

GPS Surface Reflection Technology Requirements for Space Applications

Final Report to the Earth Science Technology Office (ESTO)

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Science Rationale

It has been shown that the reflected GPS signal contains information that can be used to determine several important quantities in oceanographic, coastal and wetlands remote sensing. Techniques to exploit this embedded information are expected to find many applications in the Natural Hazards theme and the Season to Interannual Climate Variability theme of the Mission to Planet Earth Science Research Plan. Data extracted from the reflected GPS signal will complement three of the 24 identified EOS measurements: surface wind fields, ocean surface topography (from the ocean focus) and surface wetness (from the land focus).

In the Natural Hazards theme, measurements using reflected GPS signals have the potential to aid in monitoring and assessment of floods from aircraft by providing an all weather mapping capability. A similar technique could be applied to determine soil moisture and assist in assessment of drought conditions. Aircraft experimentation has already demonstrated this mapping capability.

Correlation properties of a GPS signal that has been bistatically scattered from the rough sea surface have already experimentally demonstrated to be capable of accurately determining surface wind speeds. Theory predicts that wind direction information is contained in the reflected signal as well. The measurement of surface wind vectors has applications in tracking severe storms and hurricanes and could also aid in the assessment of coastal hazards. This measurement technique was first disclosed in Katzberg, et al.'s 1998 patent application.

An important element of the Natural Hazards theme is the collaboration and technology transfer with other agencies having the responsibility to provide operational climate and disaster management information. This is perhaps the element in which this new technology will most likely find its niche. The instrumentation needed to receive and process reflected GPS data is simple and very low cost. Already, experimental systems, consisting of commercially available GPS receivers and 486-class computers are being lent to NOAA Coastal Services Center in Charleston, S.C., Naval Postgraduate School in Monterey, CA., and the University of Colorado at Boulder for testing as part of the research efforts at those institutions. These systems for aircraft or ground (tower) based installations cost a few thousand dollars, consume 10-12 watts of power and require only

very small antennas. A satellite instrument, while possibly needing a somewhat larger antenna and a larger number of code-correlators, would still be smaller and consume an order of magnitude less power than state of the art monostatic radar instruments (scatterometers and altimeters). This could enable a large orbiting constellation of sea state monitoring satellites to give weather services and disaster management agencies very rapid global wind field information to aid them in tracking severe storms.

Many of the same advantages that this instrument has for Natural Hazards research would also justify its application to the study of Seasonal to Interannual climate variability. A low cost, and low impact instrument could be manifested as a secondary payload on a large number of satellite missions and therefore increase the coverage of the world's oceans over that presently provided by a few active sensors on dedicated spacecraft. The subsequent increase in density of ocean surface winds measurements would give better sampling of the underlying physical processes. The higher spatial resolution of this data set would be utilized to improve the fidelity of numerical climate models.

Improved sampling of the ionospheric total electron content (TEC) over the oceans is possible through detection of the reflected GPS signal at both the L1 and L2 frequencies [Katzberg and Garrison, 1996]. The benefit of this information to Earth science measurements is in the improvement of the ionospheric models used in the correction of single frequency altimeters used to measure ocean circulation. Through use of a nadir-oriented GPS antenna and properly designed receiver on the altimeter satellite, an estimate of subsatellite TEC could be generated simultaneously with the altimeter measurement. Incorporation of localized ionospheric measurements into existing ionospheric models used for post-processing could provide accuracy equivalent to a dual-frequency altimeter. This technique will not require flying a second transmitter as part of the altimeter mission.

Measurement Description

Several Earth remote sensing quantities can be obtained from the reflected GPS signal. This study considered the following; Ocean surface wind vectors, salinity, wet ground extent, soil moisture and ionospheric total electron content (TEC).

To understand the physical principles upon which these measurements are based, one must first understand the structure of the incident GPS signal. It is a right hand circularly polarized L-band signal at two frequencies (1575.142 MHz for L1 and 1227.6 MHz for L2) modulated with a pseudorandom noise (PRN) code. This code, while generated by a deterministic analytical function, has many of the mathematical properties of white noise. Specifically, the autocorrelation of this code will only give a large positive value for delays (lags) of less than one "chip", with a maximum value at a delay of zero. This correlation property is the key to the positioning capability of GPS. Two modulation frequencies are used for this PRN code; 1.023MHz for the C/A code which is generated by an unclassified formula, and 10.23 MHz for the P(Y) code. The Department of Defense has the capability to encrypt the P(Y) code in order to deny access to unauthorized users. Whereas codes at both frequencies are provided on the L1 carrier

separated in phase by 90 degrees, only the P(Y) code is provided on the L2 carrier.

In conventional applications of GPS for positioning, the higher frequency, or equivalently the shorter “chip” length, means that tracking of the P(Y) code will usually result in a finer measurement precision than tracking the C/A code. For applications of the reflected signal studied in this report, this may not always be the case. In fact, for some cases that are discussed later, C/A code has advantages over P(Y) code. These advantages are the result of the smaller P(Y) code chip length illuminating a smaller annulus on the reflecting surface and therefore returning a weaker signal per delay “bin”, as compared to that for the C/A code. Additionally, the P(Y) code transmission is 3dB weaker at L1 than C/A, and 6 dB weaker at L2.

The disadvantage of depending entirely upon C/A code for the study of reflected signals is that it only exists on the L1 frequency. Therefore, measurement techniques requiring dual frequencies cannot presently be made with the C/A code. All of these concerns must be considered in the presence of an ongoing re-design of the GPS system in which proposals exist for civilian access to dual frequencies.

In a reflection from a perfectly flat surface (ideal specular reflection) the reflected signal follows only one path, and contains a single PRN code at one time delay. This path is the shortest distance from the transmitting GPS satellite to the receiver, as shown in figure 1. When the cross-correlation between the replica PRN code inside the GPS receiver and the received reflected signal is computed, it produces a sharp peak as shown in figure 2. In this situation, the correlation theoretically will not have non-zero values for lags larger than +/- 1 code chip relative to the specular point time delay.

