GPS Radio Occultation Data Assimilation using GSI

Lidia Cucurull

NOAA/NWS/NCEP/EMC

GSI Community Tutorial, 21-23 August 2012

Topics covered during this talk

- Characteristics of the GPS RO technique
- Choices for a Forward Operator
- Assimilation of GPS RO observations within GSI

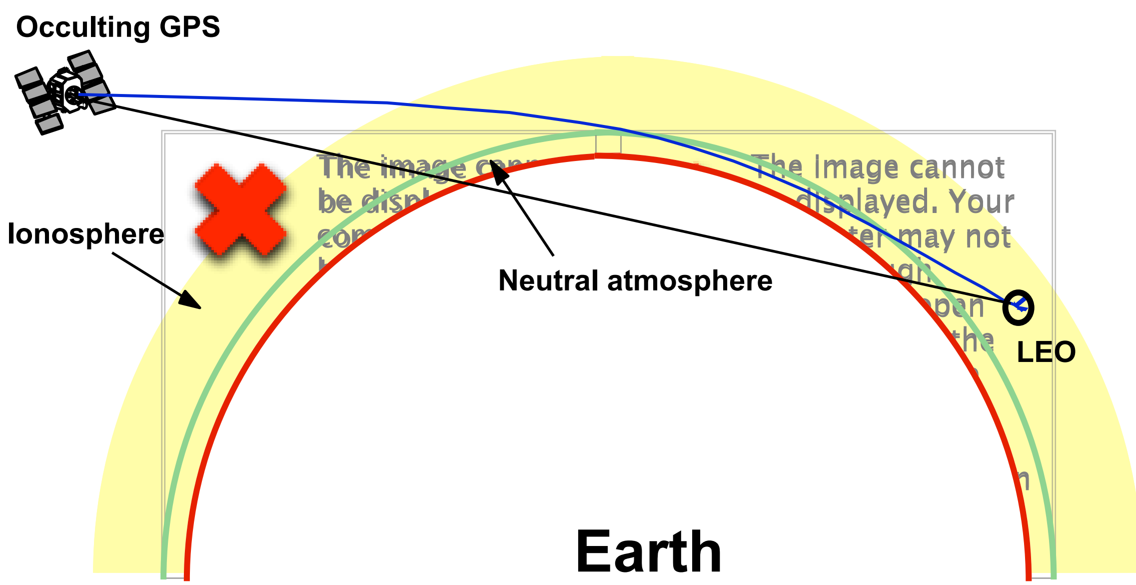
Characteristics of the GPS RO technique

Radio Occultation concept

■ An occultation occurs when a GPS (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).

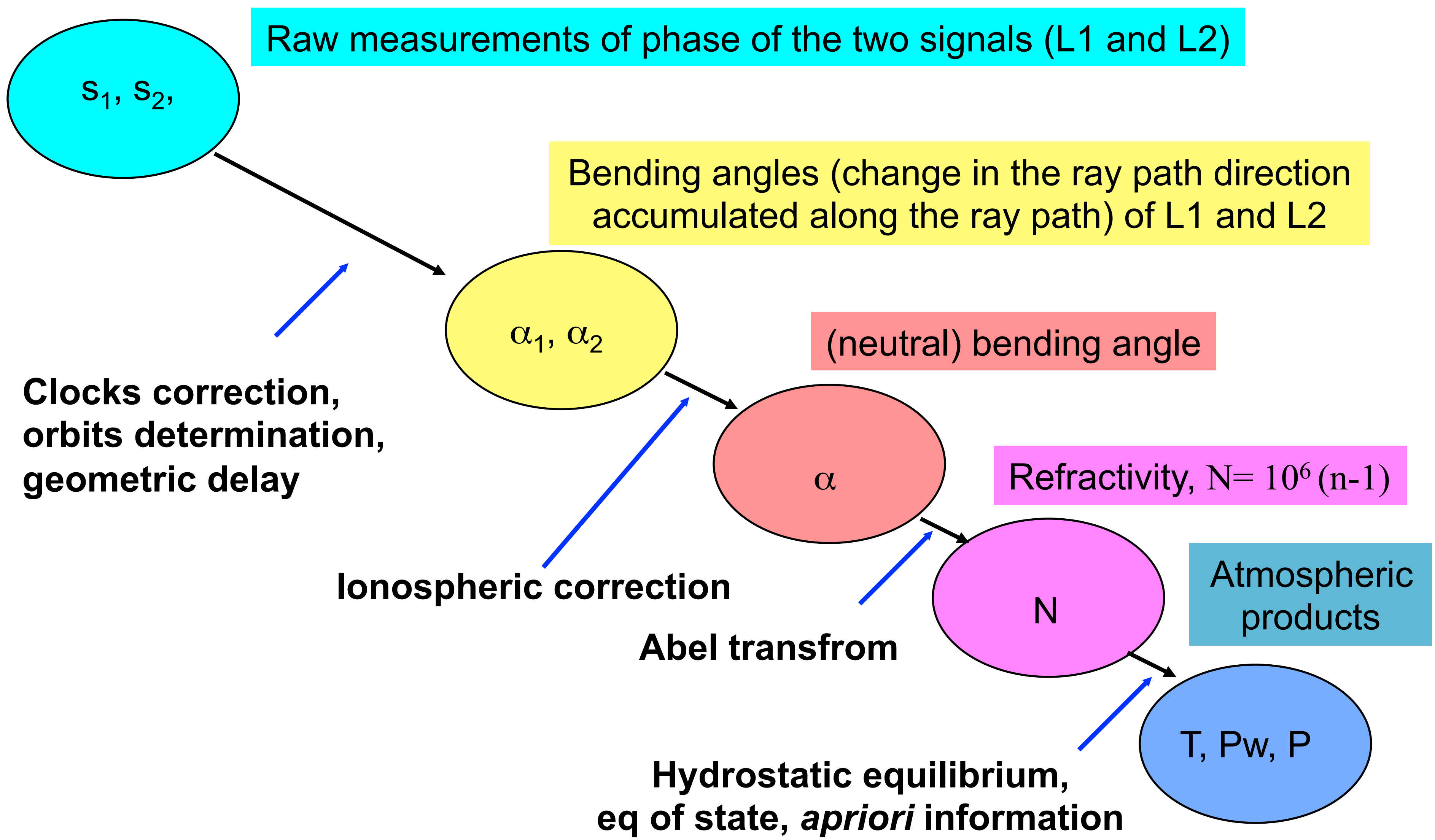
■ During an occultation (~ 3min) the ray path slices through the atmosphere



