GPS: A New Tool for Ocean Science

Attila Komjathy
University of Colorado at Boulder

James L. Garrison
NASA Goddard Space Flight Center

Valery Zavorotny
Cooperative Institute for Research in Environmental Sciences, National Oceanic and Atmospheric Administration, Environmental Technology Laboratory

There is an old adage in science and engineering: One person's signal is another person's noise. Most GPS users consider signals arriving at their receiver's antenna from nearby reflecting surfaces (multipath) to be noise, as their presence reduces positioning accuracy by interfering with the signals received directly from the satellites. Some researchers, however, are using GPS signals reflected off the ocean surface as a valuable new information source in remote-sensing applications. By analyzing the reflections, they can determine such characteristics as wave heights, wind speeds, and wind direction. In this month's column, one group of researchers describes this innovative remote-sensing technique and some of the interesting results it has already obtained.

The authors are Attila Komjathy, James Garrison, and Valery Zavorotny. Dr. Komjathy, a research associate at the University of Colorado's Center for Astrodynamics Research, received his Ph.D. from the University of New Brunswick in 1997. His dissertation, on ionospheric total electron content mapping using GPS, won a Canadian Governal General's Gold Medal. Dr. Garrison, a research scientist with NASA's Goddard Space Flight Center, received his Ph.D. in 1997 from the University of Colorado. His present research focuses on developing GPS receiver software and retrieval algorithms for estimating geophysical parameters from reflected signals. Dr. Zavorotny is a research scientist at the Cooperative Institute for Research in Environmental Sciences, National Oceanic and Atmospheric Administration, Environmental Technology Laboratory in Boulder. With a Ph.D. awarded by the (former) U.S.S.R. Academy of Sciences' Institute of Atmospheric Physics in 1979, he is investigating optical- and radio-wave propagation through random media, wave scattering from rough surfaces, and oceanographic remote-sensing techniques.

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the "Columnists" section on page 4.

Multipath is a common error source affecting GPS use for positioning and navigation. Researchers have only recently recognized, however, that a special kind of multipath — that from GPS signals reflected off the sea surface — can be used as a tool for oceanographic remote sensing.

Because ocean surface roughness affects GPS signal reflection, researchers can use the resulting multipath signal to determine such factors as wave height, wind speed, and wind direction. The reflected signal's strength is also a discriminator between wet and dry ground areas and, therefore, could be applied to coastal and wetland mapping. In some ways, this GPS application's discovery was similar to that of using GPS to map the ionosphere's total electron content (TEC) by measuring propagation delay differences between the L1 and L2 frequencies. In both cases, scientists recognized that a phenomenon usually regarded as a positioning error source actually contains useful scientific data.

To achieve high resolution, conventional radar remote-sensing of the oceans requires dedicated transmitters and receivers with large directional antennas. Because of their special structure, however, GPS signals can provide complementary information about ocean characteristics from a relatively small patch of sea surface without the need for a directional antenna. In addition, GPS only requires a receiver, not a transmitter, because the GPS satellite constellation provides illumination for free. All of this makes reflected GPS signals very attractive for use as an earth remote-sensing probe.

In this article, we demonstrate wind retrieval (estimate its speed) from reflected signals obtained by a GPS receiver on board an aircraft to illustrate the potential of using GPS for remote-sensing applications. Before showing those results, we provide some background on radar remote sensing and discuss the theoretical model we used to interpret reflection data. This model describes the power and correlation properties of the reflected GPS signals as a function of scattering geometry and environmental parameters related to the reflecting surface.

BISTATIC SURFACE SCATTERING

In radar remote-sensing nomenclature, we can characterize GPS as a *bistatic radar scatterometer*. Bistatic radar uses a transmitter and receiver separated by a distance comparable to the target distance and records the forward scatter from the transmitter in the direction of the receiver. In contrast, monostatic radars employ a transmitter and receiver at the same location (often times using the same antenna) and measure the backscattered radiation. Although the majority of radars in use today are monostatic, it is interesting to note that early military radars were bistatic. In the past, bistatic radar systems employing an orbiting transmitter and an earth-based receiver have been used for lunar and planetary explorations.

In addition, microwave ocean remote-sensing experiments were conducted in the United States in the seventies using bistatic scattering that employed a communication satellite transmitter and airborne receiver. In the early nineties, Russian researchers also performed an experiment with a spaceborne bistatic scheme for ocean remote sensing. For the experiment, they mounted a narrow-band decimeter radiation transmitter on a low-orbit satellite and a receiver on a geosynchronous communication satellite.