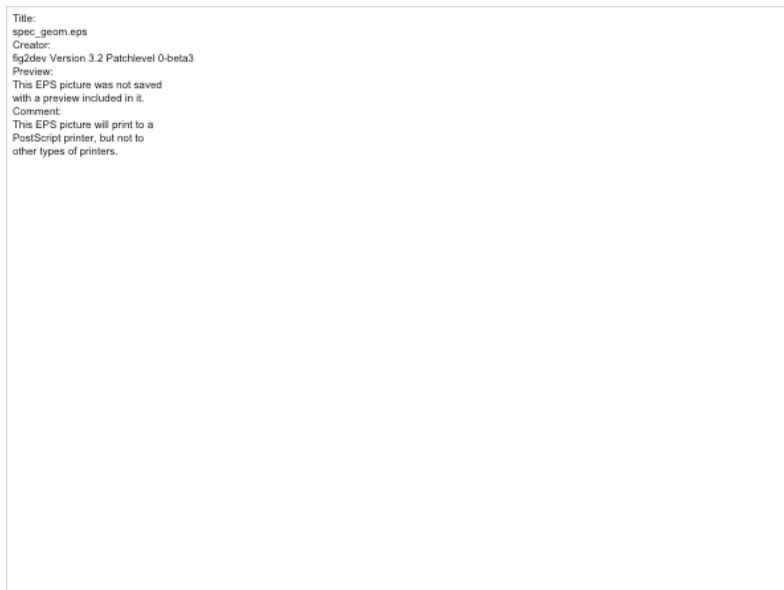


Figure 1. Specular reflection geometry.

As the reflecting surface becomes rougher, however, there are reflections from points at longer time delays than the specular point. This geometry is illustrated in figure 3, which

shows the areas of a constant time delay mapping ellipses on an approximated flat Earth. When a similar cross-correlation is performed with the PRN code replica, the resulting function is wider, as illustrated in figure 4. This cross-correlation can have non-zero values at longer lags than 1 code chip, however would theoretically be zero for lags shorter than -1 code chip measured relative to the specular point delay because no signal can reach the receiver with a shorter travel time than that from the specular point. One way to visualize this process it to imagine the cross-correlation in figure 4 composed of a weighted sum of autocorrelation functions (each as in figure 1) computed at the various time delays indicated on figure 3.

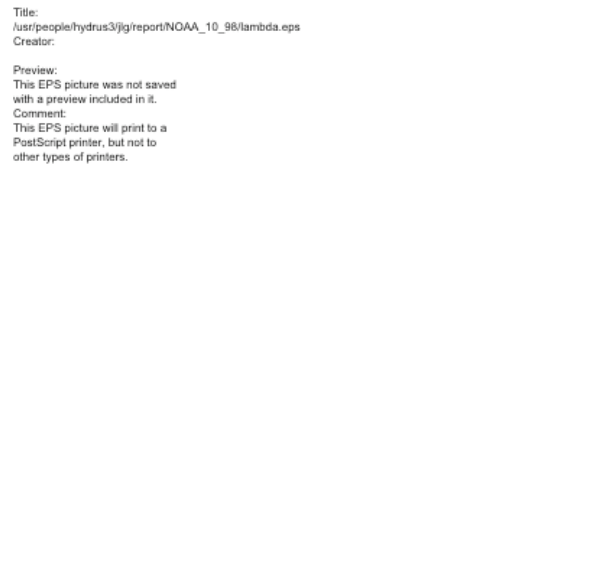


Figure 2. Autocorrelation of direct, or specularly reflected GPS signal

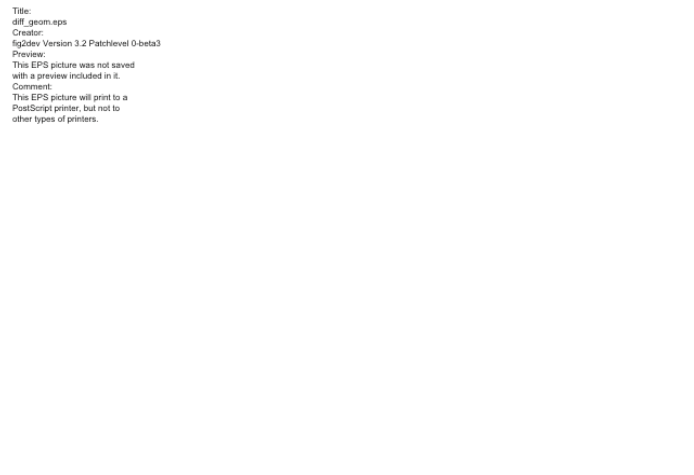


Figure 3. Diffuse (rough surface) reflection geometry.

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Figure 4. Autocorrelation of diffusely reflected GPS signals, showing parametric dependence on sea state (wind speed)

It has long been demonstrated, theoretically and experimentally, that the statistics of ocean surface slopes are dependent upon surface wind speeds [Cox and Munk, 1954]. The statistical distribution of surface facets will determine the magnitude of the “weights” of the aforementioned sum of autocorrelation functions. This will, consequently determine the shape of the cross-correlation function (as shown in figure 4) computed for this sum. The shape of this function can be recorded using a modified GPS receiver, and when matched against theoretical predictions, used to determine wind speed [Katzberg, et. al., patent application 1998].

All of the explanation thus far, has assumed that the reflected signal was down-converted at a single specific frequency. For a moving receiver, however, the reflected signal is distributed not only in time delay (range) as described above, but also in frequency (Doppler). Conceptually, it is a simple manner to design a receiver which not only records the shape of this cross-correlation as a one-dimensional function of delay, but as a two dimensional function of delay and Doppler. More information, specifically the wind direction, could be determined through the dependence of the cross-correlation on Doppler frequency. This has been predicted in some recent numerical simulations performed by the University of Colorado at Boulder [Armatys, 1998] for aircraft altitudes plotted in figure 5.

