

Airborne GPS Down-Looking Occultation Experiments

Takayuki Yoshihara, Naoki Fujii, Kazuaki Hoshinoo, Keisuke Matsunaga, Shinji Saitoh, Takeyasu Sakai,
Electronic Navigation Research Institute (ENRI), Independent Administrative Institution, Japan
Toshitaka Tsuda, Yuichi Aoyama, Satoshi Danno,
Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Japan

BIOGRAPHY

Takayuki Yoshihara is a researcher at Electronic Navigation Research Institute (ENRI), independent administrative institution (IAI), Japan. He received his Ph.D. in GPS application for meteorology from Kyoto University, 2001. His research interests are ionospheric and tropospheric propagation delay of GPS satellite signals. His research currently includes evaluation of atmospheric error on Ground-Based Augmentation System (GBAS), and development of GPS down-looking occultation observation using aircraft.

Naoki Fujii is the leader of GBAS research group and a principle researcher of ENRI. He was charged with development of the siting criteria of Instrument Landing System (ILS), Microwave Landing System (MLS) and Aircraft Address Monitoring System (AAMS) in ENRI. He is currently working in field of the development of Ground-Based Augmentation Systems for GNSS.

Kazuaki Hoshinoo is a principal researcher of ENRI. He is the director of MSAS research program in ENRI and is a member of the MSAS Technical Review Board of JCAB. He chairs Ionosphere Working Group of the Board.

Keisuke Matsunaga is a researcher of ENRI. He received his M. Sc. in 1996 from Kyoto University and worked for the development of LSI at Mitsubishi Electric Corporation from 1996 to 1999. He joined ENRI in 1999, and is currently studying ionospheric effects on MSAS.

Shinji Saitoh is a researcher at ENRI. He received M. Eng. in Electronic Engineering from the University of Electro-Communications (UEC) in 1998. He joined ENRI, the Ministry of Transport (MOT) in 1998. Currently, he is researching in the area of GPS and GBAS. He belongs to GBAS research group in ENRI.

Takeyasu Sakai is a senior researcher of Electronic Navigation Research Institute, Japan. He received his Dr.

Eng. in 2000 from Waseda University and is currently analyzing and developing ionospheric algorithms for Japanese MSAS program.

Toshitaka Tsuda is a professor at Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Japan. He received his Ph.D. in Meteor Rader from Kyoto University, 1982. His research interests include atmospheric gravity waves, middle and upper atmospheric research, and GPS occultation measurements from LEO satellite, mountaintop and airplane.

Yuichi Aoyama is JSPS research fellow at RISH, Kyoto Univ. He received his Ph.D. in atmospheric excitation and gravity response to the Earth rotation variations from Grad. Univ. Advanced Studies, 2000. Recent his research interest includes developing measurement and analysis techniques for GPS occultations from LEO satellite, mountaintop, and airplane.

Satoshi Danno is a master course student at RISH, Kyoto Univ. His research interest is estimation of the water vapor distribution in the lower troposphere from the mountain-based and airborne GPS occultation.

ABSTRACT

GPS down-looking occultation method, a kind of GPS occultation observation, is expected to be able to estimate tropospheric water vapor profile below a receiver location with aids of temperature profile obtained from local-scale atmospheric numerical model. It is required to continuously observe Doppler shift of the radio signal transmitted from the occultation GPS satellite at the location as high altitude as possible, because the altitude limits the upper bound of resulting profile. With a GPS receiver installed on the top of mountain, "mountain-based GPS down-looking occultation" campaigns have been already performed on the top of Mt. Fuji and a technique to measure water vapor profile from observed Doppler shift have been developed. We aim to apply this

novel technique to “airborne GPS down-looking occultation”, which can (i) expand resulting profile range up to a flight level; and (ii) be performed almost everywhere unlike the mountain-based method. The observational principle of airborne GPS down-looking occultation is fundamentally identical to mountain-based method except the movement of receiving location.

Occultation GPS satellite should be tracked to the elevation angle as low as possible even below the horizon, so that the lower bound of resulting water vapor profile will be expanded almost to the ground. A special receiver called “down-looking receiver” or “DL receiver” was designed for continuous tracking of occultation GPS satellite for this purpose. The receiver system has two antennas, one is at the top of aircraft (for timing and positioning) and another is installed side of aircraft (for tracking occultation satellite). The receiver also has special receiving functions, for example, it can perform the signal reception of the occultation GPS satellite using the side antenna with synchronization to the signal from the top antenna.

In order to accomplish airborne GPS down-looking occultation experiment, we have to estimate accurate velocity of the side antenna motion with an accuracy of several mm/s even in post-processing. Therefore, GPS/INS hybrid positioning system was employed and installed on the experimental aircraft to estimate aircraft velocity and attitude.

We have conducted six flight experiments since October 2003 and obtained more than 30 datasets of occultation events using the equipment consisting of the previous two elements. We investigated data qualities using the first experiment data. Our receiver successfully tracked the signal from occultation GPS satellite continuously down to the elevation angle of -3.5 degrees at a flight level of about 6 km. The sea surface reflection significantly affected the received occultation GPS satellite signal, so we have investigated some correction method to remove this effect using a special function of the DL receiver. We have to extract atmospheric contribution from Doppler shift measurement with the side antenna using aircraft velocity and attitude from GPS/INS measurements. So far, we have investigated the accuracy of aircraft attitude derived from real time solution of IMU, comparing with side-top single difference in phase measurements of occultation GPS satellite.

