An introduction to GPS radio occultation and its use in numerical weather prediction

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1. An introduction to radio occultation

1.1. The GPS system

Radio occultation (RO) for the Earth's atmosphere currently relies on the existence of the Global Position System (GPS). GPS is a multi-purpose system which is used in positioning applications of many types, in navigation, in surveying and in many other applications. The nominal GPS network consists of a constellation of 24 satellites in near-polar orbit at a height of ~20000 km. These satellites can be precisely positioned, and their signals permit accurate positioning of other satellites. GPS also provides the source of radio signals used in radio occultation. The RO technique can, in principle, be used with signals from other Global Navigation Satellites Systems (GNSS), such as GLONASS and GALILEO.

1.2. The radio occultation technique

RO is a measurement technique for obtaining information on the vertical gradient of atmospheric refractive index, which is related to the gradients of density (and hence of temperature and pressure) and of water vapour density (Melbourne et al., 1994). When a radio signal from a transmitter on a GPS satellite passes through the limb of the atmosphere, the signal is delayed and its path is bent by gradients in the refractivity field. If this signal is intercepted by a GPS receiver on another satellite, behind the Earth's limb, then the time of receipt and the direction from which the signal is received are different from those that would have been obtained from an unrefracted path. This is illustrated in Fig.1. The angle through which the ray is deflected – the 'bending angle', α – is related in a simple way to the measured Doppler shift or phase delay of the received signal.

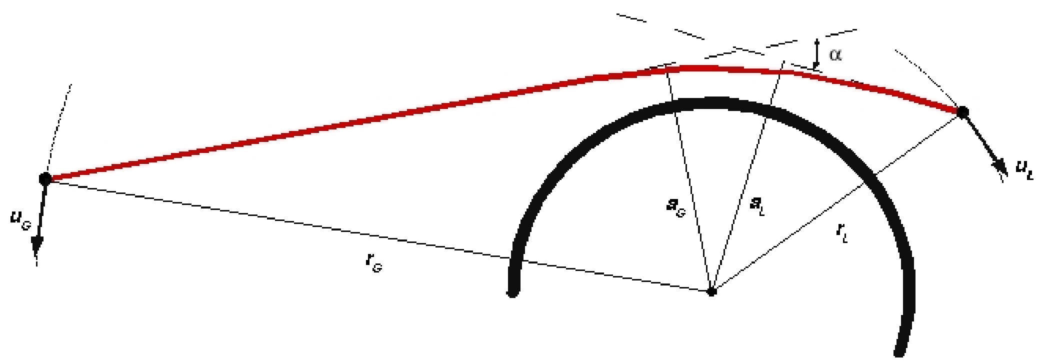

Figure 1: The geometry of a radio occultation measurement showing the refracted ray from a transmitting satellite (on the left) to a receiving satellite (on the right).

During an occultation event, the GPS satellite sets or rises relative to the receiving satellite, and the ray between them sweeps out a path of changing tangent height through the atmospheric limb; a typical occultation takes ~1 minute to profile the atmosphere (0-60 km) and thus provides a profile of bending angle against height (or, more strictly, impact parameter – a_G in Fig.1). The profile of refractive index can be derived from the profile of bending angle as described in section 1.4 below.

1.3. The physics

Refractive index and refractivity are related to meteorological variables as follows:

$$\mathbf{N} = \kappa_1 \mathbf{p} / \mathbf{T} + \kappa_2 \mathbf{e} / \mathbf{T}^2 + \kappa_3 \mathbf{n_e} / \mathbf{f}^{2} + \kappa_4 \mathbf{W} \tag{1}$$

where N = refractivity = (n -1) x 10^6, n = refractive index, p = pressure, T = temperature, e = water vapour pressure, n_e = electron density, f = frequency, W = liquid water density, and κ_i, i = 1→ 4, are coefficients.

The 4th term, caused by atmospheric scattering, is negligible at GPS frequencies. The 3rd term is significant but can be corrected by using measurements at the two GPS frequencies of 1.575 and 1.227 GHz. The 2nd term, caused by water vapour, dominates in the lower troposphere but becomes negligible in the upper troposphere and stratosphere, where the bending is dominated by density gradients.

