Atmospheric and Ocean Sensing with GNSS

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Summary. The 1980s and 1990s saw the Global Positioning System (GPS) transform space geodesy from an elite national enterprise to one open to the individual researcher. By adapting the tools from that endeavor we are learning to probe the atmosphere and the ocean surface in novel ways, including ground-based sensing of atmospheric moisture; space-based profiling of atmospheric refractivity by active limb sounding; and global ocean altimetry with reflected signals. Ground-based GPS moisture sensing is already being tested for weather prediction. Limb sounding is less mature but offers a variety of attractions, including high accuracy, stability, and resolution; all-weather operation, and low cost. GPS "reflectometry" is least advanced but shows promise for a number of niche applications.

Key words: GPS, GNSS, occultation, limb-sounding, bi-static radar, reflectometry

1. Introduction

GPS atmospheric sounding first arose as a necessary element of ground-based GPS geodesy. It had been recognized from the earliest days that the effects of atmospheric moisture would ultimately limit the accuracy of space geodesy [e.g., Davis et al., 1985]. A good deal of attention was therefore given to possible calibration techniques. One of the most effective strategies involved modeling the zenith delay as a random walk and estimating a delay correction at every time step – typically every few minutes [Lichten and Border, 1987].

Although zenith delay estimates were at first treated as "nuisance" parameters, it was soon found that with reliable surface pressure data to calibrate the "dry" delay, these estimates provided measurements of the wet delay as accurate as any known [Elgered et al., 2003]. The wet delay solutions can be readily converted to estimates of precipitable water (PW) for use in weather and climate modeling. Alternatively, the delay estimates can be assimilated directly into weather models [Ha et al., 2003; Ridal and Gustafsson, 2003]. It quickly became evident that GPS networks could provide a windfall of atmospheric moisture data – one of the most critical quantities for numerical weather prediction (NWP).

2. Atmospheric Sounding from Space

In the late 1980s a few groups began to consider the possibility of atmospheric limb sounding from Earth orbit by active radio occultation, using GNSS signals as sources. This was inspired by the success of planetary radio occultation over the

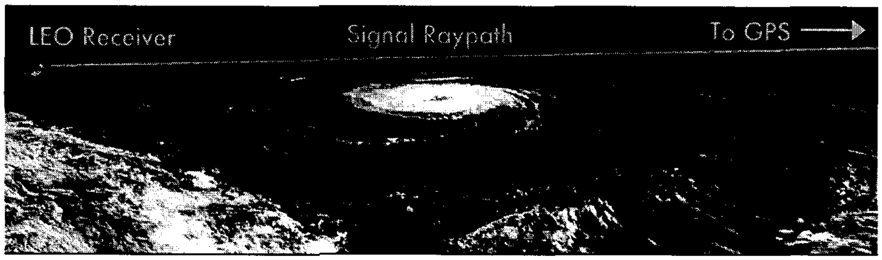

Fig. 1. Observing geometry for atmospheric limb sounding by GPS radio occultation.

previous 25 years, beginning with the 1964 Mariner IV mission to Mars [Fjeldbo, 1964; Kliore et al., 1964]. Although Earth radio occultation was suggested in the 1960s, the first practical GNSS technique did not appear until Yunck et al. [1988]. The first GPS occultation flight experiment was GPS/MET, led by the University Corporation for Atmospheric Research (UCAR) in Boulder [Rocken et al., 1997].

Figure 1 illustrates the GNSS occultation geometry. A low Earth orbiter (LEO) tracks GNSS signals as they rise and set through the atmosphere, measuring the changing carrier phase at both L-band frequencies. The atmosphere acts as a lens, bending and retarding the signals, inducing an additional path delay that leads to additional accumulated phase and a Doppler shift. Depending on the observing geometry, it may take a minute or more for the observed signal to pass from the top of the atmosphere (~100 km altitude) to the surface, or vice versa. Since the changing geometry is dominated by the rapid motion of the LEO, most soundings occur within ±45° of the forward and reverse velocity directions.

Radio occultation differs fundamentally from ground-based zenith delay estimation. Because we are looking at (usually) a single ray traversing the atmosphere horizontally, we obtain extremely high vertical resolution – of the order of 100 m from the surface to the stratosphere. Moreover, the technique yields a diversity of atmospheric parameters distributed evenly around the globe, enabling a broader variety of applications [Anthes et al., 2000]. In addition, from the precisely known observing geometry we can compute the effective absolute height of each measurement to better than 10 m, enabling the computation of precise pressure gradients, contour maps, and such derived products as geostrophic wind fields in the troposphere and stratosphere. This ability to recover precise "geopotential heights" is unique among spaceborne sensors.