INTRODUCTION

GPS occultation observation is a powerful and useful GPS application for monitoring the Earth’s atmosphere. Through the fact that refractive index profile can be provided using GPS occultation data, it is expected for estimating and monitoring various parameters associated

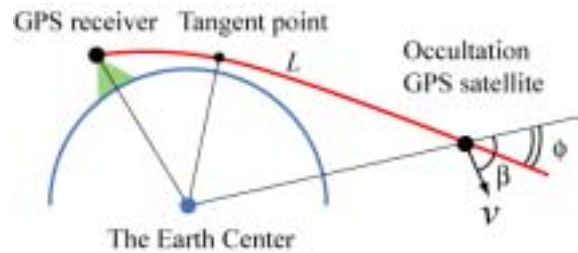


Figure 1: Geometry relationship between an occultation GPS satellite and a receiving point on the top of mountain.

with the atmospheric refractivity, i.e., electron density in ionosphere, temperature, water vapor density, etc. For example, GPS occultation measurements at LEO (Low Earth Orbiting-satellite) provide stratospheric temperature profiles [1].

As a novel technique of GPS occultation observation, GPS down-looking occultation measurement is expected to estimate refractive index profile below a receiving point and to retrieve water vapor profile with aids of temperature results from atmospheric numerical model for local-scale analysis and so on [2]. In this method, it is required to continuously observe Doppler shift of the radio signal transmitted from GPS satellite with a low and a negative elevation angles. Then, dual frequency GPS observation makes the ionospheric effect removable.

Observed Doppler shift f_d is described as shown in Equation (1) using a frequency of carrier phase f , a speed of light c , a propagation path length L , occultation GPS satellite velocity v , angle β between a radius direction and velocity of occultation GPS satellite, and angle ϕ between a radius and a propagation path directions at location of occultation GPS satellite (See Figure 1).

$$f_d = -\frac{f}{c} \frac{dL}{dt} = -\frac{f}{c} v \cos(\beta - \phi) \quad (1)$$

Using Equation (1), it is possible to make Doppler shift correspond to changing rate of “bending” ray path length with unknown parameter of ϕ . Assuming that the atmospheric refractive index is homogeneous in the horizontal layer with a same altitude, a refractive index profile can be derived from a time series of Doppler shift measurements in post-processing [3]. With a proper temperature profile, a water vapor profile can be obtained. A typical observational period for a GPS occultation event is about 30 minutes.

In order to expand a height range of resulting water vapor profile from down-looking GPS occultation observation, we have to receive occultation GPS satellite signal at the location as high altitude as possible because the altitude limits the upper bound of resulting profile. On the other hand, the lower bound of estimated water vapor profile depends on signal tracking sensitivity of GPS receiver.

Research Institute for Sustainable Humanosphere (RISH), Kyoto University and Meteorological Research Institute (MRI), Japan performed observational campaigns on the top of Mt. Fuji (elevation: 3,776 m) in cooperation with NASA/JPL in summer 2001 and 2002 [4]. In these campaigns, a GPS receiver of TurboRouge SNR-8000 was set up and operated with a sampling rate of 50 Hz. They successfully estimated water vapor profiles below and around the top of Mt. Fuji with a horizontal scale of several hundreds kilometers. In a case of mountain-based down-looking observation, we can obtain many water vapor profiles around the mountain and it will be powerful data for understanding meteorological local-scale phenomena. However, it will not provide water vapor profile above the top of mountain and away from receiving point.

DOWN-LOOKING OBSERVATION USING AIRCRAFT

For a further application of this technique, we are going to develop another down-looking observation technique using aircraft (“airborne GPS down-looking occultation”; see Figure 2) in order to (i) expand the upper bound of resulting water vapor profile up to a flight level (i.e., typically 6 km with our experimental aircraft) and to (ii) make observation possible everywhere.

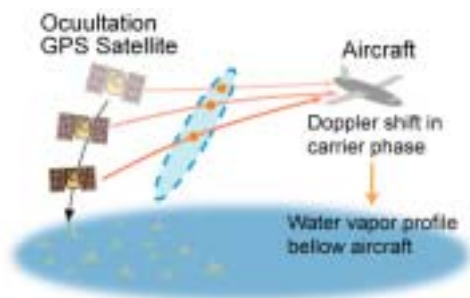


Figure 2: Airborne GPS down-looking occultation

To accomplish airborne GPS down-looking observation, there are mainly two subjects. At first, occultation GPS satellite should be tracked to the elevation angle as low as possible even below the horizon. In order to expand a lower bound of resulting water vapor profile almost to the ground, tracking sensitivity for the occultation GPS satellite signal have to be improved. Because receiving signal intensity of occultation GPS satellite with a low elevation angle is weak, it may be significantly affected and degraded by radio interferences associated with the sea and the ground reflection, multi-path effect from aircraft body, and so on. Therefore, we also need some new functions to investigate characteristics of occultation GPS satellite signal received on aircraft. It is also required for a GPS receiver to assign a channel to a specific

occultation GPS satellite with a high sample rate of 10–100 Hz.

As the second subject, we have to observe occultation GPS satellite signal on aircraft with a complex movement. Because GPS down-looking occultation method is based on measurement of Doppler shift in carrier phase, we have to distinguish atmospheric propagation effect from the both motions of a receiving antenna on aircraft and occultation GPS satellite. Namely, it is required to extract atmospheric effect by subtracting change rate of geometrical distance between a receiving antenna and an occultation GPS satellite from observed Doppler shift. Therefore, it is required to estimate a receiving antenna motion with an accuracy of several mm/s in post-processing during a GPS occultation event of 30-40 minutes with a straight and level flight over several hundred kilometers.

