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TOWARDS GPS SURFACE REFLECTION REMOTE SENSING OF SEA ICE CONDITIONS*

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ABSTRACT

This paper describes the research to extend the application of Global Positioning System (GPS) signal reflections, received by airborne instruments, to cryospheric remote sensing. The characteristics of the GPS signals and equipment afford the possibility of new measurements not possible with existing radar and passive microwave systems. In particular, the GPS receiving systems are small and light-weight, and as such are particularly well suited to be deployed on small aircraft or satellite platforms with minimal impact. Our preliminary models and experimental results indicate that reflected GPS signals have potential to provide information on the presence and condition of sea and fresh-water ice as well as the freeze/thaw state of frozen ground. In this paper we show results from aircraft experiments over the ice pack near Barrow, Alaska suggesting correlation between forward scattered GPS returns and RADARSAT backscattered signals.

1. INTRODUCTION

In 1996, Drs. Katzberg and Garrison of NASA Langley Research Center (LaRC) developed the revolutionary idea of using of reflected GPS signals for remote sensing applications, resulting in a series of publications describing the theory and mechanisms for this technique [Katzberg and Garrison, 1996] and presenting preliminary experimental results [Garrison et al., 1997]. Collaborations among researchers at LaRC, NASA Goddard Space Flight Center, the Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado at Boulder and National Oceanic and Atmospheric Administration (NOAA)/Environmental Technology Laboratory (ETL) have developed to pursue this line of research. This research team has advanced the understanding of reflected GPS signals and provided direct experimental evidence of their application to ocean remote sensing and mapping. The current investigation into cryospheric applications of GPS reflections is based upon a proposal made by Drs. Katzberg and Garrison, to collect GPS signals reflected by ice surfaces, and the acquisition of the first such measurements from sea ice in the Beaufort Sea in April 1998.

In addition to our research effort there are parallel and complementary investigations of ocean reflected GPS signals being conducted by the Jet Propulsion Laboratory (JPL) and the European Space Agency (ESA), focused primarily on the application of reflected GPS signal tracking to altimetry [Martin-Neira, 1993]. These groups have conducted a number of experiments from static locations and aircraft, and investigated signals received from a spaceborne antenna [Lowe et al., 1998].

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The application of reflected GPS signals to remote sensing of surface conditions may be particularly useful for investigations of the state of polar sea ice cover because of the environmental characteristics of these regions. In situ or aerial mapping of sea ice conditions presents unique difficulties for conventional instrumentation, including an inaccessible and hostile environment, low light levels much of the year, and persistent cloud cover [Barry et al., 1993]. Investigations of sea ice conditions thus rely heavily on satellite remote sensing and occasional field campaigns. Remote sensing of the Arctic and Antarctic ice cover is typically done via a combination of active microwave remote sensing using Synthetic Aperture Radar (SAR), passive microwave sensing, and imaging in optical and thermal wavelengths. No single sensor is capable of providing the range of observations needed. For example, SAR images have sufficient spatial resolution to resolve detailed ice features, but repeat times of existing satellites are relatively long compared to the rate of change of open water fraction in the ice pack. Furthermore, SAR data carry a substantial penalty in cost for acquisition and processing. Spaceborne passive microwave sensors offer more frequent coverage at several wavelengths, but with substantially lower spatial resolution. Optical and thermal sensors provide a middle ground in resolution and temporal sampling between SAR and passive microwave satellites, but are limited by cloud cover and visibility conditions.

Reflected GPS signal remote sensing may offer considerable advantages for augmenting these data types. In a sense, reflected GPS signal measurements that are gated by the code structure, are a combination of microwave active and passive remote sensing, where the radiation source is independent of the sensing system, but which still exhibits a potentially strong signal relative to microwave radiation emitted by the surface. Receivers to measure GPS returns are relatively small and inexpensive. The current systems consist of two small GPS antennas, a modified GPS receiver, processor, data recorder, and cables. The system can be operated using a standard personal computer, or as a self-contained package. This package weighs less than 5 kg, operates on battery power, and can be installed on virtually any type of aircraft. The systems could therefore be carried on-board aircraft flights of opportunity such as ice reconnaissance missions, supply flights to field camps, and airline routes that cross the Arctic. Reflected GPS signal measurements therefore provide some of the positive elements of existing microwave sensors, but at much lower cost and with added value such as a continuously-available GPS signal and the potential for reflected signal recording obtained from many possible platforms. The potential also exists for using reflected GPS measurements as a ground-based tool for monitoring nearby ice and soil conditions from fixed locations.

