PRELIMINARY RESULTS FROM THE

GPS-REFLECTIONS MEDITERRANEAN BALLOON EXPERIMENT (GPSR MEBEX) [*]

J. L. Garrison

NASA Goddard Space Flight Center

Greenbelt, MD, 20771

G. Ruffini, A. Rius, E. Cardellach

Institut d'Estudis Espacials de Catalunya (IEEC), CSIC Research Unit, Gran Capità 2-4, 08034

Barcelona, Spain

D. Masters, M. Armatys

Colorado Center for Astrodynamics Research

University of Colorado, Boulder, CO, 80309

V. Zavorotny

Cooperative Institute for Research in Environmental Sciences (CIRES)

University of Colorado, Boulder, CO, 80309

ORIGINAL

---

[*] Presented at the Sixth International Conference on Remote Sensing for Marine and Coastal Environments, Charleston, South Carolina, 1-3 May 2000.

ABSTRACT

An experiment to collect bistatically scattered GPS signals from a balloon at 37 km altitude has been conducted. This experiment represented the highest altitude to date that such signals were successfully recorded. The flight took place in August 1999 over the Mediterranean sea, between a launch in Sicily and recovery near Nerpio, a town in the Sierra de Segura, Albacete province of Huelva, Spain. Results from this experiment are presented, showing the waveform shape as compared to theoretical calculations. These results will be used to validate analytical models which form the basis of wind vector retrieval algorithms. These algorithms are already being validated from aircraft altitudes, but may be applied to data from future spacebourne GPS receivers. Surface wind data from radiosondes were used for comparison. This experiment was a cooperative project between NASA, the IEEC in Barcelona, and the University of Colorado at Boulder.

1.0 INTRODUCTION

Measurement and tracking of ocean storm strength and sea state are important elements in the monitoring of natural hazards. Radar remote sensing instruments, such as scatterometers have been used as surface wind speed measurements. These techniques have developed from the first aircraft observations relating the backscatter coefficient to wind speed in the late 1960s, through the first satellite demonstration on Skylab in 1973 (Ulaby et al., 1981, pp 10) to the present state of the art instruments; NSCAT (Graf et al., 1998) and QuickSCAT. Altimeters can also generate a measurement of wind speed and significant wave height from the shape of a reflected pulse.

Recently, an new remote sensing technique has been developed (Garrison et al., 1998) which uses the (forward) scattered signal from satellite navigation systems such as GPS or GLONASS. The earliest work on this concept, with an emphasis on altimetry, can be found in (Martiín-Neira, 1993), (Martiín-Neira, 1996). This wind vector retrieval technique measures the change in shape of the cross-correlation function between the reflected signal and the reference PRN code. This cross-correlation has been shown to be related to the mean square facet slope of the reflecting surface (Zavorotny and Voronovich, in press), which has long been known to be empirically related to surface wind speed (Cox and Munk, 1994). Subtle anisotropy in the cross-correlation function may also be used to determine the wind direction if a sufficient signal to noise ratio is available (Armatys, 1999).

The use of the forward scatter of the GPS signal in this application has several advantages over conventional scatterometers. It requires only a low-power (10W) receiver as user equipment, (as compared to 198 W for the Sea Winds instrument (Graf et al., 1998)) This instrumentation could reuse a significant amount of hardware already developed and space qualified for GPS navigation use (for example, the airborne GPS receivers used to date have been un-modified navigation hardware with only software changes, coupled with reversed polarity antennas). Furthermore, reflected power is not directly measured, rather the shape of the cross-correlation function is fitted against analytical or empirical models. The "process gain" of spread spectrum signal allows the extraction of useful data from an extremely weak signal. For these two reasons, reflected GPS technique can use uncalibrated omni-directional antennas several centimeters in diameter to collect scientifically valid data from aircraft altitudes. Making use of reflections from 10 or more visible GPS satellites would give a wide distribution of data samples. The use of low gain antennas, as described above, could provide this coverage without the need for scanning.

Analytical models have already been developed and have compared well against the large body of existing data, collected mostly from aircraft at altitudes below 8Km. These models have been used both as the basis of wind vector retrieval algorithms (Komjathy et al., in press) (Garrison et al., in review), as well as extrapolated to predict the signal to noise ratio from a similar instrument used in low earth orbit. Retrievals have shown a precision of 2 meters/sec in comparison to TOPEX, providing confidence in these models when applied to aircraft altitudes and velocities. Extrapolation of these models to satellite altitudes and velocities, however, has never been demonstrated with experimental data. It was therefore determined that collection of a segment of data from very high altitudes would serve to validate these models, and the joint NASA-IEEC MEBEX project was formulated with this purpose.