EQUIPMENT SET-UP ON THE AIRCRAFT

We have developed equipment to accomplish the previous two subjects and set up on the experimental aircraft of Electronic Navigation Research Institute (ENRI), Japan (See Figure 3).



Figure 3: The experimental aircraft of ENRI (Beechcraft B99 airliner)

A New Receiver System Designed for Airborne GPS Down-Looking Experiments

For the first subject, we developed a special receiver called “down-looking receiver” or “DL receiver”, which was designed for continuous tracking of occultation GPS satellite. The receiver system has two antennas. One is installed at the top of aircraft and used for timing and positioning (antenna type: Tecom TYPE 401170). And another antenna is installed in the nose corn of the aircraft and it is tilted 90 degrees for tracking radio signals from the horizon (antenna type: Sensor systems S67-1574-14; See Figures 3 and 4). In order to observe occultation GPS satellite signal with a view direction of either left or right direction, two antennas were installed at the both sides.

We can manually select either the left or the right antenna for occultation GPS satellite direction.

Since we use two GPS antennas (i.e. positioning and occultation antennas), the DL receiver was designed for simultaneously observing two signals. Namely, the DL receiver can perform the signal reception of the occultation satellite using the side antenna with synchronization to the signal from the top antenna. A

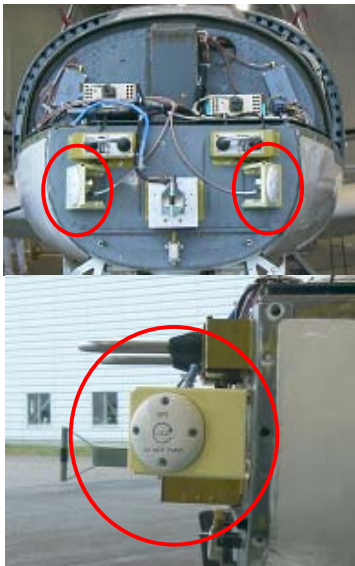


Figure 4: (Top) Two side antennas looking at the left and right for occultation GPS observation; (Bottom) Left antenna

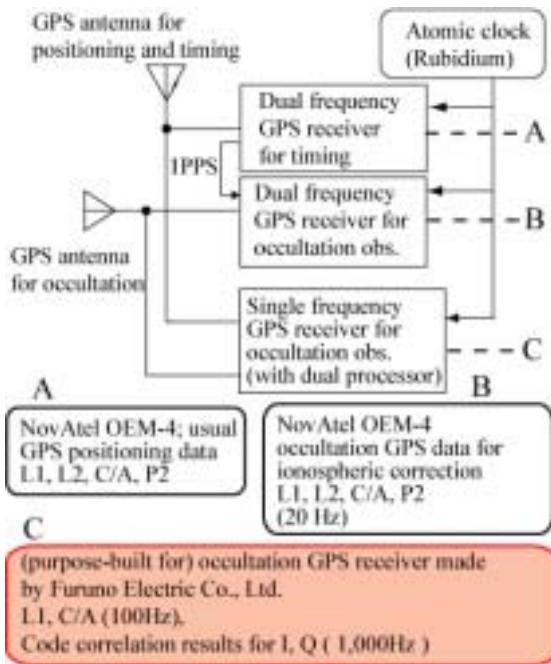


Figure 5: Down-looking (DL) receiver system for airborne GPS down-looking experiments.

block diagram of DL receiver is shown in Figure 5. The DL receiver consists of two segments that are synchronized by a rubidium atomic clock. The main is a L1-C/A single frequency receiver (C in Figure 5; purpose-built receiver; Furuno Electric Co., Ltd.) that has a special capability for GPS occultation observation and some intelligent functions. The other segment contains two dual frequency receivers (A and B in Figure 5; NovAtel OEM-4) for ionospheric correction.

The main segment is a dual front-end receiver with dual processor. It has the following functions;

1. The main segment has dual front-ends of 16 channels for each antenna signal and can measure Doppler shift in carrier phase with a high sampling rate of 10-100 Hz).
2. We can assign a channel for a specific GPS satellite even if it is out of view from receiving location. Namely, it is designed to continuously track occultation GPS satellite signal as long as it can.
3. Because a processor for observing the occultation signal with the side antenna has synchronized with another processor for the top antenna signal, it can always track occultation GPS satellite signal even if there is only one satellite in a view direction of the side antenna.
4. It can also output code correlation results for In-phase and Quadrature-phase (I, Q) every C/A code length (i.e. with a sampling rate of 1,000Hz) with the side antenna signal. This function is useful and powerful for investigating weak signal of occultation GPS satellite. It also has output terminals for the both analog and digitalized IF signals.

GPS/INS Hybrid Positioning System

For the second subject, i.e. estimation of receiving antenna motion with an accuracy of several mm/s, GPS/INS hybrid positioning system was employed. In

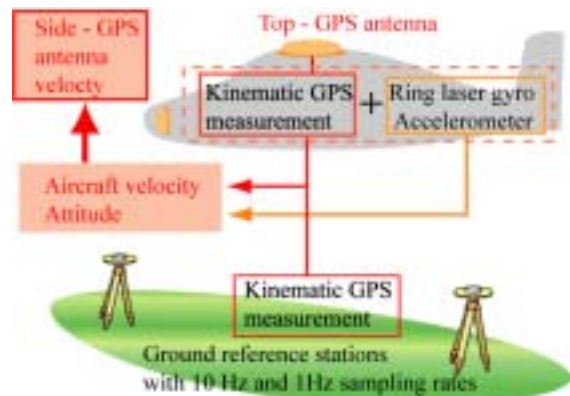


Figure 6: GPS/INS measurements

Table1: Specification of IMU

Ring laser gyro (X, Y, Z)	
Gyro input range	409.5 deg./sec
Gyro rate bias	0.005 deg./h
Gyro random walk	0.0013 deg./ \sqrt{h}
Accelerometer (X, Y, Z)	
Accelerometer range	20 G
Accelerometer bias	44.2 μ G