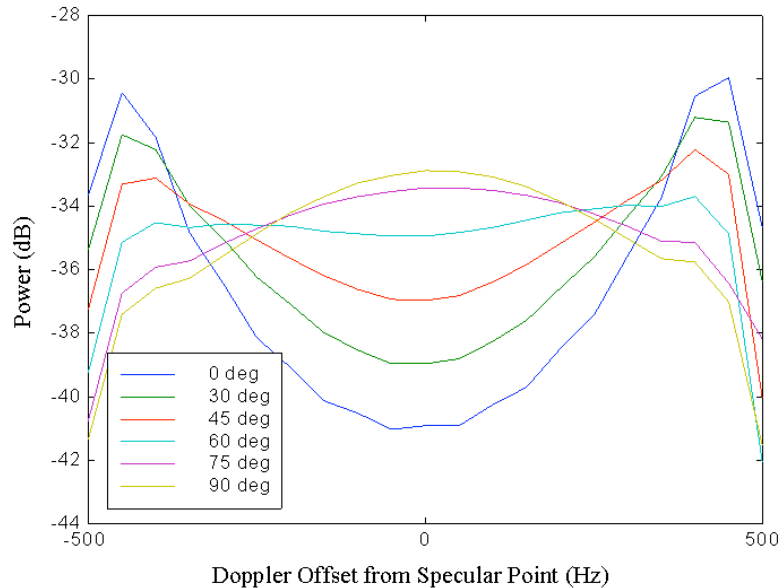


Figure 5. Correlation power vs. Doppler frequency, dependence on wind direction [Armatys, 1998]

Science requirements for surface wind speed measurement assumed in this study were set by comparison to the performance of existing scatterometers. Typical numbers give a ground resolution of 50km with a 2-day repeat cycle. A measurement accuracy of 2 meters/second for wind speed and 20 degrees for wind direction is also comparable with these instruments. (For example, Sea Winds.)

Scatterometers have flown on aircraft since the 1950s, with the first space based experimentation taking place on Skylab in 1973 [Moore and Young, 1977]. The first orbiting scatterometer capable of producing research-quality data was flown on SeaSat in 1978 [Grantham et al., 1977] [Ulaby, et al., 1981]. All of these instruments operated by measuring backscatter from a transmitted pulse. Measurement of the strength of the returned signal indicated the scattering cross-section, which was related to the surface wind speed and weakly related to the wind direction. Determination of this relationship required extensive aircraft flight campaigns and the reduction of a large amount of experimental data. Later scatterometers were able to utilize the spread in Doppler frequency to isolate smaller areas on the surface of the ocean. The present state of the art scatterometers is the SeaWinds instrument on Quick SCAT, scheduled for launch in spring, 1999.

Satellite altimeters, such as TOPEX or GEOSAT are also able to generate wind speed measurements, in addition to ocean topography. This is possible because of the known

shape of the transmitted waveform. Following reflection, the shape of the returned waveform contains information about the wave height (leading edge slope) and wind speed (trailing edge slope). The physical principles underlying the bistatic reflected GPS measurement concept embody features of both altimeters and the scatterometers.

Potential benefits of the reflected GPS wind vector measurement in comparison to the present state of practice of backscatter radar remote sensing include the following: Using an existing source of illumination will eliminate the need for a transmitter. This will reduce the instrument mass and power by an order of magnitude, at least. Spread spectrum signal processing allows the instrument to produce measurements from very weak received power and therefore very small antennas. (A conventional navigation receiver works with a signal 16dB below the noise floor of the receiver itself.).

Another very important advantage of this technique relates to the way the data is normalized. The processing currently being done with reflected GPS data involves determining the shape of a correlation function normalized to have a constant area of 1-chip. This measurement removes the calibration of antenna gain pattern and does not involve any absolute measurement of power. Furthermore, this normalization was found to reduce the statistical variation in the reflected signal collected at aircraft altitudes as illustrated in figure 6. This finding indicates that there is correlation between the reflected signal in different range bins and that each range-bin often is not wide enough to sample a complete ensemble of surface statistics. This statistical effect may not be significant from satellite altitudes, however, because the range bins represent much larger areas on the surface of the ocean.

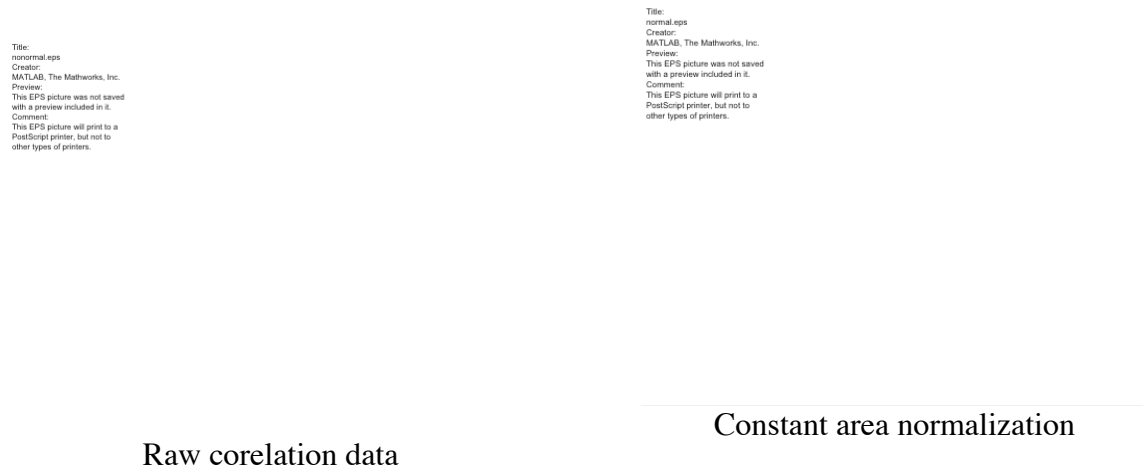


Figure 6. Normalization of reflected GPS waveform.