In 1993, the European Space Agency's Manuel Martín–Neira first suggested using GPS satellites as a signal source for bistatic surface scattering. He proposed a concept for ocean altimetry using reflected GPS signals. Subsequently, in 1994, French engineers reported the accidental acquisition of ocean reflected GPS signals by an aircraft receiver. Two researchers at the National Aeronautics and Space Administration's (NASA's) Langley Research Center, Stephen J. Katzberg and James L. Garrison, recognized the potential of these reflected signals for oceanographic and ionospheric remote sensing.

Katzberg and Garrison first analytically predicted the change in GPS signal structure following an ocean reflection. Then, they experimentally demonstrated the intentional tracking of the reflected signal from an aircraft using a left-hand circularly polarized (LHCP) antenna and a conventional geodetic-quality GPS receiver. (Upon scattering, the right-hand circularly polarized [RHCP] GPS signal reverses its polarization to become a predominantly LHCP signal.)

These researchers further predicted that several geophysical parameters influence GPS-signal interaction with the earth's surface. For instance, if the sea surface is reasonably calm, then the surface resembles a mirror and any GPS satellite appears (figuratively) as an image behind the mirror. Because the additional distance traversed to the aircraft or spacecraft (in low-Earth orbit) is only a small fraction of the distance to the GPS satellite, the power of the reflected-signal is insignificantly reduced. Moreover, water's reflectance (the percentage of the intensity reflected) is more than 60 percent, resulting in only a small loss in signal power. The ocean is rarely calm enough to achieve mirror-like conditions, and as the surface becomes rougher, the signal characteristics become more complex. It is from the GPS-signal modification caused by a rough sea that we can derive perhaps the most important remote-sensing application of reflected GPS signals: wind-speed retrieval.

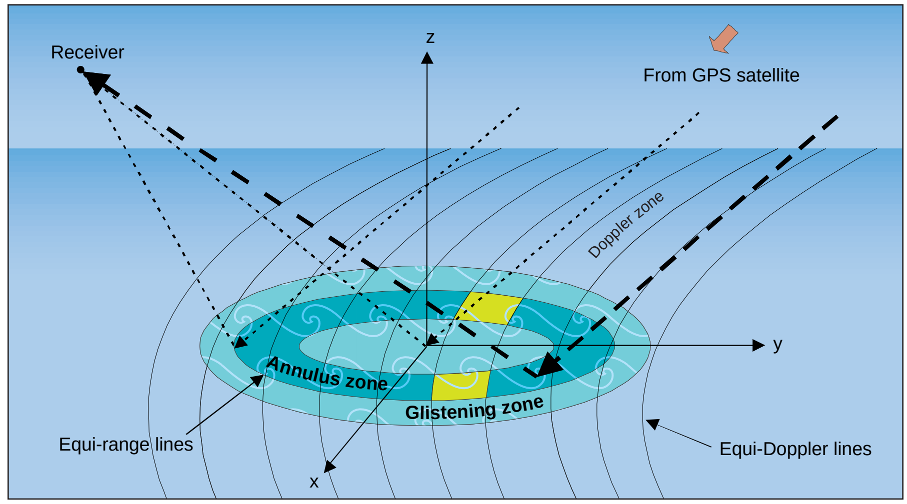

Figure 1. By combining code-range and Doppler measurements, a receiver can distinguish particular patches of the ocean surface illuminated by GPS signals.

SIGNAL MODELING

We need a theoretical model to better understand how the geometry of an experiment, the statistical and electrodynamical properties of reflecting surfaces, and other factors affect scattered GPS signals. Even without a model, however, we can make some qualitative observations by realizing that bistatic scattering is a phenomenon we experience frequently. For example, the sun and moon are natural illuminators (transmitters) of the earth's surface, and the human eye is a distant detector (receiver). The reflection of these bodies on the ocean forms a *glistening zone*, or a distinct, extended area that participates in reflecting radiation toward an observer's eye. Early studies of this optical phenomenon showed that the glistening zone's size and shape — including brightness distribution inside the zone — depend on the properties of the reflecting surface.