2.1 RECEIVER DESCRIPTION

The receiver used for these experiments was a modification of the Delay-Mapping receiver originally used on aircraft flight campaigns (Komjathy et al., 1999). A schematic of this receiver is shown in Figure 1. Two RF front-ends are used, one is fed by a conventional right-hand circularly polarized (RHCP) antenna oriented to receiver direct line of sight GPS signals, the other is connected to an left-hand circularly polarized (LHCP) antenna oriented to receive the reflected signals. Whereas the direct signals are tracked using delay-lock loops and carrier frequency lock loops as on any navigation receiver, the reflected signal is not tracked at all. Rather, an array of correlator channels are controlled "open-loop" to process the reflected signal and generate correlation power (sum of the In-phase squared and Quadrature squared) at a range of code delays relative to the direct line of sight signal. These post-correlation samples are then averaged to reduce data rates, and stored to a solid state hard drive. The receiver hardware is based around a commercially available GPS development system (Plessey, 1995), and is controlled by a PC-104 based real time computer.

Additional complications were present due to the requirement that the system operate autonomously, and be able to re-start at unknown times in the trajectory. This was accomplished with minimal modifications to the existing code, and setting up scripts to cyclically call the following sequence:

- Cold start sequence, Total duration of 30 minutes; Searches for satellites and determines an initial position estimate, and identifies highest elevation satellite. This will allow the receiver to initialize without any prior knowledge of position.
- Parallel Delay Mapping Receiver: Specular Tracking (PDMR-Spec), 20 minutes, given the highest elevation satellite, collects continuous data in 12 correlators, separated at 1/2 code chip intervals, set near the specular point location predicted for the highest elevation satellites. Tracking of the direct line of sight signal for the same PRN must also be maintained during this time in order to properly align the code phase for the reflection channels. 100 samples of waveform data are averaged and stored to disk at a rate of 10 Hz.

- Parallel Delay Mapping Receiver: Search (PDMR-Search), 20 minutes, same correlator architecture as PDMR-Spec. No prior knowledge of vehicle position and path length delay are assumed, however. Searches delay space by slewing code delay in the reflected channels by 1/2 code chip increments until the power in bin no. 4 exceeds a threshold. A simple controller is then used to maintain maximum power in bin number 4 by incrementing code phase by plus or minus half-code chips.

- Serial Delay Mapping Receiver: SDMR, 60 minutes, tracks up to six direct satellites through the direct RF front end. Uses this information to assign each of the lower RF front ends to the same satellite, and then sequentially steps through relative delays in the lower channels in 1/2 code chip steps. This code has the advantage of the PDMR in that it only requires an external position solution (from Cold Start) to initialize its warm start. Once 4 or more satellites are tracked from direct signals, the SDMR will automatically predict specular point offsets and properly align the reflected signal channels. The disadvantage is in the reduced signal to noise ratio, because of sequencing through 32 delay steps once every 100 ms as opposed to the continuous averaging of 1ms accumulations at the same delay for the complete 100 ms time. This allows only $1/100^{TH}$ of the post-correlation integration time to be applied to each correlator which results in a signal to noise ratio reduction of about 1/10 (10 dB). In the SDMR, a new sample of the waveform is available at a rate of 10Hz. These are passed through a moving average filter and written to disk at a rate of 1 Hz.

- System Reboot

The hardware used for this experiment was very similar to that flown for the much shorter duration Virginia Space Grant Consortium (VSGC) balloon launch in 1998 (Garrison and Katzberg, in press). Figure 2 shows a photograph of this instrument when it was assembled at the Langley Research Center for the VSGC experiment.

The receiver front end uses an automatic gain control to maintain a constant mean value of the noise floor, however on the VSGC launch, a drift in this noise floor was observed when the balloon reached very high altitudes. It was suspected that this drift was the result of thermal effects on the receiver hardware.

These effects were later reproduced using a thermal vacuum chamber in the Guidance, Navigation and Control Center of the NASA Goddard Space Flight Center, prior to the re-flight on GPSR-MEBEX. However, none of the data retrieved from the MEBEX experiment has shown these effects. This is probably the result of better insulation of the instrument on this flight as compared to the VSGC mission.

2.0 EXPERIMENT PLAN

The GPSR-MEBEX flight was made possible by payload space provided by the Agenzia Spaziale Italiana [*]/ Instituto Nacional de Tecnica Aerospacial [†] (ASI/INTA) Transmediterranean Balloon Campaign. The flight path of this experiment is indicated on the map in Figure 3. Launch took place at 20:22 UTC August 2nd 1999. After a brief detour inland from local winds, the balloon crossed into the Mediterranean. Following a four hour ascent, the balloon maintained an altitude between 35 and 37 km for approximately 14 hours as shown in the plot in Figure 4. Stratospheric winds took the experiment near the coast of Africa before returning to higher latitudes. It crossed over Spanish land at 35 Hours. The satellites recorded in the reflection channels for both SDMR and PDMR are indicated in Figure 5

3.0 DATA REDUCTION

Following the successful flight, the complete instrument was returned to GSFC where the solid state hard drive was removed and the raw (level 0) measurement data was retrieved and transferred to the University of Colorado for processing. Additional tracking data, collected by ASI using GPS was also available.

The data post-processing performs the following functions to generate a set of level 1a data which will be released to the scientific community through a World Wide Web site maintained by the University of Colorado.

- Numerically determine the location of the specular reflection point on the WGS-84 ellipsoidal model of the Earth.

---

[*] Italian Space Agency

[†] Spanish Institute for Aerospace Techniques

- Compute the correct path length delay between a direct and reflected signal.
- Translate the location of each delay bin, relative to the predicted delay to the specular point on the WGS-84 ellipsoid.