2.1 Performance

A geodetic receiver can measure the instantaneous carrier phase rate to a few mm/sec. With GNSS-based precise LEO orbit determination, we can isolate the atmospheric Doppler shift to better than 0.1 mm/sec. At 70 km altitude the excess atmosphere path delay is negligible; at the surface, it can reach 2.5 km, with rates exceeding 100 m/sec, or nearly a million times the measurement precision. The standard occultation analysis assumptions – local spherical symmetry, hydrostatic equilibrium, mixing ratios of atmospheric constituents – while imperfect, are good in most instances and result in relatively small refractivity errors.

Extensive studies [Kursinski et al., 1997; Hajj et al., 2002] suggest that because the major errors tend to be random or quasi-random, averaging of multiple profiles for long-term climate studies could yield an effective temperature error of less than 0.1 K. That assessment includes expected long-term bias variations; that is, the averaged profiles may be absolutely accurate, independent of the instrument used or the time flown, to better than 0.1 K over a sizable altitude range, an improvement by a factor of anywhere from 10 to 40 over current global techniques.

2.2 Climate Signal Detection

Perhaps the greatest concern in Earth science today is global climate change. A central question is whether Earth has entered a period of accelerated warming and, if so, to what extent this may result from human activity [e.g., Mann et al., 2003]. To discern the effects of various drivers we require precise data from all levels of the atmosphere, something that at present is extremely difficult to obtain globally.

Human-induced global warming may be in the range of 0.1-0.3 K per decade at the surface [Houghton et al., 1990], and even subtler (or reversed) in upper strata. To identify such faint signals we require great precision and long-term stability in our sensors – a level of 0.1 K/decade or better. Current spaceborne sensors fall well short of this. The sensor suite is dominated by passive radiometers, primarily IR and microwave, including MODIS, MISR, AIRS/AMSU, MLS, and AVIRIS. Although great ingenuity is employed in the design and operation of these instruments to maintain precise calibration, on the scale of a decade or more this is extremely difficult to achieve. Sensor aging and replacement with new designs undermine stability. Over a decade or more, the best that can reasonably be achieved with these systems is ~1 K absolute stability.

In an open solicitation released in 2002, NASA declared: "Perhaps the greatest roadblock to our understanding of climate variability and change is the lack of robust and unbiased long-term global observations." They went on to say that for climate monitoring "the focus is on...construction of consistent datasets from multi-instrument, multi-platform, and...multi-year observations with careful attention to calibration...over the lifetime of the measurement" [NASA, 2002].

With GNSS occultation each profile is largely self-calibrating and virtually independent of the particular instrument used or when in its lifetime the profile is acquired. One can argue that the only evolution will be further improvement in the already exceptional accuracy as retrieval techniques and instrument characteristics are refined, and GNSS signal strength is boosted. Equally important, GNSS occultation will provide absolute calibration data that will normalize and stabilize atmospheric products from sensors now in place.

2.3 Early Experimental Results

Establishing average temperature accuracies of 0.1 K or better over an extended altitude range is difficult at best. The primary standards to date have been of two types: radiosonde data and climate analyses generated by the US National Center for Environmental Predictions (NCEP) and by the European Center for Medium-Range Weather Forecasting (ECMWF), derived by assimilating radiosonde and space data into numerical models. In neither case can we expect better than about 1 K accuracy from the comparison data.

Figure 2 summarizes more than 4000 CHAMP refractivity profiles from May and June 2001, compared with ECMWF daily analyses [Beyerle et al., 2003]. The GFZ team has used two different techniques: standard "geometric optics" as described above (blue), and a "canonical transform" technique (red) developed by Gorbunov [2002], which offers several practical advantages. The solid curves are for the whole earth while the dashed curves are for the northern hemisphere, for which, owing to more abundant data, the analyses are expected to be somewhat better. Mean offsets (left) and sigmas (r) correspond roughly to temperature mean offsets of 0.5 K and sigmas of 1-2 K, above 2-3 km. See also Hajj et al. [2003].

2.4 CHAMP/SAC-C Comparisons

Analysis prospects improved markedly when the Argentine SAC-C spacecraft carrying a second BlackJack occultation receiver was launched into a quite different orbit in November 2000. For the first time we could directly compare data from two occultation instruments, provided they occasionally observed the same region at about the same time. Such coincidences are rare but not unknown. Of more than 60,000 soundings acquired from 10 July 2001 to 9 June 2002, sixty pairs occurred within 200 km and 30 min of one another. Of those, fewer than 30 pairs were within 100 km and 30 min of one another. As these coincidences are not exact there are in fact real differences of ~0.1K between pairs.