Because of the GPS transmitter's remoteness, one can expect to receive the scattered signal only from the area around a nominal specular point on the mean sea surface as indicated in Figure 1. In the case of nongrazing incidence, large-scale (larger than several radio wavelengths) surface components mostly produce this scattering. The power scattered toward the receiver decreases significantly as the reflection point moves away from the nominal specular point until a distance is reached at which scattering from a small-scale surface component starts to play a role.

This is the same phenomenon we experience, as mentioned earlier, when we observe — albeit in the optical part of the electromagnetic (EM) spectrum — a glistening sun or moon path on the surface of a lake or sea. With changes to the EM radiation wavelength and angular extent of the source, we have the very same physical phenomenon that is manifested in the scattering of the GPS signal from a rough surface. For convenience, we refer to the sea-surface area contributing to the quasi-specular GPS-signal reflection toward a receiver as the glistening zone, keeping in mind the optical analogy.

Theoretical Model. We can model GPS signals reflected by the ocean surface and received by an airborne (or spaceborne) receiver using the geometric optics limit of the Kirchhoff approximation for the short-wave, bistatic, rough-surface scattering problem, assuming that a downward-looking LHCP antenna intercepts only the scattered signal and is insensitive to the direct signal. (The physics of the scattering problem is quite complex and a number of great minds, including the nineteenth century German scholar Gustav Kirchhoff, have worked on the problem. Geometric optics allows us to approximate the interaction of EM waves with scattering surfaces using the concept of light [or radio] rays.) Kirchhoff approximation implies that we deal with a "smooth" rough surface that can be approximated with a tangent plane at any point on the surface.

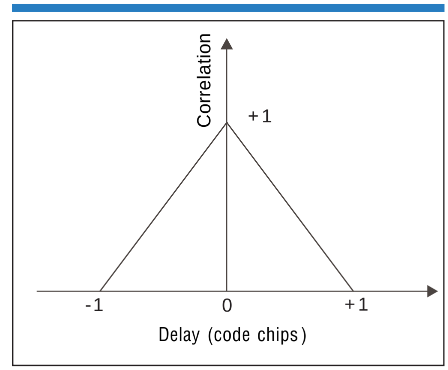

Figure 2. The lambda function defines the autocorrelation properties of the satellite PRN code.

The scattered signal arriving at the receiver is described by an equation similar to the well known bistatic radar equation, developed by researchers from the National Oceanic and Atmospheric Administration, Environmental Technology Laboratory. The equation gives an expression for the average reflected power in a form of a surface integral. The integration includes antenna gain, the *lambda* function (Λ), which defines the autocorrelation properties of the satellite pseudorandom noise (PRN) code (see Figure 2), and the Doppler spreading function, which describes the GPS carrier-phase decorrelation above the surface upon reflection. A quantity known as sigma (σ) is also part of the radar equation, denoting the normalized, bistatic, scattering cross-section of the ocean surface.

The numerical and analytical computation of the integral yields a reflected signal power as a function of code-delay and carrier-frequency shift. The *lambda* function acts as a range-gate on the received signal, only accumulating signal power from an elliptic ring (also known as the annulus zone) for a specific code delay or range. As shown in Figure 1, the center of the annulus zone coincides with the nominal specular point on the surface, which is seen at the same elevation angle from both the receiver and transmitter points. Figure 1 also illustrates that the Doppler spreading function of the radar equation singles out a scattered signal from a hyperbolic Doppler zone within which the GPS carrier acquires a specific Doppler shift.

The normalized bistatic scattering cross-section, σ, is determined by the probability density function of surface slopes and the scattering vector. The width of σ describes the glistening surface produced by the quasi-specular points on the sea surface. The effect of wind speed and direction appears in the distribution of surface slopes. The stronger the wind, the greater the slope variance. Likewise, the direction of the corresponding maximum slope variance coincides with the wind direction. It is important to note that ultimately the relationship between surface winds and surface facet slope statistics makes it possible to measure wind direction and speed using ocean-reflected GPS signals.

The product of antenna gain and the *lambda* function is called the footprint. Together with the Doppler spreading function, it serves to discriminate the portion of the glistening zone that can contribute to the received signal. This allows us to map the reflected-signal power distribution as a function of delay relative to the specular point and down-conversion (Doppler) frequency. The footprint function is also a critical part of wind (or surface roughness) retrieval, because it permits mapping of the probability density function of the surface slopes.