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

GPS transmits at two different frequencies: ~1.6 GHz (L1) and ~1.3 GHz (L2).

choice of ‘observations’



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.

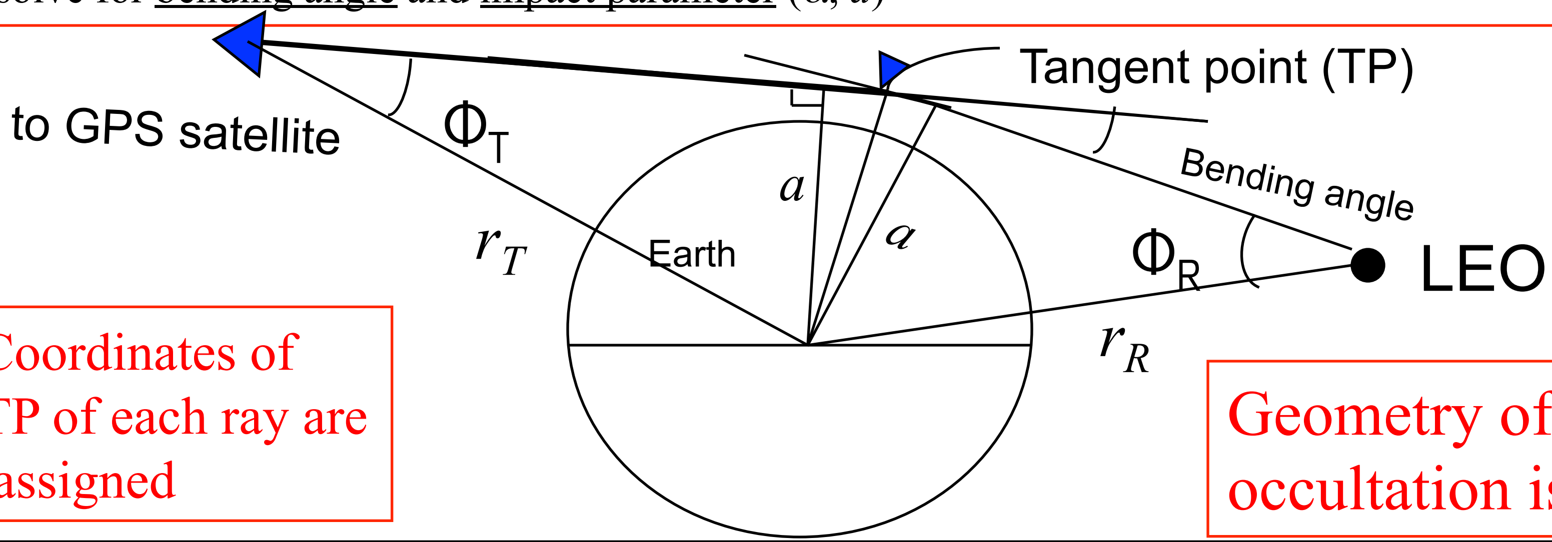
Bending angle (cont’d)

Global Spherical symmetry: ***n=n(r)*** ⇨ $\boxed{r\, n \sin(\Phi) = \text{ctant} = a}$ 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

$$\boxed{n_T\, r_T \sin(\Phi_T) = n_R\, r_R \sin(\Phi_R) = a}$$

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 (~$1/f^2$) 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 (~ 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)