2. MEASUREMENT METHODS

The use of GPS in a bistatic radar configuration to measure surface properties relies upon our ability to extract information from the reflected signal. For standard GPS navigation applications, the receiver's main functions are to measure the signal delay from the satellite (the pseudorange measurement) and the rate of change of the range (the Doppler measurement). Conversely, in our remote sensing application, the primary measurement is the received power from a reflected signal for a variety of delays and Doppler values. The basis of this measurement and its sensitivity to the surface conditions is discussed in the following paragraphs.

Each GPS satellite transmits two right hand circularly polarized (RHCP) L-band signals at 1.57542 GHz and 1.2276 GHz. These carrier signals are modulated by unique pseudorandom noise (PRN) codes with an autocorrelation function similar to the ideal autocorrelation function shown in Figure 1. The autocorrelation power has a triangular shape, or Lambda function (Λ), which is suppressed at delays of more than ± 1 chip (300 m for the civilian (C/A) code). To acquire and track a signal, a conventional GPS receiver generates a local replica of the code for the particular satellite signal to be tracked, compensating for the expected Doppler shift and computing the cross-correlation between the replica and the incoming codes.

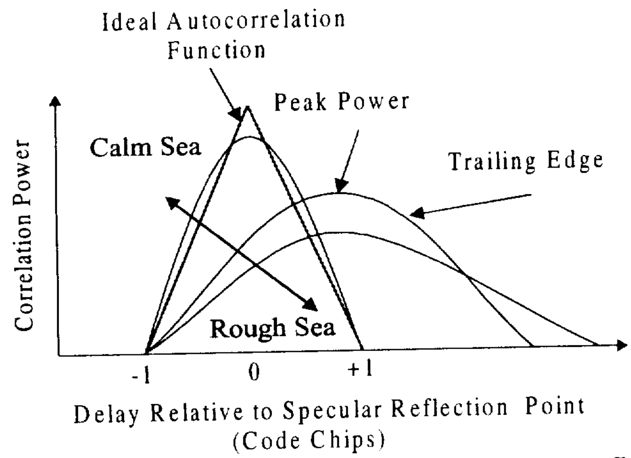

Figure 1. Correlation function shapes for ideal direct GPS signal and for reflected signals from rough surfaces.

When a GPS signal encounters an ideal, smooth reflecting surface, specular reflection occurs at a single point. The reflected signal code structure remains, but the polarization of the wave is reversed to left-hand circular polarization (LHCP), and the signal power is decreased. If, however, the surface is rough relative to the GPS wavelength of 19 cm, reflections are produced by multiple facets on the surface. This creates a so-called glistening zone around the ideal specular point and results in a distribution of varying ranges and Doppler shifts, as shown in Figure 2a. To measure GPS signals reflected from land and sea surfaces, we modify a typical receiver to measure correlation power at these offset values of delay and Doppler using a nadir-pointing LHCP antenna. In Figure 2b, we illustrate the type of swath coverage that GPS provides. Because of the multiplicity of GPS transmitters the receiver can observe a number of simultaneous footprints on the surface. This is to point out that while the system does not provide imaging in a standard sense (like a cross-scanning system, for example), it does provide more spatial coverage than from a sensor that is only able to view one ground point at a time.

