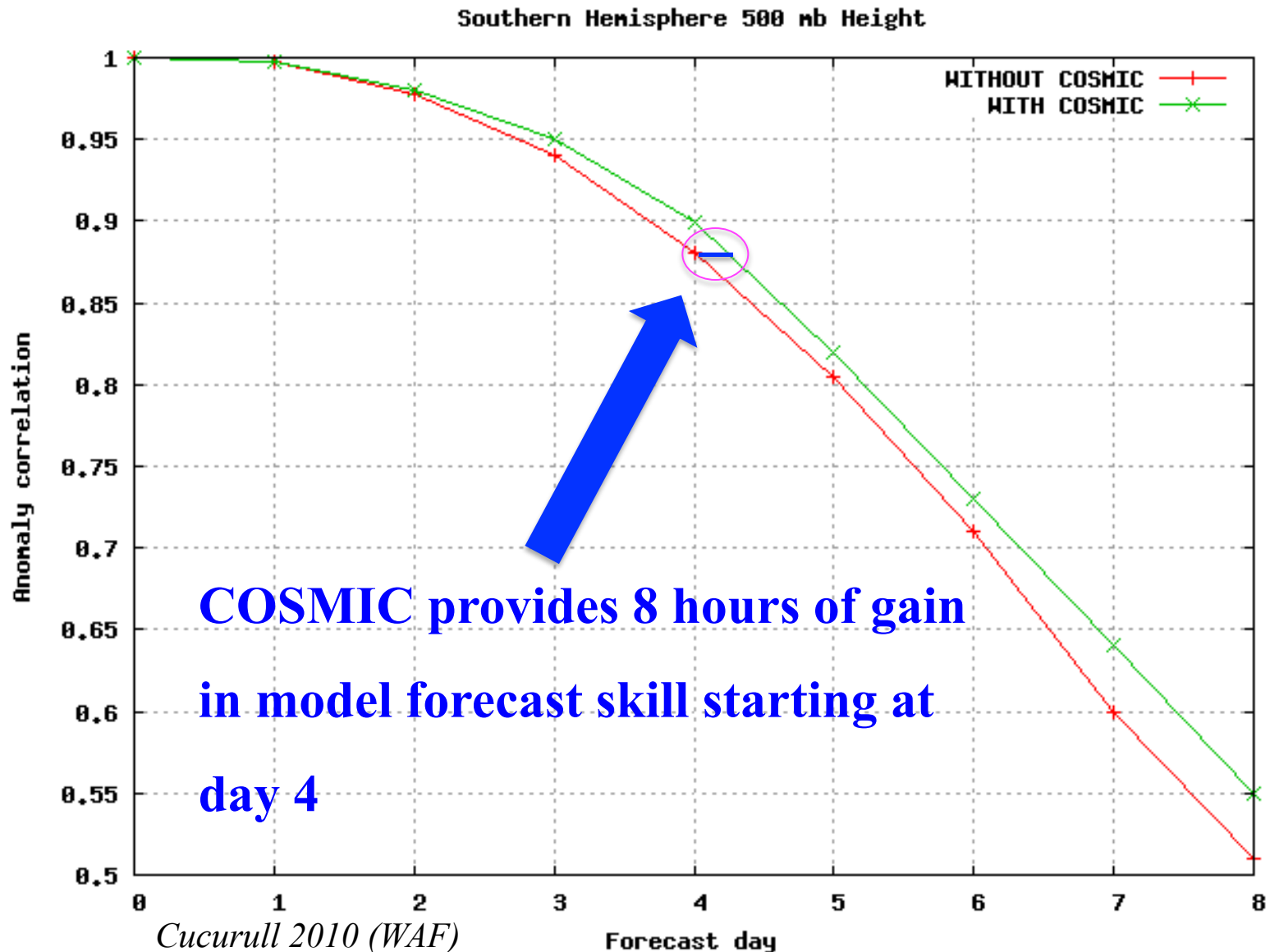


Radio Occultation ranks very high

Contribution in Forecast Error Reduction (%)



