GPS radio occultation (GPS-RO): Lecture 1 – Principles and NWP use

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Photos by Cosmonaut Oleg Artemyev.
Taken from the International Space Station in 2014.
Outline

• GPS-RO Principles
  – GPS (should really be “GNSS”) measurement geometry.
  – Basic physics, some history …
  – GPS radio occultation and “Classical” GPS-RO temperature retrieval.
  – Some limitations.

• Assimilation of GPS-RO data
  – Information content and resolution estimates from 1D-Var.
  – 4D-Var assimilation of GPS-RO measurements (GPS-RO null space).
  – Move to more complicated 2D operators.

• Summary and conclusions.

• Lecture 2 will cover forecast impact, reanalysis applications, climate trends, diagnosis of boundary layer height, etc.
GPS-RO Principles
What are GNSS, GPS etc.?

Satellites in Medium Earth Orbit (~20,000km) emit radio signals. For navigation purposes, the time taken to receive the signals from multiple satellites is used to calculate the position of the receiver.

- **GNSS** (Global Navigation Satellite System) is a generic name for any system where satellite signals are used for navigation globally.
  - **GPS** (Global Positioning System) is the original US system and by far the most widely used (e.g. satnavs). Until recently, only GPS was used for RO.
  - **Galileo** is a European GNSS system.
  - **GLONASS** is the Russian system (COSMIC-2 and Spire have a GLONASS capability).
  - **BeiDou** is the Chinese system (and includes geostationary satellites).
Atmospheric measurements made using GPS signals – three types

GPS Radio Occultation (profile information from the atmospheric limb)

Ground-based GPS (Column integrated water vapour)

Wind speed information from signal reflected from ocean surface (“GNSS-reflectometry”)

GPS Receiver placed on satellite in Low Earth Orbit (LEO)
The basic GPS-RO physics – Snel’s Law

(Not “Snell”, Peter Janssen)

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

\[
\frac{C}{v} = n
\]

- Snel's Law of refraction – bending occurs when refractive index changes. In the atmosphere the refractive index varies continuously.

\[
\sin i_1 \cdot n_1 = \sin i_2 \cdot n_2
\]

\[
n_2 > n_1
\]
The basic GPS-RO physics – Snel’s Law

(Not “Snell”, Peter Janssen)

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

\[
n = \frac{c}{v}
\]

In the atmosphere, the refractive index varies smoothly, though sharp gradients can occur.

\[
n_1 \sin i_1 = n_2 \sin i_2
\]
Radio occultation (RO) measurements have been used by to study planetary atmospheres (Mars, Venus) since the 1960s. It is an active technique. The paths of radio signals are bent by refractive index gradients in the atmosphere/ionosphere.

Occultation Experiment: Results of the First Direct Measurement of Mars’s Atmosphere and Ionosphere

Abstract. Changes in the frequency, phase, and amplitude of the Mariner IV radio signal, caused by passage through the atmosphere and ionosphere of Mars, were observed immediately before and after occultation by the planet. Preliminary analysis of these effects has yielded estimates of the refractivity and density of the atmosphere near the surface, the scale height in the atmosphere, and the electron density profile of the Martian ionosphere. The atmospheric density, temperature, and scale height are lower than previously predicted, as are the maximum density, temperature, scale height, and altitude of the ionosphere.

Radio Occultation: Some Background (2)


Sensing the Earth’s Atmosphere with Occultation Satellites

BRUCE LUSIGNAN, GARY MODRELL, ANGUS MORRISON, JOSE POMALAZA, STUDENT MEMBER, IEEE AND STEVEN G. UNGAR, STUDENT MEMBER, IEEE

Fig. 1. Basic geometry of occultation measurement.
Radio Occultation: Some Background (3)

• The ideas outlined in 1969 seem to have got lost. Probably because the costs looked prohibitive.

• … but then the GPS constellation was launched in the 1980s – an excellent, free source of radio waves for RO.

• Use of GPS signals for RO discussed at the Jet Propulsion Laboratory (JPL) in late 1980s (e.g. Tom Yunck).