Figure 7: Inertial Measurement Unit (IMU)

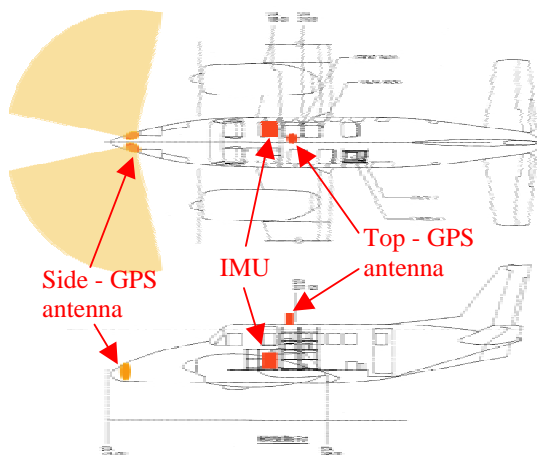


Figure 8: Locations of experimental equipment on aircraft. The left and right hatched areas show horizontal view ranges using the left and the right side antenna, respectively.

order to estimate motion of the side antenna for observing occultation GPS satellite signal, we need attitude rate information to compensate velocity of the side antenna relative to the top antenna, because the aircraft position and velocity are measured based on the position of the top antenna. Using GPS/INS hybrid positioning system including ground reference GPS stations, we aim to estimate accurate velocity of the side antenna motion in post-processing (See Figure 6).

GPS/INS hybrid positioning system consists of an inertial measurement unit (IMU; JIMS-250R, Japan Aviation Electronics Industry, Co., Ltd.) and a GPS unit (NovAtel

Table2: Fundamental observation parameters

Flight	
Flight level	21,000ft
Flight time	2 hours
Data for estimation of velocity	
IMU measurements	
Acceleration and Attitude	50 Hz
GPS on aircraft	10 Hz
GPS at the base airport	10 Hz
GEONET stations	1 Hz
Data for observing occultation signal	
Single frequency (L1-C/A)	100 Hz
Code correlation results for I, Q (L1-C/A)	1,000 Hz
Dual frequency (L1-C/A, L2-P2)	10 Hz

OEM-4). Photograph of IMU is shown in Figure 7 and general specifications are shown in Table 1. IMU measures angular velocities and accelerations for three components. Although an original sampling rate of IMU is 250 Hz, the firmware outputs filtered data with a sampling rate of 50 Hz. It also calculates a position, velocity and attitude combining with results of GPS unit in real time.

Setup on the Experimental Aircraft and Ground GPS Reference Stations

The equipment has been set up on the experimental aircraft of ENRI as shown in Figure 8. The hatched areas show horizontal view range using the side antennas. We have to decide the side antenna's velocity from the results of the top GPS data and IMU measurement using geometrical relationship among the elements of the equipment.

We further set up a ground GPS reference station at the base airport and few stations along a flight course with a sampling rate of 10 Hz. Additionally, GPS Earth Observation Network (GEONET) data with a sampling rate of 1 Hz was provided from the Geographical Survey Institute (GSI), Japan. Therefore, we selected flight courses over the area that has denser 1Hz stations, i.e. over or near the land.

RESULTS FROM FLIGHT EXPERIMENTS

We have performed airborne GPS down-looking observation campaign six times around the northern part and the southwestern part of Japan since October 2003. We have successfully obtained total of 30 setting-occultation events through the four seasons. The primary results from a campaign around Sendai airport on October 18-25, 2003 will follow below. The fundamental

observation parameters in this campaign were summarized in Table 2.

We investigated occultation data qualities based on three viewpoints below, which will be described in the following subsection in order.

1. We firstly investigated general characteristics of occultation satellite signal. The minimum view angle of receivable occultation satellite specifies the lowest height of resulting water vapor profile. Therefore, it is important to investigate how weak occultation signal can be tracked.
2. Occultation signal intensity is weak. Therefore, it will be affected by reflection signal from the sea or the ground surface, especially in the side antenna measurement. Therefore, we investigated reflection effect on occultation GPS satellite signal using a special function of the DL receiver.
3. To accomplish our final purpose, we have to estimate accurate velocity of the side antenna's motion combining with ground reference stations. However, we firstly investigated the real time solution of aircraft attitude that were calculated from IMU measurements combining with GPS unit only on aircraft.

General Characteristics of Occultation Satellite Signal

We show an experimental flight data to observe a setting event with occultation GPS satellite of PRN 5 on October 15, 2003. Figure 9 shows the flight course at 4:10-6:00UT. The experimental aircraft took off the Sendai airport (4:10UT), which was the base airport of our experimental aircraft, and firstly went to the south-southwest direction. After turning, it straightly flew along a north-northeast direction at a level of about 21,000ft (corresponding to

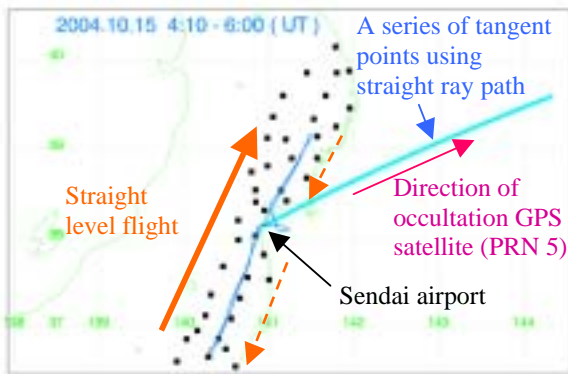


Figure 9: Blue line shows flight course on October 15, 2003. The series of tangent points in straight ray path from occultation GPS satellite of PRN05 to aircraft locations are also plotted. A black point shows GEONET 1Hz station.