To perform this function, the precise GPS ephemerides from the National Geodetic Survey (NGS) were used. An error in the receiver software on this mission prevented the satellite numbers used in the parallel receiver segments from being recorded. This information was later inferred during post-processing from the satellites selected and tracked during the previous cold start phase and then from the latter serial receiver phase. A check on proper selection of satellite number was made by comparing the location of the waveform in delay space relative to the specular point location. From this altitude, the path length difference between satellites at different elevations is very large, and if the wrong satellite was selected, then the waveform would be translated away from the specular point delay by much larger than a few chips. This served to validate selection of the correct satellite.

4.0 PRELIMINARY RESULTS

Waveforms from the level 1a data set were scaled to have a constant area at each sample time, t, according to:

$$\bar{Y}_i(t) = \frac{Y_i(t) - NF}{\Sigma_i^N (Y_i(t) - NF)} \tag{1}$$

In which NF is the noise floor, and i is the sample from a single correlator. For these experiments, a measured noise floor, obtained from the average power in the first delay bin was used. Experience with the aircraft data shows that this serves to take out uncertainty in the calibration between the direct and reflected antennas as well as longer period variations which were observed in the total reflected power.

All of the data presented in this paper was from the SDMR segments.

5.1 RADIOSONDE DATA COMPARISON

Waveform data collected from this experiment, and post-processed to the level 1a data format described above has been distributed to the experiment partners. Preliminary comparisons to radiosonde data collected at three different locations surrounding the Mediterranean Sea have already been made. These data were obtained from the NOAA Forecast Systems Laboratory [‡]. The analytical model from (Zavorotny and Voronovich, in press) was used to generate predictions of the waveform shape based upon the measured surface wind speeds from the radiosondes. Figures 7, 8 and 9 show the georeferenced, level 1a data from the SDMR during three segment indicated at the points on figure Figure 6. An exponential series of the form (Garrison and Katzberg, in press)

$$Y^2(\tau) \approx \exp\left[\sum_{i=0}^{N} a_i(\tau - \tau_0)^i\right] \tag{2}$$

has has been fit to the measured waveform to obtain a "mean" shape over each segment of data. The location of these measurements relative to the location of the radiosonde stations, and the nearest wind speed measurement and time for each station are shown on Figure 6.

These figures indicate that the analytical models match the experimentally measured trends. The present lack of simultaneous space and time measurements makes a more exact comparison difficult. It is hoped that soon QuickSCAT, TOPEX and meteorological data will be available to offer a better comparison.

5.2 QUICKSCAT AND TOPEX COMPARISON

Waveform data from three segments of the mission (indicated on Figure 3 in the previous section) in which the balloon ground track crosses the QuickSCAT ground track will be used for comparison against analytical model predictions given the windspeed retrievals from the QuickSCAT instrument.

5.3 MM5 MODEL COMPARISONS

[‡] http://raob.fsl.noaa.gov/Raob_Software.html

Another source of comparison truth data is presently being collected from the European Center for Medium-Range Weather Forecasts (ECMWF) [§]. It is expected that these data will be available in February, 2000. These measurements will be used to initialize the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) [¶]. which could extrapolate wind vector measurements to the time and location of the balloon flight path.

5.0 CONCLUSION

A large body of data has been collected on reflected GPS signal structure at very high altitudes. Preliminary investigation of this data agrees with the predictions of analytical models. Further work will have to be done to more closely compare these measurements to other sources of data in the area in which the flight was conducted. Future work includes comparison with MM5 analysis over the Mediterranean using ECMWF initialization boundary conditions data and comparison against satellite data from altimeters and scatterometers. Results from this experiment will be used to improve the retrieval algorithms which would be used on future satellite based instruments.

[§] http://www.ecmwf.int

[¶] http://box.mmm.ucar.edu/mm5

Bibliography

M. Armatys, *Receiver Algorithms for Estimation of Sea-Surface Parameters Using Reflected GPS Signals*, Dissertation Prospectus, University of Colorado, Boulder, CO, December 21, 1999.

C. Cox and W. Munk, "Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter," *Journal of the Optical Society of America*, Vol. 44, No. 11, pp 838–850, November, 1994.

J. L. Garrison and S. J. Katzberg, "The Application of Reflected GPS Signals to Ocean Remote Sensing," *Remote Sensing of Environment* in press.

J. L. Garrison, S. J. Katzberg, and M. I. Hill, "Effect of Sea Roughness on Bistatically Scattered Range Coded Signals from the Global Positioning System," *Geophysical Research Letters*, Vol. 25, No. 13, pp 2257–2260, July 1, 1998.

J. L. Garrison, A. Komjathy, V. U. Zavorotny, and S. J. Katzberg, "wind Speed Measurement from Bistatically Scattered GPS Signals," *IEEE Trans. Geosci. Remote Sensing* in press.

J. Graf, C. Sasaki, C. Winn, W. T. Lui, W. Tsai, M. Freilich, and D. Long, "NASA Scatterometer Experiment," *ACTA Astronautica*, Vol. 43, No. 7, pp 367–407, 1998.

