Systematic Errors in GNSS Radio Occultation Data - Part 1

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(I) Observing Climate with Radio Occultations

Radio occultation (RO) measurements provide a combination of:
- Long-term stability and self-calibration.
- Global coverage, observations over oceans and continents.
- All-weather capability (L-band signals), during day and night.
- High vertical resolution (0.5-1.5 km) and high accuracy (ΔT < 1 K).

By measuring the phase to a reference GPS satellite during a RO event and observing both the “occulted” and the reference GPS satellites with a ground station (“double differencing”) remaining clock errors on the receiving satellite can be removed and the measurement can thus be made traceable to the S.I. definition of the second, qualifying it as a potential climate benchmark measurement.

(II) Consistency of RO Data

The overlap of different RO missions (CHAMP, GRACE-A, and six FORMOSAT/COSMIC (F3C)) allows for the inspection of systematic differences between RO climatologies. (1) Monthly refractivity differences relative to the satellite mean (averaged from 10 km to 30 km altitude) don’t show instationarities or trends in any record – but the influence of different sampling. The sampling error can be estimated and subtracted (2), revealing a convincing data consistency. Values for individual months are < 0.05 K in almost any case, mean values for the entire period are 0.00 K for each satellite.

(III) Errors due to the obliquity of profiles

Even though RO climatologies from different satellites are very consistent (1.2), there might be systematic errors, which are common to all of them. Therefore we started to look closely at possibly remaining systematic error sources.

RO data are commonly regarded as vertical profiles, but the RO method does not provide vertical scans of the atmosphere. As it is not a constant in a strict sense, the mean weighted static apparent temperature change με is 77.6 K/mb and k₂ = 3.73 10⁵ K/mb². The value of k₂ depends therefore on the composition of dry air – in a pure CO₂ atmosphere it would be 133.1 K/mb, and a doubling of CO₂ from 280 ppm to 560 ppm leads to a (modest) increase of k₂ by 0.05 % - corresponding to an apparent temperature change of 0.14 K under normal conditions. Although small compared to the actual temperature change resulting from CO₂ doubling, it should be kept in mind that k₂ is not a constant in a strict sense.

With the permanent dipole moment of water vapour, µ, we get:

\[ k_2 = \frac{10^6}{6k_g} \mu^2. \]

(IV) Results of a simulation study

The obliquity of the RO profiles (4) clearly increases with the incidence angle of the RO measurement rays (3) with respect to the orbit plane of the receiving satellite (azimuth angle). This leads to increasing systematic differences to vertical reference profiles – which are, however, considerably reduced (up to a factor of 24) when the retrieved tangent point trajectory (which is a very good approximation to the “true” one) is properly taken into account (5). The mean absolute bias of dry temperature between 20 km and 25 km altitude. The mean absolute bias reduces when climatological ensembles of RO profiles are compared with vertical reference profiles. We have performed an end-to-end simulation study using high-resolution analysis fields (T999L91) from the European Centre for Medium-Range Weather Forecasts (ECMWF) to simulate a representative ensemble of RO profiles via high-precision 3D ray tracing.

(V) Coefficients used in the retrieval process

All current RO retrievals use a “classic” set of (measured) coefficients, relating atmospheric microwave refractivity, temperature, pressure, and water vapor partial pressure, µ, e.g. (Smith and Weintraub, 1953), thereby neglecting the non-ideal gas behavior of air:

\[ N = k_1 \frac{p}{T} + k_2 \frac{e}{T^2}, \]

where k₁ = 77.6 K/mb and k₂ = 3.73 10⁵ K/mb² are the mean weighted static polarizability of dry air.

(AI) Radio Occultation

Radio Occultation (RO) measurements are performed in a tangent point on a satellite or a ground station that is seen by a satellite, setting behind the Earth’s horizon in occultation geometry (6). The relative motion of the satellite provides a scan through the atmosphere as the ray path (radio signal, λ = 20 cm) penetrates increasingly denser atmospheric layers, resulting in cumulative slowing and bending of the ray (a). “Atmospheric delays” can be compared with mm accuracy and are then inverted to very accurate atmospheric profiles of refractivity, density, pressure, and dry temperature, with inherent accurate height information.

References - For further details see (open access):


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Our RO climatologies are available via www.wegcenter.at/globclim