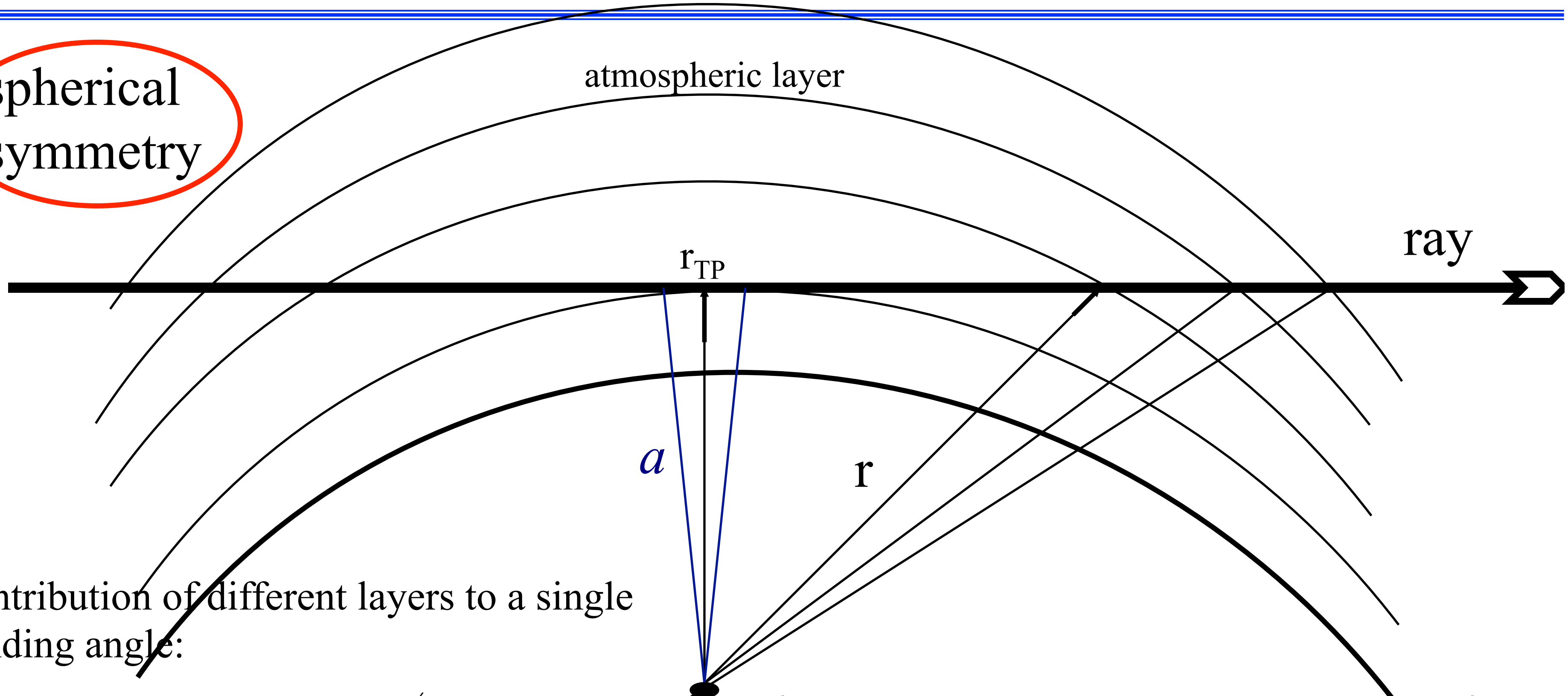
$$n(r_{TP}) = \exp\left[1/\Pi \int_{a_1}^{\infty} \frac{\alpha(a)}{(a^2 - a_1{}^2)^{1/2}}\, da\right]$$

$$n r_{TP} = a_1$$

- 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 (~ 3,000 rays)

Rationale for Abel inversion

spherical symmetry



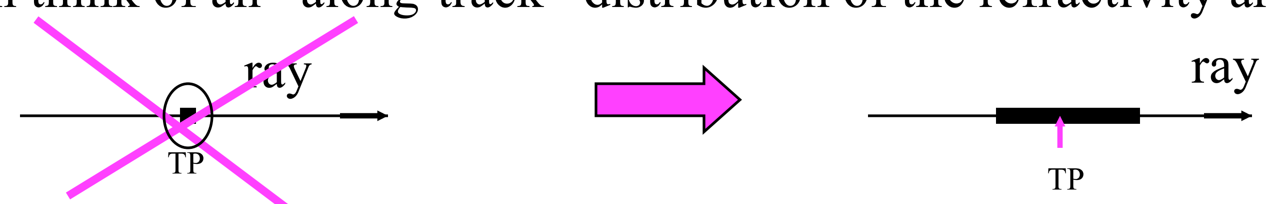
Contribution of different layers to a single bending angle:

$$\alpha(a) = 2a \int_{r_{TP}}^{\infty} \frac{d \ln n \big/ dr}{(n^2 r^2 - a^2)^{1/2}}\, dr \quad \Longrightarrow \quad \left\{ \begin{array}{l} n(r_{TP}) = \exp\left[1/\Pi \displaystyle\int_{a1}^{\infty} \frac{\alpha(a)}{(a^2 - a_1^{\,2})^{1/2}}\, da \right] \\ n r_{TP} = a_1 \end{array} \right\}$$