A. Komjathy, J. L. Garrison, and V. U. Zavorotny, "GPS: A New Tool for Ocean Science," *GPS World*, pages 50–56, April, 1999.

A. Komjathy, V. U. Zavorotny, P. Axelrad, G. H. Born, and J. L. Garrison, "GPS Signal Scattering from Sea Surface: Wind Speed Retrieval Using Experimental Data and Theoretical Model," *Remote Sensing of Environment* in press.

M. Martiín-Neira, "A passive reflectometry and interferometry system (PARIS): application to ocean altimetry," *ESA Journal*, Vol. 17, pp 331–355, 1993.

M. Martiín-Neira, *Altimetry Method*, U.S. Patent, August 13, 1996.

GPS Bulder-2 Designer's Guide, GEC Plessey Semiconductors, April, 1995.

F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave Remote Sensing: Active and Passive*, volume 1 Artech House, Inc., 1981.

V. U. Zavorotny and A. Voronovich, "Scattering of GPS Signals from the Ocean With Wind Remote Sensing Application," *IEEE Trans. Geosci. Remote Sensing* in press.

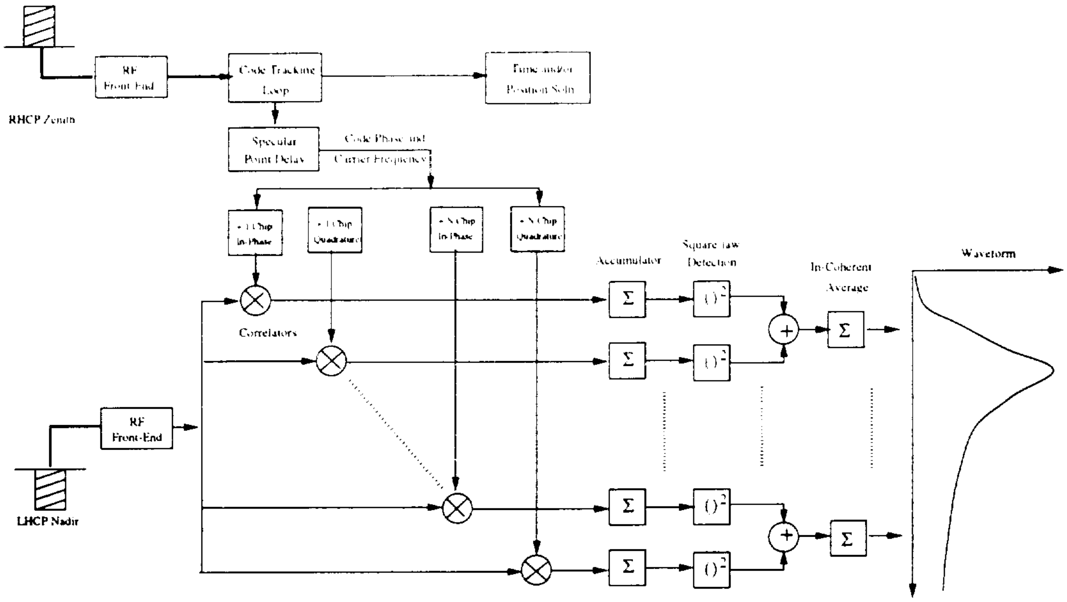

Figure 1: Schematic of Delay Mapping Receiver

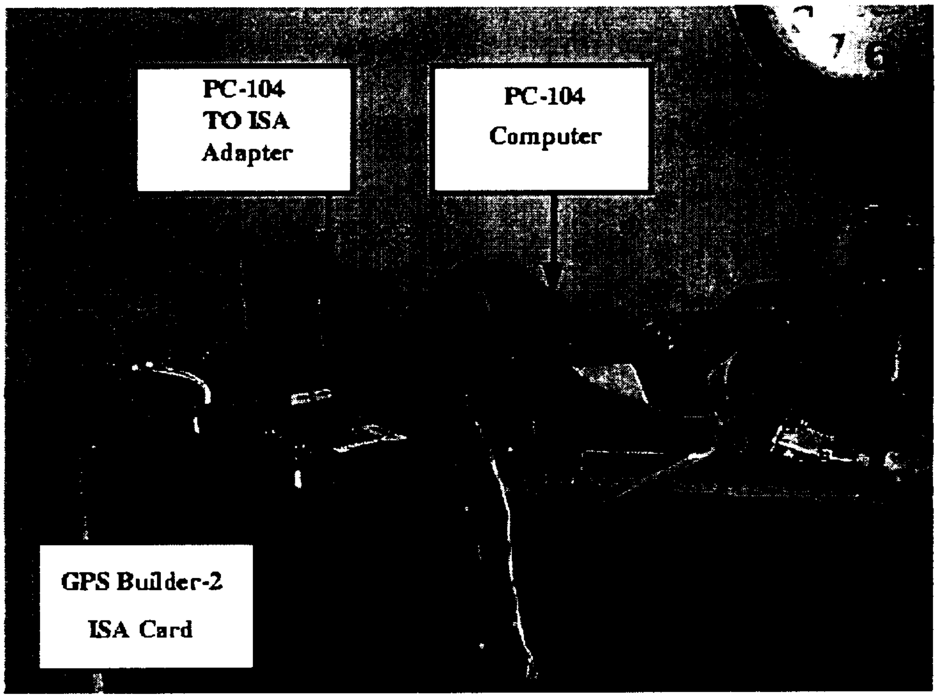