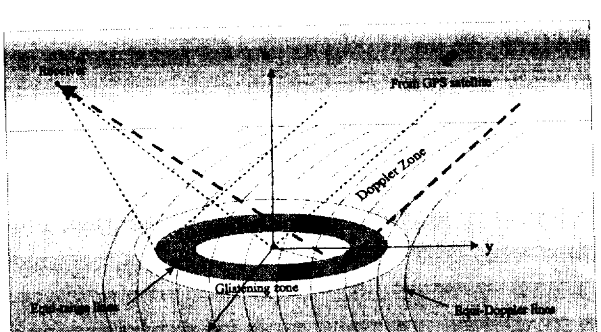

Figure 2a. Illustration of glistening zone (adapted from Komjathy et al., 1999).

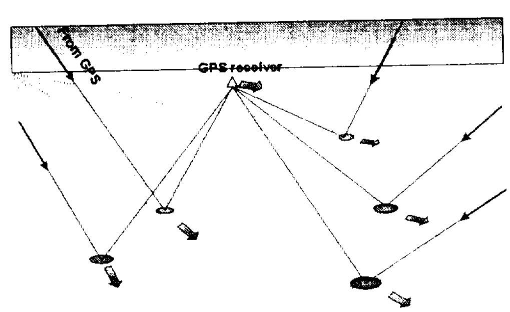

Figure 2b. GPS swath coverage.

Recent efforts to understand and use GPS signals reflected from ocean surfaces have focused upon retrieving wind speed and direction based on analysis of return signal shape [Katzberg et al., 1998; Garrison and Katzberg, 1998; Garrison et al., 1997; 1998; 1999; Lin et al. 1999; Clifford et al., 1999; Zavorotny and Voronovich 1999a; 1999b; Komjathy et al., 1998; 1999].

Our preliminary modeling and experiments suggest that the reflected GPS signal is very sensitive to the presence of sea ice, and furthermore, contains information related to ice conditions. However, much remains to be done to determine the consistency of the signal return from ice surfaces; to investigate the information content of the signals; and to develop simplified retrieval algorithms to extract the cryospheric conditions. Given the unique potential offered by reflected GPS signal sensing (e.g., L-band observations, forward-scattering sensing, low-cost and simple devices useable on any type of aircraft, etc) and the geophysical significance of additional sea ice and permafrost data, research to investigate and exploit GPS returns from ice and frozen ground is warranted.

3. BACKGROUND

Our preliminary experiment to observe GPS reflections from Arctic sea ice showed that for the moderate altitudes of the airborne GPS receiver, the reflected signal shape was fairly consistent (sharp, narrow waveform throughout the flight) indicating that ice surface roughness variations were not significant at L-band. On the other hand, the peak power was found to change significantly along the flight track. This behavior of the signal is a clear indication of the sensitivity to ice reflections. Correlations seen in our preliminary comparison between RADARSAT backscatter and GPS forward scattered data indicate that the GPS signal may indeed provide useful information regarding ice conditions, in addition to the basic ability to detect the presence of sea ice.

The reflection coefficient of a frozen sea surface is determined by the effective dielectric constant of ice and, under some conditions, by the dielectric constant of the underlying water. The latter is important for thin ice conditions where a significant portion of the radio wave energy may reach the second interface, between the ice and water. The effective dielectric constant of ice depends on various factors, such as an ice composition, salinity, temperature, density, age, origin, morphology, etc. [Vant, 1978; Shohr, 1998]. Because first-year ice has needle-like inclusions of brine (predominantly oriented along the vertical direction), this variety of ice is notably anisotropic. Therefore, the dielectric constant is a tensor rather than a scalar constant [Stogryn, 1987]. This makes the problem of modeling and interpreting the GPS signal scattering from ice rather challenging. At the same time, the sensitivity of the GPS scattered signal to these complex ice characteristics makes it a particularly attractive remote sensing tool.

The potential of reflected GPS signal mapping presents differences and complimentary features to conventional techniques based on radars (including synthetic aperture radars (SAR) and microwave radiometers. Real-aperture radars use shorter wavelengths (C-, X-, K-bands) primarily to allow for a high enough surface resolution and signal-to-noise ratio with relatively compact antennas. Synthetic aperture radars can use a broader range of radio wavelengths, starting from P- and L-bands up to X-band. These types of radars are mainstays for mapping of ice cover [Livingstone, et al., 1987a; Livingstone, et al., 1987b; Drinkwater, 1991], and provide a valuable source of data for comparison with our GPS reflection observations in order to identify common features of the ice fields.

