An Overview on GNSS Radio Occultation

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Outline

- Basic concepts
- Physic of atmosphere
- Ground-based GNSS atmosphere 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 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!


**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.

\[ n = \frac{c}{v} \quad \Rightarrow \quad N = (n - 1) \times 10^6 \quad \text{Refractivity index!} \]

- Snell's law of refraction

\[ n_1 \sin i_1 = n_2 \sin i_2 \]
Ground base GNSS Atmosphere Sounding

Earth's centre

Atmosphere
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

\[
\Delta \phi = \int_{G}^{R} n(s)ds - S = (n(s) - 1)10^6 \quad \Rightarrow \quad ZTD(T, P, P_w)
\]

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

STATION: DRUM, 28 days, bias corrected to 21/4

Sample data:
- Sum of observations: 1816
- RMS: 0.77356 (0.77358)
- Bias: 3.50235 (3.50235)
- SD: 0.79924 (0.79824)
- Correlation: 0.975741 (0.975741)
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

Atmosphere

Earth

Atmosphere

GNSS

LEO

r_0

α

n

a
Radio Occultation Background

- Radio occultation (RO) measurements have been used to study planetary atmospheres, such as Mars and Venus, since the 1960’s. It’s 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 = 1.2276 GHz (~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.
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 $\phi(i), \phi(i+1), \ldots$ at the two GPS frequencies,
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.
Calculating 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.
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
\[ a = n_L r_L \sin(\phi_L) = n_R r_R \sin(\phi_R) = \text{const.} \]
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:

\[ a = n_L r_L \sin(\phi_L) = \]
\[ = n_R r_R \sin(\phi_R) = \text{const}. \]

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).
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 as a pair simultaneously from the Doppler.
Processing of GNSS-RO observations

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

\[
(f_D)_i = \frac{1}{f_i} \frac{d\Delta\phi_i}{dt}, \quad i = 1, 2
\]

- Calculate zenith angle \( \phi_G \)

- 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:

\[
v_{L_t} - v_{G_t} = \frac{d\Delta\phi_i}{dt} + v_{L_s} - v_{L_s}
\]

\[
-v_L \cos(\phi_L - \beta_L) - v_G \cos(\phi_G + \beta_G) = \frac{d\Delta\phi_i}{dt} - v_L \cos(\psi_L - \beta_L) - v_G \cos(\psi_G + \beta_G)
\]
Processing of GNSS-RO observations
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

\[ \delta_G = \phi_G - \psi_G \quad \delta_L = \phi_L - \psi_L \]

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

\[ \alpha_i = \delta_{G,i} + \delta_{L,i}, \quad i = 1, 2 \quad a_i = r_L \sin \phi_{L,i}, \quad i = 1, 2 \]
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 $t$)
    \[
    \phi_3(t) = \frac{f_1^2 \phi_1(t) - f_2^2 \phi_2(t)}{f_1^2 - f_2^2}
    \]
  - Linear Ionosphere free combination of bending angles at two frequencies L1 and L2 (at the same impact factor $a$)
    \[
    \alpha_3(t) = \frac{f_1^2 \alpha_1(a) - f_2^2 \alpha_2(a)}{f_1^2 - f_2^2}
    \]
Ionosphere correction

Residual Atmospheric Phase

Phase [m] vs. Time [s]

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 \(\text{~}50-90\ \text{km}\), 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):

\[ \alpha(a) = -2a \int_{a}^{\infty} \frac{d \ln n}{dx} \frac{1}{\sqrt{x^2 - a^2}} \, dx \]

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)
  \[ \alpha(a) = -2a \int_a^\infty \frac{d \ln n}{dx} \, dx \]
Deriving the refractive index profiles (onion)
Deriving the refractive index profiles

\[
\frac{\alpha_i(a)}{2a_i} = -\int_a^\infty \frac{d \ln n}{\sqrt{x^2 - a^2}} \, dx
\]

\[
\frac{\alpha_i(a)}{2a_i} \approx -\sum_{k=1}^i \nabla n_k \frac{\Delta x_k}{\sqrt{x_k^2 - a_i^2}}
\]

\[
\begin{pmatrix}
\frac{\alpha_1}{2a_1} \\
\vdots \\
\frac{\alpha_i}{2a_i}
\end{pmatrix}
\approx
\begin{pmatrix}
A_{11} & \cdots & \cdots \\
\vdots & \ddots & \vdots \\
A_{i1} & \cdots & A_{ik}
\end{pmatrix}
\begin{pmatrix}
\nabla n_1 \\
\vdots \\
\nabla n_k
\end{pmatrix}
\]

\[
A_{ik} = \frac{\Delta x_k}{\sqrt{x_k^2 - a_i^2}} = \ln \left| x_{k-1} + \sqrt{x_{k-1}^2 - x_i^2} \right| - \ln \left| x_k + \sqrt{x_k^2 - x_i^2} \right|
\]
Deriving the refractive index profiles

\[ l = A \nabla n \quad \rightarrow \quad \nabla n = A^{-1}l \quad \rightarrow \quad n = ? \]