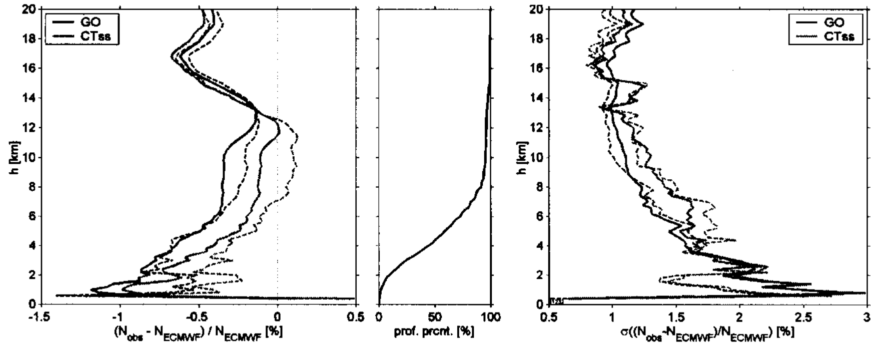

Fig. 2. Summary of 4,043 CHAMP refractivity profiles made with geometric optics (blue) and canonical transform techniques, differenced with ECMWF analyses. Standard deviations (right) and mean offsets (left) are similar to those of GPS/MET. (Beyerle et al., 2003).

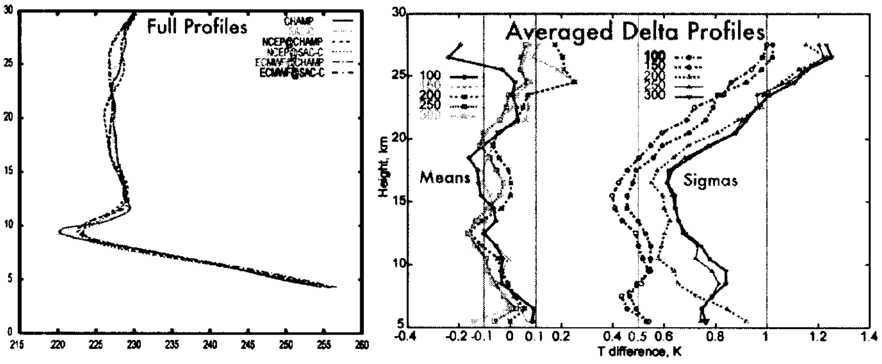

Fig. 3. Coincident profile pair from CHAMP and SAC-C plotted against NCEP and ECMWF analyses at each profile location (left); and the average differences of several dozen coincident pairs at five different maximum separations (right). (Hajj et al., 2003)

Figure 3 compares CHAMP and SAC-C occultations. The left panel shows a typical coincident pair (solid red and green) plotted together with standard NCEP and ECMWF analyses for the locations and times of the two profiles. What stands out is the closeness of the occultation profiles despite their differences in space, time, and observing angle. Both differ noticeably from the analyses, which are similar to one another but lack fine vertical detail. As the weather analyses involve a fair degree of smoothing, they cannot reliably capture such sharp features as the tropopause at ~9.5 km shown in the occultations. That two occultations acquired from different angles agree so exactly in this detail is compelling.

Figure 3 also shows the mean differences and sigmas for all occultation pairs coincident within 30 min, for maximum separations ranging from 100 to 300 km. Between 5 and 25 km altitude the average differences fall within or near 0.1 K. Compare this with Fig. 2 showing differences with the weather analyses, in which the mean offsets are ~5 times greater. For the closest pairs, the sigmas (which represent the combined errors of two profiles) are near 0.5 K at 20 km and below. These increase for wider separations, presumably because of actual differences between the sampled locations. For further discussion see Hajj et al. [2003].

These results are far from conclusive; there could well be common biases or trends in the occultation profiles not revealed in the comparisons. Indeed, we know that at higher altitudes where the bending is small and the retrieval is initialized (above 30 km), and also near the surface where the observations can become corrupted by complex atmospheric effects, biases can creep in. The causes of such biases, however, are well understood and refined techniques are now in development that promise to reduce them considerably.

