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# PASSIVE ALTIMETER STUDY USING GPS FLIGHT DATA (PREPRINT)

L.L. Liou, J.B. Tsui, D.M. Lin, J. Schamus, F. van Graas, and Y.T.J. Morton

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# NOTICE



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# Passive Altimeter Study Using GPS Flight Data

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## ABSTRACT

Software GPS receiver results are presented for an over-land, passive altimeter application utilizing GPS signals. The flight data were collected using a DC-3 aircraft operated by Ohio University. The flight took place over southeast Ohio, where the terrain is hilly and forested. The GPS receiver on board the aircraft contains two channels. One channel has a right-hand-circular-

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## INTRODUCTION

The reflection of the GPS signal from the earth's surface is generally considered a nuisance when accurate positioning is desired. However, the reflected signal contains useful information about the reflecting surface. If the reflecting surface is water, the signal can be easily detected due to the large reflection coefficient of water. Applications that make use of reflected GPS signals over water include oceanic remote sensing and marine metrology [1, 2]. When the surface is not smooth, the signal is reflected through the scattering of the glistening zone. The surface conditions can be determined through an analysis of the Doppler shift of the reflected signals and the code delay of the autocorrelation function. In addition, the path delay difference between the direct and reflected signal provides information on the receiver’s height with respect to the reflecting surface. Application of this technique as an altimeter for aviation is attracting interest [3, 4]. The altimeter application takes advantage of the well-organized GPS signal which is available almost any time, anywhere. Also, the altimeter is passive: the aircraft does not need to transmit a signal, which reduces the danger of self-exposure.

Previous passive altimeter studies over both water and dry surfaces are reported in [3, 4]. On the water surface, the reflected GPS signal is strong enough to be easily acquired and tracked. Studies conducted over land on the west coast and central Texas demonstrates that the altimeter application over dry surfaces is also feasible [4]. In the latter study, the altimeter contains two antennas; one is right hand circularly polarized (RHCP), and the second is left hand circularly polarized (LHCP). The RHCP antenna primarily receives the direct GPS signals, while the LHCP antenna primarily receives the reflected signals. An analog correlator was used to perform the integral correlation.

In the experiment reported in this paper, a similar two-antenna configuration was installed on the DC-3 research aircraft operated by Ohio University. The top-mounted antenna is RHCP, while the bottom-mounted antenna is LHCP. Figure 1 shows a picture of the DC-3 aircraft and the two antenna locations. The signals from both antennas are downconverted and sampled at a rate of 5 Msamples per second (Msps) in a 2.2 MHz bandwidth. All signal processing is performed in software using GPS software receiver processing algorithms [5]. The software approach deviates from the conventional hardware approach which is limited by the functional performance of each individual component in the system. The software is implemented in a signal processing chip that performs flexible functions such as varying an analog-to-digital (A/D) converter's sampling rate, implementing numerical filter and modulation schemes, optimization of the algorithm for enhancing the signal to noise/interference ratio, etc. [6]. The software approach is particular attractive for the GPS altimeter, since different acquisition and tracking strategies can be tested in software. The software approach relies on the performance of digital signal processing (DSP) chips and portable computer technologies. In this study, all signal processing was performed in offline mode. The results obtained indicate that a real-time GPS passive altimeter using the software approach is feasible.

The experiment including the equipment and the flight trajectories are briefly described. This is followed by the presentation and the discussion of the signals received by both RHCP and LHCP antenna channels. Based on the signal's characteristics, a signal processing algorithm is developed and the results are presented and discussed. The paper is concluded with a summary.

## EXPERIMENT

The GPS data were collected on a DC-3 aircraft. The flight took place over southeastern Ohio. The ground surface is mainly forested, and the terrain consists mostly of rolling hills with shallow slopes. Flight logs contain information of the various scenarios that were encountered during the flight experiment. Table I lists some of the logs that were studied in this paper.