1.4. Retrieval

In the case of a spherically symmetric atmosphere, the bending angle α can be derived (Melbourne at el., 1994), using Snell's Law of refraction and geometrical considerations, from the refractive index profile:

$$\alpha(\mathbf{a}) = -2\mathbf{a} \int_{\mathbf{a}}^{\infty} \left[\mathbf{d}\ \mathbf{ln}\left(\mathbf{n}(\mathbf{a}')\right) / \mathbf{da}' \right] \cdot \left(\mathbf{a}'^2 - \mathbf{a}^2\right)^{-1/2} \cdot \mathbf{da}' , \tag{2}$$

where n(a) is the profile of refractive index as a function of impact parameter.

This can be inverted analytically, using the Abel transform, to give the profile of refractive index:

$$\mathbf{n}(\mathbf{a}) = \mathbf{exp} \left\{ \pi^{-1} \int_{\mathbf{a}}^{\infty} \alpha(\mathbf{a}') \cdot \left(\mathbf{a}'^2 - \mathbf{a}^2\right)^{-1/2} \cdot \mathbf{da}' \right\} , \tag{3}$$

where α(a) is the profile of bending angles as a function of impact parameter.

1.5. Radio occultation characteristics

For a RO receiver on a satellite in a high inclination orbit, RO measurements are globally distributed in a quasi-random manner. They provide temperature information for the stratosphere and upper troposphere, and humidity information for the lower troposphere. They have a high vertical resolution of 0.5-1 km, but low horizontal resolution of ~200 km. They provide information of low noise, equivalent to random errors in temperature of ~1K. Moreover their systematic errors are very low: <0.2K and probably better, as required for climate monitoring. RO measurements are 'all-weather', as they are negligibly affected by cloud and precipitation. The space/time sampling of the measurements is determined by the number of GPS receivers multiplied by the number of transmitters; a constellation of 6 satellites (receiving signals from 24 GPS satellites) can provide ~3000 occultations per day. Furthermore, by the standards of space-borne remote sensing, they are relatively inexpensive. The vertical information content from RO data is highly complementary to that from advanced infra-red sounders such as IASI, as discussed in section 4.

1.6. Radio occultation missions

RO was first demonstrated for the Earth's atmosphere with the GPS/MET mission from 1995 to 1997 (Kursinski et al., 1996; Rocken et al., 1997) and continued by the CHAMP mission from 2000 (Wickert et al., 2001). From 2006, the COSMIC mission (Anthes et al., 2000; Anthes et al., 2008) has been particularly important because of its higher number of RO receivers. Missions from which data have been available to NWP centres are summarised in Table 1.

GPS/MET	1995-97	Experimental, selected periods only
CHAMP	2000-	Experimental, continuous since 2001; near-real time since 2006
SAC-C	2000-	sporadic measurements, experimental
GRACE-A	2002-	Experimental, continuous since 2001; near-real time since 2006
COSMIC	2006-	demonstration mission, **6 satellites**; near-real time since 2006
MetOp/GRAS	2006-	operational from 2008

Table 1: Radio occultation missions

These missions are discussed in more detail in other papers in these Proceedings, together with plans for future radio occultation missions.

2. An introduction to variational data assimilation

Ideally, in order to define the initial state of the atmosphere for a numerical weather prediction (NWP) system, we might wish to solve the Bayesian problem: what is the probability of atmospheric state, x, given observations, y^o? or

$$\text{evaluate}: \ \mathbf{P}\left(\mathbf{x} \mid \mathbf{y}^{\mathbf{o}}\right) = \ \mathbf{P}\left(\mathbf{y}^{\mathbf{o}} \mid \mathbf{x}\right) \ \cdot \ \mathbf{P}\left(\mathbf{x}\right) \ / \ \mathbf{P}(\mathbf{y}^{\mathbf{o}}) \ . \tag{4}$$

It is far beyond the scope of present day computer power to estimate the full probability density function (PDF) and it probably always will be. Ensemble methods may be able to explore sufficient aspects of it to be useful.