• In 1996 the proof of concept atmospheric RO experiment, “GPS/MET”, – funded by the US NSF – demonstrated useful temperature information could be derived from the GPS-RO measurements. (There are plans to use this in reanalysis – tests show an improved fit to radiosonde temperatures).
GPS-RO: Basic idea

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).

As it passes through a limb of the atmosphere, the GPS signal velocity is modified in the ionosphere and neutral atmosphere because the refractive index is not unity, **and the path is bent because of gradients in the refractive index**.

GPS-RO is based on analysing the **bending caused by the neutral atmosphere** along ray paths between a GPS satellite and a receiver placed on a low-earth-orbiting (LEO) satellite.
GPS-RO geometry. “Bending angles”

(Classical mechanics: e.g, Compare this picture with the deflection of a charged particle by a spherical potential!)

Setting occultation: as the LEO moves behind the earth we obtain a profile of bending angles, $\alpha$, as a function of impact parameter, $a$. The impact parameter is the distance of closest approach for the straight line path. It is directly analogous to angular momentum of a particle.
GPS-RO characteristics

- **Good vertical resolution**: 100m to 1km.

- **Around 70% of the bending occurs over a ~450km section of ray-path**, centred on the tangent point (point closest to surface) – it has a broad horizontal weighting function, with a ~Gaussian shape to first order!

- **All weather capability**: not significantly affected by cloud or rain (unlike many radiances).

- Bias-free. It is not a radiometric observation and is tied to atomic clocks.

- The bending is ~1-2 degree at the surface, falling exponentially with height. The scale-height of the decay is approximately the density scale-height (~6-7km).

- A profile of bending angles from ~60km tangent height to the surface takes about 2 minutes. Tangent point drifts in the horizontal by ~200 km during the measurement.
RO processing and retrievals:

How to get temperature profiles using the “classical” retrieval.
How to get meaningful information?

Process:

Excess phase: this is what we measure

Doppler shift

Bending angle (L1 and L2)

Ionospherically-corrected bending angle

Refractivity / refractive index

Temperature

Assumptions are required at each step.

Let’s go through these steps.
GPS receivers do not measure temperatures/ray bending directly!

The GPS receiver on the LEO satellite measures a time series of phase-delays $\phi(i-1), \phi(i), \phi(i+1), \ldots$ at the two GPS frequencies:

\[
\begin{align*}
L1 &= 1.57542 \text{ GHz} \\
L2 &= 1.22760 \text{ GHz}
\end{align*}
\]

The phase delays are “calibrated” to remove special and general relativistic effects and to remove the GPS and LEO clock errors – calibration is referenced to atomic clocks. (“Differencing”, see Hajj et al. (2002), JASTP, 64, 451 – 469).

We know accurately where the satellites are. Calculate **Excess phase delays**: i.e. remove straight line path delay, $\Delta\phi(i)$.

A time series of **Doppler shifts** at L1 and L2 are calculated by differentiating the excess phase delays with respect to time.
Processing of the GPS-RO observations (2)

The ray bending that is caused by gradients in the atmosphere and ionosphere modify the L1 and L2 Doppler values, but deriving the bending angles, $\alpha$, from the Doppler values is an ill-posed problem (an infinite set of bending angles could produce the same Doppler).

The problem is made well posed by assuming the impact parameter, given by

$$a = nr\sin\psi$$

has the same value at both the satellites.

Given accurate position and velocity estimates for the satellites, and making the impact parameter assumption, the bending angle, $\alpha$, as a function of impact parameter $a$ can be derived simultaneously from the Doppler shift.
The ionospheric correction

Every ray passes through the ionosphere!
We have to isolate the atmospheric component of the bending angle. The ionosphere is dispersive, but the neutral atmosphere is not and so we can take a linear combination of the L1 and L2 bending angles to obtain the “corrected” bending angle. See Vorob’ev + Krasil’nikov, (1994), Phys. Atmos. Ocean, 29, 602-609.

\[ \alpha(a) = c \alpha_{L1}(a) - (c - 1) \alpha_{L2}(a) \]

“Corrected” bending angles

Constant given in terms of the L1 and L2 frequencies.

How good is the correction? Does it introduce biases that vary in time with solar cycle?