The two GPS antennas are mounted on the top and bottom of the fuselage, where the top antenna is almost directly above the bottom antenna at a distance of approximately 2.5 meters. For the data analysis in this paper, no adjustments were made for the vertical offset between the antennas, since the primary focus of this paper is the tracking performance of the signals received by the bottom antenna. The top-mounted antenna is a standard aviation patch antenna, while the bottom-mounted antenna is an experimental cross-v dipole provided by dB-Systems, Inc. The cross-v dipole provides two linear polarization outputs, which are input to a quadrature combiner to obtain LHCP.

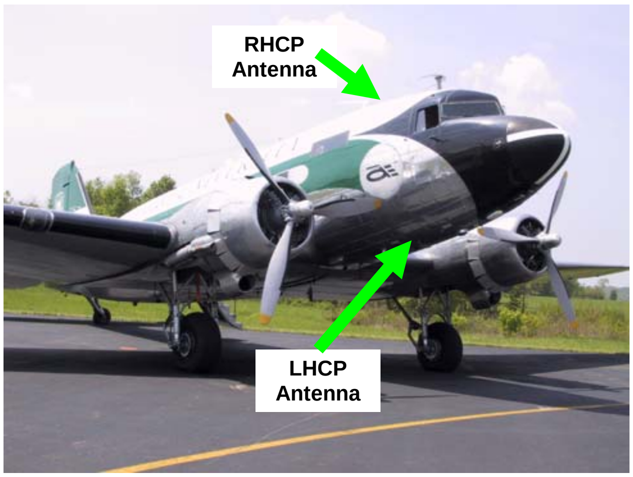


Figure 1. DC-3 Research aircraft with a top-mounted RHCP antenna and a bottom-mounted LHCP antenna.

A typical software GPS receiver architecture is used [5]. The Local Oscillator downconverts the L1 frequency (1.57542 GHz), and the signal is digitized by an A/D converter with a sampling rate of 5 Msps. The resulting digitized signal is centered at 1.27 MHz.

**SIGNAL CHARACTERISTICS**

Figure 2 shows a schematic of the relative positions between the aircraft, the satellite and the reflection surface. From a straightforward geometry analysis, the aircraft height H is given by:

$$H = \frac{\Delta L}{2\sin(\alpha)}$$

where ΔL is the path difference between the direct and the reflected signals, α is the specular angle. The Doppler frequency shift of the reflected signal is given by:

$$f_r = f_d - 2\dot{H}\sin(\alpha)/\lambda_0$$

where $f_d$ and $f_r$ are the Doppler shifts of direct and reflected signals, respectively, and $\lambda_0$ is the wavelength of the $L_1$ frequency. The second term on the right hand side is simply the time derivative of the path difference divided by the wavelength. The time derivative of the path difference results from three possible factors. One is the height change due to the aircraft's velocity in the vertical direction; the second is the elevation change at the specular point of the reflection path; and the third is a change in the reflection point, which can cause an abrupt change in the Doppler shift of the reflected signal as well as the length of the reflection path. For example, if the aircraft is descending at a typical approach rate of 3 m/s over a smooth ground, and α is $30^o$, then the difference between the Doppler shifts from the direct and reflected signals is approximately 16 Hz.

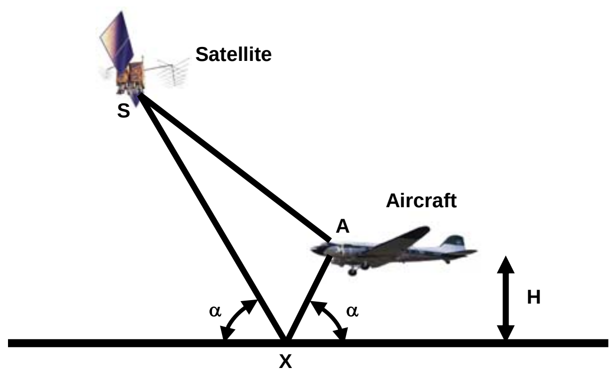


Figure 2. The schematics of the relative position of the aircraft, satellite, the reflection point, the specular angle and the height of the aircraft. The path difference ΔL = SXA - SA.