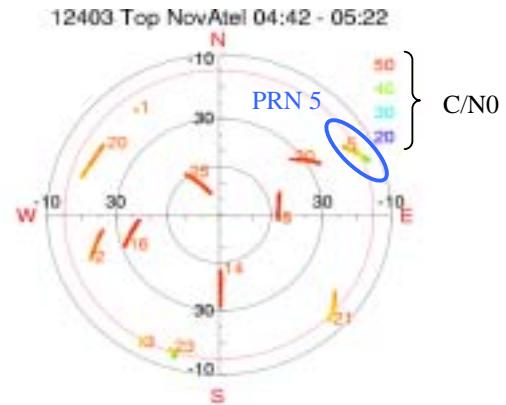


Figure 10: GPS satellites that were observed by the dual frequency segment of the DL receiver with the top antenna during a straight level flight with an altitude of about 6.4km (4:42-5:22UT on Oct. 15, 2003) were plotted in sky chart. A red circle indicates a satellite elevation angle of 0 degree. Colors show receiving intensity C/N0 of L1.



Figure 11: The same as Figure 10 except for GPS satellites that were observed with the side antenna were plotted.

6,400.8 meters) and we started observing the occultation GPS satellite signal with elevation angle of about 7 degrees. After about 40-minute level flight (4:40-5:23UT), we confirmed occultation GPS satellite signal was receivable no longer and the aircraft turned toward the Sendai airport.

“Tangent point”, which means the point where distance between ray path and the earth surface is minimum (See Figure 1), was calculated using a straight path and was also plotted in Figure 9 by a series of blue points with a satellite elevation angle below 0 degree. This figure shows that the equivalent observational point moved several 100 km away from the flight course. Namely, airborne GPS down-looking observation can observe water vapor profile with a horizontal range of several 100 km away.

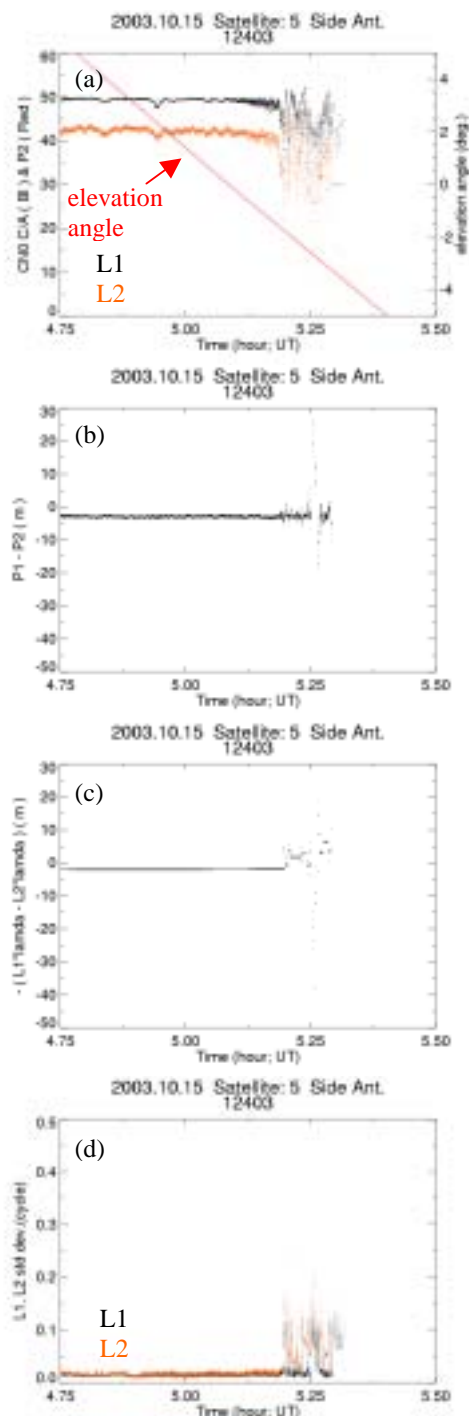


Figure 12: Occultation GPS satellite signal (PRN 5) that was observed by the dual frequency segment of the DL receiver with the side antenna during a straight level flight on October 15, 2003. From the top to the bottom figures, (a) receiving intensity in C/N0, (b) pseudo-range difference between C/A and P2, (c) geometry-free linear combination of L1 and L2, and (d) standard deviation in carrier phase measurements were plotted.

Figure 10 and 11 respectively show GPS satellite directions that were observed by dual frequency segment of the DL receiver with the top and the side antennas at 4:42 - 5:22UT during a straight level flight. In the both figures, colors indicate signal intensities (in C/N0) of L1 signal. It was clearly that the signal intensity of occultation GPS satellite received with the side antenna was larger than the top antenna. Therefore, these results suggest that it is necessary to point GPS antenna to the side direction for GPS occultation observation.