It is important to note that the L-band GPS receiver with a small hemispherical antenna can achieve the same or even better surface resolution than real-aperture radars. This is because the return is gated or limited by the code structure of the GPS signal (by the chip length). Therefore, the surface resolution of the GPS mapping receiver does not depend on the size of the antenna (actually, for aircraft altitudes, we use a small, low-directional antenna). Another difference is that radio waves at the C-, X-, and K-bands typically used in radar systems cannot significantly penetrate the ice depth, so their signatures mostly provide information about the surface roughness, such as floe ridges, broken ice, frost flowers, and fine-scale roughness at the snow-ice interface [e.g., Melling, 1998]. The L-band radio waves penetrate to a greater depth, therefore their scattering provides additional information about the internal ice structure.

Because reflectivity and emissivity of a medium are related, the bistatic geometry suggests instructive parallels between this technique and microwave radiometry. L band is desirable for radiometry due to the sensitivity of these waves to the composition and thickness of the medium. L-band radiances thus can provide information on ice layering, ice thickness, and soil moisture at significant depth. However, use of this band puts severe limits on the spatial resolution obtainable by L-band radiometers flying at higher altitudes. In contrast, L-band reflected GPS signal measurements obtained at typical aircraft altitudes can be expected to yield a spatial resolution at the order of 100 meters, with comparable measurements from spacecraft altitude providing an expected spatial resolution between 10 and 20 km.

4. MODELING CONSIDERATIONS

From a general point of view there is no significant difference between modeling of the GPS signal scattering from an ocean surface and from sea ice, or from other natural medium, such as frozen soil. The basic bistatic radar equation obtained in Zavorotny and Voronovich, (1999a), which describes a so-called waveform, the dependence of the received power over the time delay, holds also for the case of the sea ice or soil scattering. The only factor in this equation related to properties of ice or soil is the normalized bistatic cross section (NBCS) of the surface. The strength of the received signal, which is related to the peak of the waveform, is proportional to the value of the NBCS. The NBCS for the LHCP signal in forward direction can be described in the geometric optics limit of the Kirchhoff approximation [Zavorotny and Voronovich, 1999b]. For RHCP this approximation does not work, and the first-order small-slope approximation is needed [Zavorotny and Voronovich, 1999b].

The NBCS depends on two parameters related to the scattering medium – the reflectance and the surface roughness. The reflection coefficient or reflectance can be expressed through the effective dielectric permittivity of the medium. The latter is a complex function of physical and structural property of the medium. For example, in L-band the effective dielectric permittivity of ice is sensitive to salinity, temperature, composition, and age of ice [Golden, 1995]. Similarly, different types of soil have different dielectric permittivities. That is seen from both laboratory and airborne radiometric measurements that indicate that soil emissivity increases substantially from wet soils to frozen soils in the frequency ranging from 0.6 to 1.67 GHz due to difference in dielectric constant between liquid water and ice [Komarov et al., 1993].

The second parameter is surface roughness. Roughness has a direct effect on the width of the GPS reflection waveform, and indirectly modifies the peak value of the return. In order to separate the contribution of roughness and reflectance we could use a model based on the small-slope approximation or additional observational data. Unfortunately, use of the model requires knowledge of the surface elevation spectrum, a characterization that is rarely available in the literature (see, e.g., a surface model presented in [Dierking et al. 1997]). An alternative approach is to measure the reflected signal with both LHCP and RHCP antennas and determine the roughness from the ratio of the signals. This removes the sensitivity to roughness and facilitates the extraction of reflectance. Subsequently, the individual signal components can be used to determine the roughness.