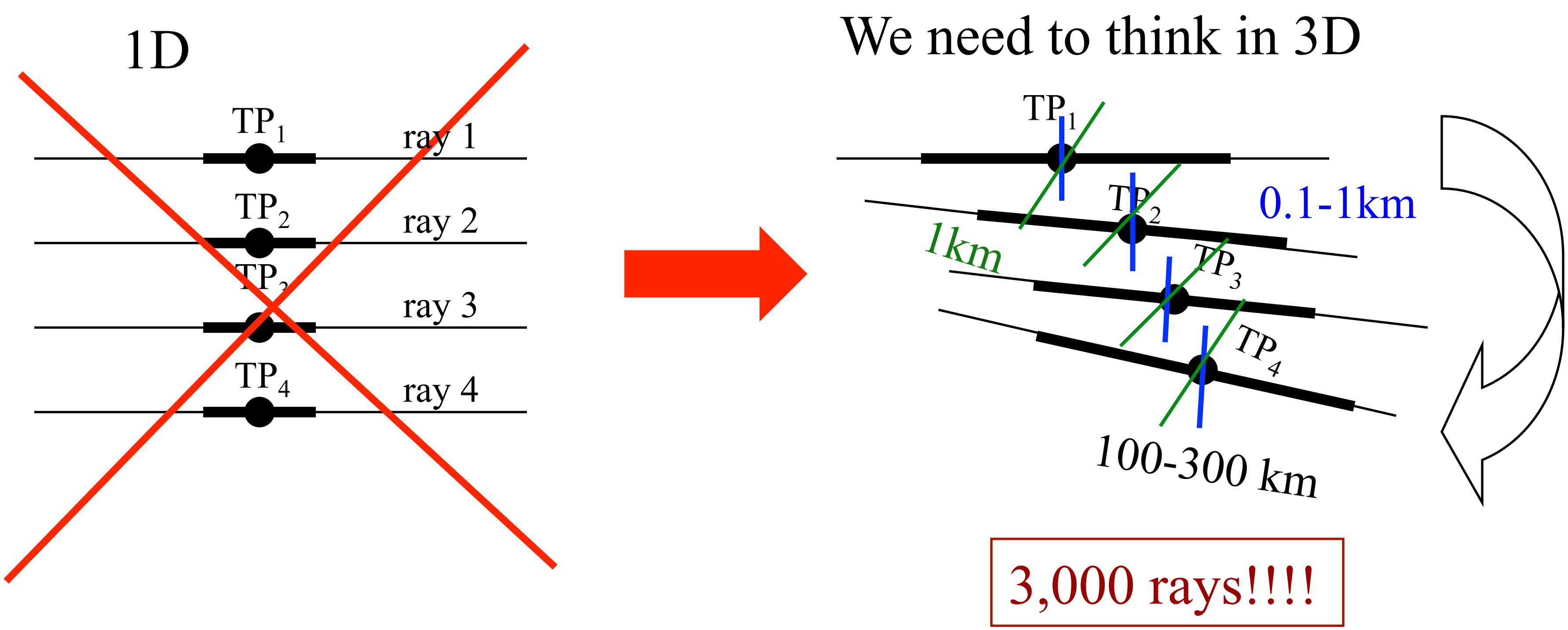
Larger contribution when larger gradient and closer to r_{TP} -> integral peaks at r_{TP}

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.



Geometry of a GPS RO profile



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:

$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{P_w}{T^2} - 40.3\times10^{6}\frac{n_e}{f^2} + O\left(\frac{1}{f^3}\right) + \cancel{1.4\times W_w + 0.6\times W_i}$$

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

height of tangent point

ionosphere

ionospheric term dominates and the rest of the contributions can be ignored. N directly corresponds to **electron density**

~ 70 km

"dry" ($P_w \sim 0$) atmosphere
P and T

the ionospheric correction removes the 1st order ionospheric term ($1/f^2$) because GPS has two frequencies.

neutral atmosphere
(hydrostratic term dominates)

~ 6 km

"wet" atmosphere (P,T, P_w)

"Dry" atmosphere: *P* and *T*

- Where the contribution of the water vapor to the refractivity can be neglected (T> 240K) 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 m=mean molecular mass of dry air, R=gas constant