The upward channel with the RHCP GPS antenna is intended to receive the direct GPS signal. The downward channel with the LHCP antenna is intended to receive only the reflected GPS signal. However, due to antenna back lobes that are not necessarily LHCP, the bottom antenna also receives some direct GPS signals. The relative strength between these two signals seems to depend on the relative positions of the satellite and the receiver, and the height of the aircraft, but the exact dependency is not known. The direct GPS signal strength versus coherent integration time is shown in Figure 3. It shows that if the frequency is tuned to the Doppler shift of the direct GPS signal, the signal strength is proportional to the integration time at least up to 150 milliseconds (ms). If the signal is mistuned, the correlation energy reveals an oscillatory behavior, as expected. For an integration time of 100 ms, a frequency offset of 10 Hz will cause the correlation energy to be minimal, since the first 50 ms will be out of phase with the second 50 ms. Figure 4 shows the result of the reflected GPS signal strength versus integration time. The signal is tuned to within 10 Hz of the direct GPS signal's Doppler shift.

The signal strength increases as integration time increases, but only up to 40-60 ms. As the integration time increases, the correlation energy either saturates or decreases. This result indicates a mistuned Doppler frequency, which means that the Doppler frequency is changing during the integration time period. This is most likely caused by changes in the reflection path.

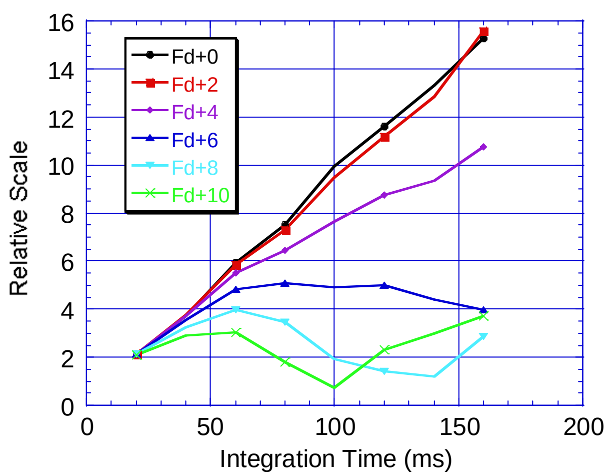


Figure 3. The direct GPS signal strength vs. integration time. Fd is the direct GPS signal's Doppler shift.

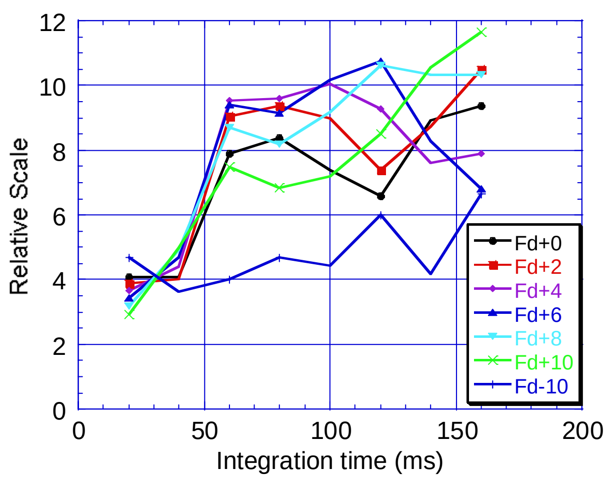


Figure 4. The reflected GPS signal strength vs. integration time. Fd is the direct GPS signal's Doppler shift.

## ALGORITHM

The strategy for the signal processing is to set up a reference signal based on the information obtained from the upward channel. This reference signal is then used to correlate the reflected GPS signal received by the downward channel. Based on the observed signal characteristic mentioned above and the sample calculation of the Doppler difference between the direct and reflected signals, a 20 ms coherent integration was used to enhance the signal-to-noise ratio (S/N). This is followed by a summation of ten consecutive coherent integrations.