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,

\[ n = \nabla n \Delta x \]

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

\[ N_i(h_i) = N_0 + \sum_{i=1}^{k} n_i \cdot 10^6, \quad h_i = \frac{a_i}{n(a_i)} - r_c = r - r_c \]

\( h_i \) 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:

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

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 \( T > 240 \)K
- 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

Ionosphere term dominates
The rest can be neglected, and $N$ directly corresponds to electron density

Neutral atmosphere (dry term dominates)

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

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,

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

- $+ \text{ equation of state:}$

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

$M$: mean molecular mass
$R$: gas constant

- $+ \text{ hydrostatic equilibrium:}$

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

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!
We can derive the pressure by integrating the hydrostatic equation:

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

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 \(~5\text{-}25\text{km}\).
Retrieval of atmospheric key parameters

GPS/MET Temperature Sounding

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

Height of TP

~70 km

Neutral atmosphere (dry term dominates)

\[ P_w \approx 0, \quad P,T \]

~7 km

Neutral atmosphere (hydrostatic term dominates)

\[ T,P,P_w \]

Ionosphere term dominates

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

Ionospheric corr. is necessary
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!)

\[ N(z) = (n(z) - 1)10^6 = 77.6 \frac{P(z)}{T(z)} + 3.73 \times 10^5 \frac{P_w(z)}{T^2(z)} \]

The simplest formulation, but it is widely used in GNSS-RO.
Moisture atmosphere: $P$, $P_w$ 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).
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).

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

Source: Dr. Lidia Cucurull (NOAA)
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.
Atmospheric ducting: if the refractive index gradient exceeds a critical value the signal is lost power!

\[-\frac{dn}{dr} \geq \frac{1}{R_e}\]
Deriving the refractive index profiles

Neutral atmosphere (dry term dominates)

\[ P_w \approx 0, \quad P, T \]

Neutral atmosphere (hydrostatic term dominates)

\[ T, P, P_w \]

Ionosphere term dominates

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

~70 km

~7 km

Ionospheric corr. is necessary
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

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

Profile of electron density
~70 km
Neutral atmosphere (dry term dominates)
Statistical optimization

Profile of pressure and temp.
~7 km
Neutral atmosphere (hydrostatic term dominates)

Profile of \( T, P, P_w \) with info. from model or a-priori data
GNSS-RO Data Processing

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

\[ S_1, S_2, \]

Bending angles of L1 and L2

\[ \alpha_1, \alpha_2 \]

Clocks correction, orbits determination, geometric delay

Ionospheric correction

Abel transform

Hydrostatic equilibrium, eq of state, apriori information

(neutral) bending angle

Refractivity

Atmospheric products

\[ T, P_w, P \]
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** (Constellation 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

ECMWF Data Coverage (All obs DA) - GPSRO
15/APR/2009; 00 UTC
Total number of obs = 634
GNSS-RO CHAMP Results
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).
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
• **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 \(~7-25\) km; better than \(~2\) mb rms error (\(~0.5\) mb bias) in \(P_w\)
GNSS-RO precision (comparison FM3-FM4)

Number of pairs

0.2% (N) precision between 10-20 km

\[ \sim 0.05 K \text{ in temperature!} \]

Schreiner et al., 2007
GNSS-RO Resolution
**GNSS-RO Resolution (Vertical)**

- Bending angle is created by the contribution of different atmosphere layers (vertical gradient of refractivity).

- For each TP, the maximum layer interval which contributes 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
• 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!
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. Horiz. resolution improved deploying more LEOs), trading off temp. resolution vs. spatial resolution.
- **Density or number of rays** (deploying more LEOs)

\[ \begin{align*}
L & \sim 100 - 300 \text{ km} \\
Z & \sim 0.1 - 1 \text{ km} \\
D & \sim 1 \text{ km}
\end{align*} \]
GNSS-RO Data Assimilation (DA) in ECMWF model
• 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)

Clocks correction, orbits determination, geometric delay

Bending angles of L1 and L2

(neutral) bending angle

Refraction

Ionospheric correction

Abel transform

Hydrostatic equilibrium, eq of state, apriori information

T, Pw, P

Atmospheric products
Choice of observations in DA

- **L1 and L2 carrier phase**
  - Not practical

- **L1 and L2 bending angles**
  - Not good enough

- **Neutral Atmospheric bending angle (ray tracing)**
  - Not practical

- **Linearized non-local observation (distribution around TP)**
  - Possible choices

- **Local refractivity, bending angle (single value at TP)**
  - Retrieved atmospheric key parameters

  \[ T, P, P_w \]
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