- + 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

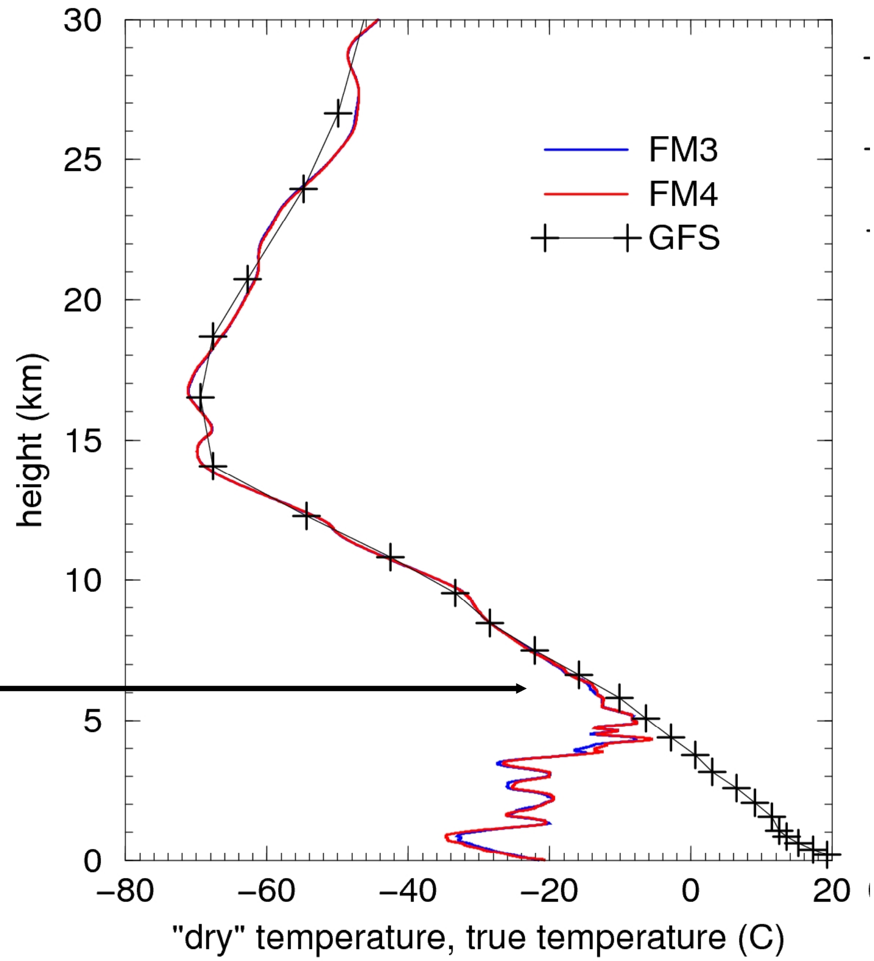
$$N = 77.6\frac{P}{T}$$

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)

Products from RO processing (UCAR/CDAAC)

Profiles of electron density

~ 80-800 km

Profiles of α (*a,lat,lon*) and *N* (*z,lat,lon*)

~ 0-60 km

"dry" profiles of *T* (*Z,lat,lon*) and *P* (*Z,lat,lon*)

1dvar "wet" profiles (GFS for real time and ECMWF for post-processing) of *T* (*Z,lat,lon*), *P* (*Z,lat,lon*), *q* (*Z,lat,lon*)

~ 0-40 km

All the products are computed in real-time (for operational weather prediction) and in post-processed mode (more accurate orbits, unified processing software, for climate studies).

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
- Inexpensive compared to other sensors