Figure 12 shows occultation GPS satellite data of PRN 5 that was received by the dual frequency segment of the DL receiver with the right-side antenna. The receiving intensities with satellite elevation angles below about -2 degrees began to change greatly and cycle-slip was frequently occurred as shown in (a) and (c). Then, large standard deviation over 0.1 cycles was observed in the both L1 and L2 phase measurements as shown in (c). Moreover, periods of large standard deviation were longer in L2 than in L1 measurement. However, large variation of ionospheric delay was not almost observed as shown in (b). Therefore, it was seemed that the reason of the cycle-slip occurrences was a decrease of receiving intensity that originated not in a complex ionosphere structure but in long propagation path length and phasing effect of reflection signal from the sea surface. Note that geometry-free combination of L1 and L2 phase measurements was represented in reversed sign so as to be the same sign of pseudo-range difference. These results suggest that ionospheric delay model should be introduced to use L1-only data with an invalid period of L2 measurement.

In Figure 13, we further show the receiving intensity that was observed by the purpose-built segment of the DL receiver, which was single frequency receiver. We recognized that it continuously tracked the occultation GPS satellite signal almost without cycle-slip down to about -3.5 degrees.

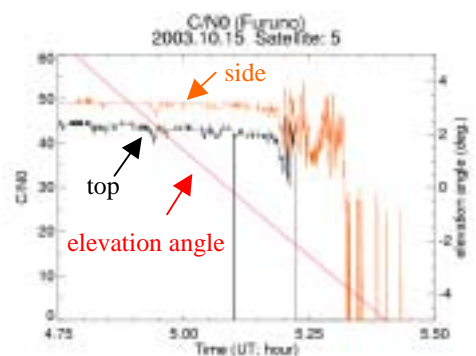


Figure 13: Receiving intensities in C/N0 that were observed by the single frequency segment of the DL receiver with the top (black line) and the side (orange line) antenna during a straight level flight on October 15, 2003.

Effect of Sea Reflection Signal

Secondary, we investigated the sea reflection effect on phase measurement. Because the side occultation antenna is pointed to side direction and the arrival direction of occultation GPS satellite signal was above the sea, receiving signal with the side antenna will be more significantly affected by the sea reflection than the signal with the top antenna.

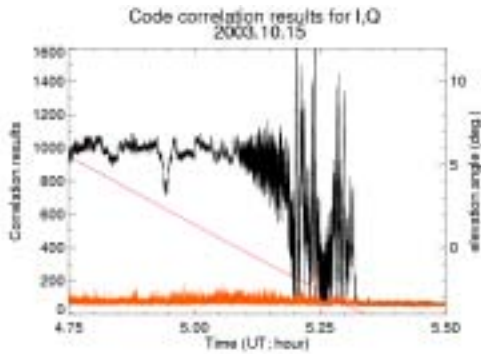


Figure 14: Code correlation results for In-phase (black line) and Quadrature-phase (orange line) at the same period of Figure 13. A red line indicated elevation angle of occultation GPS satellite.

The purpose-built segment of the DL receiver has a special function that can observe L1-C/A code correlation results for I, Q of the side antenna signal with a sampling rate of 1,000 Hz. Using this function, we can investigate tracking status, especially, variation of receiving intensity in carrier phase. Therefore, it is useful for investigating scintillation phenomena associated with reflection from the sea surface, ionospheric TEC (Total Electron Contents) variation and so on. Figure 14 shows code correlation results for I, Q at 4:45-5:30UT on October 15, 2003.

GPS satellite movement produces a changing of propagation path difference between a direct and a reflected radio waves. Although propagation path difference also depends on flight altitude, aircraft movement with a constant level flight produces almost no changing of it. Arrival signal consists of a direct signal and a reflection radio wave with attenuation and a phase variation that was produced from the propagation path difference. Therefore, a changing of the propagation path difference due to GPS satellite movement produces periodic variations of not only amplitude but also phase measurement error in carrier phase. A variation of phase measurement error causes a large Doppler shift error, especially in a case of short-period variation (i.e. with a large change rate of path difference).

We investigated the sea reflection effect on a changing of receiving intensity using I, Q code correlation results. For