Notably, the signal power's integration across an entire glistening zone remains almost constant (neglecting losses caused by complex dielectric permittivity of the sea water) because of the energy conservation law. Therefore, if the footprint function remained constant across the glistening surface, the scattered power expressed by the radar equation would be independent of the probability density function width and thus would contain no information about the surface roughness. The only way to obtain this information is by mapping the glistening zone — by measuring power at a range of code delays and Doppler frequencies and thereby indirectly determining the slope probability density function.

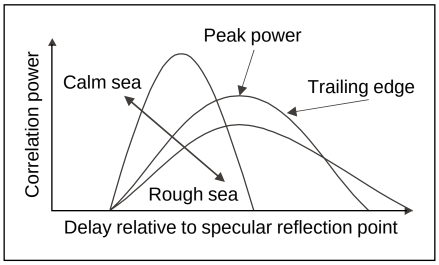

Figure 3. The shape of the correlation power versus code delay waveform is a function of ocean surface roughness and hence wind speed.

Wind-speed Remote Sensing. For our experiment, we further simplified the above theoretical model for the specific conditions of GPS scattering observed from an airborne platform. This simplification is based on two characteristics of our experiment: (a) use of low-gain (wide beam) transmitting and receiving antennas; (b) aircraft heights and speeds as well as integration times short enough that the Doppler spreading across the entire glistening surface is insignificant.

For our purposes, the term σ in the radar equation carries the information about surface roughness and thus surface wind. Changes in wind conditions produce variations in the statistical properties of the surface facets, therefore affecting the σ value. Furthermore, the radar equation tells us that a change in wind affects the distribution of postcorrelation power as a function of time delay. Once this power function has been analytically determined, we can measure wind speed above an ocean surface by mapping the dependence of average postcorrelation power versus relative code delay and Doppler frequency.

Qualitatively, the model predicts that the power versus delay curve will broaden (flatten out) and the normalized maximum signal power will decrease as receiver height and/or wind speed increases (see Figure 3). Two regions of interest in the power versus delay curves provide the most information about surface conditions: the maximum (peak) and the tails. The functional relationship between power and delay also depends on the receiver height and satellite elevation angle.

Calculations show that at low receiver heights (less than 1 kilometer) and at reasonable wind speeds, the shape of the power curves does not significantly differ from the shape of the direct signal. The influence of the sea-surface roughness (and, therefore, the wind) on the reflected signals begins at alti-

FURTHER READING

For an in-depth analysis of electromagnetic wave scattering, see

- *The Scattering of Electromagnetic Waves from Rough Surfaces,* by P. Beckmann and A. Spizzichino, Pergamon Press, New York, 1963.

For a discussion of how sea-surface roughness can be determined from a glistening sea surface, see

- "Measurements of the Roughness of the Sea Surface from Photographs of the Sun's Glitter," by C. Cox and W. Munk, in *Journal of the Optical Society of America,* Vol. 44, No. 11, pp. 838–850, 1954.

For information regarding radar remote sensing from space, see

- *Spaceborne Radar Remote Sensing: Applications and Techniques,* by C. Elachi, IEEE Press, New York, 1988.

For one of the first papers detailing the characteristics of GPS-reflected signals, see

- "Characterization of Multipath on Land and Sea at GPS Frequencies," by J.C. Auber, A. Bibaut, and J.M. Rigal, published in the *Proceedings of ION GPS–94, the 7th International Technical Meeting of the Satellite Division of The Institute of Navigation,* Salt Lake City, Utah, September 20–23, 1994, pp. 1155–1171.

For further details about using GPS reflected signals for ocean science, see

- "GPS Sounding of Ocean Surface Waves: Theoretical Assessment," by C.F. Clifford, V. I. Tatarskii, A. G. Voronovich, and V. U. Zavorotny, published in the *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium: Sensing and Managing the Environment,* Seattle, Washington, July 6–10, 1998 pp. 2005–2007.
- "Effect of Sea Roughness on Bistatically Scattered Range Coded Signals from the Global Positioning System," by J.L. Garrison, S.J. Katzberg, and M.I. Hill, in *Geophysical Research Letters,* Vol. 25, No. 13, pp. 2257–2260, 1998.
- "GPS Signal Scattering from Sea Surface: Comparison Between Experimental Data and Theoretical Model," by A. Komjathy, V. Zavorotny, P. Axelrad, G. Born, and J. Garrison, published in the *Proceedings of the Fifth International Conference on Remote Sensing for Marine and Coastal Environments,* San Diego, California, October 5–7, 1998, Vol. 1, pp. 530–539. Links to an online version of this paper can be found at <http://www-ccar.colorado.edu/~komjathy/>.
- "Utilizing GPS to Determine Ionospheric Delay Over the Ocean," by S.J. Katzberg and J.L. Garrison, Technical Memorandum TM-4750, NASA Langley Research Center, 1996. This document is also available as a PDF file from <http://techreports.larc.nasa.gov/ltrs/PDF/NASA-96-tm4750.pdf>.

