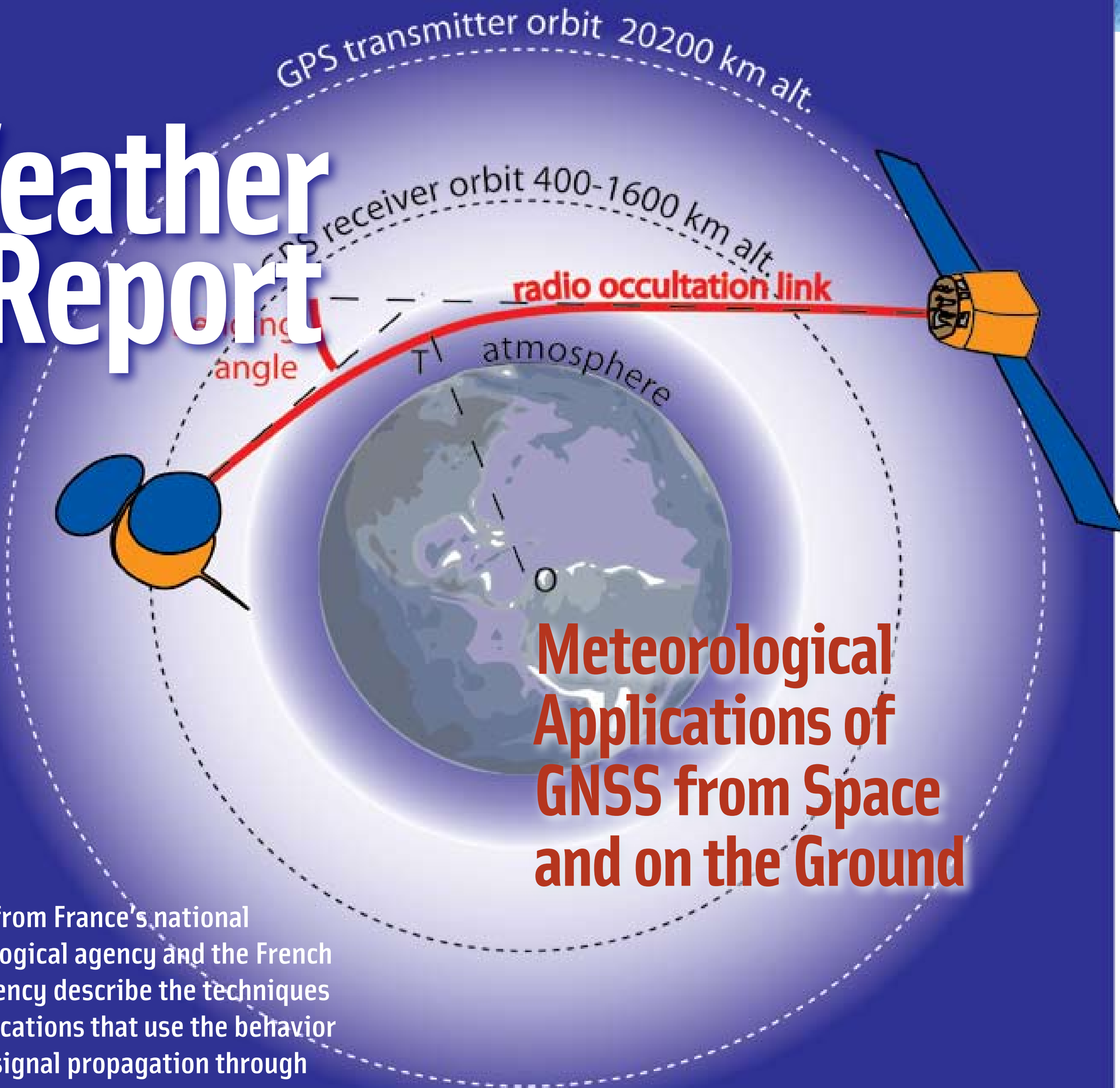
Weather Report



Meteorological Applications of GNSS from Space and on the Ground

Authors from France's national meteorological agency and the French space agency describe the techniques and applications that use the behavior of GNSS signal propagation through the Earth's atmosphere to predict the weather and monitor climate change.

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The year 2007 marked the 50th anniversary of the first man-made artificial satellite carrying a radio transmitter. Launched by the former Soviet Union in 1957, the Sputnik satellite preceded the first constellation of GPS satellites by more than three decades.

Beginning with launch of its first satellite in 1978 through declaration of full operational capability in 1995, the U.S. Global Positioning System has broadcast accurate and stable radio signals. These GPS signals have now become a source of information for exploratory and routine monitoring of the Earth's atmosphere, using data collected by GPS receivers located on the ground or in space.

Experiments exploiting these ground- or space-based GPS techniques were first reported as far back as 1992 and 1995, respectively. (For further discussion of these pioneering efforts, see the articles by M. Bevis et alia [1992] and E. R. Kursinki et alia [1995] in the Additional Resources section at the end of this article.) Similar measurements are now routinely available to national meteorological services worldwide.

The measurements collected by these two techniques can be useful to meteorologists provided that ancillary (external) information is available with which to retrieve such data as integrated water vapor (for ground-based GPS measurements) or profiles of temperature and humidity (for space-borne GPS measurements).

However, the addition of such information convolves the error patterns in the meteorological retrievals, making them more difficult to use in an error-reduction scheme such as those commonly employed in numerical weather prediction (NWP) and assimilation systems. For that reason, NWP assimilation makes direct use of data closer to the raw measurements, for which the error patterns are better characterized.

This article presents the methodology for assimilating the GPS-based measurements into the NWP system of the French national weather service (Météo-France). We describe the error reductions obtained by this method in estimating atmospheric conditions and making subsequent weather forecasts.

The article further considers the application of these observations for climate monitoring. Finally, we discuss the perspectives on these questions that will be allowed by the future Galileo system (as, of course, the perspectives allowed by Compass, GLONASS, IRNSS, etc., could have been similarly discussed).