Impact with RO data at NCEP





Challenges

■ Non-spherical symmetry

- Remember: spherical symmetry is needed because otherwise we can't
 - » recover (α, a) from Doppler shift (α is a multi-evaluated function of a)
 - » Invert profiles of (α, a) to get profiles of (N, z)
- Horizontal gradients of refractivity will affect the retrieval of bending angles and refractivities

■ Turbulence, strong convection, noise

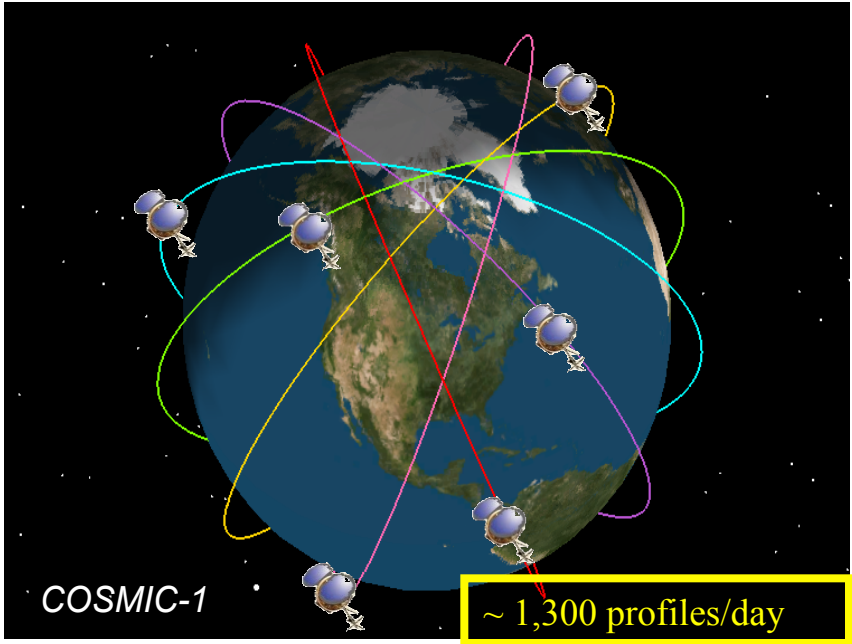
■ Super-refraction or ducting conditions

- Super-refraction occurs when the vertical gradient of N within a layer is so large (layer of super-refraction) than the ray never leaves the atmosphere (internal ray)
- This is not a problem for (α, a) – although other problems exist if bending angles affected by super-refraction conditions are assimilated
- It is a problem when retrieving $N(r_{TP})$ through Abel inversion (small negative bias)

