GPS radio occultation lecture 2
Impact/ some applications

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NWP SAF lecture 2, March 4, 2020

http://www.romsaf.org/

• See presentations at:
  
  
  – [https://cpaess.ucar.edu/cosmic-10th-data-users-workshop-irowg-6-thursday-agenda](https://cpaess.ucar.edu/cosmic-10th-data-users-workshop-irowg-6-thursday-agenda)
  
Outline

**Aim:** provide an overview of some GPS-RO applications

Recap from lecture 1
- GPS-RO information content, key characteristics core region, etc.

*As you might expect, many applications are related to the main GPS-RO measurement characteristics in the “core region”.*

- GPS-RO impact in NWP systems.
- Key observation climate reanalyses.
- Climate monitoring.
- The Future(?) Retrieving heavy precipitation, LEO/LEO
- Summary

- **EMAIL me** for space weather/surface pressure information/PBL/radiosonde bias correction.
Recap

• All satellite measurements have strengths and weaknesses. The aim is to construct a robust *global observing system* with a good balance of the different types, given their information content.

• GPS-RO measurements are useful because they complement satellite radiances.
  – Assimilation without bias correction
  – Good vertical resolution

• The information content is largest in the “core region”, between 7-35 km, *and I will demonstrate* we see a large NWP impact on upper-tropospheric and lower/middle stratospheric temperatures.
GPS-RO and IASI: 1DVAR simulations

Collard and Healy 2003, QJRMS:

Expected retrieval error:

Power to resolve a peak-shaped error in background: Averaging Kernel.
NWP impact of GPS-RO in recent experiments
Observing system experiments for main observing systems (Tech memo 839)
https://www.ecmwf.int/en/elibrary/18859-global-observing-system-experiments-ecmwf-assimilation-system

• Denial experiments, relative to a Control with the full observing system, for:
  – Microwave radiances
  – Infrared sounder radiances
  – GPSRO
  – AMVs
  – All conventional observations

• Periods:
  – 1 June – 30 September 2016; 1 December 2017 – 31 March 2018; (ie 2 x 4 months)

• Resolution:
  – Model resolution Tco399 (~28 km); incremental analysis resolution TL255 (~80 km)

EXPERIMENTS pre-date Metop-C GRAS and COSMIC2 - which currently being tested (5000 occultations in a tropical band)
Number of observations/satellites assimilated in Control

Proportion of assimilated observations

- All MW
- IR sounder
- Others
- Conventional obs
- AMVs
- GPSRO

~2%
Tropospheric height scores (Z500)

6-Jun-2016 to 31-Mar-2018 from 426 to 464 samples. Verified against own-analysis.
Confidence range 95% with AR(2) inflation and Sidak correction for 20 independent tests.

Z: SH -90° to -20°, 500hPa

Z: NH 20° to 90°, 500hPa

Normalized difference

Forecast day

MW denial – Control
IR sounder denial – Control
GPSRO denial – Control
AMV denial – Control
Conventional obs denial – Control
Fit to Radiosonde temperatures in (SH)

Instrument(s): TEMP–T  Area(s): S.Hemis
From 00Z 6–Jun–2016 to 12Z 31–Mar–2018

- MW denial
- IR sounder denial
- GPSRO denial
- AMV denial
- Conventional obs denial
- Control

Pressure [hPa]

Analysis std. dev. [%], normalised

FG std. dev. [%], normalised
Fit to Radiosonde temperatures in (SH)
Tropical wind (interesting result)

Instrument(s): AIREP AMprofiler EUprofiler JPprofiler PILOT TEMP – Uwind Vwind
Area(s): Tropics
From 00Z 6–Jun–2016 to 12Z 31–Mar–2018

- Analysis std. dev. [%], normalised [a]
- FG std. dev. [%], normalised [b]

Legend:
- MW denial
- IR sounder denial
- GPSRO denial
- AMV denial
- Conventional obs denial
- Control

100% = Control
ASIDE: Zonally averaged zonal winds retrieved from a ROM SAF monthly mean GPS-RO geopotential climatology

Compute the “balanced” GPS-RO zonal winds from the second derivative of the zonally averaged geopotential height

\[
\overline{U} \approx -\frac{1}{\beta} \frac{\partial^2 \phi}{\partial y^2}
\]

\[
\beta = \frac{2\Omega}{a}
\]

FUB is the Free University Berlin radiosonde zonal wind climatology at Singapore.
Climate reanalysis applications
Climate reanalysis applications

• We have only had large quantities of GPS-RO since 2006.