The re-use of hardware that has already been developed and space-qualified for GPS navigation applications is another important advantage of this measurement technique. Significant cost savings would be realized in the development of an operational instrument by making use of component technologies that are already in existence.

Ground wetness, allowing mapping of wetlands and flooded areas, has also already been demonstrated from aircraft. Soil moisture may also be obtainable from the reflected GPS signal. These measurements derive from the difference in L-band reflectivity between wet and dry ground. It is, however, questionable how meaningful these measurements would be from an orbiting instrument, because of the significantly sparser sampling. Figure 7 illustrates these results. On these maps, a threshold has been set on the received signal power to indicate a ground reflection. The marker size indicates the relative strength of the reflected signal.

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Figure 7. Demonstration of wetlands mapping capability

The measurement of ionospheric TEC is obtained, conceptually, by "tracking" of the reflected signal in both the L1 and L2 frequencies, and then forming a linear combination of the two resulting pseudoranges [Katzberg and Garrison, in press]. This linear combination removes the tropospheric delay and results in a measurement of the sum of the TEC values along both the incident and the reflected ray paths. Existing ionospheric models which can ingest ground-based GPS data could be modified to include this new measurement by interpreting it as a linear combination of two measurements observed from a "virtual" ground station located at the specular reflection point.

The "tracking" of a diffusely reflected signal is understood to mean the determination of the best estimate of the relative time delay between the L1 and the L2 signal measured along the reflected ray path through the specular point. Spread of the reflected power over a wide range of time delays, which is the basis for the sea state measurement, would make use of a conventional delay lock loop for "tracking" impossible. A greater problem would be presented if the reflected GPS signal is attempted to be used as an altimeter,

because in that case it is the absolute path length, not the difference between the L1 and L2 paths, that must be determined.

The requirements for providing meaningful corrections to the TEC models are set by the "correlation distance" of these models. This is the distance away from a ground-based measurement site to which the measurement no longer provides a useful correction to the model. Experience with existing models, including PRISM [Daniell, et. al, 1993], IRI-90 [Bilitza, 1990] shows that 300 – 400 km is a reasonable number for the correlation distance in the ionosphere [Schreiner, et. al., 1997].

The measurement of salinity is based upon an entirely new application of the physical principles of bistatic scattering and the unique signal structure of the GPS transmission. Details of the proposed salinity measurement technique are proprietary. Conventional methods of remote sensing for measurement of salinity use microwave emission. This technique requires large antennas and extensive calibration. Even the effects of "galactic noise", the cosmic background radiation that has reflected from the ocean surface is an effect that must be accounted for.

Measurement Concept

Future evolution of several elements of this instrumentation was considered in this study. These are: the receiver hardware, data reduction techniques, and mission/orbit design. An early demonstration flight on a Space Shuttle opportunity is also outlined.

The existing delay-mapping receivers built by the Langley Research Center are quite simple devices. These receivers collected the squared output of the autocorrelation process in a number of range bins spaced at intervals of one half a code chip. These bins were slaved to a tracking loop locked on the direct signal from a given satellite so as to follow the predicted specular point (in effect an "open-loop" tracking of the reflected signal). This receiver is shown schematically in figure 8.

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Figure 8. Delay-mapping receiver

An operational spacecraft receiver will be essentially the same device, except with a larger number of correlators, separated in Doppler frequency as well as time delay (range). The hardware components of this instrument must also meet the requirements for space qualification. This may not be a significant problem, because all of the Langley and Goddard development of this receiver was based upon a commercially available chipset manufactured by MITEL Inc (formerly GEC Plessey). A space qualified orbital navigation and time receiver, the PiVoT, is already in advanced development at the Goddard Space Flight Center. The PiVoT uses the same MITEL chipset as the existing aircraft receiver. Therefore much of the software developed for the aircraft receiver, and the experience gained in working with the MITEL chipset, could be transferred and re-used on the satellite receiver. Furthermore, the PiVoT was conceived as an "open-architecture" receiver. The hardware can be expanded relatively easily through the addition of more correlator boards, for example, without re-design of any circuitry. Source code for all of the low-level software operations necessary to extract the waveform data is non-proprietary and available from MITEL for a nominal license cost.

The most logical path to follow, in converting the existing "breadboard" aircraft receiver into a space flight instrument, is to expand upon the existing PiVoT receiver design. Each of the receiver cards in the PiVoT can track up to 24 channels through up to 4 different RF front ends. This will allow up to 48 discrete range-Doppler cells to be allocated per receiver card. (Each "channel" in a GPS receiver contains a delay lock loop using two correlators, one early and one late.) At least one correlator chip (12 channels) in the set must track a direct GPS signal in the conventional manner in order to properly align the range-Doppler cells with respect to the reflected signal specular point. The technical

challenges are how to properly feed the incoming signal to several different cards, and how to properly align each card, having its own independent quartz oscillator, with the direct signal. Several options were considered.

First, the simplest solution is to split both a direct and a reflected RF signal after the antenna preamplifier and feed it into several, completely independent, receiver cards. This concept is illustrated in figure 9. The advantages of this method are that the existing design for the hardware can be used as-is without any modifications. Each card will independently track the direct signal and align the subset of range-Doppler bins allocated to it. Each card will generate its own time delay and Doppler frequency reference with respect to the direct signal and report the correlation power in the reflected bins without any relationship to the other cards.

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Figure 9. PiVoT with multiple, independent receiver cards.