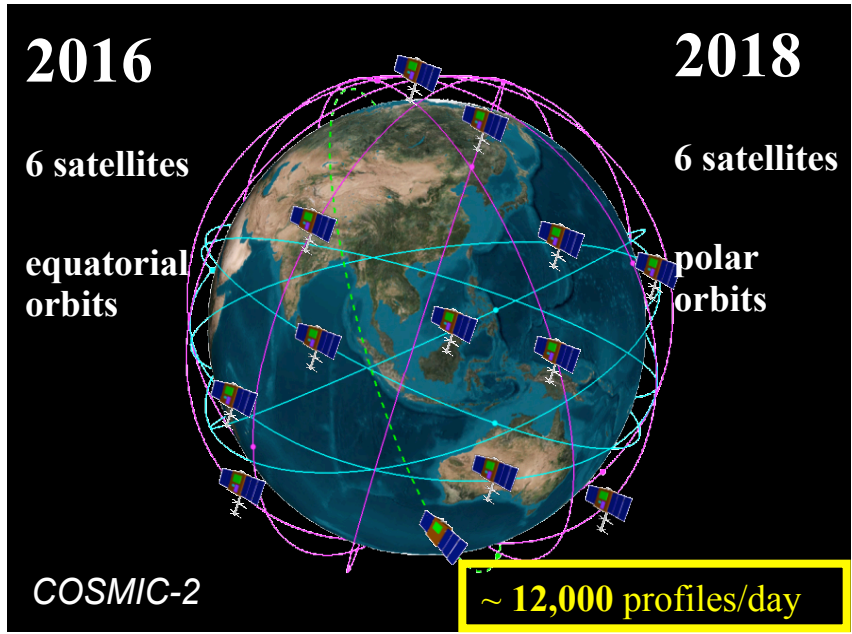
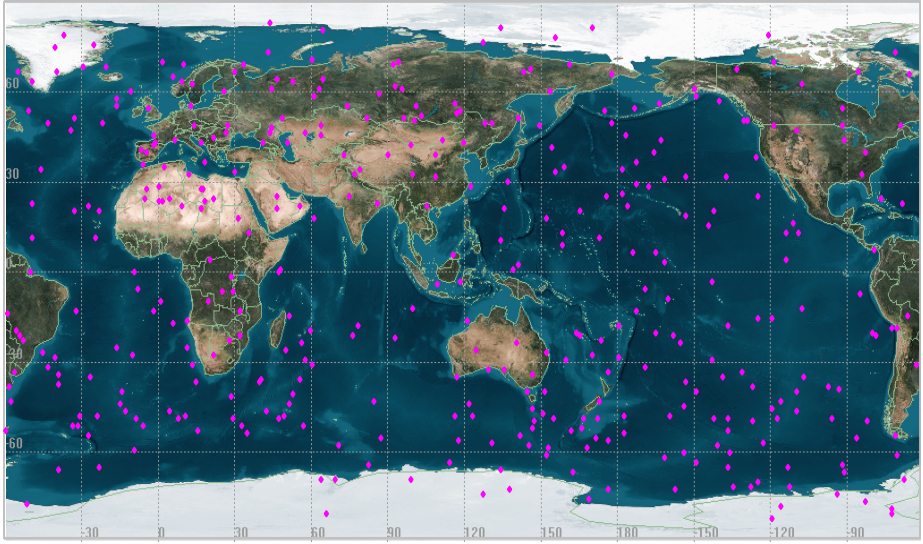


Summary and outlook

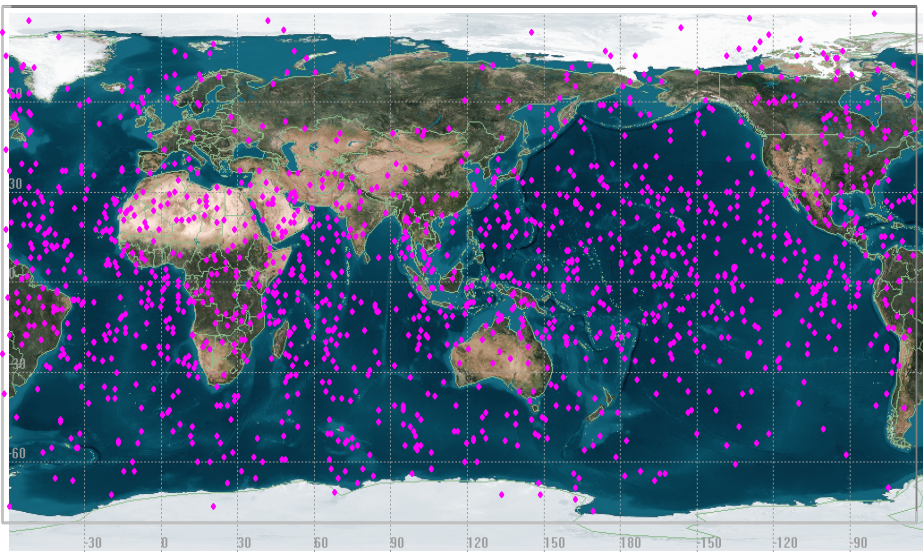
- NOAA/NCEP has been successfully assimilating GPS RO observations into its Global Data Assimilation System since 1 May 2007
- Results indicate that GPS RO observations contain unique information on the atmospheric state of the atmosphere (high accuracy, high vertical resolution, very small systematic difference vs. model compared to other satellite data, global coverage, all weather conditions, ...)
- Future work within the DA community is focusing on improving the forward operators for GPS RO measurements (capability to assimilate rawer products, account for horizontal gradients of refractivity, ...) & getting ready for the operational assimilation of COSMIC-2



COSMIC-1 Occultations – 3 Hrs Coverage



COSMIC-2 Occultations – 3 Hrs Coverage





That's it!

Thanks for your attention!!