YES, the retrieved temperatures will be sensitive to this!
The ionospheric correction: a simulated example

High up, the ionosphere dominates the L1 and L2 signals, but they are affected differently to each other.

Low down, the atmospheric signal dominates and the lines overlap.

The “correction” is very big!
Deriving the refractive index profiles

Assuming local spherical symmetry, we can use an **Abel transform** to retrieve a refractive index profile

\[ n(x) = \exp \left( \frac{1}{\pi} \int_{x}^{\infty} \frac{\alpha(a)}{\sqrt{a^2 - x^2}} da \right) \]

The inverse Abel transform can be used to obtain the bending angle profile for a given refractive index profile (i.e. the inversion).

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

**Corrected Bending angle** as a function of impact parameter

Note the upper-limit of the integral! **A priori** information needed to extrapolate to infinity.

Convenient variable (\(x=nr\)) (refractive index * radius)
In order to derive refractivity the **noisy, corrected** bending angle profiles must be extrapolated to infinity – *i.e., we have to introduce a-priori simulated bending angles.*

This blending of the observed and simulated bending angles is called “**statistical optimisation**”. Consider the (matrix) equation:

\[ \alpha_{so} = \alpha_m + K(\alpha - \alpha_m) \]

We use this “blended” profile in the Abel transform to get refractivity!

It’s a linear combination of simulated bending angles from a climatology model (e.g., MSIS)

The gain matrix, \( K \), determines the relative contribution of the model. **By ~60 km the merged profile is dominated by the model contribution.**
The refractive index (or refractivity) is related to the pressure, temperature and vapour pressure using two experimentally-determined constants (from the 1950s and 1960s!)

\[ N = 10^6 (n - 1) = \frac{c_1 P}{T} + \frac{c_2 P_w}{T^2} \]

If the water vapour is negligible, the 2\textsuperscript{nd} term = 0, and the refractivity is proportional to the density

\[ N \approx \frac{c_1 P}{T} = c_1 R \rho \]

This two-term expression is probably the simplest formulation for refractivity, but it is widely used in GPS-RO.

We now use an alternative three term formulation, including non-ideal gas effects.

So, although we don’t know the values of P and T, we can use the ideal gas equation to retrieve a vertical profile of density!
“Dry pressure” retrieval

The refractivity profile is retrieved from the statistically optimised bending angles.

But we also need to estimate the temperature on a pressure level to integrate the hydrostatic equation

\[ P(z) = P(z_u) - \frac{1}{c_1 R} \int_{z}^{z_u} N(z) g(z) dz \]

Overall, I would be sceptical about GPS-RO temperature retrievals above \(~5\) hPa. Be aware that the temperature will be very sensitive to the a priori.
Final step: “Dry temperature” retrieval

We can derive the pressure by integrating the hydrostatic equation:

\[ P(z) = P(z_u) - \frac{1}{c_1 R} \int_{Z}^{z_u} N(z) g(z) dz \]

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

\[ T(z) = c_1 \frac{P(z)}{N(z)} \]

High up, the a priori strongly affects the retrieval. Low down, any water vapour will affect the accuracy.

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

e.g., See Rocken et al, 1997, JGR, 102, D25, 29849-29866.
GPS/MET Temperature Sounding
(Kursinski et al, 1996, Science, 271, 1107-1110, Fig2a)

GPS/MET - thick solid.
Radiosonde – thin solid.
Dotted - ECMWF analysis.

Results like this by JPL and UCAR in mid 1990s got the subject moving.

(Location 69N, 83W.
01.33 UT, 5th May, 1995)
Some complexities:
Mostly lower-troposphere
Some subtleties, limitations, complications …

• **GPS-RO is useful data**, BUT if you want to assimilate any new data, you have to think about the limitations of the technique in order to:

  • choose a reasonable assimilation strategy (e.g., noting again that GPS-RO does not measure temperature directly).

  • obtain a realistic error covariance matrix estimate, $R$.

**Limitations:** In GPS-RO we often talk about the core region - a vertical interval between ~8-35 km - where the GPS-RO information content is highest. The GPS-RO signal-to-noise falls outside this interval.
Outside the core-region
Troposphere: we can’t neglect water vapour

Difference between the lines show the impact of water vapour.