At present, most operational NWP systems use a variational (or equivalent) approach, in which we ask the question: what is the most probable atmospheric state, x, given observations, y^o ? or

$$\text{maximise}: \ \mathbf{P}\left(\mathbf{x} \mid \mathbf{y}^{\mathbf{o}}\right) = \ \mathbf{P}\left(\mathbf{y}^{\mathbf{o}} \mid \mathbf{x}\right) \ \cdot \ \mathbf{P}\left(\mathbf{x}\right) / \ \mathbf{P}\left(\mathbf{y}^{\mathbf{o}}\right) \ , \tag{5}$$

which is equivalent to

$$\text{maximise}: \ \mathbf{ln}\left\{\mathbf{P}\left(\mathbf{x} \mid \mathbf{y}^{\mathbf{o}}\right)\right\} = \ \mathbf{ln}\left\{\mathbf{P}\left(\mathbf{y}^{\mathbf{o}} \mid \mathbf{x}\right)\right\} \ + \ \mathbf{ln}\left\{\mathbf{P}\left(\mathbf{x}\right)\right\} \ + \ \mathbf{constant} \ . \tag{6}$$

If all the PDFs are Gaussian, then this is the same as minimising a **penalty or cost function**:

$$J\left[\mathbf{x}\right] \ = \ ½ \ \left(\mathbf{x}-\mathbf{x}^{\mathbf{b}}\right)^{\mathbf{T}} \mathbf{B}^{-1} \ \left(\mathbf{x}-\mathbf{x}^{\mathbf{b}}\right) \ + \ ½ \ \left(\mathbf{y}^{\mathbf{o}} - H\left[\mathbf{x}\right]\right)^{\mathbf{T}} \left(\mathbf{E}+\mathbf{F}\right)^{-1} \ \left(\mathbf{y}^{\mathbf{o}} - H\left[\mathbf{x}\right]\right) \ , \tag{7}$$

where x^b is the background field, B is the background error covariance, H[x] is the observation operator, and E and F are the error covariances of observations and observation operator. (See Lorenc, 1986).

The optimal analysis can be found by minimizing eq.(7) or by solving its gradient equation:

$$\nabla\mathbf{x}J\left[\mathbf{x}\right]^{\ \mathbf{T}} \ = \ \mathbf{B}^{-1}\left(\mathbf{x}-\mathbf{x}^{\mathbf{b}}\right) \ + \ \nabla_{\mathbf{x}}H\left[\mathbf{x}\right]^{\mathbf{T}}\left(\mathbf{E}+\mathbf{F}\right)^{-1} \ \left(\mathbf{y}^{\mathbf{o}} - H\left[\mathbf{x}\right]\right) \ = \ \mathbf{0} \ . \tag{8}$$

Therefore, to assimilate observations y^o, we need an appropriate observation operator H[x] and a good characterization of the errors in the observations and those in the observation operator.

For each satellite observation type to be assimilated into a NWP model, one is usually faced with a choice as to the form in which the data are best assimilated, and particularly the amount of pre-processing they undergo prior to assimilation. The common features of this choice can be illustrated using Fig.2, which shows schematically the main elements of the data assimilation process. At the bottom of the figure is shown the continuous cycle of forecast-assimilate-forecast operations. For each assimilation cycle, the NWP model background fields are interpolated to the space-time of each observation and then passed through an 'observation' operator to create 'forecast observations'. The observations undergo some form of pre-processing, which can be more or less complicated. For example, satellite sounding radiances may be heavily pre-processed to generate a retrieved atmospheric profile, or they may be lightly pre-processed and presented to the assimilation system as radiances. The pre-processed observations are then compared with the 'forecast observations'; their differences are called 'observation increments'. The data assimilation procedure then converts the observation increments, through a process of mapping and weighting, into 'analysis increments' which are added to the NWP background field to generate the final analysis.