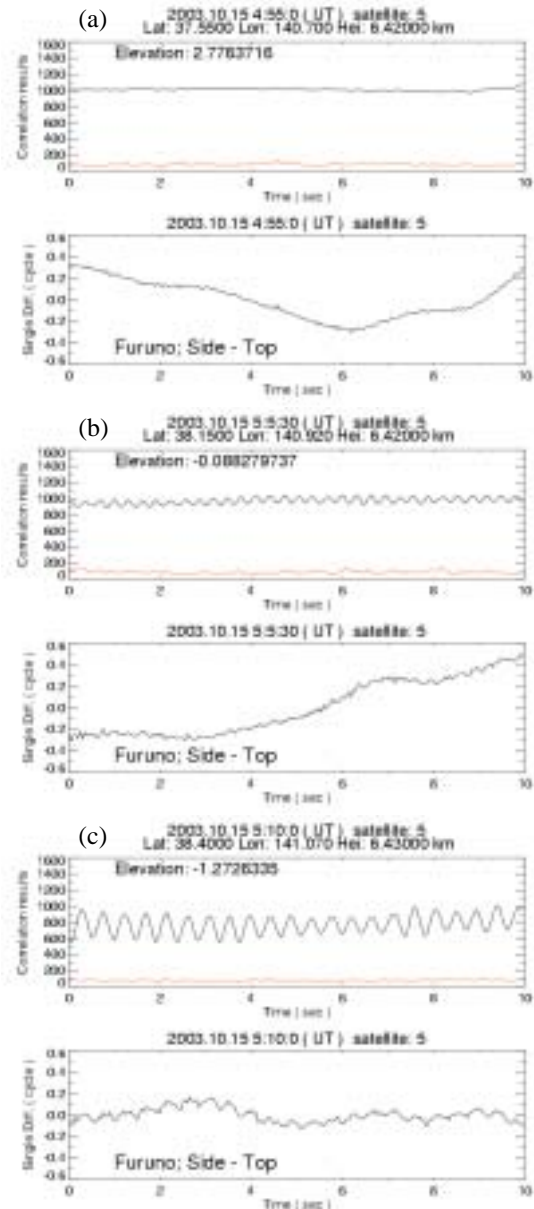


Figure 15: Code correlation results and single difference results of occultation GPS satellite PRN05 using the single frequency segment of the DL receiver at (a) 4:55:00UT, (b) 5:05:30UT and (c) 5:10:00UT on October 15, respectively. The top and the bottom in each pair show code correlation results (I: Black line, Q: Orange line) and single difference between L1 phase measurements with the side and the top antennas during 10 seconds, respectively. Note that the both results in the top and the bottom were averaged with a time window of 0.05 seconds. The original sampling intervals of code correlation results and phase measurements were 1,000 Hz and 100 Hz, respectively.

evaluating phase measurement error, we further performed single difference analysis between the side and the top carrier phase measurements assuming that occultation GPS satellite signal with the top antenna was not significantly affected by the sea reflection signal.

Figure 15 shows the results for the occultation GPS satellite of PRN05 using the single frequency segment of the DL receiver on October 15, 2003. The top and the bottom panels in each pair show I, Q code correlation results with the side antenna and single difference between L1 phase measurements with the side and the top antenna during 10 seconds, respectively. Note that the both results were averaged with a time window of 0.05 seconds. In a case of a satellite elevation angle of about 2.78 degrees, no periodic variation was observed in the both code correlation and single difference results as shown in Figure 15 (a). Moreover, single difference almost consisted of attitude variation of the experimental aircraft. However, in cases of elevation angles of -0.09 and -1.27 degrees in Figure 15 (b) and (c), effects on reflection signal from the sea surface were contained in the both code correlation and single difference results. These variation periods and phases were consistent with each other. We could also recognize that the variation period was larger with lower satellite elevation angles. It was also consistent that changing rate of path difference length between a direct and a reflected signal was more slowly with lower satellite elevation angles. These results suggest that we have to average Doppler shift in carrier phase of the occultation GPS satellite with the same interval of receiving intensity variation.

Validation of Attitude from IMU Using Single Difference Analysis

To accomplish our final purpose, we have to estimate accurate side antenna velocity combining with the ground reference stations. However, we firstly investigated the real time solution of aircraft attitude that were calculated from the IMU with GPS unit results only on aircraft, comparing the side-top single difference analysis in the previous subsection. Note that IMU data was not good because of some problems on October 15, 2003. Therefore, we used another data set that was observed on October 23, 2003.

Figure 16 shows IMU attitude at 1:10-1:50UT on October 23, 2003. In this period, the experimental aircraft flew almost straightly except around 1:15UT and 1:30UT. From the IMU attitude, geometrical differential range between occultation GPS satellite to the both of the side and top antennas could be calculated. We compared these differential ranges with single difference between carrier phase measurements with the side and top antenna.

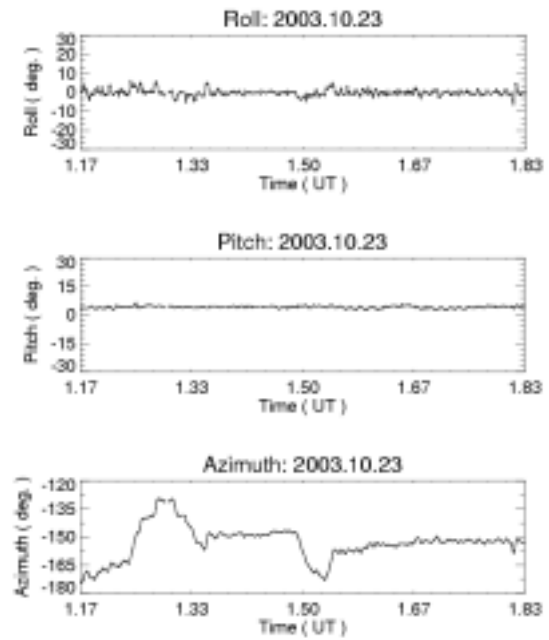


Figure 16: The real time solution of aircraft attitude that were calculated from the IMU at 1:10-1:50UT on October 23, 2003.

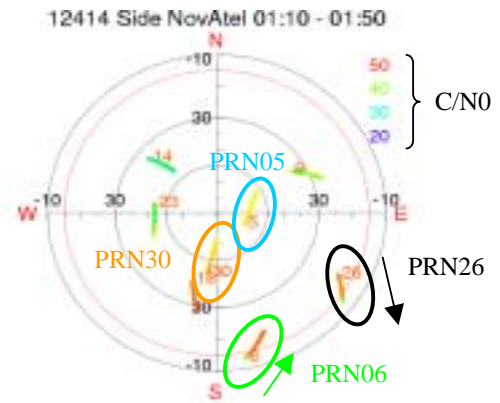


Figure 17: GPS satellites that were observed by the dual frequency segment of the DL receiver with the side antenna during an almost straight level flight at 1:10-1:50UT on Oct. 23, 2003. A red circle indicates a satellite view angle of 0 degree. Colors indicate receiving intensity of L1-C/A in C/N0.