Choices for a Forward Operator

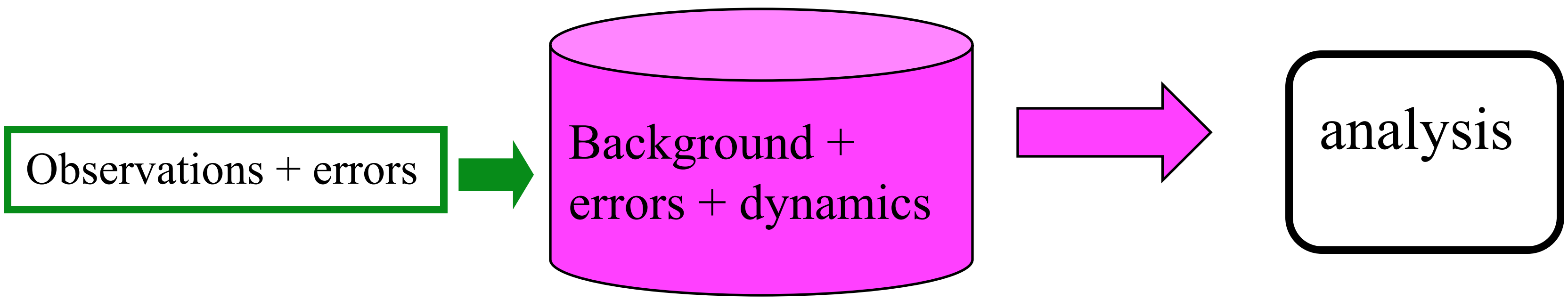
Assimilation of RO data

- 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**

Variational assimilation of RO data

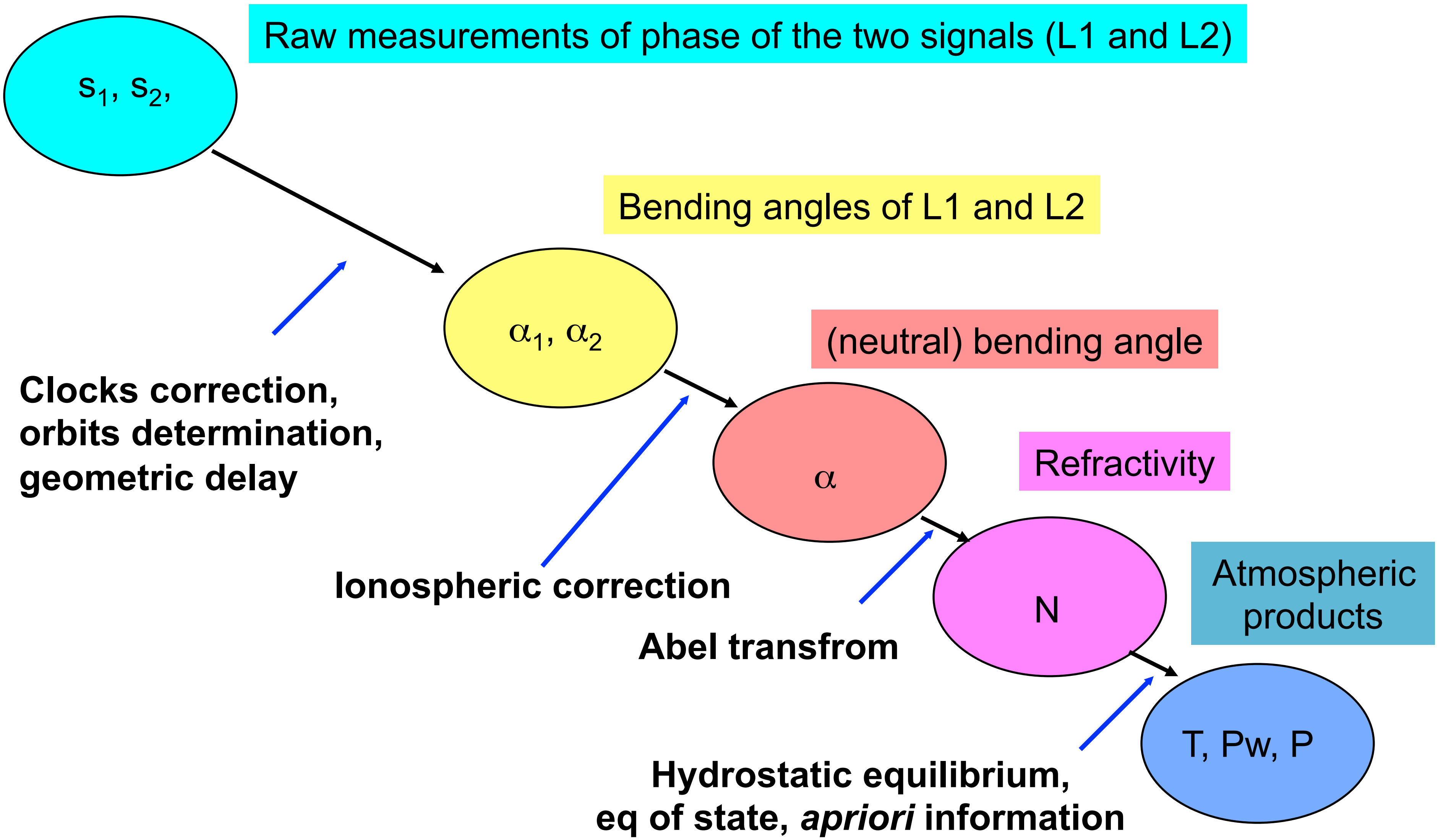
- In Variational Analysis (e.g. 3D- or 4D-VAR), we minimize the cost function:

$$J(\mathbf{x})=(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)+(\mathbf{y}_0-H(\mathbf{x}))^T(\mathbf{O}+\mathbf{F})^{-1}(\mathbf{y}_0-H(\mathbf{x})) + \mathbf{Jc}$$



- where $\mathbf{x}$ is the analysis vector, $\mathbf{x}_b$ is the background vector, $\mathbf{y}_0$ is the observation vector, **(O+F)** is the observation error covariance matrix (**F** is the representativeness error) and **B** is the background error covariance matrix.
- ***H*** is the forward model (observation operator) which transforms the model variables (e.g. *T, u, v, q* and *P*) to the observed variable (e.g. radiance, bending angle, refractivity, or other observables).
- We first need to decide what do we want to assimilate

choice of ‘observations’



Choice of observation operators

Complexity

L1, L2 phase

L1, L2 bending angle

Not practical

Neutral atmosphere bending angle (ray-tracing)

Linearized nonlocal observation operator (distribution around TP)

Local refractivity, Local bending angle (single value at TP)