• **Claim**: GPS-RO measurements should not be biased.
  
  – It should be possible to introduce data from new instruments without overlap periods for calibration.
  
  – No discontinuities in time-series as a result of interchange of GPS-RO instruments.

• **Bending angle time series derived from the ERA-Interim reanalysis can be used to investigate this claim.**
Global bending angle (o-b)/b departure statistics from ECMWF operations for Aug.20 to Sept. 20, 2009
Consistency of GPS-RO bending angles (ERA-Interim Reanalysis, Paul Poli)
GPS-RO and the bias correction of radiances

• “Bias correction schemes for satellite radiances need to be grounded by a reference.” The reference measurements are often called “anchor” measurements.

• “Recommendation to NWP Centres” to identify part of global observing system (e.g. high quality Radio-sondes, GPS Radio Occultation) as reference network which is actively assimilated but NOT bias corrected against an NWP system.”
VarBC is used at ECMWF
Dee, QJRMS (2007), 131, pp 3323-3343

• Bias corrected radiances are assimilated.

\[ \tilde{y} = y - b(\beta, x) \]

\[ b(\beta, x) = \sum_i \beta_i p(x) \]

\[ J(x, \beta) = (x_b - x)^T B_x^{-1} (x_b - x) \]

\[ + (\beta_b - \beta)^T B_\beta^{-1} (\beta_b - \beta) + \]

\[ (y - b(\beta, x) - H(x))^T R^{-1} (y - b(\beta, x) - H(x)) \]

• VarBC assumes an unbiased model.

In the 4D-Var, we minimize an augmented cost function, where the bias coefficients are estimated.
Experiment removing GPS-RO from ERA-Interim (Dec. 08, Jan-Feb 09)

- Impact on bias correction. E.g., globally averaged Metop-A, AMSU-A channel 9 bias correction.
GPS-RO have improved the consistency between climate reanalyses in the upper-troposphere and lower/middle stratosphere

Compare ERA-Interim, JRA-55, MERRA, MERRA2, ERA5 reanalysis
Tropical tropopause temperature

MERRA is warmer than ERA-Interim throughout.
Tropical tropopause temperature

MERRA is warmer than ERA-Interim throughout.

ERA-Interim and JRA-55 assimilate GPSRO data, and come together in 2006. ERA-Interim warms and JRA-55 cools when significant amounts of GPSRO data start to be assimilated.
Tropical tropopause temperature

12-month running-mean tropical-mean 100hPa temperatures (°C)

- Significant amounts of GPSRO data assimilated in ERA-Interim, JRA-55 and MERRA-2

MERRA is warmer than ERA-Interim throughout.

ERA-Interim and JRA-55 assimilate GPSRO data, and come together in 2006. ERA-Interim warms and JRA-55 cools when significant amounts of GPSRO data start to be assimilated.

ERA5 and MERRA2 assimilate GPSRO data. They come together in 2006 along with ERA-Interim and JRA-55, but are much closer throughout.
Lower stratospheric global temperature bias in ERA5

The version of the assimilating model used for ERA5 has a larger cold bias in the lower stratosphere than the version used for ERA-Interim.

The cold bias is controlled by assimilating GPSRO data.

Radiosonde data exert a less-effective control on bias in ERA5 than they do in ERA-Interim.

See ERA 5.1 Tech Memo 859

https://www.ecmwf.int/en/publications/technical-memoranda
An indirect impact of GPS-RO on stratospheric humidity in reanalyses?

• Recall from lecture 1, that the stratospheric humidity is set to 0 in the “classical” temperature retrieval:

\[ N = 10^6 (n - 1) \]

\[ = \frac{c_1 P}{T} + \frac{c_2 P}{T^2} \]

• This is reasonable because the contribution to the refractivity in the stratosphere from humidity is negligible. The GPS-RO alone does not provide information about stratospheric humidity.