Ground-Based GPS Measurements

As mentioned earlier, ground-based stations monitoring the signals broadcast by the GPS transmitters have been used since 1992 for meteorological purposes. The ionosphere and the neutral atmosphere both induce a delay in the propagation of the GPS signals as compared to propagation in a vacuum.

Because of the dispersive nature of the ionosphere, measurements made on the two GPS frequencies (L1 and L2) enable observers to assess a neutral atmosphere-only delay. Several GPS links (see **Figure 1a**) are required to retrieve a zenith total delay (ZTD) above the receiving station, using to this end mapping functions such as described in the article by A. E. Niell cited in Additional Resources.

The ZTD can be expressed as

$$ZTD = \int_{\text{receiving station}}^{\text{top-of-atmosphere}} [n(h)-1]\, dh \quad (1)$$

where $n(h)$ denotes the atmospheric refractive index as a function of height. The atmospheric refractive index n at radio frequencies is usually expressed in terms of the radio refractivity $N = (n\text{-}1)\cdot 10^6$. In the neutral atmosphere, the Smith and Weintraub formula derived in 1953 relates radio refractivity N to pressure P, temperature T, and water vapor partial pressure e as follows:

$$N = b_1 \frac{P}{T} + b_2 \frac{e}{T^2} \quad (2)$$

where $b_1 = 77.6$ K.hPa^{-1} and $b_2 = 37.3\cdot 10^4$ K^2.hPa^{-1}. More recent research has reevaluated that relationship, taking into account the increase of the CO_2 concentration observed in the atmosphere.

The temporal resolution of ZTD estimates is typically between 5–60 minutes but it should be noted that the errors in ZTD are correlated in time. The area sensed by a "ZTD measurement" extends in the horizontal up to about a 17-kilometer radius around the station. Note, this assumes that the ZTD is obtained from raw measurements from various GPS satellites at equally distributed azimuth angles and down to 10 degrees elevation angle, and that most of the ZTD information comes from the part of the atmosphere located below three kilometers altitude.

The inversion of a measured ZTD into retrieval of an integrated water vapor (IWV) content requires independent estimates of surface pressure (P_s) and mean atmospheric column temperature (T_m). The surface pressure enables us to estimate the so-called hydrostatic contribution to the ZTD (about 2.3 millimeters of delay per one hectopascal of surface pressure), while the remaining "wet" delay contribution can be scaled via a conversion factor into IWV.

The conversion factor is T_m-dependent but is typically about 6.5 millimeters of delay per one millimeter of IWV. Although two pieces of information (P_s, T_m) are thus required to yield the meteorological product (IWV) from the ZTD, this technique is valid in all weather conditions and can be useful to monitor in near real-time maps of IWV when a network of GPS receivers is available. Such maps can, for example, be used by weather forecasters in conjunction with radar and satellite measurements to help track severe weather events.

For example, in the United States, IWV data are derived in near real-time from ZTD data collected by a vast network of ground-based GPS stations covering the continental United States. In

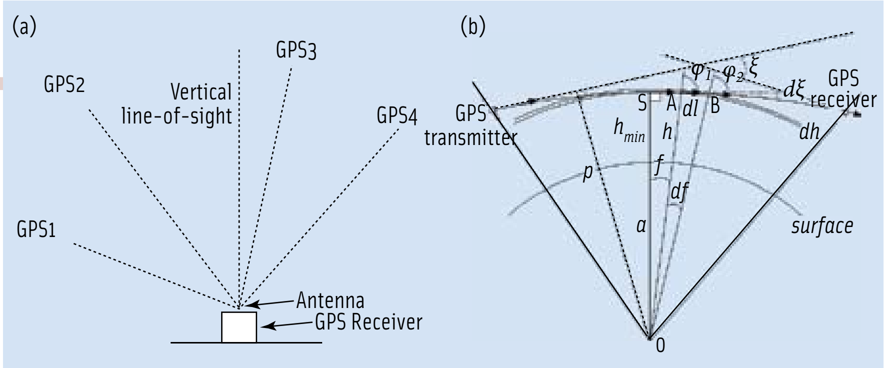

FIGURE 1 Geometry of GPS meteorological observations (not to scale): (a) with a ground-based GPS receiver, the zenith total delay (ZTD) observation characterizes the total atmospheric delay at the vertical of the GPS receiving station, but several GPS links are in fact required, as illustrated here with several hypothetical GPS satellites viewed under different azimuth and zenith angles; (b) with a spaceborne GPS receiver in LEO orbit (between 400-1600 km altitude), a GPS radio occultation involves a GPS transmitter located in MEO orbit at about 20,000-kilometer altitude; the radio link is incident with an asymptotic ray-miss distance *p* with respect to the local centre of curvature of the Earth *O*. Because of refraction this ray is bent towards the Earth's surface and the distance of closest approach is the tangent height h_{min}. The contribution of an atmospheric slab of thickness *dh* at altitude *h* to the bending angle ξ for that ray is noted $d\xi$.

Japan, a dense network of GPS stations was established, originally for geodetic purposes, but may now also serve meteorology.

In Europe, several initiatives have helped gather expertise and methods so that ZTD data from European GPS stations belonging to various networks can be made available in near real-time for meteorological applications and national meteorological services' use worldwide. These include Action 716 ("Exploitation of Ground-Based GPS for Climate And Numerical Weather Prediction Applications") of the European Cooperation in the Field of Scientific and Technical Research (COST-716) along with the following projects: Meteorological Applications of GPS Integrated Column Water Vapour Measurements in the Western Mediterranean (MAGIC), Targeting Optimal Use of GPS Humidity measurements in meteorology (TOUGH), and most recently the EUMETNET GPS water vapor program (E-GVAP, on the web: <http://egvap.dmi.dk>).

In the E-GVAP framework, raw measurement data originating from more than 600 European GPS stations are now processed into ZTDs by more than 10 analysis centers within less than 90 minutes after data collection. Note that some stations are simultaneously processed by several analysis centers for inter-comparison and validation purposes.