Possible choices

Retrieved T, q, and P

Not good enough

Assimilation of GPS RO observations within GSI

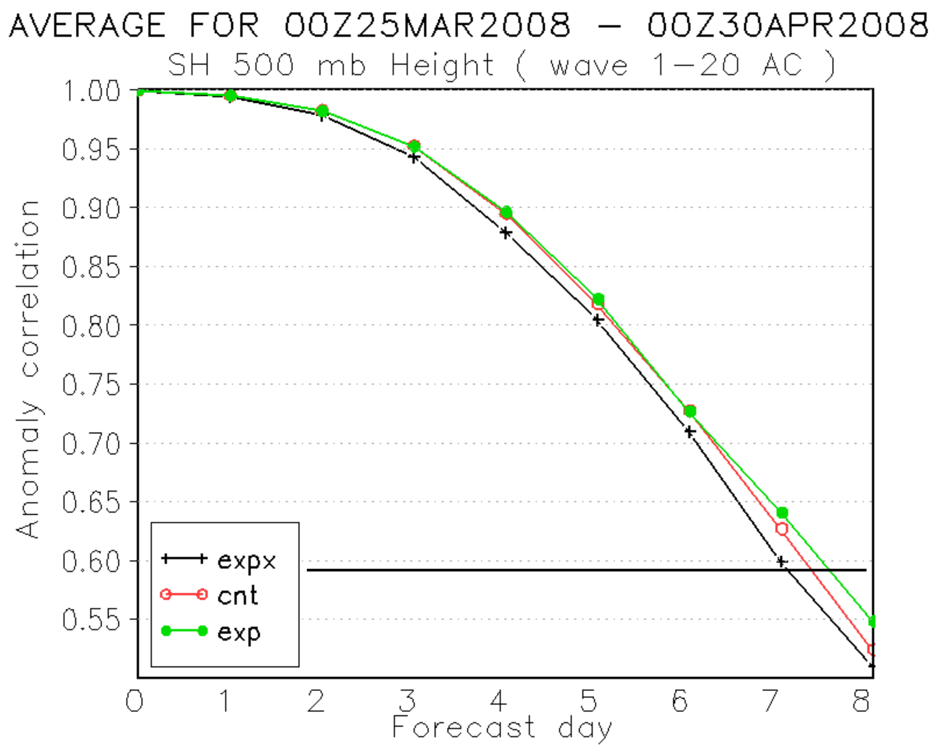
Forward Model for refractivity

$$N = 77.60\frac{P_d}{T} + 70.4\frac{P_w}{T} + 3.739\times 10^{-5}\frac{P_w}{T^2}$$

- (1) Geometric height of observation is converted to geopotential height.
- (2) Observation is located between two model levels.
- (3) Model variables of pressure, (virtual) temperature and specific humidity are interpolated to observation location.
- (4) Model refractivity is computed from the interpolated values.
- The assimilation algorithm produces increments of
  - surface pressure
  - water vapor of levels surrounding the observation
  - (virtual) temperature of levels surrounding the observation and all levels below the observation (ie. an observation is allowed to modify its position in the vertical)
- Each observation is treated independently (we account for the drift of the tangent point within a profile)
- QC & obs error structure have tuned in GSI for GFS and NAM up to 30 km.

Impact with COSMIC

- AC scores (the higher the better) as a function of the forecast day for the 500 mb gph in Southern Hemisphere
- 40-day experiments:
  - **expx (NO COSMIC)**
  - **cnt (old RO assimilation code - with COSMIC)**
  - **exp (ops, updated RO assimilation code - with COSMIC)**



COSMIC provides 8 hours of gain in model forecast skill starting at day 4 !!!

Forward Model for refractivity (cont'd)

- Relatively *easy* to implement: interpolation of modeled pressure, water vapor and temperature values from the model grid points to the location of the observation. [Dependence of the geometric height of model levels on the model variables needs to be taken into account as well.]
- However, the resulting modeled refractivity would only match the *retrieved* refractivity (assuming perfect model and retrieved refractivities) if the atmosphere were strictly spherically symmetric.
- Ignores the existence of horizontal gradients of refractivity in the atmosphere (global spherical symmetry approximation).
- Some climatology or auxiliary information is necessary to retrieve refractivities from bending angle profiles.
- Formally, under super-refraction conditions, conversion of bending angles to refractivities results in a negative bias inside and below the super-refraction layer.

Bending angle observations

- Make use of approximation of local, rather than global, spherical symmetry around the ray path tangent height.
- Not weighted with climatology information.
- Do not suffer from the formal negative bias in the lower troposphere caused by super-refraction conditions.
- Measurement errors are vertically less correlated than refractivity profiles because there is no use of an Abel transform.
- Retrieved earlier than refractivity in the processing of the GPS RO observations, which makes it more attractive from a data assimilation point of view.
- However, their use in data assimilation algorithms is more challenging due to the large variability of the vertical gradients of refractivity.
  - Lower vertical resolution of NWP models compared to the GPS RO observations.
  - Ionospheric-residual noise in the mid-upper stratosphere due to the ionospheric compensation.

Bending angle observations (cont'd)

- A forward operator to assimilate bending angle observations has been developed, implemented and tested at NCEP. Quality control procedures and observation error characterization have been tuned accordingly.
- An earlier version of this forward operator was available at NCEP in 2006 (*Cucurull et al. 2007*). The updated bending angle code has many improvements over the earlier version.
- Introduction to NBAM (NCEP Bending Angle Model).

Forward Model for bending angle: NBAM

$$\alpha(a) = -2a\int_a^{\infty} \frac{d\ln n/dx}{(x^2 - a^2)^{1/2}}\,dx$$

$$(x = nr)$$

- The standard bending angle forward operator is singular at the lower limit of the integral and under super-refraction conditions.
- NBAM avoids the numerical singularity by evaluating the integral in a new grid.
- The integral is then evaluated in an equally spaced grid, so the trapezoidal rule can be easily and <u>accurately</u> applied.
- NBAM does not require the refractivity to decay exponentially with height (only above the model top).
- NBAM makes use of a quadratic interpolator that preserves continuity of the refractivity values and their derivatives in both the model model vertical grid and the new integration grid.
- QC and observation errors have been tuned similarly to refractivity.
- As all the implemented FO at NCEP, the drift of the tangent point is taken into account (*Folsche et al*., 2011; *Cucurull*, 2011; *Healy*, 2011, *pers. comm*.)