Simulated ignoring water vapour.

We need a variational system to reliably retrieve water vapour information.
Physical limitations in the lower troposphere

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

\[
\frac{\partial}{\partial r} \left( \frac{\partial \alpha}{\partial a} \right) \leq \frac{1}{R_e}
\]

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 as the ray does not emerge.

Not affected by clouds? But we often get ducting conditions near the top of stratocumulus clouds.
Limitations – lower troposphere

• **Atmospheric Multipath** processing – more than one ray is measured by the receiver at a given time:

  - Single ray region – geometric ray optics approach ok!
  - **Multipath**: More than one ray arrives at the receiver. They interfere.

• The amplitude of the signal can fluctuate rapidly.

• **Wave optics retrievals** – these are elegant co-ordinate transforms. Without these, we would not be able to make good use of GPS-RO in the troposphere. *(These still assume spherical symmetry)*: e.g., Full Spectral Inversion. Jensen et al 2003, Rad. Sci., 38, 10.1029/2002RS002763. **Canonical transforms**, Gorbunov and Lauritsen, 2004, Rad. Sci., 39, RS4010, doi:10.1029/2003RS002971

• **Improved GPS receiver software**: Open-loop processing.
Assimilation of GPS-RO data:
What observations are available?
How do we use them?
Pros and cons.
Data availability

• The “proof of concept” GPS/MET mission 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 (~2700 profiles per day):
  – Missions of opportunity: TerraSAR-X and Tandem-X.
  – The COSMIC constellation of (originally) 6 LEO satellites was launched 2006. Now, only satellite number 6 is regularly providing data.
  – The GRAS instruments on Metop-A, Metop-B and Metop-C (assimilated since 14th March 2019) provides 3x~600 profiles per day. GRAS is the only fully operational instrument.
  – The GNOS instrument on the Chinese satellite FY-3C has been assimilated since March 2018. Data from FY-3D are also available.
  – KOMPSAT-5 is being assimilated.
  – COSMIC-2 is a tropical constellation of 6 satellites and data became available recently
  – PAZ – a Spanish mission with a unique polarimetric (precipitation) capability.

• Near future
  – GRACE Follow-On.
  – Commercial companies (Spire, PlanetIQ, GeoOptics,…) have begun to launch satellites with RO instruments.
ECMWF data coverage (all observations) - GPSRO
25/02/2020 06
Total number of obs = 17683
Why are GPS-RO observations useful for NWP given that we already have millions of radiance measurements?

**GPS-RO complements the radiances!**

Observations are useful if they provide new information.

1) RO can be assimilated **without bias correction**. The observations are good for highlighting model errors/biases. Most satellite radiance observations require bias correction to the model. GPS-RO measurements anchor the bias correction of radiance measurements.

Importance of anchor measurements in weak constraint 4D-Var. (Climate/reanalysis applications). More on this in the next lecture.

2) GPS-RO (limb sounders in general) have **sharper weighting functions in the vertical** compared to radiances and therefore have good vertical resolution properties. The GPS-RO measurements can “see” vertical structures that are in the **null space** of the satellite radiances.
Use of GPS-RO in NWP

• NWP centres assimilate either bending angle (most!) or refractivity.

• The classical retrieval is very useful for understanding the basic physics of the measurement, but it is not recommended for use in NWP.
  – The pre-processing steps and a-priori information required to retrieve temperature complicate the error statistics by introducing error correlations.
  – Bending angles do not have significant vertical error correlations, but refractivities do (because of the Abel integral)!

• We can test 1D bending angle and refractivity observation operators in 1D-Var retrievals to estimate the information content and vertical resolution of the measurements.
1D forward model (=“observation operator”)
Going from model variables to observed quantities

Assume that a **single model column** represents the state of the entire portion of atmosphere traversed by the ray.