Figure 2a shows the locations of all ground-based GPS stations (617 total) whose data were received at Météo-France for the six-hour time period centered at 00UTC on July 8, 2007, for a total number of 24,508 ZTD observations. In France Météo-France has teamed up with the Institut Géographique National (IGN) in 2007 for joining E-GVAP.

We should note that recent efforts have focused on attempting to reconstruct receiver-to-satellite atmospheric delays along the slanted lines-of-sight shown in Figure 1a. These observations could be used for NWP assimilation or lower tropospheric tomography. Research indicates that the azimuthally asymmetric contribution to the estimated slanted path delays is limited to a few parts per thousand of the atmospheric delay. It also suggests that the estimated slanted path delays can present significant errors for extremely asymmetric situations.

Spaceborne GPS Measurements: Radio Occultation

The article by R. A. Anthes et alia (and references therein) cited in Additional Resources provides a detailed review of the GPS radio occultation technique for weather and climate applications. We provide here a brief description of the remote sensing methodology.

A so-called GPS radio occultation occurs whenever a GPS receiver (e.g., onboard a low-earth-orbiting spacecraft) sees a satellite of the GPS constellation set or rise behind the Earth's horizon. During a setting occultation event, the radio link crosses the atmospheric limb until the signal disappears as it is blocked by the solid surface of the Earth or tracking is lost at the receiver. As the radio link descends in the atmosphere, the signals undergo increasing phase delays as compared to their propagation in a vacuum.

From the receiver point of view, the wave fronts arrive with increasing timing separations (the result of atmospheric-induced Doppler shift on the received frequencies). Provided the kinematic Doppler shift caused by the differential motion of the platforms can be calculated with the help of accurate transmitter and receiver positions and velocities, the atmospheric contribution can be assessed from the measured carrier Doppler shifts at the receiver. Note that in practice single-differencing at the spaceborne receiver may be required to correct for receiver clock errors.

In 1995, the first GPS radio occultation proof-of-concept experiment — GPS/MET — was conducted, followed by similar experiments onboard satellites, e.g., CHAMP (Challenging Minisatellite Payload), SAC-C (Satellite Argentina Científicas – C), GRACE (Gravity Recovery and Climate Experiment), and

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the six-satellite constellation FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate <http://www.cosmic.ucar.edu>).

Figure 1b shows the geometry of a GPS radio occultation event. The measurement vertical resolution is restricted by diffraction to the first Fresnel zone, which is about 0.5 kilometer in the troposphere and 1.4 kilometer in the stratosphere. Doppler data can be acquired at a higher sampling resolution, but the information content is then smeared in the vertical when the raw phase data are smoothed during processing.

If we define the horizontal resolution along the ray as the horizontal extent required to cross a layer slab of thickness equal to the vertical resolution, this horizontal resolution is about 150–250 kilometers. In practice a local center of curvature of the Earth needs to be calculated for each occultation event in order to account for the oblateness of the Earth.

The raw measurements of a GPS radio occultation are carrier phase time series measurements, at both frequencies L1 and L2. Assuming local spherical symmetry, we can derive a time series of impact parameters and bending angles for both frequencies. Due to the dispersive nature of the ionosphere, a combination of the bending angles on both frequencies can be used to retrieve ionosphere-only bending and neutral atmosphere–only bending angles.

Radio-holographic methods can also be applied at this point to correct for multi-path effects and for diffraction effects (and thus enhance the vertical resolution), using both phase and amplitude data.

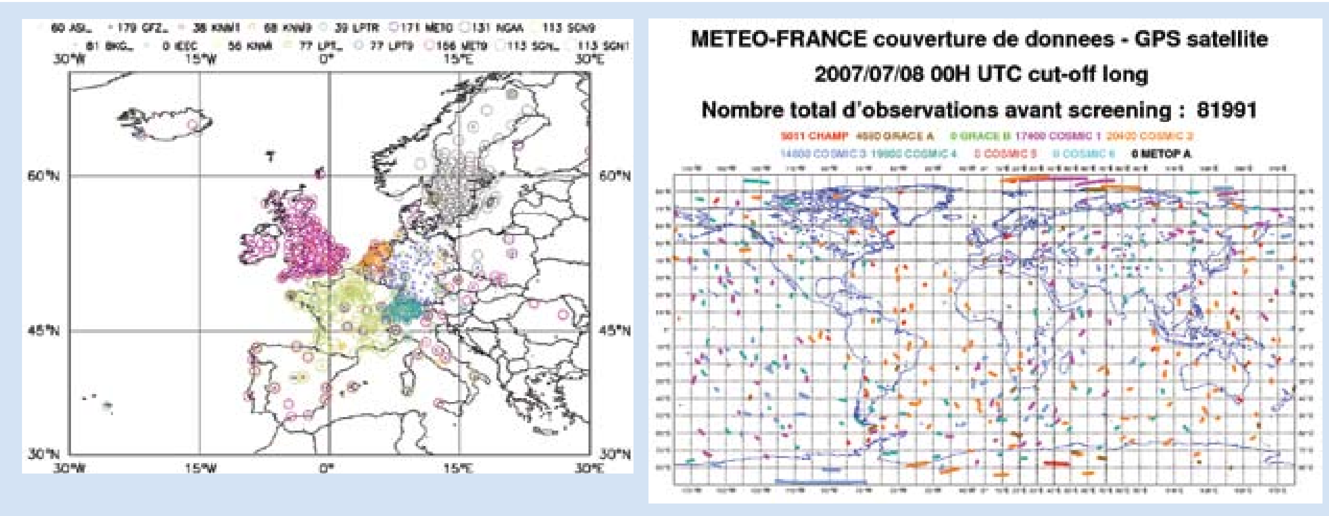

FIGURE 2 Maps of GPS observations received at Météo-France in near real-time on 8 July 2007 00 UTC (+/- 3 hours) : (left) European ground-based GPS ZTD observations (analysis centers indicated at the top along with the number of stations processed by each – a few stations fall outside the map area) ; (right) GPS radio occultation from several satellites (total counts per satellite indicated at the top ; courtesy of Météo-France DPREVI/COMPAS