NBAM characteristics

- Enables the assimilation of GPS RO observations up to 50 km – QC procedures and observation error structures have been tuned up to this height.
- Algorithms to include the compressibility factors in the computation of the geopotential heights have been implemented to compute a more accurate forward operator for GPS RO (following *Aparicio et al. 2009*).
- Both refractivity and bending angle codes have the option to use the compressibility factors.
- When the compressibility factors are used, the GPS RO forward operators use a more accurate set of refractive indices (Rüeger coefficients).
- The use of compressibility factors will affect the assimilation of GPS RO observations as well as all the observations that use geopotential heights. In fact, any subroutine within the assimilation code that makes use of the geopotential heights will be affected by the changes.
- Details on the design and implementation of NBAM can be found in *Cucurull et al. 2012, submitted to JGR.*
- <u>Since NBAM reverses the procedure of assimilating refractivities, it still suffers from errors induced by deviations from spherical symmetry.</u>

Submitting a job with GSI

Select type of 'observation' in running script (or namelist)

```
&OBS_INPUT
………
dfile(11)='gpsrobufr', dtype(11)='$gps_dtype',   dplat(11)=' ',  dsis(11)='gps',     \
      dval(11)=0.0, dthin(11)=0, dsfcalc(11)=0,
………
$OBSINPUT
/
```

where $gps_dtype="gps_ref" for refractivity and "gps_bnd" for bending angle

```
&SETUP
 miter=2,niter(1)=100,niter(2)=150,
 niter_no_qc(1)=50,niter_no_qc(2)=0,
 write_diag(1)=.true.,write_diag(2)=.false.,write_diag(3)=.true.,
 qoption=2,
 gencode=$IGEN,factqmin=5.0,factqmax=5.0,deltim=$DELTIM,
 ndat=67,iguess=-1,
 oneobtest=.false.,retrieval=.false.,l_foto=.false.,
 use_pbl=.false.,use_compress=.true.,nsig_ext=12,gpstop=50.,
 use_gfs_nemsio=.false.,
 $SETUP
/
```

Only meaningful for bending angles

Defines the use of Bevis or Rüeger coefficients

global_convinfo.txt

Select what missions to assimilate (iuse=1) or monitor (iuse=-1)

!otype	type	sub	iuse	twindow	numgrp	ngroup	nmiter	gross	ermax	ermin	var_b	var_pg	ithin	rmesh	pmesh	npred	
gps	004	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**METOP-A**
gps	041	0	-1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**CHAMP**
gps	722	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**GRACE-A**
gps	723	0	-1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**GRACE-B**
gps	740	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	
gps	741	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	
gps	742	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**COSMIC**
gps	743	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	
gps	744	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	
gps	745	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	
gps	820	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**SAC-C (global)**
gps	042	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**TerraSAR-X (global)**
gps	786	0	1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**C/NOFS (global)**
gps	421	0	-1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**OCEANSAT-2**
gps	003	0	-1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**METOP-B**
gps	821	0	-1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**SAC-D/Aquarius**
gps	440	0	-1	3.0	0	0	0	10.0	10.0	1.0	10.0	0.000000	0	0.	0.	0	**Megha-Tropiques**

read_obs.f90

- Reads refractivity/bending angle observations from bufr files (~ 300 values are available in each profile of refractivity and bending angle)
- Applies initial quality control (as specified by provider)
- Performs ‘sanity’ QC (correct date, acceptable values for variables, etc)
- Assigns initial error to the observations
- Stores information and prints out basic output (# profiles/mission, total number of good/bad observations, refractivity/bending angle selection, etc)

setuprhsall.f90

```
!          Set up GPS local refractivity data
         else if(ditype(is) == 'gps')then
           if(obstype=='gps_ref')then
             call setupref(lunin,mype,awork(1,i_gps),nele,nobs,toss_gps_sub,is,init_pass,last_pass)

!            Set up GPS local bending angle data
           else if(obstype=='gps_bnd')then
             call setupbend(lunin,mype,awork(1,i_gps),nele,nobs,toss_gps_sub,is,init_pass,last_pass)
           end if
         end if
```

```
! Finalize qc and accumulate statistics for GPSRO data
  call genstats_gps(bwork,awork(1,i_gps),toss_gps_sub,conv_diagsave,mype)
```

Forward operator for *N(z)*

- Computed in setupref.f90 Pressure at the location of the observations
  - Simulate observed refractivity (local, 3-term expression, Bevis/Rüeger coefficients)
  - Tune for representativeness errors
  - Apply quality control procedures
  - Observations above 30 km are rejected
  - Calculate and store the Jacobians for minimization
  - Store diagnostic information
  - <u>Parameters have been tuned for NCEP's global GFS/GSI and regional NAM only</u>

Forward operator for $\alpha(a)$

- Computed in setupbend.f90
  - Refractivity index-radius product
  - Simulate observed bending angle (calls other subroutines to compute Lagrangians interpolators)
  - Tune for representativeness errors
  - Apply quality control procedures
  - Observations above 50 km are rejected
  - Calculate and store the Jacobians for minimization
  - Store diagnostic information
  - Parameters have been tuned for NCEP's global GFS/GSI only
- Operational configuration in NCEP's Global Data Assimilation System (hybrid GSI).

genstats.f90

- Unifies QC procedures among tasks – it might modify the QC of the observations
- Adjusts observation error ratio based on "superobs" factor
- Accumulates statistics
- If requested, writes information to diagnostic file

intgps.f90 & stpgps.f90

- Drive the algorithms for GPS RO component during the minimization
- Nothing special, similar to the the minimization routines for other observations
- Diagnostic information for GPS RO observations is stored in unit 212

References of GPSRO in GSI

- L. Cucurull, J. C. Derber, and R. J. Purser 2012: A bending angle forward operator for GPS Radio Occultation measurements, JGR, *in review.*
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