The combination of these measurements into the instrument output data stream will be done in software outside of the receiver. One disadvantage of this system is that each split of the incoming signal will result in a 3dB decrease in signal power. This decrease, however, comes after the preamplifiers so it will not significantly effect the signal to noise ratio of the measurement as long as the signal strength is within the input specifications of the RF front end. This is the result of the inherent robustness of GPS receivers to signal strength variations.

Another disadvantage in utilizing independent receiver cards is the difficulty of accounting for the differential path lengths between the top and bottom RF inputs on each separate card. This could possibly be done once on the ground with a reference signal. The long-term behavior of this calibration, however, is unknown. Some method should

be available to validate this calibration on orbit.

One technique to remove these biases, which have different values for each receiver card, is to include them as an additional unknown states in the parameter estimation applied to post-processing the data and estimate wind vectors. As described later, this is already being done for the single-card aircraft receiver. A highly parallel receiver, with many such biases, could result in a large data-reduction burden. However, one should understand that this technique would only add 1 additional unknown for each set of 24 new measurements.

The gain of the different RF front ends may be slightly different. This too will require calibration. The constant-area scaling of the waveform would be very difficult to achieve in this manner, with each group of 24 samples having a different gain.

Finally, requiring a separate unit tracking the direct signal for each card is not the most efficient use of hardware, allowing only the addition of 24 correlators per new card.

One attempt to reduce some of the problems inherent in splitting the RF input described above is to have only a single RF front end feeding multiple correlators. This will require splitting the 2-bit digitized signal (sign bit and magnitude bit) from a single RF front end and feeding it to multiple correlator chips. This is illustrated conceptually in figure 10. In this manner, the same oscillator is used to drive multiple cards, which would solve some of the synchronization problems. One RF front end is used for all of the reflected channels, assuring that constant gain is used for all bins. This receiver design does require hardware modifications to the receiver card itself as well as a proper termination of the 5.7MHz sampled data and 10MHz oscillator signals. This may not be a trivial problem and could require significant redesign of the PiVoT architecture.

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Figure 10. PiVoT with multiple receiver cards, fed by same RF front end.

One suggestion was made to avoid having to add another connector onto the card itself, is to distribute these signals to the other cards through unused lines in the backplane. The PCI bus has a bandwidth of 66 MHz and could handle these non-standard signals. This idea is illustrated in figure 11. The possibility of interference must be evaluated for this concept, however.

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Figure 11. Concept of distributing digitized signals along the backplane

As the number of channels becomes very large, the task of controlling all of them through software starts to become the limiting factor. At this stage, the reliance upon existing hardware originally designed for closed loop tracking of a direct GPS signal could become more of a burden than an asset. The collection of reflected GPS data is an open-loop process and there is no need to control the code generation phase and rate via a feedback loop. With this in mind, it is conceivable to design a specialized reflected GPS processor capable of performing parallel correlations at hundreds of range-Doppler cells. Programmable logic devices (PLDs) make a good platform for such a specialized correlator. This is advisable because PLDs work best on problems that require a large number of simple calculations to be performed simultaneously. One example of this is in code breaking and deciphering. [Electronic Frontier Foundation, 1998].

Use of a specialized receiver as described above will further allow one to sample the direct signal and use that as the source of the code to de-spread the reflected signal. This technique utilizes the fact that even if the formula generating the PRN code is unknown, the same code sequence is present in the transmitted and the reflected signal. This is similar to other codeless GPS techniques, for example the determination of the ionospheric delay through cross-correlating the L1 and L2 signals [MacDoran, 1984]. This receiver is illustrated in figure 12.

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Figure 12. Receiver concept using direct signal to extract (possibly unknown) PRN sequence.

A further advantage of sampling the direct signal to obtain the "code" is that digital broadcast signals other than GPS or GLONASS could be used as the source of the bistatic illumination. If the digital modulation of these signals contains information which is significantly "random" such that the cross-correlation has the properties described above, then the same technique could be applied using those signals. This will allow a wide range of satellite geometries and different frequencies to be used which will expand the range of measurements that are available.

As the size and complexity of the range-Doppler space increases further, the question becomes: at which point it becomes more efficient to simply digitize the reflected signal and store or downlink it for post-processing? A number of receiver systems already developed are capable of collecting this raw data and performing the necessary correlations through a "software receiver" [Akos, 1997]. Such instrumentation could be useful at this early stage of development, because it allows a very general data set to be collected once. Afterwards, a wide range of post-processing techniques could be attempted, varying the spacing and width of the range and Doppler bins. However, the volume of data that is required in this technique is enormous.

For this reason, such a system might be impractical for an orbital science instrument. It is more useful in experimental systems in which an on-board recording system could collect the data for post-processing. The practical uses of this receiver are therefore limited to aircraft and the Space Shuttle. If telemetry is required, then some storage must be available on board that could be used to "buffer" segments of the data collected at 11.4 Mbits/sec (sign and magnitude sampled at 5.7 MHz) from the MITEL front end for the

lower speed transfer and download as shown conceptually in figure 13.

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Figure 13. Concept for direct recording of digitized IF data.

This trade study of receiver architecture can be illustrated in the drawing below

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The number of range and Doppler cells are the driving force in determining which method is the most efficient.

Although it is not inconceivable that hundreds or even thousands of these correlators will be necessary to fully map out the characteristics of the reflected signal, there are limits to the payoff in measurement quality in adding more correlators. The extent of the range-Doppler space is ultimately determined by the glistening surface on the ocean. It may, however, be desirable to look at sub-sections of this space to avoid averaging geophysical parameters over too extensive of an area. The spacing between these cells required to generate independent measurements is going to be limited by sampling theory and the correlation length of surface properties. Little will be gained by having bins so close that the signal they receive is strongly correlated.