5. EXPERIMENTS AND DATA ANALYSIS

Most of the GPS reflection experiments to date have been conducted with the Delay Mapping Receiver (DMR) designed by Drs. Katzberg and Garrison [Garrison et al. 1997], based on the GEC Plessey (now MITEL) GPSBuilder-2 [GEC Plessey, 1996]. The DMR has two antenna inputs to allow standard tracking of direct signals using a zenith-pointed RHCP antenna and correlation measurements of reflected signals using a downward-pointed LHCP antenna. The innovation of this design is that unlike a conventional GPS receiver, the DMR does not attempt to perform closed-loop tracking of the reflected signal but rather, it uses some of the receiver channels to make measurements of the correlation between the reflected signal and shifted versions of the local signal replica. This provides a trace of the reflected signal correlation as a function of code delay, thus mapping the return from annular regions of the glistening zone.

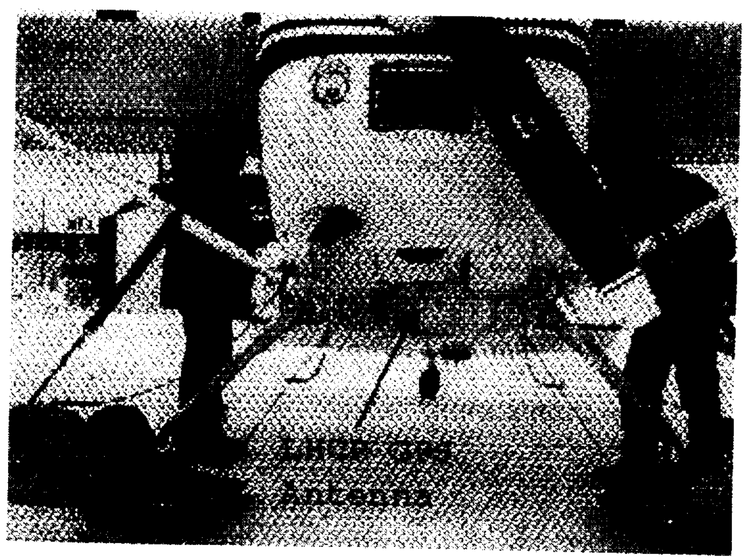

Figure 3. Installation of the DMR receiving system on the Cessna 185 at Barrow, Alaska. The LHCP antenna is shown, installed on a removable inspection plate. The RHCP antenna is located in the cockpit, temporarily mounted beneath a skylight.

Following the suggestions of Drs. Katzberg and Garrison who proposed tests of the DMR over sea ice, the first measurements of reflected GPS data from sea ice were collected by Dr. Maslanik in the Beaufort Sea in April 1998. During the experiment, the GPS system was tested with antennas mounted on a boom and held over various ice surfaces at different heights ranging from 30 cm to 20 m. Each antenna was mounted on a small 20 cm by 20 cm aluminum ground plane, with the two plates then attached to provide the up-looking and down-looking mount for the antennas. A second reflected GPS data set was collected north of Barrow, Alaska in April 1999, using the same system but in this case mounted on a Cessna 185 (see Figure 3). Approximately 2 hours of data were collected in conjunction with a National Ice Center (NIC) reconnaissance flight and nearly coincident in time with a RADARSAT overpass.

We have analyzed both the shape and peak amplitude of the measured waveforms from the low altitude boom tests and the airborne experiment. The Beaufort Sea boom measurements indicated a distinct (i.e. sharp and narrow waveforms) reflected signal from sea ice. However, using our existing hardware and analysis techniques, measurements from such low heights above the surface provide a low signal-to-noise ratio and are difficult to interpret compared to data acquired from aircraft altitude. The aircraft results from Barrow experiment showed similar, sharp and narrow waveform shape with highly variable peak power. To evaluate the Barrow GPS returns, we compared the results to RADARSAT backscatter intensity data from imagery provided by NIC, oblique aerial photographs, visual observations provided by the NIC ice reconnaissance flight. The GPS surface-reflected peak power values were overlaid onto the RADARSAT image by georeferencing the image and performing coordinate transformations between the GPS specular reflection points and the RADARSAT data.