First, calculate the refractivity on model levels:

\[
N(x) = \frac{c_1 P(x)}{T(x)} + \frac{c_2 P_w(x)}{T(x)^2}
\]

Convert to refractive index:

\[
n(x) = 1 + 10^{-6} N(x)
\]

Use Abel transform to calculate bending angle (assuming ~exponential variation of N(x) between model levels):

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

I.e. we simulate the bending angles from the model fields.

See Healy & Thépaut, 2006 for more details of how to compute this integral.
The 1D-Var retrieval minimises the cost function ($\mathbf{x}$ means model state vector here!):

$$J(\mathbf{x}) = \frac{1}{2} (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + \frac{1}{2} (\mathbf{y}_m - H(\mathbf{x}))^T \mathbf{R}^{-1} (\mathbf{y}_m - H(\mathbf{x}))$$

The 1D-Var approach provides a framework for testing observation operators that we might use in 3D/4D-Var assimilation.

The information is partitioned between increments in temperature, humidity and surface pressure, according to their relative uncertainties.

We can also investigate various information content measures.
1D bending angle Jacobian (weighting function) for temperature
(Normalised with the peak value)

\[ \frac{\partial \alpha}{\partial T} \]

Weighting function peaks at the pressure levels above and below the ray tangent point. Bending related to vertical gradient of refractivity:

\[ N = \frac{cP}{T} \]

\[ \Delta \alpha \propto (N_i - N_u) \]

Increase the T on the lower level – reduce the N gradient – less bending!

Increase the T on the upper level – increase N gradient more bending!

Very sharp weighting function in the vertical – we can resolve structures that nadir sounders cannot!
The refractivity Jacobian is even sharper, but vertical correlations are larger.

(See also Eyre, ECMWF Tech Memo 199, 1994)
GPS-RO and IASI: 1D-Var simulations

Healy and Collard 2003, QJRMS:

Expected retrieval error:

Co-located RO and IASI observations are assimilated in a 1D-Var.
1D bending angle assimilation at Met Office, NCEP, MF, ECMWF (until 2014)

• Most centres assimilate bending angles with a 1D operator: ignore the 2D nature of the measurement and use a single model column to integrate

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

• The forward model, H(x) is quite simple:
  – evaluate geopotential heights of model levels
  – convert geopotential height to geometric height and radius values
  – evaluate the refractivity, N, on model levels from P, T and Q.
  – Integrate, assuming refractivity varies \( \sim (\text{exponentially} \times \text{quadratic}) \) between model levels. (Solution in terms of the Gaussian error function).
  – Include tangent point drift (May 2011).
  – 2D operator operational at ECMWF since 2014 (later in talk).
1D bending angle assimilation at Met Office, NCEP, MF, ECMWF (until 2014)

• **Most centres assimilate bending angles with a 1D operator**: ignore the 2D nature of the measurement and use a **single model column** to integrate.

  Note the dependence on geopotential height and Q in the forward model!

  In principle, GPS-RO provides surface pressure and tropospheric humidity information to the analysis via the adjoint of the forward model.

• The forward model, $H(x)$ is quite simple:
  – evaluate geopotential heights of model levels
  – convert geopotential height to geometric height and radius values
  – evaluate the refractivity, $N$, on model levels **from P, T and Q**.
  – Integrate, assuming refractivity varies $\sim (exponentially*quadratic)$ between model levels. (*Solution in terms of the Gaussian error function*).
  – Include tangent point drift (May 2011).
  – 2D operator operational at ECMWF since 2014 (later in talk).
Assumed (global) observation errors and actual (o-b) departure statistics

Consistent with o-b stats.

Assumed (global) observation errors and actual (o-b) departure statistics

Consistent with o-b stats.

O-B vertical correlations are small for **bending angles**, so correlated observation errors can be neglected.

Correlations are much larger for **refractivity**, so these should be accounted for in $\mathbf{R}$. 
Impact of GPS-RO on ECMWF operational biases against radiosonde measurements

Operational implementation (COSMIC 1-6 and CHAMP)
GPS-RO also has a “null space”

The measurement is related to density (∼P/T) on height levels and this ambiguity means that the effect of some temperature perturbations can’t be measured. Assume two levels separated by z, with temperature variation $T(z)$ between them. Now add positive perturbation $\Delta T(z) \sim \exp(z/H)$, where H is the density scale height.