A signal to noise estimate was performed to determine the number of range and Doppler bins necessary for an orbiting C/A code receiver at an altitude of 525 km. The “worst case” dispersion of reflected power in range and Doppler frequency was used, assuming a 20 meter/sec wind speed and a receiver moving in the same plane as the transmitter. A GPS satellite directly overhead was also assumed. A uniformly illuminated “glistening surface”, limited in extent by the mean square slope of reflecting facets was assumed. This surface will reflect significant power distributed over a range of 40 code chips. The distribution of frequency was estimated to be +/- 8.3 KHz. In order to fully sample this space requires correlators separated by one half code chip in delay, and 1KHz in frequency. Using these numbers gives an extent of 80 by 18 correlators, or a total of 1440 correlators to fully map out the range-Doppler space at this worst case condition.

These numbers assume that every range-Doppler bin contains independent useful information. Models for the waveform shape dependence on wind speed and direction show that the wind speed information exists mostly in the range bins, measured at zero Doppler offset, and the wind direction information is contained mostly in the Doppler bins measured at a fixed range from the specular point. This dependence, for aircraft altitudes, is shown in figure 14 for range and figure 5 for Doppler. With this in mind, the total number of correlator channels necessary could be reduce to only 18 set at the Doppler frequency of the specular point and 80 separated at 1 KHz Doppler bins, along a distant range bin from the specular point. This arrangement requires a total of 98 correlators which are arranged as shown in figure 15.

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Figure 14. Experimental measurements of waveform shape from aircraft

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Figure 15. Arrangement of range-Doppler correlators for wind speed and direction measurement.

One consideration, in determining the size of the Doppler bins, is the “coherent” integration time of the in-phase and quadrature samples inside the receiver. So far, the

MITEL default of 1 ms has been assumed, giving a Doppler bandwidth of 1KHz. Using a longer integration time will result in narrower Doppler bins. This will require more correlators to fully map out the waveform dependence on Doppler frequency, but may show a stronger sensitivity to the wind direction. On the other hand, summing the contribution from several range or Doppler bins could improve the signal to noise ratio.

The retrieval algorithm that will be used to estimate wind speed and direction is an integral part of this measurement concept. The development of this algorithm will have to ultimately be done in concert with the specification of the layout of the range-Doppler space on the receiver. Experience with aircraft are demonstrating that samples spaced at 1/2 code chip separation in range are sufficient to determine wind speed with a precision, in comparison to TOPEX of better than 2 meters per second. With the wider dispersion at satellite altitudes, however, sparser separation may be acceptable.

The measurement of ocean surface wind speed has already been demonstrated from aircraft altitudes [Garrison, et. al., 1998]. These results used an empirical data reduction of the width of cross-correlation function to the “ground truth” wind speed measured from NOAA buoys on several days of aircraft experimentation conducted under widely varying sea states (less than 1 meter/sec to over 12 meters/second). These results are shown in figure 16. More recent measurements [Garrison and Katzberg, 1998] using an improved receiver on three flights under the TOPEX/Poseidon ground track have generated data sets which are being directly compared against TOPEX for wind speed determination.




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Figure 16. Empirical data reduction

Analytical models [Zavorotny and Voronovich, 1998] match the measured waveforms very closely. By determining the trailing edge slope of these waveforms, wind speed measurements with a precision of 2 meters per second, in comparison to TOPEX data, have been made [Komjathy, et al., 1998]. Recent attempts (unpublished) by Garrison have approximated the Zavorotny model by an exponential of a polynomial.

This approximation allowed conventional parameter estimation techniques (least squares) to be used to vary the shape of the waveform to determine the best estimate of a 3 state vector containing wind speed, specular point delay offset, and a scale factor. These preliminary results are shown in figure 17. As this one example shows, these results match TOPEX to a precision of approximately 1 meter per second for slow wind speeds and even better for high wind speeds. One must remember, however, that the TOPEX measurements themselves are subject to errors in comparison to ground truth.



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Figure 17. Parametric estimation of wind speed from waveform shape.

Data reduction techniques are of interest to both the technologist and the scientists. This is an important area that needs to be developed in order to fully realize the potential of this measurement. The results thus far indicate that a model derived from theory alone matches the measured data quite closely.

This promises that the reflected GPS technique will not require such extensive calibration

as conventional backscatter instruments have. On the other hand, effects such as Bragg scattering are not included in the Zavorotny model. There is some indication that these effects may be present in the aircraft data. Reflection at low wind speeds (below 4 meters/sec) is also not well modeled by this theory. This is because the theory assumes a "very rough" surface in which the diffuse scattering predominates. At these slow wind speeds, some component of specular reflection may also be present.

This range of low wind speeds may in fact be better measured by this instrument than by conventional scatterometers and altimeters. This is because a bistatic reflection (forward scatter) is strongest at slow wind speeds. An opposite dependence is shown for backscatter. In this application, reflected GPS signals may provide measurements that are complementary to the existing radar remote sensing instruments. This is another potential advantage of this instrument which should be pursued in addition to the capability to providing existing measurements at a significantly lower cost. The theory of scattering in this wind speed regime, however, is not well developed and some improvement of these models by empirical fitting of experimental data will probably be necessary.

The next step in data processing techniques is to derive similar methods for wind direction based upon the distribution of correlator power into Doppler bins as illustrated in figure 5. The signal strength in the range bins in which there is the most sensitivity to wind direction is very weak. Aircraft flight tests should be conducted at a high enough altitude and speed that the Doppler spreading becomes more apparent and can be detected in range bins closer to the specular point, which have higher signal power. Once the form of this data extraction method has been proven from aircraft, it must be adapted for the larger range of Doppler frequencies and spread of range as encountered in orbit.