The following lists the main algorithm steps to process the two-channel GPS flight data:

1. Process upward-channel GPS data and obtain satellite and receiver locations.
2. Obtain tracking information, including C/A code delay, Doppler frequency and navigation data.
3. For each satellite that is visible within 45 degrees from zenith, process the following:
   - Generate a reference signal using information from step 2
   - Correlate the downward-channel signal with the reference signal
   - Sum 10 consecutive 20-ms coherent integrations
   - Obtain the correlation peak and find the code delay
4. Calculate flight height with information of the specular angle from step 1, and the path length difference from the code delays in steps 2 and 3.
5. Calculate flight height by averaging the results among all the selected satellites.

In step 3, only satellites that are within 45 degrees from zenith are used, since their signals are reflected nearly directly beneath the airplane. Moreover, the height error due to the uncertainty of the code delay and the specular angle is small when the specular angle is close to $90^o$. Therefore, satellites that are within 45 degrees from zenith are selected so that the specular angle is not too far away from zenith, while the height result can be averaged among multiple satellites to increase accuracy.

The averaging schema for step 5 was developed as follows. The terrain has a statistically distributed slope near the specular point, such that the correlation function has a clutter-like feature. If the surface is more rugged, a noisier correlation function would be expected. The code delay determined from the correlation peak contains uncertainty. Assume that the standard deviation of the code delay is inversely proportional to the ratio of the peak value to the standard deviation of the autocorrelation. Based on the stochastic principle [7], the averaging scheme used to calculate the height is:

$$H_{ave} = \frac{\sum_{m_1,m_2\bullet\bullet\bullet m_N}^{m_1\neq m_2\neq\bullet\bullet\bullet\neq m_N} \sigma_{m_1}{}^2\sigma_{m_2}{}^2\bullet\bullet\bullet\sigma_{m_{N-1}}{}^2 H_{m_N}}{\sum_{m_1,m_2\bullet\bullet\bullet m_{N-1}}^{m_1\neq m_2\neq\bullet\bullet\bullet\neq m_{N-1}} \sigma_{m_1}{}^2\sigma_{m_2}{}^2\bullet\bullet\bullet\sigma_{m_{N-1}}{}^2}$$

where $\sigma_{mi}$ is the standard deviation of the correlation function for the $m_i$-th satellite, and N is the total number of the satellites whose signals were processed. The average of the standard deviation is:

$$\sigma_{ave}^{-2} = \sum_{m=1}^{N} \sigma_m^{-2}$$

## RESULTS AND DISCUSSION

Table I lists excerpts from the flight logs that record the flight maneuver scenarios. The data file labeled D101702m collected at a flight altitude of 4000 ft was processed. Figure 5 shows the skyplot of the visible satellites during that flight segment [8]. To demonstrate the code delay as a function of specular angle, the correlation functions using the C/A codes of satellites 1, 3 and 31 are processed and presented. Satellite 1 has the largest, and satellite 31 has the smallest specular angle among the three. The results for satellite 1 are shown in Figures 6 and 7. Figure 6 shows the correlation function versus code delay time index for a 20-ms coherent integration. The correlation peak occurs at a code delay with the time index of 30. Figure 7 shows the correlation function versus code delay time index as a result of the summation of ten consecutive 20-ms coherent integrations. Figure 7 demonstrates that the two-step time integration further enhances the S/N, and the correlation peak is easier to locate when compared to only using the 20-ms coherent integration step. Figures 8 and 9 show the correlation results from the two-step time integration for satellites 3 and 31, respectively. The code delay occurs at the time indices 30, 23 and 13, for satellite 1, 3 and 31, respectively. This is expected according to the relation between the flight height and the specular angle. The peak of the correlation function in the actual flight height calculation is determined more accurately using a three-point interpolation method. Also, the actual flight height calculation does not take satellite 31 into the pool for averaging, since it has an inclination angle of 69°, which is more than 45°. The results for satellite 31 are provided for comparison purposes.

Both the flight height from mean sea level (MSL) and the earth surface are shown in Figure 10 for the data file labeled D101702m. The flight height from MSL is the direct result from processing the upward channel GPS signal. The flight height from the earth surface is the result of the processing of the upward and downward channels using the algorithm described previously. Figure 11 shows the result for D102102n, in which the aircraft is descending from 2400 meters. Figure 12 shows the result for D102102m in which the pilots intended to fly at a height of 500 ft over the Ohio River. Figure 13 shows the results for D101702I where the plane is landing and taking off. It shows a segment where the height above ground is close to zero.