Assuming spherical symmetry, the integration of Bouguer's formula enables us to relate the profile of atmospheric refractive index to the bending angle ξ observed for a ray with impact parameter p and tangent height h_{min}, noting a the local radius of curvature of the Earth:

$$\xi(p) = -2p \int_{h_{\min}}^{TOA} \frac{dn}{dh} \cdot \frac{1}{n} \cdot \frac{1}{\sqrt{n(h)^2 \cdot (a+h)^2 - p^2}} \, dh \qquad (3)$$

To the first order, spherical symmetry is a reasonable approximation for modelling the refraction of the radio path within the Earth's atmosphere. However, this approximation is known to lead to important errors when the radio signal encounters strong horizontal gradients of refractive index. Within an occultation plane, for example, using a global atmospheric model that featured a horizontal resolution of 1x1.25 degree (latitude, longitude), this error has been estimated to average less than 1.5 percent RMS of the bending angle.

This finding is consistent with the error reduction obtained in the fit to observed SAC-C and CHAMP bending angles when a two-dimensional ray-tracing scheme was used to carry the refraction calculations from that same global model. We should point out that larger effects may be detected with a higher resolution model (closer to real atmospheric gradients). Other research, using simulations from a meso-scale atmospheric model (horizontal resolution of 12 kilometers) over the United Kingdom, has shown that out-of-plane bending can also occur.

Another aspect of the retrieval process that can lead to errors because of departure from spherical symmetry is the drift of the tangent point during an occultation. This can lead to larger errors in the modelling of bending angles, up to 15 percent RMS in terms of bending angle. Figure 2b shows the individual tangent point locations for which a retrieved bending angle was measured by the CHAMP, GRACE, and FORMOSAT-3/COSMIC experiments. The tangent point drift appears more obvious for the occultations in the polar regions, but this is an artefact of the projection.

NWP Applications and Methodology

Let us now turn to the practical application of these methods in numerical weather prediction, where we begin with a closer look at specific methodologies, including the assimilation of data into NWP models and its application by the French meteorological agency, Météo-France. We will then more closely examine separate GPS ground-based and space-based (radio occultation) approaches.

Operational NWP requires a regular update of the atmospheric state model estimate. This process (so-called *analysis*) is typically conducted four times a day (00, 06, 12, 18 UTC) with the help of meteorological observations and an a priori estimate. The a priori estimate is usually a forecast generated by a circulation model run from the previous analysis.

Such meteorological observations have a diverse nature. They include, for example, *in situ* measurements from radiosondes, aircraft, buoys, ground and ship stations, as well as satellite-based remote sensing measurements such as infrared and microwave radiometers, cloud-track winds from imagery, and surface winds from scatterometers.

The method employed at Météo-France for performing the analysis in its global NWP model and assimilation system is a four-dimensional variational (4DVAR) assimilation. More information about the 4DVAR methodology is given in the article by F. Rabier et alia (see Additional Resources). Briefly, the 3D model state (noted $\mathbf{x}$) at analysis time is estimated from a variety of meteorological observations (noted $\mathbf{y}^0$) by minimizing the following cost function:

$$J[\mathbf{x}] = (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + (H(\mathbf{x}) - \mathbf{y}^0)^T R^{-1} (H(\mathbf{x}) - \mathbf{y}^0) + J_c(\mathbf{x}) \qquad (4)$$

where $\mathbf{B}$ denotes the a priori error covariance matrix, $\mathbf{R}$ denotes the observation measurement and representativeness error covariance matrix, and H is an observation operator used to calculate simulated observations from the a priori information **x**.

This operator H involves, for example, atmospheric radiative transfer theory in order to model brightness temperature observations. The additional constraint J_c serves to avoid non-physical analysis solutions. In 4DVAR, the observation operator involves a space interpolation from the 3D model fields, with the model state propagated to the proper observation time with the help of the forecast model.

The NWP analysis is essentially a filtering process by which one tries to extract information from the observations in order to reduce the errors in the a priori state. The underlying assumption is that weather forecasting is an initial condition problem; hence, for a given weather forecast model, the improvement of the initial conditions should improve the forecast results.

The minimization of the cost function in model space relies on the following key assumptions: all error sources present a zero-mean Gaussian distribution and are uncorrelated between one another (except in 3D space for a given a priori variable type), only small departures from linearity are allowed, and the error variances are correctly specified in the matrices **B** and **R**. Any departure from these assumptions may lead to sub-optimal solutions and the misinterpretation of noise as signal (or vice versa).

Ground-Based GPS. The observation operator for simulating ground-based GPS ZTD observations involves the integration of equations (1) and (2) using the model temperature, humidity, and pressure above the vertical of each GPS station location.

For each GPS station, the mean differences between the model calculations and observation are usually non-zero, indicating that either the model or the observations (or both) present non-zero mean errors. A bias correction is applied using a mean of 10 days differences. The methodology and results of assimilation of ground-based GPS ZTD in Météo-France's NWP system is detailed in the article by P. Poli et alia (Additional Resources).

The standard deviation of the differences between model calculations and observations is the sum of the a priori error variance and observation error variance, if correlations in time are disregarded. This standard deviation exhibits large seasonal variations with stronger standard deviations in the summer when more water vapor is present.

The issue of time correlations is particularly important, as GPS solutions are not derived from individual measurements but usually with a sliding window. The assimilation scheme used at Météo-France assumes observation error variances that are station-dependent and were derived using the method described in the article by G. Desroziers et alia (Additional Resources).

Space-Based GPS: Radio Occultation. The observation operator for simulating GPS radio occultation bending angles derives from work conducted at the European Centre for Medium-range Weather Forecasts. (Additional Resources: article by S. B. Healy and J. N. Thépaut). It involves the integration of equations (3) and (2) using the model fields, without applying a bias correction.