Figure 4 shows the peak return power from GPS satellite PRN30, collected during the flight leg designated as "B2". Reflected power is plotted versus RADARSAT backscatter along the flight leg, as a function of along track epochs. In Figure 5, we show another example for the PRN03 satellite collected during a second leg of the flight. The two sets of curves indicate a positive correlation between the forward-scattered GPS peak power and the backscattared RADARSAT data for locations of high reflection coefficients, as well as some other variations in the GPS data that differ from the RADARSAT backscatter. For signals in the same frequency band and for rough surfaces, the lack of negative correlation between the peak forward-scattered GPS power and the radar backscatter indicate that the surface roughness does not play a significant role. On the other hand, the positive correlation between forward and backscattered signals suggests that the dielectric constant might be responsible for the peak power variation and therefore pointing us to different types of cryospheric conditions. This is supported by visual observations conducted and aerial photographs taken during these flights, indicating a range of ice conditions, including new, young, thick first year ice, and old ice.

Furthermore, we also believe that the differences in the GPS L-band and RADARSAT C-band signal characteristics may account for some of the observed correlation between the two observations. For example, frost flowers on young ice can yield a relatively large radar backscatter at RADARSAT's C-band wavelength, but would not modify specular scattering from the underlying smooth ice at the longer wavelength L band. Alternatively, the variations in the GPS return might originate from differences in ice roughness at the ice/water as opposed to the air/ice interface producing the majority of the radar return. Such conditions embody differences in the bistatic versus monostatic reflections as well as the use of L-band versus C-band data. Some differences are also introduced when comparing such data sets due to sensor fields of view and errors in registration although in this case the GPS and RADARSAT footprint sizes are similar. Careful analysis of the data overlays was done to assess the effect of registration errors, but data collected over areas with more uniform ice conditions are needed to better test the empirical relationships. Given the factors involved in comparing different data types, further interpretation of empirical relationships and the development of classification algorithms must be supported, guided, and tested by modeling in conjunction with the collection of additional experimental data.

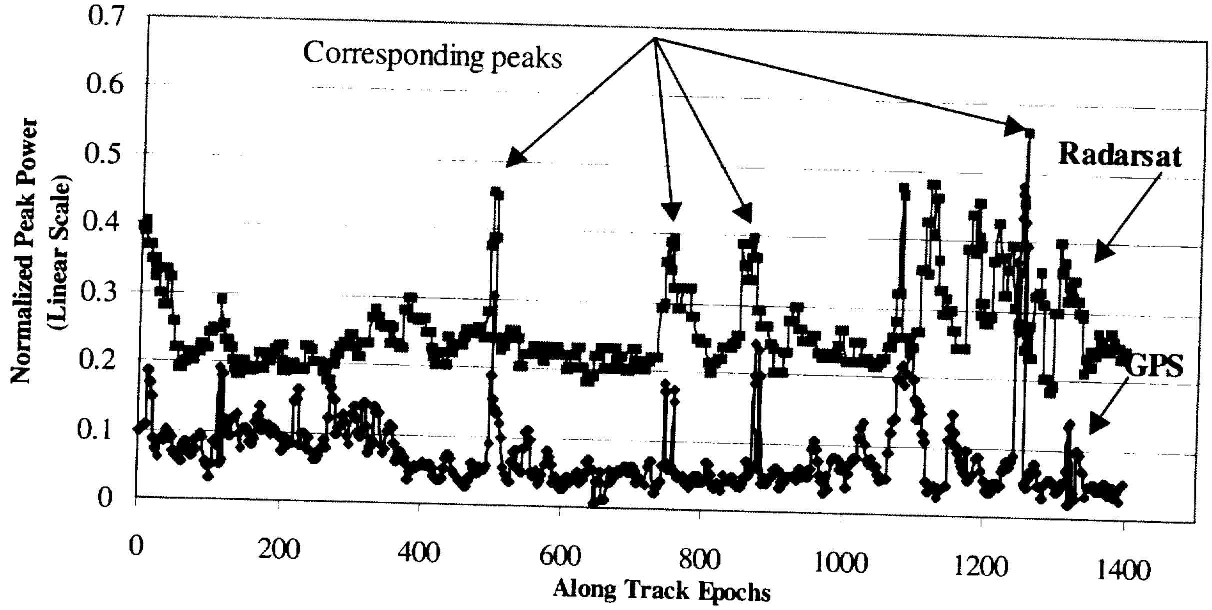

Figure 4. Normalized power plot for the PRN30, "B2" flight.