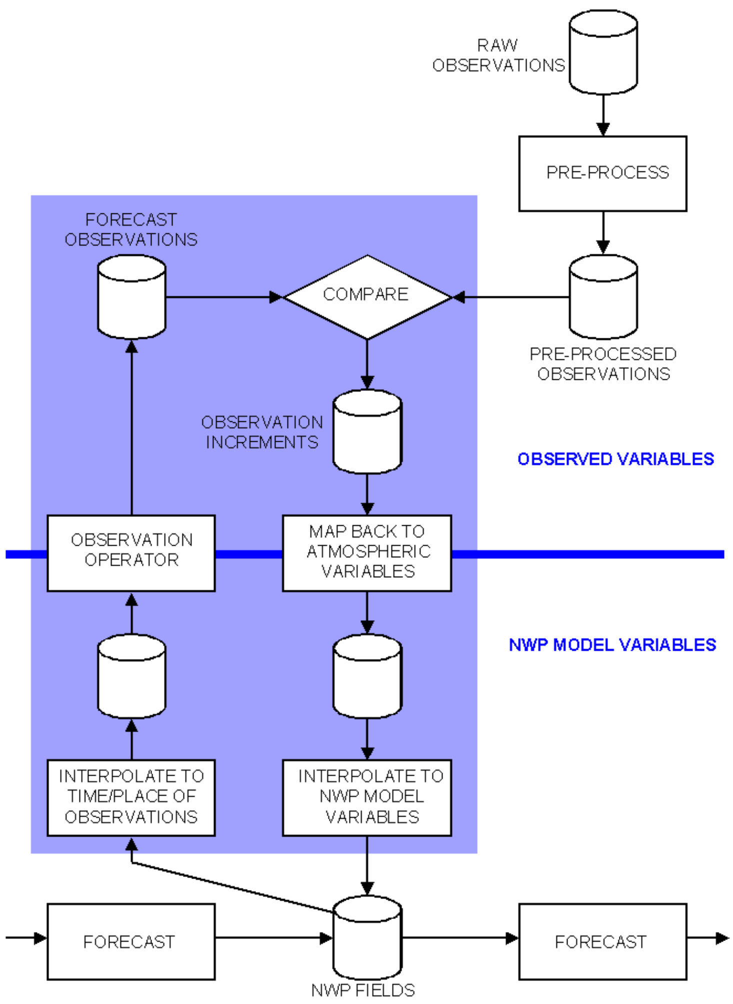

Figure 2: Illustrating schematically the assimilation of observations into a NWP model

It is important that the observation operator and the pre-processing of observations are carefully matched, so that the observation increments are the result of comparing 'like with like'. This includes the very important treatment of biases in the observations and in the observation operators. In general, if the observation operator is simple (e.g. not extending beyond simple interpolation of fields) then, for most satellite data types, the pre-processing must be complex. On the other hand, if raw or lightly pre-processed observations are assimilated, then the observation operator must be complex.

There are two principle advantages in assimilating observations close to their raw form. Firstly, the 'observation operator', H(x), can be nonlinear and this is important for many remotely-sensed observations. Variational methods no longer restrict assimilation to approximate linearization of this relationship, and this allows the true information content of the observation to be properly represented. Secondly, 'raw' measurements, in the space of the observed variables, tend to have simpler error characteristics.

On the other hand, assimilation of raw observations presents some new problems. Firstly, raw observations tend to have more complex operators. Secondly, some observations are affected by physical variables not contained in the control variable (e.g. the stratosphere above the model top, or surface variables). Thirdly, there is a logistical problem: the need to develop and maintain expertise on all satellite observation operators and associated errors, requiring resources beyond the means of a single NWP centre. It was the recognition of this problem in the mid-1990s that stimulated the search for new strategies to improve links between 'assimilation centres' and 'satellite centres' and to share the necessary work on observation operators and satellite data pre-processing software. New collaborative activities, such as the EUMETSAT Satellite Applications Facilities for NWP (NWP SAF) and for GRAS Meteorology (GRAS SAF) in Europe and the Joint Center for Satellite Data Assimilation (JCSDA) in the USA, have been the outcome.

Assimilation options for various data types were reviewed by Eyre (1997).

3. Assimilation of radio occultation data

3.1. Assimilation options

The assimilation options for RO data were first discussed by Eyre (1994) and can be summarised as follows:

(a) assimilate retrieved profiles of temperature and humidity,

(b) assimilate retrieved profiles of refractivity,

(c) assimilate bending angle profiles directly.

Option (a) has generally been rejected as it does not permit optimal treatment of one of the fundamental problems with RO: the non-separable effects of temperature and humidity on the refractivity (see eq.(1)).

Options (b) and (c) have both been tried. From a theoretical perspective, option (c) is preferred as it allows one to address another fundamental problem: the limited horizontal resolution of RO data and hence the danger of destroying information that the NWP model already contains on horizontal gradients of atmospheric fields in the vicinity of the occultation. Option (c) allows this problem to be addressed partially (although not completely, because of the assumptions of path symmetry in the derivation of the bending angle profile – see Healy 2001).