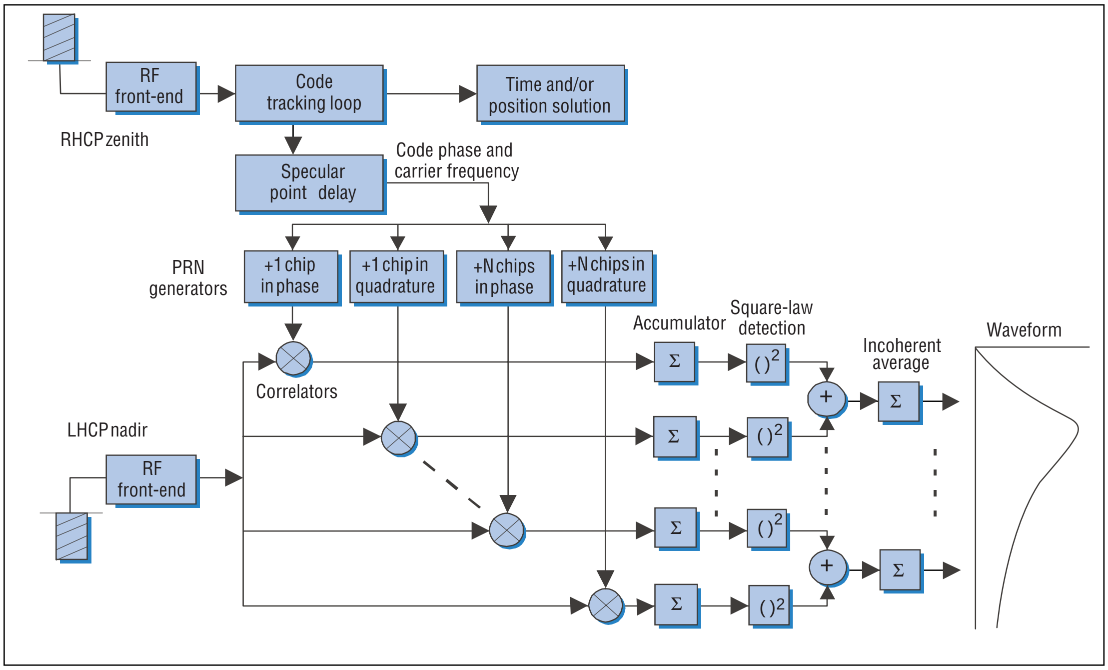

Figure 4. The delay-Doppler-mapping GPS receiver acquires reflected signals using a nadir-pointing antenna and direct signals using a zenith-pointing one. Multiple correlators are used to produce the power versus delay waveform.

tudes higher than 3 kilometers. At these altitudes, strong enough sensitivity to wind speed presents itself in both the normalized maximum power values and the tail end (trailing edge) of the normalized power curves (also known as waveforms) to make high-quality measurements feasible.

Furthermore, the model predicts that the signal power decreases with an increasing receiver altitude because of propagation losses based on "the inverse-square-distance law" despite an approximately linear increase of the annulus zone size. An assessment of a spaceborne GPS receiver indicates that the received signal power should be about 20 decibels lower than that for an airborne receiver.

DELAY-DOPPLER MAPPING

Any surface can be mapped by a remote-sensing system, provided the system has sufficient spatial resolution. This might be achieved by traditional means — that is, by using narrow-beam, high-gain receiving antennas. In our case, we can obtain high spatial resolution with wide-beam, low-gain receiving antennas by using the highly stable GPS carrier phase and its PRN code modulation. This is similar to the synthetic aperture radar technique in which Doppler frequency shifts and pulsed-signal time delays are used to create a small footprint on the mapped surface. The intersection of hyperbolic equi-Doppler zones and elliptical equirange zones form this footprint of a bistatically illuminated area (see Figure 1), with the equirange zones isolated by the *lambda* function, and the equi-Doppler zones isolated by the integration time.