Figure 2: Assembly of Delay Mapping Receiver Hardware

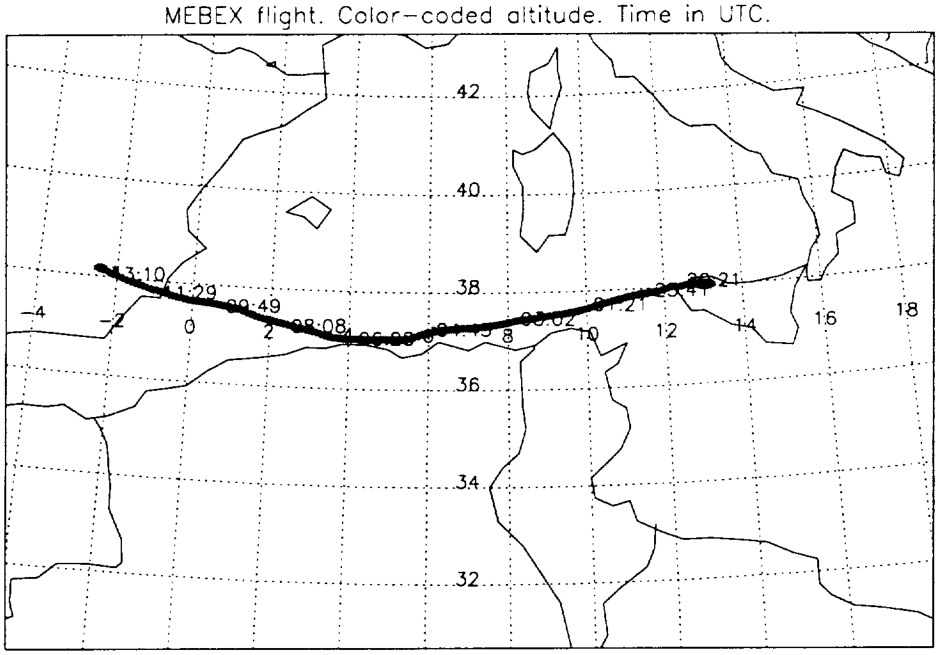

Figure 3: GPSR-MEBEX Flight Path

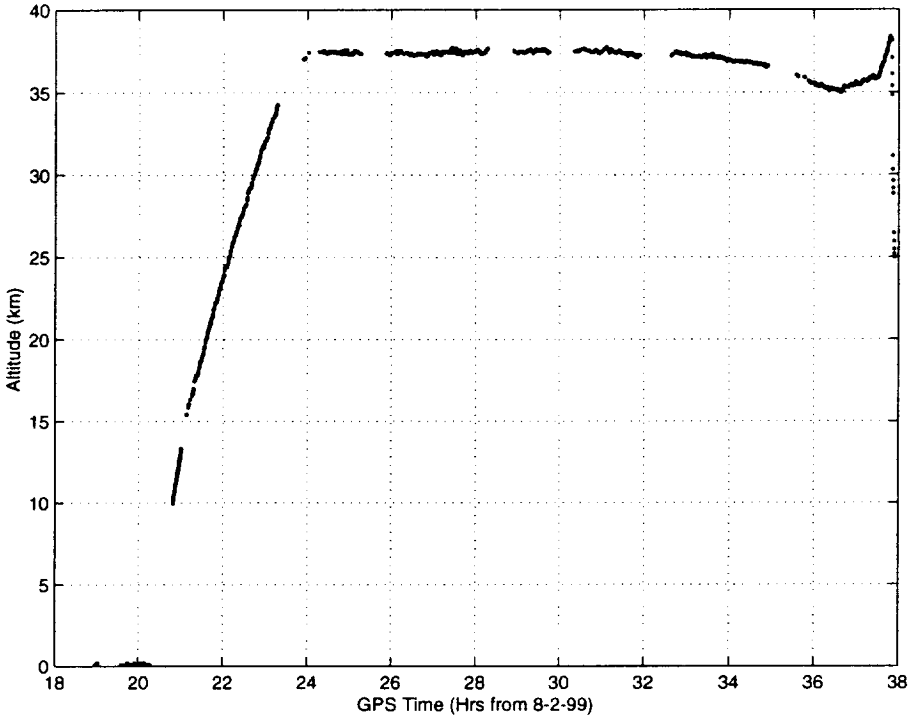

Figure 4: GPSR-MEBEX Altitude Profile

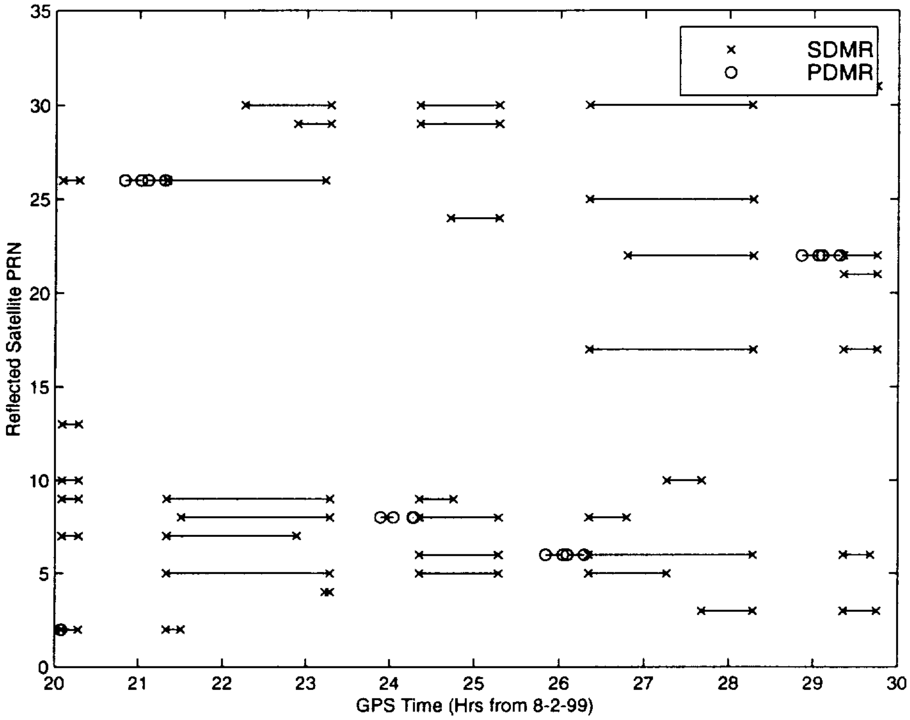

Figure 5: Satellite PRNS Recorded in the Reflection Channels

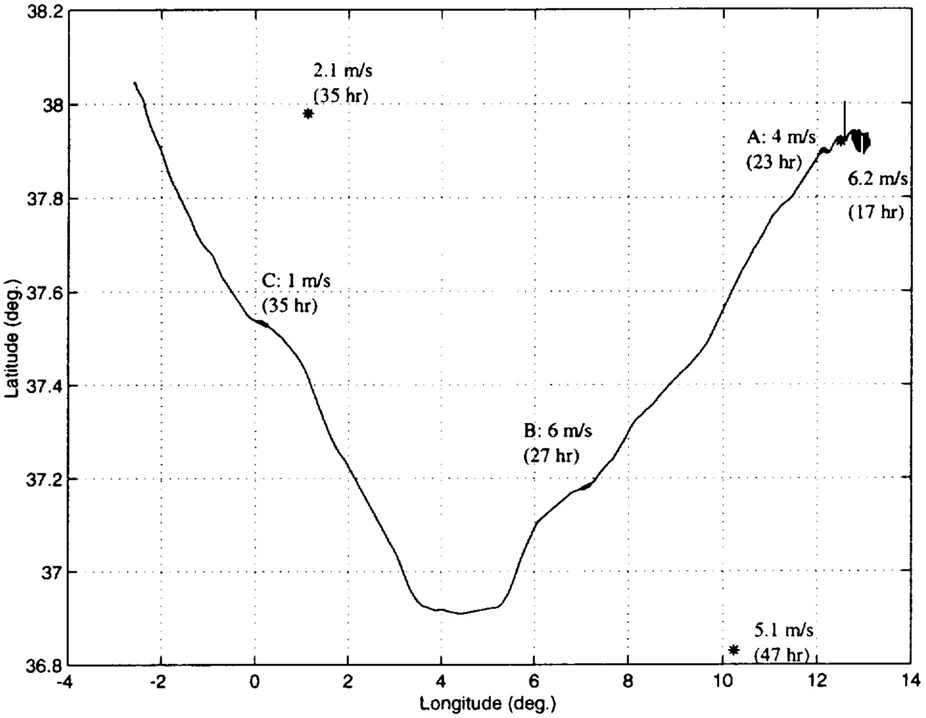