The observation error variance estimates were obtained using the G. Desroziers et alia method mentioned previously. This method has also helped show that vertical error correlations are present, possibly because of the smoothing process at Doppler shift level as suggested earlier on by simulations. Because the data assimilation system used here assumes uncorrelated observation errors, we revert to a thinning (data selection) procedure for the bending angle observations, retaining only one observation per model level and per occultation event (that is, ~20 observations per occultation up to 18 kilometers altitude).

Effect of GPS-Derived Data on NWPs

As mentioned earlier, the influence of European ground-based GPS ZTD data introduced into the Météo-France global forecasting and assimilation system was investigated previously. Over three different seasons the effect was most apparent in improved geopotential heights and, especially, in improved quantitative precipitation forecast scores over France.

Meanwhile, data collected by the GPS radio occultation technique have been available in near real-time to national meteorological services since February 2007. Several impact studies of these data have been conducted at Météo-France.

For example, data presented in Figure 3 show that the greatest positive impact can be found in analyses of the Southern hemisphere's troposphere. Note that *in situ* measurements are less dense and forecast error is typically greater for Météo-France's global model in that region.

Overall, these demonstrated benefits have resulted in Météo-France using the ZTD data and GPS radio occultations for its NWP operations since September 2006 and September 2007, respectively.

Applications for Climate

Atmospheric observations can serve climate-monitoring purposes provided that they feature a proven high accuracy and a long-term stability. With GPS-based measurements, the raw observable is a number integer (and fraction) of the GPS wavelength, whose stability is guaranteed by the atomic clocks onboard the GPS satellites, which are themselves calibrated daily with atomic clocks on the ground. Hence, GPS-based measurements of atmospheric delay are calibrated indirectly with atomic clocks.

At this stage of development in the measurement process, no other meteorological metric available today can claim such a calibration feature. However, these atmospheric-delay measurements (whether from space or from the ground) do not represent a quantity that can be used directly to characterize the climate.

Each step of the inversion process beyond this point of measuring signal-propagation delay requires particular scrutiny in order to demonstrate that the

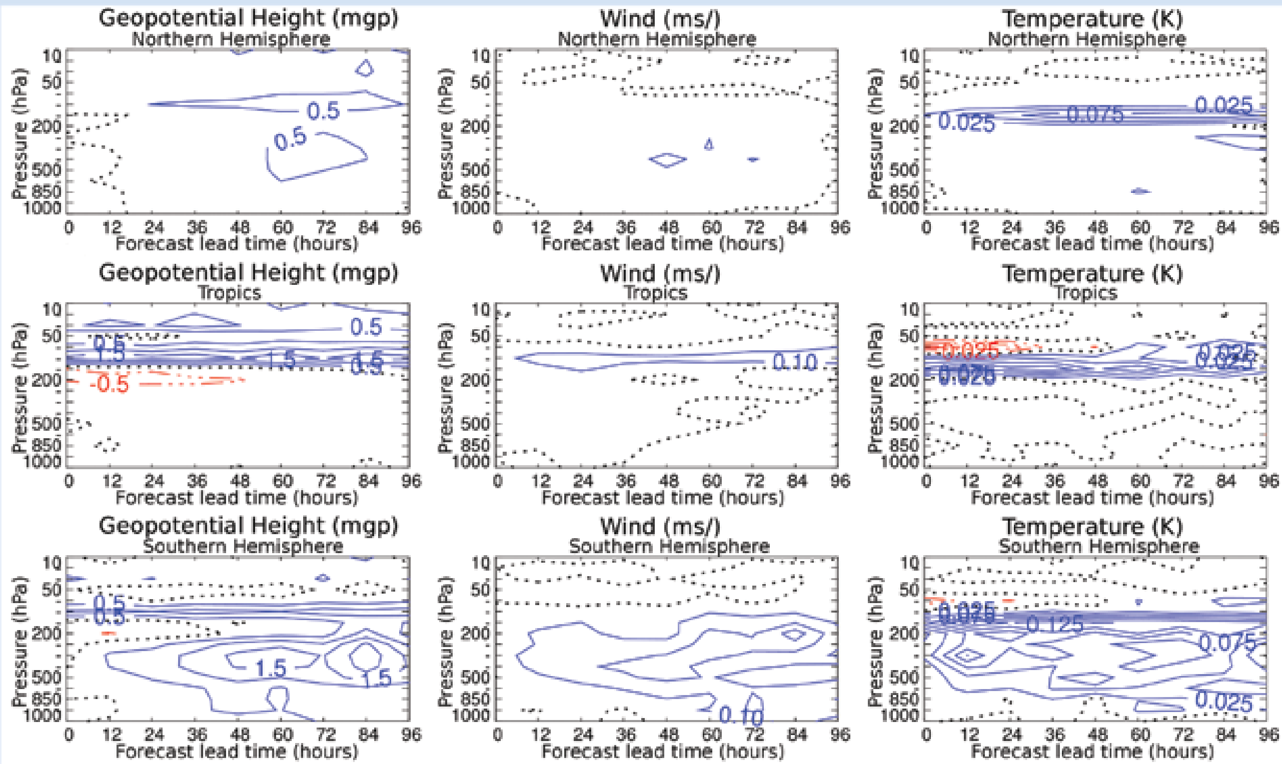

FIGURE 3 Forecast score differences for 41 forecasts (March-April 2007) to four days: RMS forecast errors from the baseline Météo-France global forecasting system (which did not assimilate any GPS radio occultation data at the time) minus similar RMS forecast errors (but when assimilating GPS radio occultation bending angles), using radiosondes as a verification, for geopotential height (in geopotential meters), wind speed (in meters/second), and temperature (in Kelvin). Solid (dotted, dashed) lines indicate a positive (zero, negative, respectively) effect, i.e., an RMS forecast error reduction (no difference, increase, respectively). The Northern hemisphere (Tropics, Southern Hemisphere) geographical domain relates to the area located between 20°N–90°N latitude (20°S–20°N, 20°S–90°S, respectively).

atomic-calibration feature is not lost to greater error sources.