The density as a function of height is almost unchanged. A priori information required to distinguish between these temperature profiles. This is the GPS-RO null space.
Null space – how does a temperature perturbation propagate through the bending angle observation operator?

The null space arises because the measurements are sensitive to density as function of height (~P(z)/T(z)). A priori information is required to split this into T(z) and P(z). We can define a temperature perturbation $\Delta T(z) \sim \exp(z/H)$ which is in the GPS-RO null space. Therefore, if the model background contains a bias of this form, the measurement can’t see or correct it.
2D forward models:

Using model information from multiple model columns.
Tracing rays through the model atmosphere

• It has been suggested that the use of 1D operators is limiting the GPS-RO impact in the troposphere.

• 1D operators assume that the entire limb of the atmosphere being sampled can be represented by a single column – a big assumption.

• ECMWF now assimilates GPS-RO with a 2D operator.

• This complicates the forward model (and, more so, the adjoint!).
Move towards 2D GPS-RO operators

The 2D operators take account of the real limb nature of the measurement, and this should reduce the forward model errors defined as

\[ H(x_t) - y_t = \varepsilon_f \]

Forward model error

Discrete representation of true state from model

Noise free observation

Reducing the forward model errors should improve our ability to retrieve information from the observation, but this must be balanced:

**Extra Information** versus **Additional Computing Costs**.

We are less likely to misinterpret information with a 2D operator.
Assimilation with a 2D observation operator

Integrate these differential equations to determine the ray path:

\[
\frac{dr}{ds} = \cos \phi \\
\frac{d\theta}{ds} = \frac{\sin \phi}{r} \\
\frac{d\phi}{ds} \approx -\sin \phi \left[ \frac{1}{r} + \left( \frac{\partial n}{\partial r} \right)_\theta \right]
\]

Rodgers, page 149
s = distance along ray path

The 2D operator requires NWP information interpolated to a plane in the vertical, i.e. **interpolated from a number of model columns.**
**1D/2D hybrid approach**

Earth’s surface (transformed here to appear horizontal, hence the bending appears to be negative)

**Computational cost**
Occultation plane described by 31 profiles with 40 km separation.
Improvement in GPS-RO \((o-b)\) departure statistics with 2D approach

\[
\frac{(o-b)}{\sigma_o} \quad \frac{(o-a)}{\sigma_o}
\]
Summary

• GPS-RO is a satellite-to-satellite active limb measurement.

• We outlined the basic physics of the GPS-RO technique and the “classical” (planetary science) retrieval of atmospheric quantities (e.g. temperature). Be wary of classical temperature retrievals above 35-40 km. They mainly contain a-priori information.

• GPS-RO Measurements do not require bias correction and are insensitive to clouds. The 1D observation operators are quite simple. GPS-RO has very good vertical resolution, but poor horizontal resolution (~450 km average).

• Information content studies suggest GPS-RO should provide good temperature information in the upper troposphere and lower/mid stratosphere. Operational assimilation and recent OSEs supports this.

• A 2D operator has been implemented at ECMWF. This improves the modelling of observations.

• More in the next lecture!
Useful GPS-RO web-sites

- International Radio Occultation Working Group (IROWG) [www.irowg.org](http://www.irowg.org)
- The COSMIC homepage [www.cosmic.ucar.edu](http://www.cosmic.ucar.edu). This contains latest information on the status of COSMIC and an extensive list of papers [www.cosmic.ucar.edu/references.html](http://www.cosmic.ucar.edu/references.html), with some links to .pdfs of the papers, workshops.
  - You can find lists of ROM SAF publications [www.romsaf.org/publications](http://www.romsaf.org/publications).
  - Links to GPS-RO monitoring pages (Data quality, data flow of GRAS, COSMIC, TerraSAR-X, FY-3C, PAZ, KOMPSAT-5, ...).
  - In addition, you can register and download for the ROM SAF’s Radio Occultation Processing Package (ROPP). This F90 software package containing pre-processing software modules, 1D-Var minimization code, bending angle and refractivity observation operators and their tangent-linear and adjoints.

Photo by O. Artemyev

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