Perhaps the greatest appeal of GNSS occultation is its potential for improving weather forecasts. As yet, with the still meager volumes of high quality data, little has been accomplished in the way of data assimilation and impact studies. But what has been done is encouraging. Preliminary assimilation studies have been reported by Zou et al. [2003], Healy et al. [2003], Kuo et al. [2003], and Aoyama et al. [2003]. Despite the sparseness of the data sets, all four report improvements in forecasts of various kinds – some going out 4 or 5 days – when occultation data were included. Healy, who typically assimilated only 40 profiles at once, comments that the "results are very encouraging [and] support the case for assimilating RO measurements operationally."

Despite these successes GNSS occultation science is still in its infancy. The gulf between the tens of daily profiles available today and a future of tens of thousands is beyond our power to bridge by intuition. In the box below we tabulate seven key attractions – the seven cardinal virtues – of GNSS limb sounding. Soon, this simple trick of radio metrology may offer a key to one of the most vexing problems in Earth science: discerning the faint signatures of global climate change. Its potential for comprehensive real-time monitoring of the global troposphere has equally profound implications for weather prediction.

Principal Attractions of GNSS Occultation

- Offers order-of-magnitude improvement in accuracy and long-term stability;
- Operates undiminished in all weather, day or night;
- Offers near-uniform global coverage from the stratopause to the surface;
- Provides unrivalled vertical resolution, to better than 100 m near the surface;
- Yields absolute geopotential heights to <10 m, permitting derivation of global pressure contours and non-equatorial geostrophic wind fields;
- Exploits different physical principles from other atmospheric sensors, remote or in situ, presenting an independent comparison and calibration standard;
- Requires only a palm-sized digital module costing less than 1 % of the tens to hundreds of M$ of many of today's passive sensors.

3. GNSS Surface Reflection

Traditional radar altimetry (e.g., Jason-1) observes vertically, obtaining one nadir height at a time. Bistatic GNSS, by contrast, can track a dozen or more reflections from many angles at once with one LEO receiver. This offers the prospect of higher temporal and spatial resolution for discerning finer scale, short-lived features, such as mesoscale eddies [Treuhaft et al., 2003], which play an important role in the transport of momentum, heat, salt, nutrients, and chemicals within the ocean. Hajj and Zuffada [2003] show that eight orbiters acquiring GPS and Galileo reflections could provide global 3-cm ocean heights in 1 day at 200-km spatial scales, or sub-decimeter heights in 4 days over 25-50 km scales.

While the technical feasibility of bistatic GNSS is clear, it remains to be seen whether the technique will offer practical advantages over alternative approaches, such as wide-swath altimetry [e.g., Rodriguez, 2001] or simply flying multiple nadir altimeters [Raney, 2001]. Here we consider some basic requirements and configurations for a practical bistatic GNSS system.

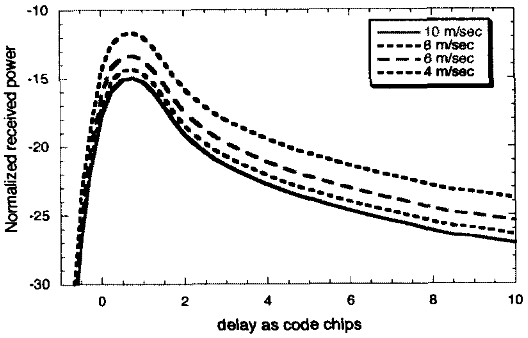

Fig. 4. Hypothetical cross-correlations of a GPS reflection with a model signal at many different lags, for four different surface wind speeds.

3.1 Basic Principles

Because the ocean is rough, a GNSS signal reflects to an orbiting receiver from an extended portion of the surface. A given wavefront will arrive first from the specular reflection point; decreasing energy will then come in from surrounding points, with greater delays. By cross-correlating the received signal against a model signal at many different delays, one can precisely map the returned energy vs delay. The function rises abruptly then decays gradually as weaker outlying reflections trail in, as illustrated in Fig. 4. The detailed shape of this function contains a good deal of information about the ocean surface.

The sharp leading edge of the correlation function permits precise determination of the arrival time – and hence total delay – of the reflection from the specular point; from that delay, along with other geometrical modeling information, one can derive an estimate of the ocean height at that point. Detailed analysis of the shape of the correlation tail can reveal information about the surface roughness, significant wave height, and wind speed.

Among the challenges in making such measurements are the weakness of the reflected signals at orbital altitude and the rapid signal de-coherence due to ocean roughness. The latter implies that under most ocean conditions and viewing geometries we cannot acquire the continuous GNSS precise phase observable.

3.2 Occultation / Reflection Synergy

There are, however, reasons for optimism. For a given delay measurement precision, the greatest sensitivity to ocean height occurs at nadir. Reflected signal quality, however, is poorest at nadir, owing both to lower returned signal strength and greater decoherence. Moreover, for a given solid angle the number of reflections to be seen is least at nadir. At the horizon, the average number of reflections per unit solid angle is fully two orders of magnitude greater than at nadir.