Readers should note that, in the following discussion, we do not raise the questions of (1) whether the trends that are observed with ground-based and radio occultation GPS are meaningful or consistent with other measurement sources, or (2) whether the projected trends of climate change would incur signals on GPS-based measurements that would be within today's estimated GPS measurement accuracy. Instead, we discuss the reverse problem of assessing the error sources that need to be quantified in order to guarantee that GPS-based measurements present irrefutable stability and can be used for climate monitoring.

From the ground, obtaining a meteorologically meaningful ZTD requires a network of GPS receiving stations. Moreover, IWV retrievals represent a step up in difficulty for this application because they require external meteorological observations, such as surface pressure and mean temperature. The stability of these external data can only be achieved through a separate process (in particular by means of periodic calibration of the associated sensors).

Focusing thus on ZTD only, this ground-based method of IWV retrieval features several sources of error, amongst which is the ionospheric contribution correction whose errors depend on the 11-year solar cycle. The homogeneity and stability (number and position of the sites) of the overall network used for performing the ZTD retrievals could also influence the stability of the particular ZTDs retrieved from above a given site. The accuracy of the GPS orbits would also need to be stable over time.

Obviously all these errors sources would need to be taken into account in a comprehensive study in order to assess the long-term stability of ZTD retrievals. Yet, the remaining advantage of ground-based GPS for climate monitoring is that the raw data collection method "only" needs to care about properly saving *metadata* (receiver, clock, and antenna information at each receiving station, assuming that the GPS satellite visibility mask remains unchanged at the stations).

Consequently, a retrieval process (analysis method) conducted after the fact —for example, after a long time series of raw data has been collected — would need a particular strategy in order to extract a climatologically meaningful time series of ZTDs measured above a selection of GPS stations featuring consistent equipment over time.

A spaceborne GPS approach to climate monitoring removes some of the constraints associated with possible environmental influences on the measurement, only to be replaced by oth-

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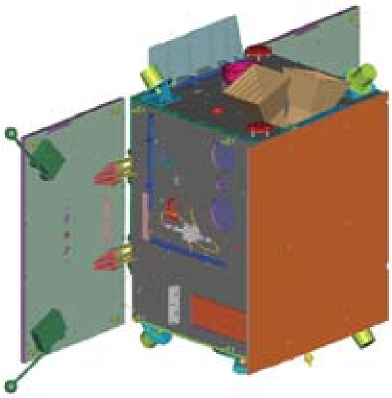
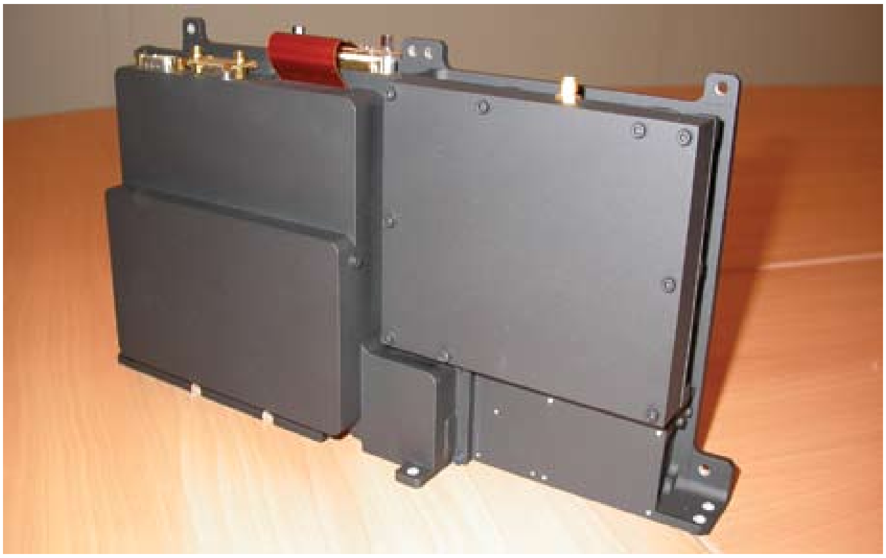


View of ESA PROBA2 microsatellite



(right) L1-L2C receiver delivered for PROBA2

ers. For example, the variation of satellite orbits and of the number of GPS transmitters over time can influence the mean local time (sampling) conditions for a given location.

Also, although the hardware on a given receiving satellite will not change over time, studies of current missions have shown that the on-board software used to track occultations can influence the quantity of measured events. This affects event sampling and can cause an artificial sampling bias change.

Assuming that a receiver's orbit-determination accuracy is not a limiting factor (below 0.05 mm/s), the first source of error that would need to be evaluated more carefully is the removal of the ionospheric contribution (signal delays).

This source of error (whose effects would become apparent over the course of 11-year solar cycles) can influence the quality of atmospheric refraction measurements for three reasons: because a combination of signals on two frequencies may only correct for the first term of the expansion of the Appleton-Hartree equation for ionosphere dispersion (thus leaving higher-order, frequency-dependent effects uncorrected), because the two radio paths at L1 and L2 in the ionosphere may differ significantly in a strongly perturbed ionosphere (and thus combining the two cannot help determine completely the ionospheric signal), and because the L2 signal cannot be tracked all the way during an occultation because of its low signal-to-noise ratio (thus requiring an extrapolation).

Quantitative upper bounds for climate-observation candidates have been determined in accordance with the levels of atmospheric signal one attempts to detect for various parameters. (See article by G. Ohring et alia cited in Additional Resources.) For example, the accuracy of temperature measurements for climate should be better than 0.5 K and their stability should be better than 0.04 K per decade in the troposphere (i.e., less than $4 \cdot 10^{-3}$ K/year). The article by A. J. Mannucci et alia (and references therein) cited in Additional Resources reports on first efforts to characterize GPS radio occultation measurement stability and accuracy with a traceability to the raw measurement.

New Receivers and Signals

To improve GPS radio occultation measurements and precise orbit determination with GPS (among other tasks), the European Space Agency developed with CNES support a qualified, second-generation, dual-frequency spaceborne GPS receiver based on commercial equipment, which uses the new L2 civil signal (L2C) in addition to GPS L1. The receiver is also compatible with ground-based C/A-code pseudolites having an RNSS uplink frequency (Lp signal = 1340 MHz).