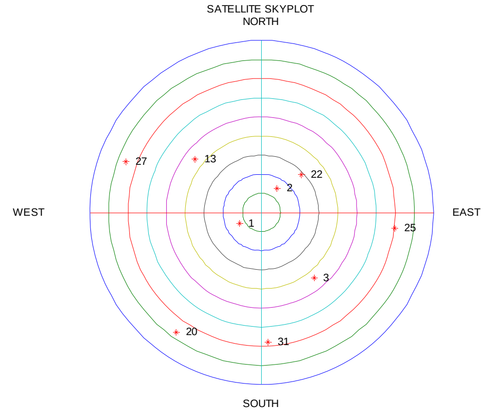


Figure 5. Skyplot showing the visible satellites during the time of flight file D101702m.

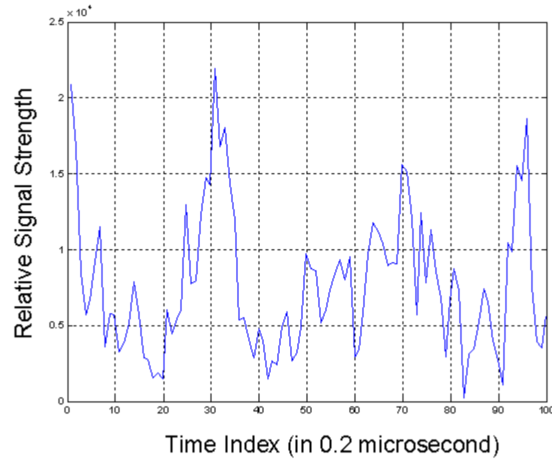


Figure 6. Correlation result using 20-ms coherent integrations for the C/A code of satellite 1.

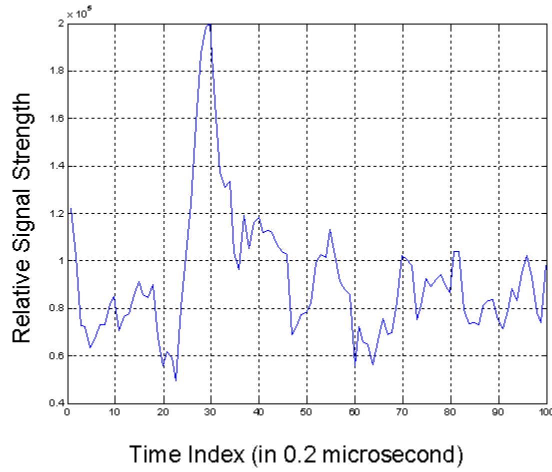


Figure 7. Correlation result using 10 noncoherent summations of 20-ms coherent integrations for the C/A code of satellite 1.

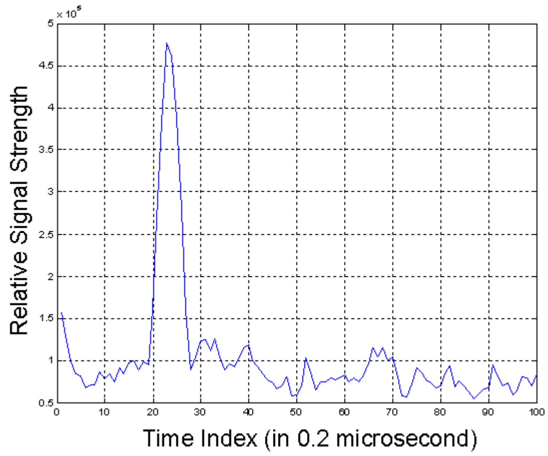


Figure 8. Correlation result using 10 noncoherent summations of 20-ms coherent integrations for the C/A code of satellite 3.