• However, air enters the stratosphere primarily in the tropics (The Brewer-Dobson Circulation). The composition of the air is determined by the tropical tropopause layer (TTL).

• The air passing through the TTL is dehydrated at the cold point tropopause, leading to the extreme dryness in the stratosphere.
Physical processes in the tropical tropopause layer and their roles in a changing climate

William J. Randel* and Eric J. Jensen²

![Graphs showing water vapour and tropopause temperature trends over time with correlation plots for winter-spring and summer-autumn periods.](image-url)
Tropical stratospheric humidity from ERA5/ERA-Interim

COSMIC is active in ERA-Int in Dec 2006.

COSMIC warms the tropical tropopause.  
⇒ Moister stratosphere.  
⇒ Gradient $\frac{d(Q_s)}{d(T_{cp})} \sim 0.5$ ppmv/K

See also ERA 5.1 Tech Memo 85

https://www.ecmwf.int/en/publications/technical-memoranda
Comparing Q reanalyses in the stratosphere

Note the SPARC community emphasise that reanalysis stratospheric humidity values should be used with caution, although ERA-Interim is described as “… surprisingly reasonable …”.

Figure 15. The tropical tropopause signature is represented in reanalyses and the SWOosh merged satellite product, defined as the height-time evolution of water vapor averaged over the 15°N–15°S tropical band. Both absolute values (a) and anomalies relative to the mean water vapor seasonal cycle at each level (b) are shown. Anomalies are computed separately for each data set. Monthly mean anomalies in tropical (15°S–15°N) cold-point tropopause temperature calculated from 65 data on the native vertical resolution of each reanalysis model are shown in (c).
Climate monitoring applications

GPS-RO likely to become more important for climate monitoring as the time-series lengthens

Seems reasonable to assume that any data that does not require bias correction will be useful for monitoring the mean state.

But which variables should we monitor? Bending angles or more geophysical quantities?
Recall basic GPS-RO processing chain:

- Excess phase delays.
- Doppler shift.
- Bending angle.
- Refractivity.
- Pressure/Temp. Geopotential height.
The RoTrends Project
**ROtrends collaboration**

RO community started comparison of different processing centres in 2007 (*ROtrends*). Main aim is to validate RO as a climate benchmark, identifying the impact of processing assumptions (*structural uncertainty*).

- *ROtrends* partners: DMI, JPL, GFZ, UCAR, WEGC, and EUMETSAT
- Common focus on CHAMP data, Aug 2001 to Sep 2008
- Aiming at improved understanding of *structural uncertainty*
- while still keeping the algorithm/software development independent
- 1st Round: profile-to-profile comparison between processing centres main results described in *Ho et al.* [2012]
- 2nd Round: comparison of monthly mean climatologies main results described in *Steiner et al.* [2013]
**Initial RO-CLIM data set**

- CHAMP zonal monthly mean data: 5 deg x 200 m, 8-30 km, global coverage
- To be provided with error characteristics and sampling-error corrected means
- To be provided as an ensemble of 5 or 6 data sets
- Currently no single community RO data set – discussions ongoing
- Planned to be released during 2015 (following re-formatting, documentation, etc)
- Current focus: a) multi-mission inter-comparisons, b) high-altitude initialization
Structural uncertainty: upper-level initialization

Good agreement between ROM SAF and UCAR raw bending angles.

Upper level bias between optimized and raw bending angles, leading to biases in refractivity and dry temperature.

Blue lines: mean, st. dev.
Red lines: median, MAD
Structural uncertainty: upper-level initialization

Good agreement between ROM SAF and UCAR raw bending angles.

Upper level bias between optimized and raw bending angles, leading to biases in refractivity and dry temperature.

To me, the GPS-RO structural uncertainty is just a consequence of the GPS-RO geophysical retrieval problem being ill-posed.

A-priori information is required to retrieve geophysical parameters, and the processing centres are choosing different data.

The bending angle biases are small.
Bending angle for climate monitoring
Simulation study using the Hadley Centre climate model

Simulation studies to assess:

• potential of GPS-RO for detecting climate trends
• what variable should we monitor
• information content of GPS-RO in relation to other sensors

Simulations use:

• Met Office Hadley Centre coupled climate model (HadGEM1)
• Climate change scenario (A1B) for 2000 – 2100
• Forward modelling of the GPS-RO bending angles

Provided by Mark Ringer (Hadley Centre)
Initial comparison with observations

Problem with monitoring bending angles

• More difficult to interpret than geophysical quantities.