This receiver will be used for the first time in orbit in 2009 on board the European Space Agency's PROBA-2 LEO microsatellite. The receiver's mass is close to one kilogram, making it easy to use on board small platforms.

The CNES R&D program enabled preparation of a detailed specification for the atmospheric radio occultation software to be loaded or uploaded later onto this type of receiver. Météo-France assisted development of this specification by supplying an atmospheric-delay dynamic model appropriate for radio occultation, to properly tune the high rate, phase locked loop tracking the GPS carriers. The realization of this radio-occultation software will start in early 2009.

The deployment of the GPS satellites broadcasting L2C signals is quite rapid, with 22 such spacecraft expected to be in orbit within five years. The building up of a full constellation of L2C-transmitting satellites is important, because the U.S. government has announced plans to discontinue guaranteed access to the legacy L2 signals for use in so-called codeless or semi-codeless techniques. These techniques have been widely used for the types of meteorological applications discussed in this article.

On September 23, 2008, the office of the U.S. Assistant Secretary of Defense for Networks and Information Integration (ASD-NII) published a notice in the U.S. *Federal Register* confirming the U.S.

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government's plan to phase out support of codeless and semi-codeless access to the legacy GPS L2 signals by December 31, 2020. The U.S. government wants to encourage the civilian user community to migrate to new GPS equipment that can use the next-generation signals known as L2C and L5, as well as the current L1 C/A code.

This policy decision means that L1-L2C spaceborne GPS receivers will become the basic equipment for GPS-only precise orbit determination and/or radio occultation for any mission that could potentially continue after 2020.

Prospects for Galileo

The future Galileo system should bring about a number of improvements to the GPS-based observing systems discussed in this article so far.

First, for the second frequency required for ionospheric correction Galileo will present a higher signal-to-noise ratio than the current GPS L2. This is not so critical for the ground-based GPS measurements (except for a real-time meteorological application) as it is for the GPS radio occultation.

Indeed, that latter technique currently relies on ad hoc receivers (semi-codeless) or complex antenna schemes in order to be able to collect L2 measurements, while extrapolation is needed for tracking in the lower atmosphere. With Galileo the measurement process should be simplified in that respect.

Second, the ability for a future dual-constellation receiver to track both GPS and Galileo satellites will mean that the number of links (raw measurements) is multiplied by about two, thus yielding potentially twice as many independent observations.

Third, the future climate records from ground-based GPS or GPS radio occultation measurements on the GPS system itself would not rely on a single GNSS system. Galileo will make it possible to compare the potential drifts observed in measurements collected from either system.

Fourth, the surge in commercial applications from Galileo may contribute to making GPS and Galileo receivers' basic components more affordable and supporting improved baseline designs for scientific receivers.

Fifth, the generalized deployment of several ground (or spaceborne) networks (or constellations) of GPS and Galileo receivers could enable meteorologists to collect a wealth of measurements of opportunity. This would be possible if GPS receivers were able to conduct their primary functions of positioning (orbit determination) and timing while at the same time collecting scientific measurements with a common baseline receiver design. The amount of data collected (especially for spaceborne receivers) could be tremendous and achieved at a very little additional cost.

The more promising frequencies to be used in the future for multiple

constellation radio occultation receivers will be the ones commonly used by several systems. For instance, the case of two worldwide GNSS constellations with two confirmed common central frequencies is today unique, with GPS and Galileo and E1/L1 + E5a/L5 frequencies.

Of course, for high-end, heavy radio occultation receivers, "all frequencies in view" or "all constellations in view" (GPS/Galileo/Compass/GLONASS/IRNSS/QZSS, for instance) are better from a radio science perspective. In particular, simultaneous use of the four Galileo frequency bands — E5a, E5b, E6, and E1 — offers the possibility to directly solve the high-order terms of the ionospheric delays, to improve carrier phase ambiguity resolution and related robustness, and to obtain more accurate measurements. The use of Compass and Galileo E5b signals already being transmitted on a common frequency also looks promising, like the use of common E6 central frequency by QZSS and Galileo and probably at least another GNSS system.

Conclusions and Perspectives

Within only 10 years of the initial deployment of the GPS system, operational ground-observation networks have been set up over Europe, Japan, and the United States. At first these typicallywere for geodetic purposes, but now they enable the collecting, processing, and distributing of GPS atmospheric delay measurements to national meteorological services.

Measurements of atmospheric refraction can also be collected via the GPS radio occultation technique, which involves GPS receivers in space. Recent examples include the six-satellite constellation FORMOSAT-3/COSMIC and the GRAS (GNSS Receiver for Atmospheric Sounding) instrument on-board the MetOp satellite.

Since September 2006 and 2007, the national weather service of France, Météo-France, has been using data sets from European ground-based GPS networks and from satellites equipped with GPS radio occultation receivers for updating its operational weather prediction analyses. This decision was made after it was shown that these respective observations helped improve quantitative precipitation forecasts, and predictions of temperature and wind. More progress is expected as the number of such observations may increase; the ground network of GPS receivers is due to expand worldwide, and more satellites may carry GPS receivers of radio occultation grade.

Overall, the use of the GPS signals for meteorological observations is a good example of a measurement of opportunity in which large number of transmitters and all-weather availability have enabled meteorologists to gather ever more measurements of our atmosphere in near real-time. The potential of these observations for climate studies is significant, but further detailed sensitivity studies are required in order to evaluate the effects of possible sources of interruptions in measurements as well as trends in the stability of time-series measurements being collected.

The prospects offered by the Galileo system to meteorologists using GPS-based measurement may include improving ionospheric characterization (and correction), increasing the number of collected measurements, avoiding the reliance of such measurements on one system only (GPS), and (perhaps most importantly) collecting a large number of measurements of opportunity at very little cost.