Option (b) does not address this problem because the Abel transform, used to retrieve refractivities from bending angles, assumes that the atmosphere is spherically symmetric (i.e. contains no horizontal gradients). However, it may be possible to come close to the accuracy of bending angle assimilation by comparing measured refractivities with forecast refractivities for which the forecast profile is a carefully weighted average over the plane of the occultation.

An assimilation option intermediate between (b) and (c) is also used: assimilation of bending angle, but without allowing for the horizontal variation of the NWP field in the observation operator, i.e. a one-dimensional operator for bending angle. Compared with (b), this has the advantage of avoiding errors introduced by the use of climatological information in the smoothing of the noisy bending angle data in the upper troposphere, prior to application of the Abel transform. However, it does require the NWP model to extend sufficiently high into the stratosphere to support the computation of bending angle.

3.2. Assimilation experience

Assimilation studies on RO data are summarised by Healy and Thépaut (2006) and include results from Liu et al. (2001), Zhou et al. (2004), Poli and Joiner (2003) and Healy et al. (2005). Further results are given by Healy et al. (2007). As expected, largest impacts are found in the upper troposphere and lower stratosphere, and particularly in the S. Hemisphere. Surprisingly large impacts have been found when comparatively small numbers of observations have been assimilated, suggesting that RO data are highly complementary to other components of the Global Observing System (GOS).

Most recent results of assimilation experiments with RO data are reported in other papers in these Proceedings.

4. Information content of radio occultation data

Information is always relative, i.e. relative to what we already know, the 'prior' information. In the context of NWP, it is appropriate to measure the information content of observations relative to the knowledge of the atmospheric state contained in the background field (the short-range forecast).

It can be shown that, in the linear limit, the error covariance of the analysis is obtained from the second derivative of the cost function given by eq.(7):

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \nabla_{\mathbf{x}} H[\mathbf{x}]^{\mathrm{T}} \cdot (\mathbf{E}+\mathbf{F})^{-1} \cdot \nabla_{\mathbf{x}} H[\mathbf{x}]. \tag{9}$$

This equation can be evaluated with the values of $\nabla_X H[x]$, E and F appropriate to different observing systems, to show how much each reduces the error covariance of the background and hence increases the information content of the analysis. Collard and Healy (2003) performed such a study for RO data, for IASI data (as an example of an advanced infra-red sounder) and for the combination of the two. Their results are reproduced in Fig.3. They show that, for temperature, whereas RO data are most informative in the upper troposphere and lower stratosphere, IASI data contain more information on the lower troposphere. Conversely, for humidity, whereas RO data provide information on the lower troposphere, IASI data are most informative on the upper troposphere. In this way, advanced infra-red sounders and RO are highly complementary in terms of their information content.