• Most climate related work looks at temperature/geopotential heights.
ROM SAF work (Gleisner et al)
RO mean tropospheric temperatures

Measured (retrieved!!) geopotential height $z(p)$ and mean virtual temperature:

$$z(p) - z_s = -\frac{R \bar{T}_v}{\mu_d g_0} \cdot \ln \frac{p}{p_s} \quad \text{where} \quad \bar{T}_v = \frac{\int_p^{p_s} T_v(\dot{p}) d\ln \dot{p}}{\int_p^{p_s} d\ln \dot{p}}$$

For standard values of the constants, and at standard surface pressure ($p_s$), a 1 degree mean temperature increase of the atmospheric column raises the 100, 200, and 300 hPa pressure surfaces by 68, 47, and 36 meters, respectively.

Issues to consider:

- is the atmosphere “dry” down to the selected isobar: difference between $p$ and $p_{dry}$
- surface pressure variability (1 hPa in surf. Pressure $\Rightarrow$ 7 meter in geopot height)
- use of virtual temperature instead of physical temperature
Geopotential height at 300 hPa

– CHAMP & COSMIC, global –

CHAMP & COSMIC

Geopotential height, 90S–90N, 300hPa 2001–2014

– monthly mean anomalies (de-seasonalized) –

\[ \Delta z \text{ [m]} \]

\[ \Delta T \text{ [K]} \]

0.01 ± 0.04 K/decade


time
**RO (gph at 300 hPa) and MSU/AMSU (TLT)**

- bulk tropospheric temperatures
More recent work

Postmillennium changes in stratospheric temperature consistently resolved by GPS radio occultation and AMSU observations

S. M. Khaykin¹, B. M. Funatsu², A. Hauchecorne¹, S. Godin-Beekmann¹, C. Claud¹,³, P. Keckhut¹, A. Pazmino¹, H. Gleisner⁴, J. K. Nielsen⁴, S. Syndergaard⁴, and K. B. Lauritsen⁴

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Citation:
Study on GPS-RO and Aqua AMSU

**Purpose of study**
- To compare trends in GPS-RO and Aqua AMSU;
- To detect stratospheric temperature trends over a 15-year period.

**Monthly averaged GPS-RO data:**
- RO dry-temperature profiles from the 15-year ROM SAF CDR;
- Vertical weighted averaging of dry-temperature profiles, using fixed AMSU weighting functions;
- Monthly averaging of AMSU-averaged temperatures into 5-degree latitude bands + sampling error correction;
- Anomaly time series by subtraction of mean seasonal cycle.

**Monthly averaged AMSU data:**
- Aqua AMSU data from NOAA STAR;
- Using the inner 10 fields (swath width 500 km) to avoid limb effects;
- Monthly averaging of near-nadir data into 5 degree latitude bands;
- Anomaly time series by subtraction of mean seasonal cycle.

**Computation of trends**
- Robust linear regression on the anomaly time series, providing statistical uncertainties of the trends;

Study results published in Khaykin et al., GRL, 2017.
Global temperature anomalies: RO and AMSU

channel 9
85S – 85N

AMSU-averaged dry temperature

- monthly mean anomalies, channel 9, 85S–85N -

05/02 24-09-2017
Main findings in Khaykin et al. [GRL, 2017]

Temperature trends over 14 years for GS-RO and AMSU channels 9 to 12. GPS-RO data have been vertically averaged to simulate AMSU temperatures.

**Conclusions:**
- excellent agreement between RO and AMSU trends
- global cooling trends statistically significant in channels 11 and 12;
- cooling trends in 30 degree latitude bands are not significant;
Contribution to IPCC AR6


Compare trends retrieved from GPS-RO with other observations?

How do temperature trends in the tropics vary with height? Do the climate models look reasonable?
Comparing GPS-RO with MSU radiances (Global)

We can forward model GPS-RO anomalies to MSU ch 4 (AMSU ch 9, TLS) brightness temperatures from 2002 (CHAMP).
MSU-4 and GPS-RO anomalies 2002-2018

Good consistency between MSU-4 and GPS-RO from 2002.
Comparison with radiosondes and AIRS retrievals in tropics
THE FUTURE

Polarimetric RO (Slides, Estel Cardellach).