Figure 5 illustrates the distinct geometries for nadir and near-limb reflection sensing. The Rayleigh criterion tells us that for GNSS nadir reflections the ocean scatters coherently only for wave heights $h < 2$ cm; near the horizon, however, this

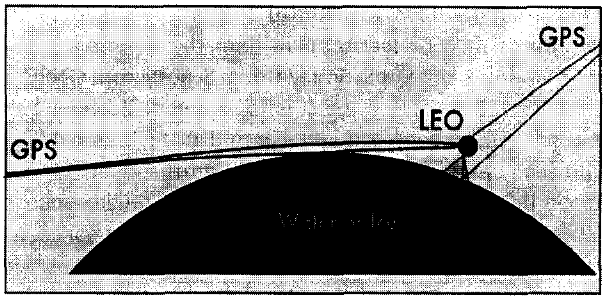

Fig. 5. The differing geometries of reflections acquired near nadir and at the horizon.

occurs for h <1 m. The former condition is almost never satisfied while the latter is satisfied much of the time, offering the prospect of precise off-nadir altimetry.

As it turns out, this is more than just a prospect. One of the bigger surprises of CHAMP and SAC-C atmospheric analysis was the discovery of glancing reflections at the horizon in a high percentage of occultation profiles.

The CHAMP science team at GeoForschungsZentrum (GFZ) in Potsdam has done a thorough study of these reflections, with promising results [Beyerle et al, 2002]. Figure 6 shows all occultations acquired by CHAMP over a 4-week period in the spring of 2001 (blue dots) together with all detected reflections (red circles). The first thing we notice is the relative absence of reflections in the tropics. This is presumed to owe to the combination of dense tropical moisture, which inhibits the penetration of all signals; the attenuation from the PN code offset; and the less frequent penetration of tropical occultations sufficiently close to the surface to yield the required small delay offsets. With coming refinements in "open-loop" signal acquisition [Sokolovskiy, 2002] and onboard modeling of the reflections, this shortfall should be alleviated.

Also evident in Fig. 6 is the presence at high latitudes of reflections in almost equal densities from water and ice, offering the possibility of cryosphere as well as ocean sensing. In fact, at high latitudes nearly all occultations occurring over water or ice are accompanied by a detectable reflection. We are thus seeing an unexpected convergence of GNSS occultation and reflectometry.

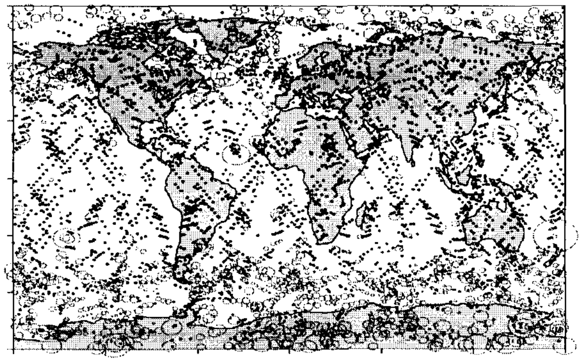

Fig. 6. Occultations acquired by CHAMP over 4 weeks in 2001 (blue dots) and accompanying reflections (red circles). Circle size indicates relative signal strength. (From Beyerle et al., 2002)

Beyerle et al. show that the reflected Doppler shift depends on the height of the reflecting surface, its slope (when ice), and the moisture density of the atmosphere, and argue that in different circumstances the signal may be used to estimate each of these. It is, however, too early to tell whether these serendipitous signals will provide information of real science value.

4. Future Prospects

The question arises, how many sensors are enough? Much is expected for atmospheric science from the first six or eight. For ocean reflections, we've seen that a dozen or so could be of value. A hint of an upper limit on useful numbers comes from a science panel convened by NASA in 1997 in Easton, Pennsylvania. Their charter was to assess the scope of Earth remote sensing data needed in the next 10-15 years to address NASA's Earth science agenda. The panel endorsed an occultation constellation providing global profiles with an average horizontal spacing of 50 km, twice per day, to initialize numerical weather models. That converts to about 400,000 profiles per day. Achieving such numbers with a 60-satellite GNSS constellation will require 250-300 LEO sensors. A constellation of six or eight occultation receivers will no doubt be incomparably superior to none. But in view of the rich history of GNSS-based science we have little doubt that the dividends will grow steadily with larger numbers, even into the hundreds.

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