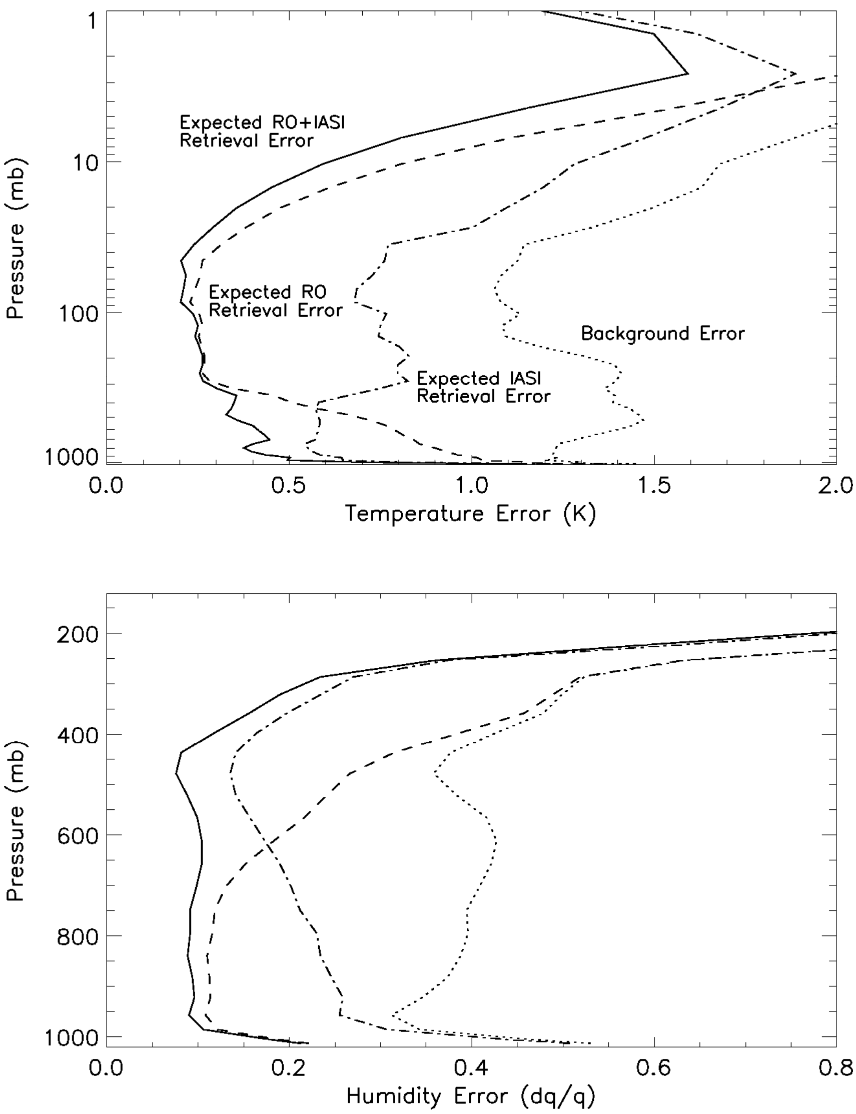

Figure 3: Simulated retrieval errors, assuming a 1D-Var retrieval technique with a forecast background, for profiles of temperature (above) and humidity (below) for RO (dashed), IASI (dot-dashed) and combined (solid). Assumed background errors are shown by the dotted lines. From Collard and Healy (2003).

5. Concluding remarks: some issues for this workshop

The use of RO data in NWP is already a success story; one decade on from the first RO data from GPS/MET, RO observations are making substantial impacts on the performance of operational NWP systems.

This workshop will provide a summary of the latest status of the use and impact of RO data in NWP, and will also address some of the outstanding questions on the use of RO data for NWP and other applications. The following list of questions is a contribution to this discussion:

a) NWP. Early impacts are very good, but what is limiting the impact? In particular, do we need to pay more attention to the relative biases between RO data and other components of the system (i.e. other observations and the NWP model itself)? The very low absolute errors of RO data make them well suited to play a crucial role in first studying and then addressing these biases.

b) Climate monitoring. RO data have been heralded as an observation source of very high absolute accuracy and stability, uniquely placed to contribute to climate monitoring. However, these expected characteristics need to be demonstrated in practice. To what extent has this been achieved?

c) Other applications. Apart from their roles in NWP and climate monitoring, RO data have other potential applications, e.g. in providing information on the height of the planetary boundary layer and via the information in signals reflected from the Earth's surface. What progress has been made in these areas?

d) Future systems. What is the size of an optimal RO constellation, in terms of number of receivers multiplied by number of transmitters? At what point does the impact of RO data on NWP performance saturate? These are important question for designing the future GOS. How can OSEs and OSSEs contribute to answering these questions?

Acronymns

CHAMP	Challenging Mini-satellite Payload (of Germany)
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
EUMETSAT	European organisation for the exploitation of Meteorological Satellites
GALILEO	Future GNSS of Europe
GLONASS	GNSS of Russia
GNSS	Global Navigation Satellite System
GOS	Global Observing System (of WMO)
GPS	Global Positioning System, GNSS of the USA
GPS/MET	GPS Meteorology satellite
GRACE-A	Gravity Recovery And Climate Experiment satellite
GRAS	GNSS Receiver for Atmospheric Sounding
IASI	Infra-red Atmospheric Sounding Interferometer
JCSDA	Joint Center for Satellite Data Assimilation (of the USA)
MetOp	Meteorological Operational satellite (of EUMETSAT and ESA)
NWP	Numerical Weather Prediction
OSE	Observing system experiment
OSSE	Observing system simulation experiment
PDF	Probability density function
RO	Radio occultation
SAC-C	Satelite de Aplicaciones Cientificas – C (of Argentina)
SAF	Satellite Application Facility (of EUMETSAT)
WMO	World Meteorological Organisation

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