Geophysical Research Letters

Sensing Heavy Precipitation With GNSS Polarimetric Radio Occultations


First published: 21 December 2018 | https://doi.org/10.1029/2018GL080412
‘TYPICAL’ GNSS RO PRODUCTS: VERTICAL PROFILES OF THERMODYNAMIC VARIABLES at the tangent point (typically temperature, pressure, humidity)
‘NEW’ GNSS-PRO PRODUCTS:
VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)
+ VERTICAL PROFILES OF INTENSE RAIN
‘NEW’ GNSS-PRO PRODUCTS:
VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)
+ VERTICAL PROFILES OF INTENSE RAIN
To understand this concept it is important to keep in mind that the big falling rain drops ARE NOT like this

but rather LIKE

Vertical dimension shorter than Horizontal dimension → different propagation delays
precipitation cell
Bistatic radar: transmitter and receiver at different locations
**L-band:** penetrates all weather systems

**RHCP:** 50% H-pol 50% V-pol

Robust to Faraday rotations
precipitation cell

$$\Delta \phi^\text{atm} = \int_L K_{dp}(l) dl$$

**Observable:** horizontally integrated polarimetric phase shift (or polarimetric phase delay):

$$\Delta \phi = \phi_H - \phi_V$$

Delay of H-pol longer than V-pol!
precipitation cell

\[ K_{dp} \]

\[ \Delta \phi_{t1} \]

\[ \Delta \phi_{t2} \]

\[ \Delta \phi_{t3} \]

\[ \Delta \phi_{tN} \]

GPS

Vertical scanning

LEO
Measurement concept being tested aboard the PAZ satellite (ROHP-PAZ experiment)
Successful launch on **February 22, 2018**, by SpaceX (Falcon9). GNSS RO experiment **activated on May 10, 2018.**
Rain rate vs polarimetric delay

Polarimetric delay as function of altitude and Cloud Top Height (cth)
Significant progress since the launch of PAZ in 2018.

A key challenge will be to demonstrate and accurate DA/retrieval approach.

EG, how do we distinguish between light rain over a long path or intense rain over a short path?

If we assimilated this data, modelling 2D aspects will be key.
THE FUTURE (?)

LEO-LEO occultation concept.

EG, See review in,

A review of low Earth orbit occultation using microwave and infrared-laser signals for monitoring the atmosphere and climate

Near-Radiosonde Quality Atmospheric

LEO-LEO Occultations near cm & mm Wavelength H$_2$O Vapor & O$_3$ Absorption Lines

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D. Ward$^2$, A. Otarola$^3$, J. McGhee$^1$, C. McCormick$^1$

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$^2$ University of Arizona, Tucson, AZ
$^3$ Thirty Meter Telescope (TMT), Pasadena, CA

Funded by NSF
22 & 183 GHz RO ActiveSpectrometer

- Profiles speed of light (like GPS RO) & attenuation of light (unlike GPS RO)

⇒ Profiles H$_2$O vapor, temperature & pressure versus height simultaneously, unlike GPS RO

  *in clear & cloudy air, over land & water*

⇒ Also O$_3$, NO$_2$, water isotopes, cloud LWC, LoS winds above 10 mb

RO: Self calibrating, no drift

Resolution: ~100 m vertical, ~50 km horiz.

H$_2$O vapor: < 3% precision, < 1% accuracy

Temperature: 0.4K precision, < 0.05 K accuracy

- Profiles of turbulence from orbit
Summary

- Given an overview of applications, and pointed to published sources where possible.

- Recent impact on NWP performance.

- The GPS-RO are now key observations for climate reanalyses and have led to improved consistency since 2006.

- Climate monitoring with GPS-RO is likely to become increasingly important. Inclusion in the IPCC AR6 is an important step.

- Introduced the polarimetric GNSS-RO and LEO-LEO concepts.

- **On going: assessment of COSMIC2 data, and we will start looking at GPS-RO data from commercial companies in 2020.**