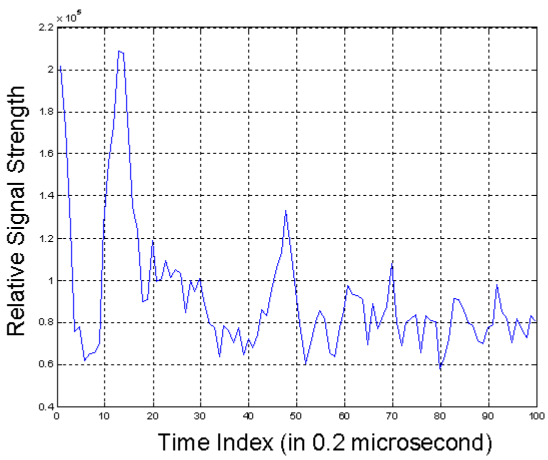


Figure 9. Correlation result using 10 noncoherent summations of 20-ms coherent integrations for the C/A code of satellite 31.

## SUMMARY

A passive GPS altimeter study was conducted. The GPS data were collected using a two-channel GPS receiver on board a DC-3 research aircraft. The upper channel with a RHCP antenna primarily received the direct GPS signal. The downward channel with a LHCP antenna was intended to primarily receive the reflected GPS signal, but it also received some of the direct signals. GPS software receiver algorithms were used to process the flight data. The upper channel provides regular GPS information with which a reference signal was generated to correlate the signal received by the downward channel. In order to enhance the S/N of the downward channel correlation function, a two-step time integration was applied, consisting of 20-ms coherent integrations followed by the noncoherent summation of 10 coherent integration results. The code delay of the downward channel with respect to that of the upward channel provides the essential data for the calculation of the aircraft height above the ground. The results presented in this paper demonstrate the feasibility of a software GPS receiver passive altimeter for a wide variety of flight scenarios.

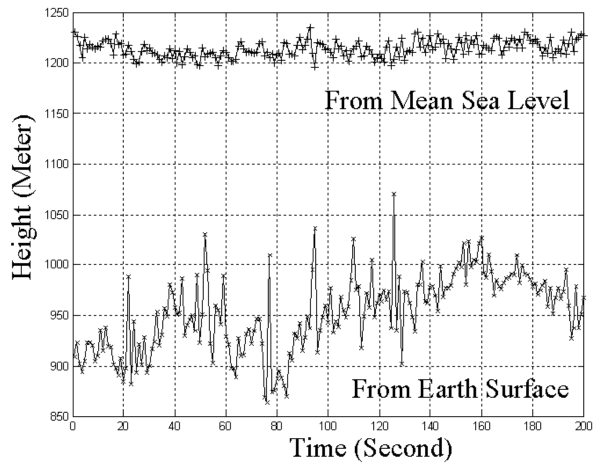


Figure 10. The upper curve is the height from mean sea level, and the lower curve is the height from the earth surface for flight file D101702n.

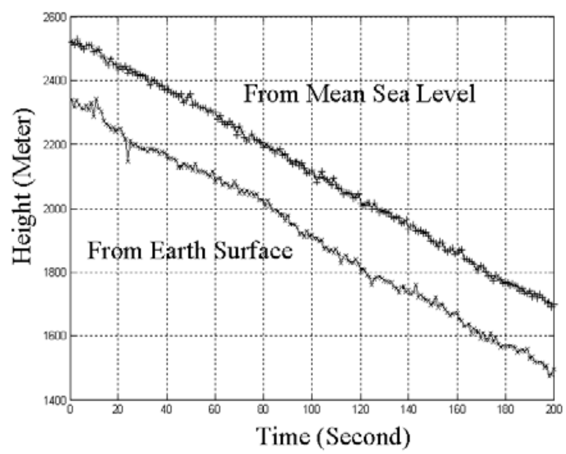


Figure 11. The upper curve is the height from mean sea level, and the lower curve is the height from the earth surface for flight file D102102n.