Figure 6: Location and Time of Radiosonde Measurements Relative to Flight Path

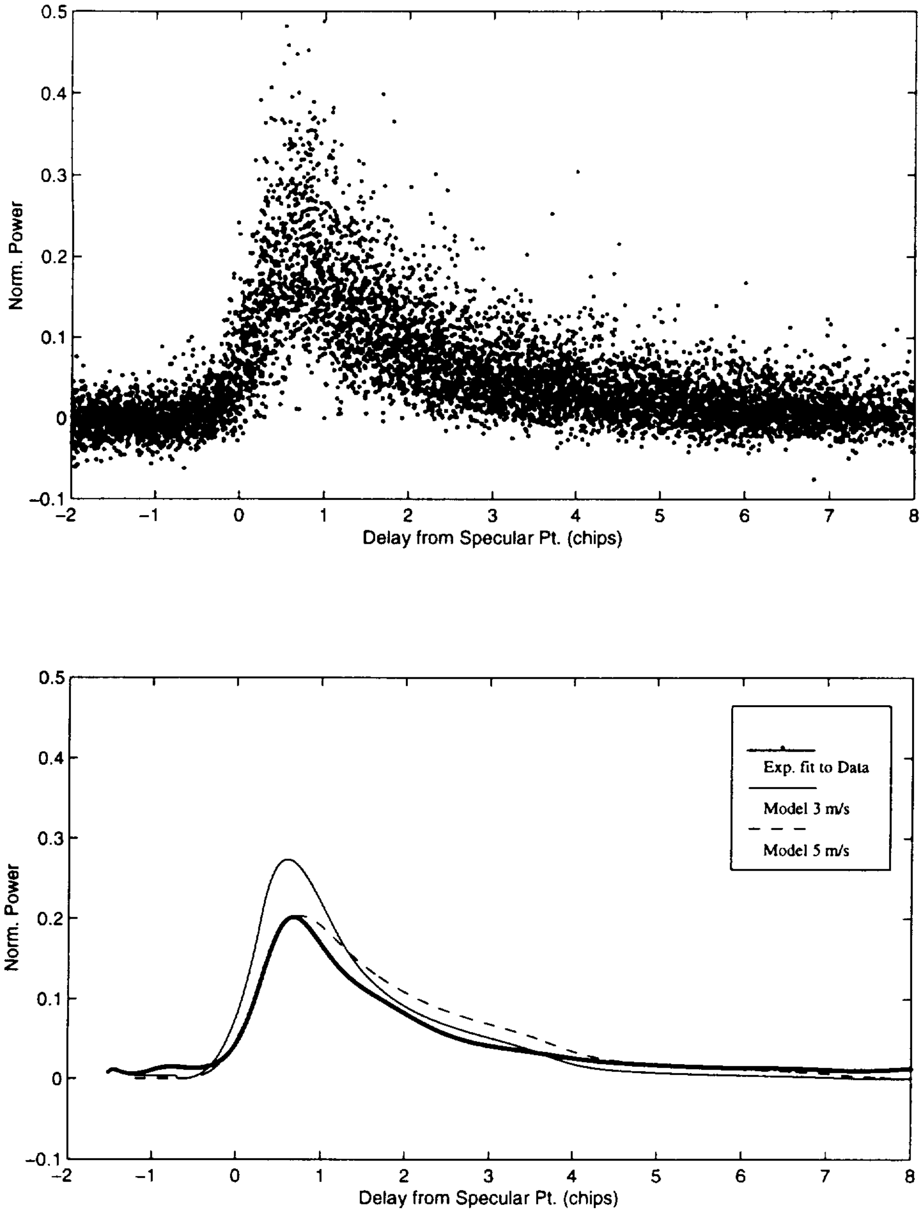

Figure 7: Reflected GPS Waveform for 400 sec. of Data at Point A

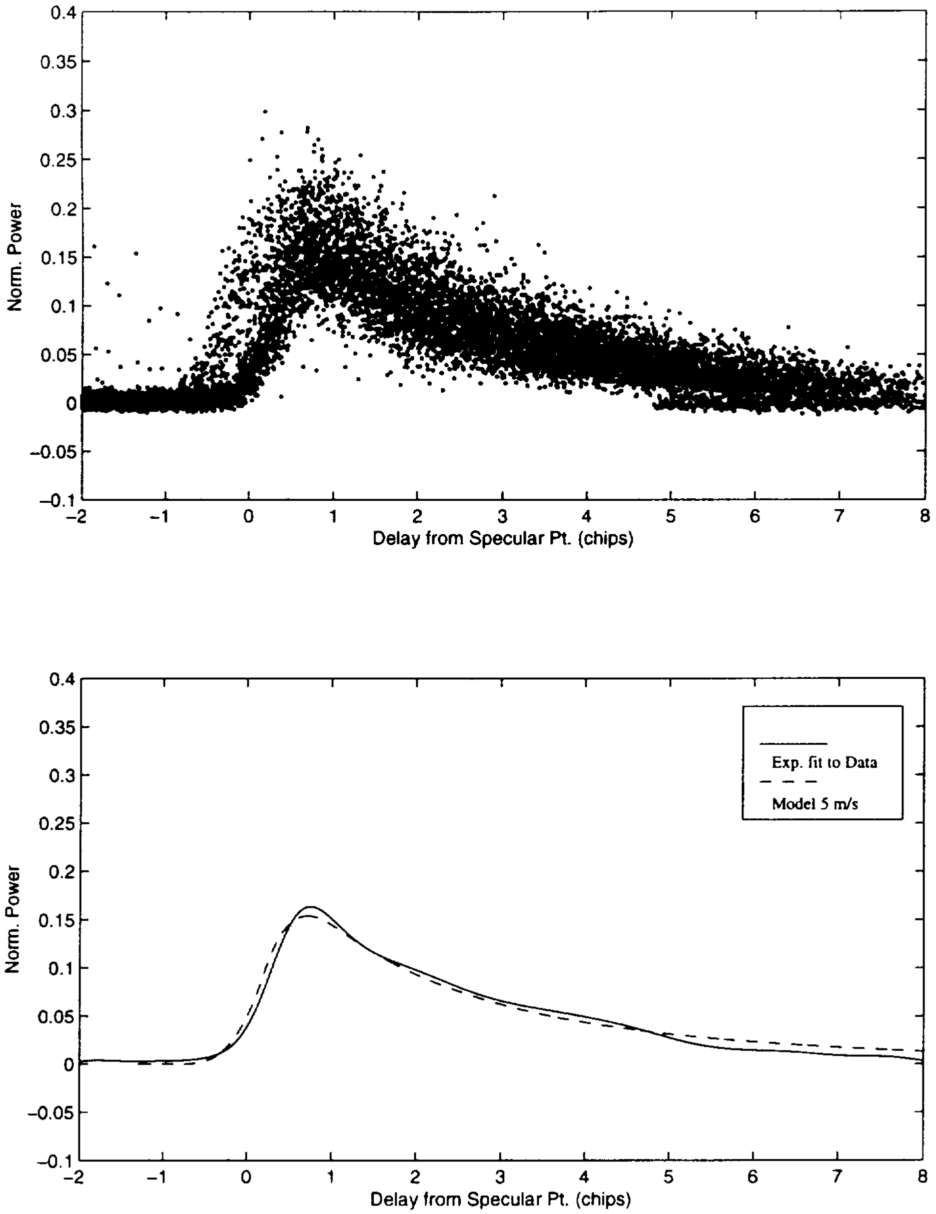

Figure 8: Reflected GPS Waveform for 600 sec. of Data at Point B

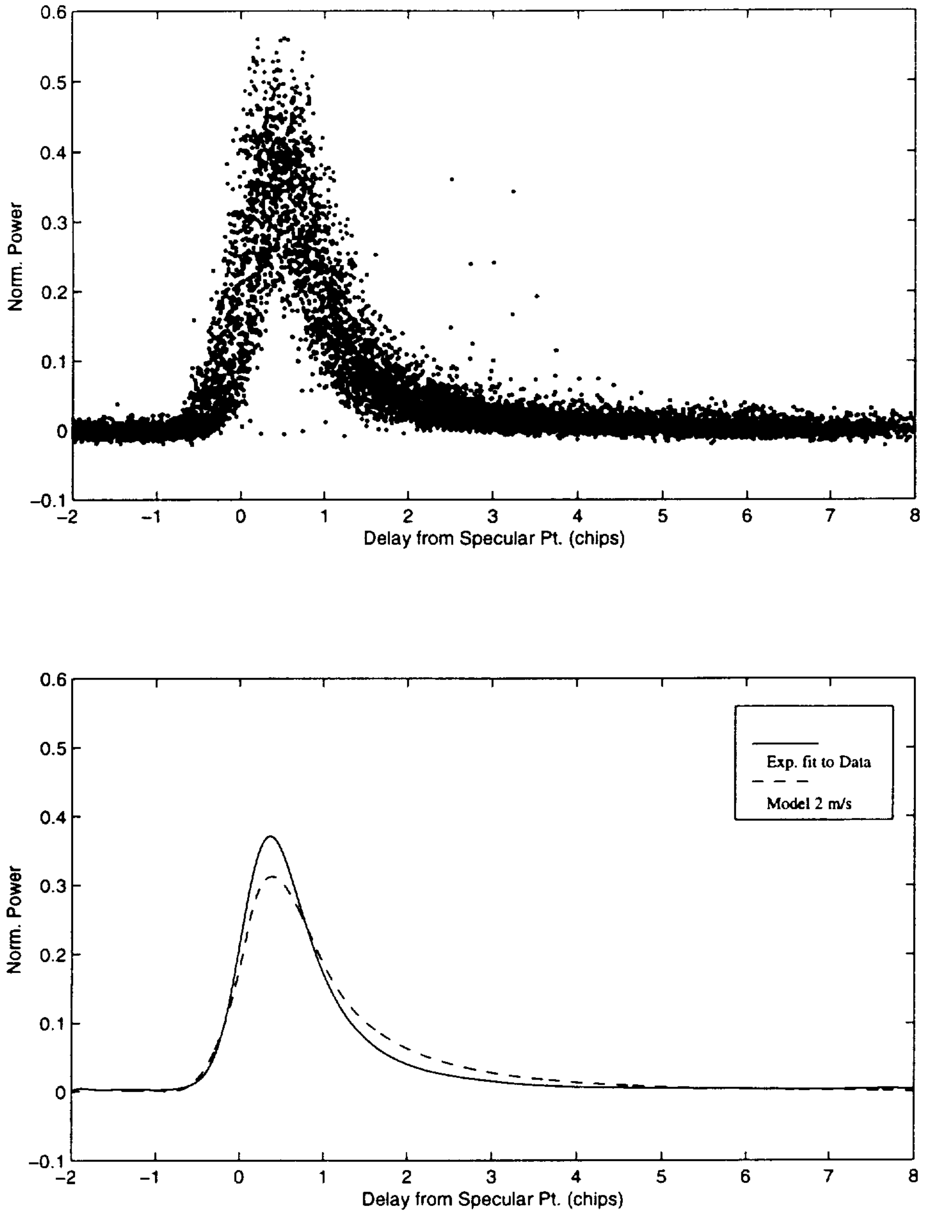

Figure 9: Reflected GPS Waveform for 600 sec. of Data at Point C