Thus far, all of the experimental work, and most of the analysis has used a single frequency C/A code receiver. Unlike positioning, in which the shorter code chip of P-code results in finer precision, there is strong indication that C/A code is preferred for this measurement. The shorter P-code chips will illuminate a narrower elliptical annulus on the reflecting surface than C/A code chips would. This results in lower power being returned per correlator. From satellite altitudes, this difference is significant. Figure 18 plots simulated waveforms for a range of typical wind speeds at the two different code frequencies. The C/A code waveform shows at least the same sensitivity to the wind speed as P-code does. The difference, however, is in the returned power which is approximately 10 dB lower for P-code. For this reason, there is no justification for utilizing P-code, with all of the associated complications, to the sea state monitoring application. In fact, there is very strong justification for using the C/A code.

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Figure 18. Comparison of reflected power at C/A and P code

The only advantage of P-code, for ocean-reflection studies, is the presence of a second frequency. Applications of dual-frequency reflected data to sea state measurement are being investigated, but the principal use of these measurements would be for the ionospheric correction.

To determine the ionospheric TEC necessarily requires two frequencies. It might not, however, require the precision of P-code. This is because of the “leverage” provided by the difference in frequency between the L-band GPS transmissions and a typical S-band altimeter. It is known that the ionospheric delay is directly proportional to the TEC and inversely proportional to the transmission frequency. A typical code tracking accuracy of 3 meters for the C/A code will result in an ionospheric delay estimation accuracy of 2 cm for a 13.7 GHz altimeter. This, of course, assumes that it is possible to determine the relative delay between the L1 and L2 reflected signals with a similar precision.

At first, one would be tempted to apply a codeless technique [MacDoran 1984] by cross-correlating the down-converted L1 and L2 signals. These techniques work well for direct signals which contain a PRN code at only a single delay. The diffusely reflected signal, however, is composed of a distribution of PRN codes over some range of delays. Using data from the previous example at 535km altitude, this range could be as large as 40 code chips. Assuming that the tracking precision depends directly upon the width of the correlation function, and a 3 meter C/A code tracking precision, this would result in a tracking precision of 120 meters. Research into techniques for determining the relative delay between L1 and L2 which do not require close-loop tracking, or cross-correlation of the two signals is presently ongoing at the Langley Research Center and the Goddard Space Flight Center.

The frequency and modulation plan of GPS is presently under review by the Department of Defense and other agencies. A future option for enhancement of this system calls for providing the same C/A code on both L1 and L2 frequencies. When this is implemented, all of the scientific objectives of ocean-reflected GPS research could be achieved with dual-frequency C/A code receivers. These receivers will not require access to the encryption keys necessary to decode the P(Y) code. Furthermore, it is possible that much of the “open-architecture” receiver development which has happened to date could be expanded to include both frequencies.

Mission design studies have been conducted by Dave Mickler of the University of Colorado under an existing NASA Langley Grant. A constellation of seven low earth orbiting reflected GPS receivers were capable of providing the ground resolution required for scatterometry, as defined above (50km ground sampling with 2 day global repeat). This satellite constellation had had seven polar orbiters at an altitude of 350 km. A low altitude is desirable because the actual strength of the weak reflected signal is not known at this time. To minimize the size and complexity of this instrument and spacecraft, use of a moderate gain, fixed nadir-oriented antenna is preferred.

This constellation provides global coverage approximately once every 2 hours. The spacing of specular points, however, samples the sub-satellite ocean surface less densely than the 50 km resolution requirement. Assuming 9 reflected GPS satellites are visible, uniformly distributed in azimuth, only approximately 4 percent of the sub-satellite visibility cone is illuminated by GPS reflections. Hence, 2 hour global coverage is necessary to obtain the 50 km measurement resolution with 2-day repeat.

If this resolution requirement could be relaxed, and a typical ocean de-correlation length of twice this resolution is assumed, adequate coverage could be provided by 4 polar orbiters. This satellite constellation has the orbiters separated by 45 degrees in right ascension of the ascending node. A typical ground track is provided in figure 19. (Mickler, unpublished communication)

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Figure 19. Ground track of 4 satellite ocean-reflection constellation

An early space flight demonstration of the delay mapping receiver was conceived as part of this system study. This engineering test instrument would be realized entirely as modifications to the software in the PiVoT receiver that is already scheduled for the Spartan 251 mission on the Space Shuttle in early 2000. This mission is to be the first space flight validation of the PiVoT receiver for navigation. (An Air Force demonstration of relative navigation is the primary objective of the Spartan 251 mission.) An opportunity exists on this mission to use one of the spare inputs to the PiVoT receiver to connect a moderate gain LHCP antenna. The window of opportunity in which to attempt the collection of ocean-reflected GPS data lasts approximately 5 orbits during which time the Spartan payload maintains an Earth-pointed orientation.

This mission is illustrated in figure 20. Signal to noise calculations, similar to those presented above except at the lower 350km shuttle orbit predict a 27 dB reduction per range-Doppler bin under the 20 meter/sec worst case conditions. The extent of the glistening surface under these conditions is approximately 26 code chips. An incoming signal to noise ratio of 15dB is comparable to the results obtained so far from aircraft. With a 6dB antenna gain over the hemispherical ones typically used and one second incoherent integration, a final signal to noise ratio of 11dB is predicted for the output of each correlator. The PiVoT receiver will have 24 correlators available to map this waveform as a function of delay.

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Figure 20. Spartan 251 reflected GPS mission

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Figure 21. Spartan 251 reflected GPS experiment antenna.

An antenna array of four patches, shown in figure 21 will have a gain of 6db over the

hemispherical ones used on previous aircraft flight campaigns. These patch antennas would be obtained as off-the-shelf commercial components, and assembled in-house at GSFC, resulting in minimal additional cost to the PiVoT integration on Spartan.. Placement of the antennas for the attitude determination, navigation, and ocean reflection experiments using the PiVoT are shown in figure 22.