Figure 17 shows GPS satellites observed by the dual frequency segment of the DL receiver with the side antenna during an almost straight level flight at 1:10-1:50UT on Oct. 23, 2003. We selected four satellites, which were including two occultation GPS satellites of PRN26 (setting) and PRN06 (rising), in order to examine the differential range analysis.

Difference between differential ranges derived from IMU attitude and the side-top single difference of L1

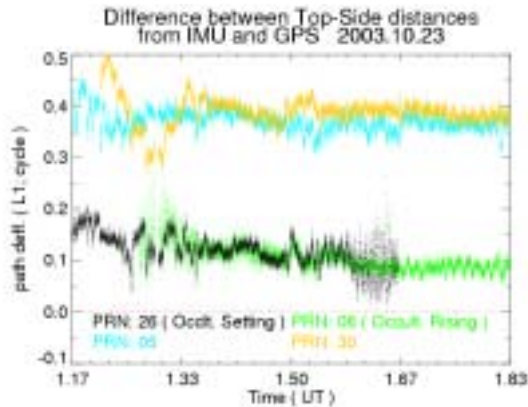


Figure 18: Difference between differential ranges derived from IMU attitude and single difference of L1 carrier phase measurements by the dual frequency segment of the DL receiver with two antennas of the side and the top at 1:10-1:50 on October 23, 2003.

measurements by the dual frequency segment of the DL receiver is shown in Figure 18. Although each difference should be 0, it had a bias error that depended on the signal arrival direction. Therefore, these bias errors seemed to be caused by antenna phase variations with the different type antennas set up on aircraft (antenna types are described in the previous section) and by multi-path effect from aircraft body.

In order to verify our expectation, we applied the same analysis to geostationary experimental data, which were observed on the top of Mt. Fuji to examine the performance of the DL receiver during September 17-19, 2003. We used the identical antennas in this experiment. As a result, there was no bias error in difference between differential ranges derived from geometrical analysis using the top and side antennas' positions and from single difference of phase measurements with two antennas. We confirmed that general features of small variations were similar to each other between aircraft and geostationary results except these bias errors.

SUMMARY

In this study, we aim to apply "mountain-based GPS down-looking occultation", which can provide tropospheric water vapor profile below the mountain top altitude, to experiment using aircraft. "Airborne GPS down-looking occultation" can expand resulting profile range up to a flight level and be performed almost everywhere.

In order to accomplish airborne GPS down-looking occultation experiment, we developed the equipment consisting of the following two elements. The one was a special receiver called by "DL receiver" which was designed for continuous tracking of occultation GPS

satellite so that the lower bound of resulting water vapor profile might be expanded almost to the ground. The other was GPS/INS hybrid positioning system to estimate accurate velocity of the side antenna motion with an accuracy of several mm/s including aircraft velocity and attitude in post-processing. We have installed the equipment on the experimental aircraft of ENRI.

We have conducted six flight experiments since October 2003 and obtained more than 30 datasets of occultation events. We investigated data qualities using the first experiment data. So far, we obtained the following results.

1. The DL receiver successfully tracked the occultation GPS satellite signal continuously down to elevation angle of -3.5 degrees with a flight level of about 6 km. However, dual frequency measurements were available down to about -2 degrees. Therefore, we have to use ionospheric delay model to remove ionospheric effect on L1-only data with an invalid period of L2.
2. Although the sea surface reflection significantly affected the occultation GPS signal, we can remove this effect using a special function of the DL receiver in the post-processing.
3. We have to extract atmospheric contribution from observed Doppler shift using aircraft velocity and attitude from GPS/INS measurements. We firstly investigated the accuracy of aircraft attitude derived from real time resolution of IMU, comparing with the side-top single difference in phase measurements of occultation GPS satellite. Although there was a bias error in difference between differential ranges derived from IMU attitude and the side-top single difference, we confirmed that general characteristics of the variation of them were similar to a result of geostationary observation on the top of Mt. Fuji except the bias error.

We successfully confirmed that the experimental data was very useful for providing water vapor profile. In order to accomplish our purpose, we have to exactly estimate the side antenna's velocity with an accuracy of about several mm/s including aircraft velocity and attitude.

In the future, if GPS receivers to observe GPS occultation signal are set up on the civilian airplane, many water vapor profile can be provided. It is expected that these results contribute improvement of the forecasting numerical model.

ACKNOWLEDGMENTS

This work was supported by a grant from the Ministry of Education, Culture, Sports, Science and Technology as the project of "Applications of Precise Satellite Positioning For Monitoring the Earth's Environment".

We appreciate Dr. Y. Shoji of Meteorological Research Institute, Japan for collaboration in the GPS occultation experiment at the Mt. Fuji weather station of the Japan Meteorological Agency in order to evaluate the performance of the DL receiver. GEONET data was provided for this project from Geographical Survey Institute, Japan.

REFERENCES

- [1] Kursinski, E.R, G.A. Hajj, K.R. Hardy, J.T. Schofield, and R. Linfield, *J. Geophys. Res.*, 102, 23429-23465, 1997
- [2] Zuffada, C., G.A. Hajj, and E.R. Kursinski, *J. Geophys. Res.*, 104, No. D20, 24435-24447, 1999
- [4] Mousa, A. and T. Tsuda, *J. Meteor. Soc. Japan*, 82, No. 1B, 427-432, 2004
- [3] Aoyama, Y., Y. Shoji, A. Mousa, T. Tsuda, H. Nakamura, *J. Meteor. Soc. Japan*, 82, No. 1B, 433-440, 2004