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Manufacturers

The dual-frequency GPS receiver to be used on the PROBA-2 satellite is a modified version of the TOPSTAR 3000 from **Thales Alenia Space**, France, with involvement of **Sideral,** Switzerland, and **Nordspace,** Norway.

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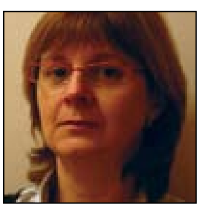
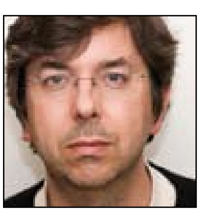
Authors

Paul Poli has led research at the NASA Goddard Space Flight Center and at Météo-France on the use of GPS data for numerical weather prediction. He finalized this work with the operational application of these data at Météo-France. He received his Ph.D. from the University of Maryland, Baltimore County, USA, and recently joined the weather reanalysis team of the European Centre for Medium-range Weather Forecasts.

Jean Pailleux, Ph.D., is currently deputy director of Météo-France research center. He helped implement the early and recent methods of data assimilation at the European Centre for Medium-range Weather Forecasts and at Météo-France. His work was instrumental in helping satellite data make the impact they have today in operational meteorology. He regularly serves as an expert for the World Meteorological Organization.



Véronique Ducrocq, Ph.D., is currently head of the research division on mid-latitude convection in Météo-France research center. She directs research to enhance the understanding and predictability of mid-latitude precipitating systems and severe weather events. Her work has promoted the use of GPS observations in meteorology to improve quantitative precipitation forecast for thunderstorms.



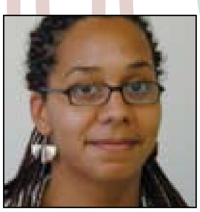
Patrick Moll is currently involved with observations handling in Météo-France numerical weather prediction system. He contributed to the research that lead to the operational assimilation of ground-based GPS data over Europe. He also contributed to the implementation of modern variational techniques at Météo-France and the European Centre for Medium-range Weather Forecasts.

Florence Rabier, Ph.D., is currently head of the observations team in Météo-France's numerical weather prediction research center. Between 1992-1998 she carried out pioneering work at the European Centre for Medium-range Weather Forecasts on four-dimensional variational data assimilation. This algorithm, still considered state-of-the-art today, is used by meteorological agencies worldwide.

Michel Mauprivez is currently deputy head of the Upper-air Observations Department of Météo-France. He joined Météo-France in 1996 after a career in the French Air Armed Forces where he held responsibilities as a telecommunications and radar Officer. His work at Meteo-France involves improving the observation network for real-time water vapor monitoring, capitalizing on existing GPS networks.

Sylvie Dufour is currently head of the Observations Prospective, Coordination and Studies Department of Météo-France. She recently helped forge an agreement with the Institut Géographique National to secure the provision to meteorology of GPS data originally intended for geodesy. She joined Météo-France from the public sector and is interested in maximizing the benefits of public-funded infrastructure.

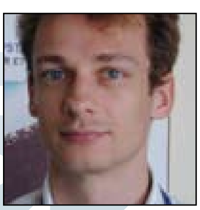
Michel Grondin has been working at CNES since 1981. He was responsible for the GPS receiver equipment on the DEMETER micro-satellite. Since July 2005 he has been working in the Transmission Techniques and Signal Processing Department. He provided support to the integration of the GPS receiver of the Alpha Magnetic Spectometer (AMS) experiment to fly on board the International Space Station. He also tuned CNES GPS L5 software receiver for use in low earth orbit with the aid of a GPS simulator. He graduated from the Ecole Superieure d'Electricité (Supélec) in Paris.



Françoise Lechat-Carvalho has been a propagation and signal processing engineer at the Transmission Technique and Signal Processing Department of CNES since 2006. She studies the propagation of GNSS signals through the troposphere and the ionosphere, the characterization of these atmospheric layers with the use of GNSS, and the propagation channel for navigation and mobile telecommunications in S-band. She is involved in the Indian-French GSAT4/GAGAN Ka-band propagation experiment. She was graduated in electronics and communication systems engineering from Institut National des Sciences Appliquées in Rennes.

Jean-Luc Issler is in charge of the Transmission Techniques and Signal Processing Department at CNES. He is involved in the development of several types of GNSS, FFRF, and TMTC equipment in Europe, for space or ground users. Issler is the French delegate to the Galileo Signal Task Force. He received in 2004 the Astronautic Prize of the AAAF (French aeronautical and space association), and in 2008 the EADS Prize of science and engineering delivered by the French Academy of Sciences, mainly for his technical work on Galileo signals and spaceborne GNSS equipment.

Antoine de Latour has been a navigation engineer in the CNES Transmission Techniques and Signal Processing Department since 2003. He is involved in the Galileo Program in which he supports the European Space Agency and the European Commission. De Latour is involved in the design of the Galileo signals, in the use of GNSS for space applications, in the GPS/Galileo radio frequency compatibility assessment, and in the development of a GNSS RF signal simulator. In particular, he studied in depth the CBOC Galileo signal definition and the PRS signal. De Latour proposed new tracking signal techniques for generic receivers and spaceborne receivers. He was graduated from the Ecole Supérieure d´Electricité (Supélec) in Paris and obtained a master's degree from the University of Stuttgart.



Lionel Ries has been a navigation expert in the Transmission Technique and signal processing (TT) Department at CNES since June 2000, where he coordinates navigation technical activities. He is responsible for research activities on GNSS2 signals, ground and spaceborne receivers, payloads, and systems. He contributed to the invention of the CBOC signal. He provided support to the 2004 US-EU agreement on GPS and Galileo. He was responiable for the development of the L1-L2C signal processing algorithms now implemented in the ASIC and processor of the TOPSTAR 3000 receiver, in the frame of a CNES R&D activity. He graduated from the Ecole Polytechnique de Bruxelles, at Brussels Free University, and received an M.S. degree from the Ecole Nationale Superieure de l'Aeronautique et de l'Espace (Supaero) in Toulouse. IG

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