Bistatic GPS Scatterometer. A typical GPS receiver acquires a signal through the combination of a delay-lock loop for code tracking and a frequency- or phase-lock-loop for tracking the Doppler-shifted carrier. The code-tracking loop is closed so as to achieve *maximum crosscorrelation* between the incoming code and a local replica of the PRN code, as shown in Figure 2.

NASA's Garrison and Katzberg developed a receiver to study GPS surface reflections by modifying a software-configurable GPS receiver to measure signal postcorrelation power at the series of discrete code-delay steps and Doppler frequencies. The modified GPS receiver and its application for sea-state sensing won the *GPS World* Applications Contest VI, published in the August 1998 *GPS World Showcase* issue. The new concept is in some sense the inverse of conventional GPS receiver designs because it seeks to ascertain the power at specific code delays as opposed to determining the code delay that maximizes the correlation power.

This "delay-Doppler-mapping receiver" concept consists of an array of correlator pairs. Each of these accumulates the results of the correlation between a locally generated PRN code replica (at some defined delay and Doppler frequency) and the in-phase and quadrature components of a down-converted, digitized reflected signal. Each of these correlator pairs can be thought of as range "bins" or "gates" in conventional radar systems. The postdetection power in each bin is computed from the sum of the squares of the in-phase and quadrature components (I^2+Q^2). The receiver can then average this postdetection power to reduce the noise in the waveform samples. Figure 4 shows a block diagram of this receiver.

Remote-Sensing Aircraft. For the receiver, Garrison and Katzberg used a commercially available GPS-development kit, which included a 12-channel correlator chip fed by two radio-frequency (RF) front ends. They employed a zenith-oriented RHCP antenna mounted on top of an aircraft fuselage to receive the direct signal through one RF front end. A nadir-oriented LHCP antenna located on the bottom of the fuselage received the reflected signal through the other RF front end. Each front end had an independent automatic gain control, ensuring that the variance of the sampled intermediate-frequency data (which, before detection, is dominated by white noise) maintains a predetermined average value.

This receiver has been used in aircraft remote-sensing experiments since the summer of 1997. It has also flown aboard a scientific balloon launched from Wallops Island, Virginia, in which waveform data was collected from an altitude of 25 kilometers. The existing receiver uses only one Doppler frequency, which corresponds to the direct signal and generates a one-dimensional map of the waveform dependence on code delay.

WIND-SPEED RETRIEVAL

For our experiment, we used the Garrison and Katzberg receiver to collect GPS surface reflection data from a Lockheed C-130 Hercules aircraft flying out of NASA's Wallops Flight Facility in Virginia in May 1998. The flight tracks followed the ground tracks of the Ocean Topography Experiment (TOPEX)

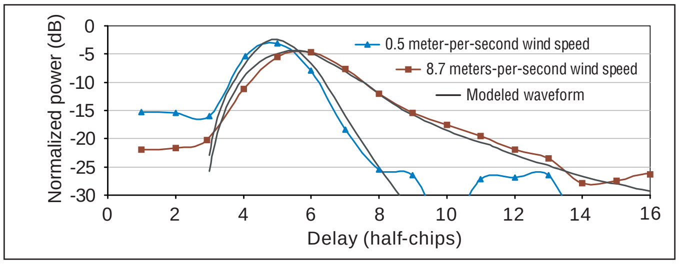

Figure 5. The experimental data from PRN02 agrees quite well with the theoretical model for two particular wind speeds.

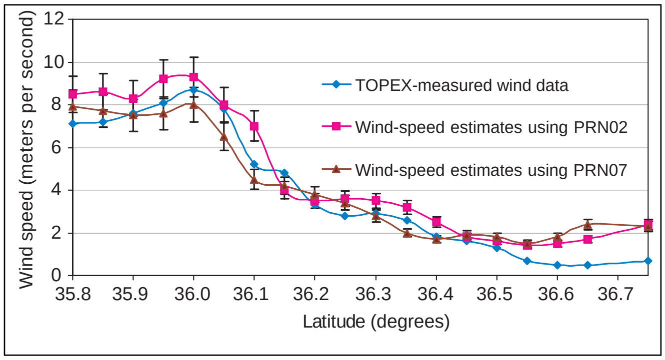

Figure 6. Wind-speed estimates using data from PRN02 and PRN07 agree favorably with results independently obtained from TOPEX satellite altimetry measurements.

altimetry satellite. We compared the data collected at a 3-kilometer altitude with the theoretical model previously described. To smooth these data, we applied a 150-second-wide, moving-average filter to the raw reflected GPS measurements. We used an adaptive signal normalization, which generates a constant area waveform, to cancel out the uncalibrated effects of antenna gain and aircraft attitude motion as well as the difference in cable loss and front-end gain between the direct and reflected signals. We then "binned" or averaged the data across discrete code delays measuring one-half code chip (which corresponds to 150 meters in range resolution). To account for variations in the noise floor of the reflected signal, we recorded the correlation power between 16 and 32 half-chip delay bins and subtracted it from the reflected signal.