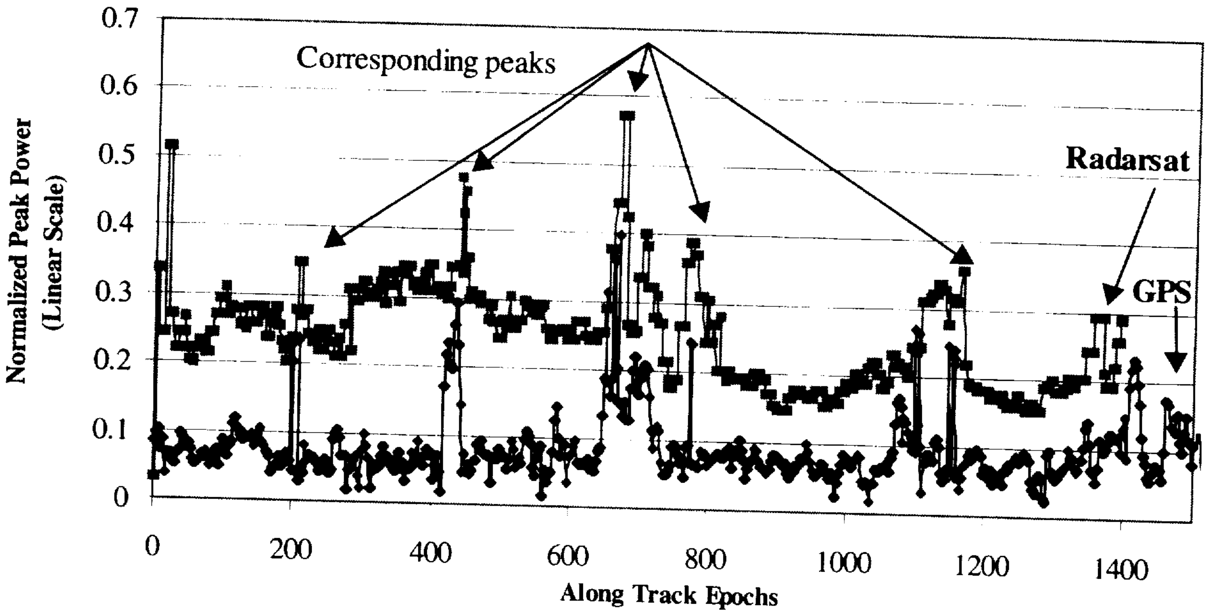

Figure 5. Normalized power plot for PRN03, "DAT" flight.

6. CONCLUSIONS AND PLANS FOR FUTURE RESEARCH

Preliminary experiments, including data acquired from aircraft flights over the ice pack near Barrow, Alaska, suggest that the reflected GPS signals contain useful information over sea ice. Given this new potential application for GPS remote sensing, an effort to investigate reflected GPS signals over sea ice is discussed in the paper. We present an effort that combines modeling background, in-situ measurements and aircraft observations to quantify the theoretical and observed relationships between reflected GPS signals and cryospheric conditions.

Future research will include an assessment of the potential of GPS bistatic reflected data for providing valuable geophysical information regarding sea ice, lake ice, and permafrost conditions, and development of algorithms to extract this information from easily obtainable, low-cost GPS measurements. Future work will also yield improved and extended models of L-band reflections from ice and soil, a suite of aircraft and supporting data sets, comparison of the capabilities of different types of GPS delay mapping receivers, and tests in several deployment modes, including deployment on aircraft and at fixed surface sites.

7. ACKNOWLEDGEMENT

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