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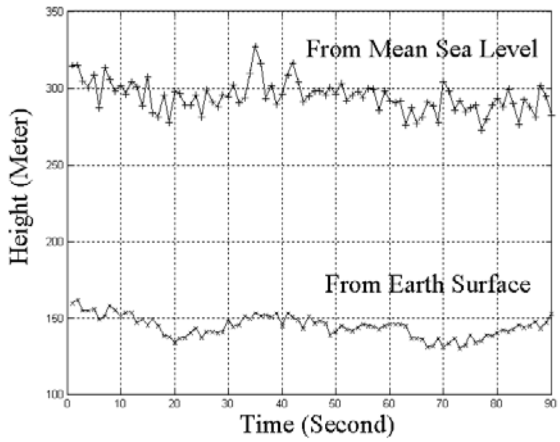

Figure 12. The upper curve is the height from mean sea level, and the lower curve is the height from the earth surface for flight file D102102m.

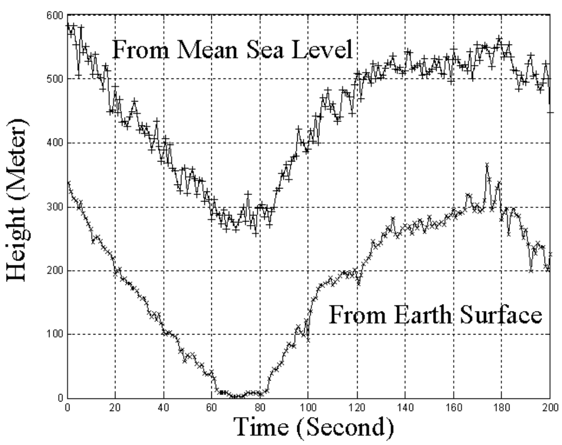

Figure 13. The upper curve is the height from mean sea level, and the lower curve is the height from the earth surface for flight file D101702I.

**Table 1. Excerpts from DC-3 flight logs on 17 and 21 October 2002**

**10/17/02 (Partial List)**

11:45 Short approach, enter glide slope @ 4000 ft, go around @ 100 ft;
Twochansynch 300, Filename: D101702I
14:59 1st 20 min leg, heading 210, altitude 4000 ft, temperature 3°C
15:01 Twochansynch 300, Filename: D101702m
15:19 Turn to heading 300, bank < 15°
15:20 2nd 20 min leg, altitude 4000 ft, temperature 3°C
15:42 15° bank turns (6 turns) initiated @ altitude 4000ft
15:50 Twochansynch 300, Filename: D101702n
16:01 15° bank turns completed

**10/21/02 (Partial List)**

15:41 Flying over Ohio River at 500 ft
Twochansynch 300, Filename: D102102m
15:57 Level out at 10000 ft
16:02 Start spiral down @ 15° bank, at 5000 ft change to 25° bank
16:02 Twochansynch 300, Filename: D102102n @10000 ft

**REFERENCES**

1. J. L. Garrison, A. Russo, M. J. Ferebee, D. Mickler and M. Armatys, "The GPS Ocean Reflection Experiment on Spartan 251", ION GPS '99, pp. 885-894, 1999.

2. A. Komjathy, J. L. Garrison, and V. Zavorotny, "GPS: A New Tool for Ocean Science", GPS World, 2000.

3. S. J. Katzberg, J. L. Garrison and C. T. Howell, "Simple Over-Water Altimeter Using GPS Reflections", ION GPS '99, pp 1819-1827, 1999.

4. D. Masters, P. Axelrad, V. Zavorotny, S. J. Katzberg and F. Lalezari, "A Passive GPS Bistatic Radar Altimeter for Aircraft Navigation", ION GPS 2001, pp. 2435-2445, 2001.

5. J. B. Tsui, "Fundamentals of Global Positioning System Receivers: A Software Approach", John Willey and Sons, Inc., New York, 2000.

6. B. Bing and N. Jayant, "A Cellphone for All Standards", IEEE Spectrum, p. 34-39, May, 2002.

7. P. S. Maybeck, "Stochastic Models, Estimation, and Control", Academic Press, New York, pp. 12, 1979.

8. M. Braasch, Private communication, Ohio University GPS satellite Doppler and position computer codes.