The TOPEX-altimeter overflight covered rapidly changing wind speeds ranging from 0.5 to 8.7 meters per second within a ground distance of 40 kilometers. Figure 5 shows some of the results. Using data from PRN02, we obtained two different waveforms for the 0.5- and 8.7-meters-per-second wind speeds. Figure 5 also displays the modeled values for these two different wind speeds.

As described earlier, agreement between measured and modeled waveforms can be assessed on the trailing edge of the waveform — in this case between –5 and –20 decibels. From the comparison, we can conclude that the agreement for the 8.7-meters-per-second wind speed appears better than that for the lower 0.5-meter-per-second speed. This may be caused by the fact that at lower wind speeds, the Rayleigh criterion of diffuse scattering (relating the wave height to the illumination wavelength) may be violated, possibly limiting the accuracy of modeled waveform for wind speeds lower than 2–3 meters per second. In Figure 5, the discrepancies between the measured and modeled waveforms at and prior to the trailing edge of the waveforms are the result of averaging measurements in discrete bins.

For every TOPEX observation, we estimated the trailing-edge slope using the GPS-measured waveforms between –5 and –20 decibels and from the theoretical model using various incremental wind speeds. We obtained the estimated wind speed by interpolating the measured slopes between the modeled ones. After processing the data, we matched the TOPEX-indicated geographic area with the location of GPS measurements to permit a direct comparison between the two techniques. In Figure 6, we display both the TOPEX-measured wind speeds and our estimates using GPS data from two of the satellites tracked during the experiment: PRN02 and PRN07.

Figure 6 also displays the 1-sigma error bars of the measured wind speeds, indicating that the errors are larger for higher wind speeds. This is explained by the fact that, for faster wind speeds, the separation between two waveform slopes (corresponding to two separate wind speeds) are smaller than at slower wind speeds. Furthermore, the figure indicates that wind speeds, independently estimated using the two satellites, show good agreement with the TOPEX-measured wind data.

CONCLUDING REMARKS

We have demonstrated that GPS signals reflected from the ocean surface and received at an aircraft altitude of 3–5 kilometers using a delay-Doppler-mapping GPS receiver can be used as a remote-sensing tool to determine ocean-surface wind speed. The results indicate a good agreement between the measured and modeled normalized signal-power waveforms during rapidly changing surface wind conditions. The inferred wind speed also shows good agreement (within 2 meters per second) with TOPEX wind-speed measurements.

We expect that surface-reflected GPS signals will find use in various other remote-sensing applications, such as wave height and salinity studies, delineation of wetlands, and monitoring ionospheric TEC above oceanic areas. Researchers at NASA-Langley, NASA-Goddard, and the University of Colorado at Boulder are now studying the feasibility of making such measurements from satellite-borne instruments. If similar results can be obtained from orbit, we will have the unique opportunity to use GPS as a global scale remote-sensing tool to infer various geophysical parameters. Surface-reflected GPS signals will soon become a new source of data for scientists to better understand the effects of such phenomena as global warming, ocean-current circulation, and climate change. ■

MANUFACTURERS

The delay-Doppler-mapping GPS receiver uses a **GEC Plessey Semiconductors** (now **Mitel Semiconductor**, Kanata, Ontario) 2021 correlator chip and two 2010 radio-frequency front ends.

Correction

In the November 1998 "Innovation" column's "Modular Arithmetic" sidebar on page 44, the FORTRAN code for converting Julian calendar dates to the Julian day number (JD) was mistakenly given as the formula for determining the Julian day number of a date in the currently used Gregorian calendar. The correct line of code, for *anno Domini* dates only, should read:

```
JD=367*Y–7*(Y+(M+9)/12)/4–3*((Y+(M–9)/7)/100+1)/4+275*M/9+D+1721029
```