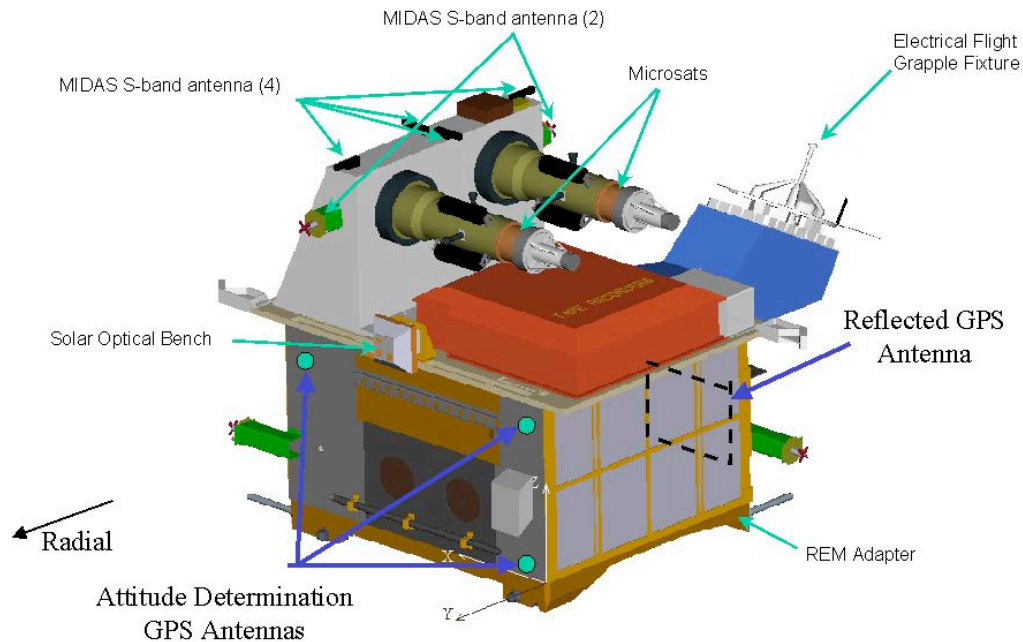


Figure 22. Proposed location of PiVoT GPS antennas on the Spartan 251 payload.

Technology Assessment

Five areas of future work necessary to evolve this technology were identified in this study:

Parallel Delay-Doppler Mapping Receiver. The existing "breadboard" aircraft instrument is limited to a maximum of 32 range-bins per 6 satellites for low SNR operations. The parallel version of this instrument uses up to 12 range-bins focussed on a single satellite to improve the signal to noise ratio by 20dB through incoherent averaging of 100 times as many samples. The size of the "waveform" mapped by these instruments and the limitation to range-only bins is the biggest limitation to collecting research quality data sets which could identify the wind vector direction dependence predicted by theory. It is recommended that an extendible receiver architecture be produced in which the practical limit to the number of range-Doppler cells in in the order of hundreds.

The absolute (to remove the large delay between direct and re-flected signals) and

relative (to reference all measurements to the specular point) placement of these cells should be controllable in software so that the receiver could be re-configured easily as the measurement concept and data processing techniques evolve. It is also highly recommended that commercially available receiver chipset (such as those sold by MITEL or SiRF) be used. In this manner, there will be little additional hardware development cost, and the software would operate with the receiver using non-proprietary interfaces.

Another path that should be considered is constructing a specialized "open loop" correlator array using PLD's. This array would be ideally suited for the continuous collection and averaging of correlation data over a "grid" of range-Doppler bins. Again the use of commercial parts and development systems would greatly reduce the cost of custom hardware development.

Wind Vector Retrieval Algorithms: Promising results have been shown using empirical as well as model-based inversions of the waveform shape to extract wind speed with a precision of better than 2 meters/sec in comparison to TOPEX/Poseidon. These algorithms need to be adapted to the signal structure that is expected from an orbiting instrument. Also, the extraction of wind direction is apparently possible using the distribution of correlation power as a function of Doppler frequency. The retrieval method for wind direction must also be derived from these theoretical predictions. Retrieval algorithms accurate for low wind speeds, below 4 meters/sec, should also be developed because of the resultant stronger signal return in bistatic scattering.

High Altitude/High Speed Aircraft Data Collection The aircraft experimentation to date has been at relatively low speeds and the effects of the spread in Doppler frequencies has not been apparent. Predictions of the dependence of wind direction on the distribution of power as a function of Doppler cells requires that measurements be made at a very low correlation power level (below -30dB relative to direct). Using the existing aircraft and receiver, this would necessitate a very long averaging time to extract the wind direction measurement. The limit on averaging time is set by the validity of the "frozen surface" assumption.

It is therefore important to perform some data collection tests on a higher speed aircraft and utilize this data to derive and validate wind direction retrieval methods that would eventually be used in conjunction with the satellite instrument.

Reflected Signal "Tracking" at L1 and L2: Using the reflected signal to extend ionospheric TEC models over the open ocean requires that this signal be "tracked" at both of these frequencies. In this application, the "tracking" of the reflected signal will be defined as estimating the differential delay between the ray paths for the L1 and the L2 frequency. Closed delay-lock loops, commonly utilized to track direct GPS signals, cannot be applied to the diffusely scattered reflected signal.

Satellite Technology Demonstration: Analytical models for bistatic scattering are not widely used in remote sensing. Recent work [Zavorotny and Voronovich, 1998], [Lin, et

al., 1999] has produced models that predicts the experimental results well for aircraft altitudes. Before an operational science mission can be proposed, it is important to validate these models, define the appropriate receiver architecture and test the complete measurement concept from orbit. It is fortunate that this instrumentation is very small (3kg or less) and consumes very little power (10-20 W). For this reason, the best early demonstration would be as a secondary payload on another mission. Candidate missions should be at least 12 months duration, operate in an Earth-pointed attitude, and be in low Earth orbit (550 km or less) to receive the strongest signal. It would be ideal if this instrument could be tested on an orbiting platform which also hosts another sensor which retrieves similar information (such as a wind-lidar).

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