SAR Formation Flying

Annex 4. Bistatic Sensor Experiment

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4.1 First Airborne Experiment and Sea Surface Height Estimation

Investigating the use of reflected Global Navigation Satellite System (GNSS) signals for remotely sensing the Earth’s surface was initiated about two decades ago [1]. Remote sensing based on processing and analysing reflected GNSS signals is commonly termed GNSS reflectometry. When building a GNSS-based remote sensing system, only the receiver needs to be designed and manufactured. The receiver platform (static or mobile; land-based, aircraft, or satellite) needs to be selected based on the specific application. In the case of an aircraft or satellite platform, the direct signal is received via a zenith-looking right-hand-circularly-polarised (RHCP) antenna, while the reflected signal is received through a nadir-looking left-hand-circularly-polarised (LHCP) antenna. The reason for such an antenna selection is that GNSS signals are designed as RHCP; however, when reflected over a ground surface, they are changed to be LHCP. In the case of a land-based platform, either two antennas are used to receive the direct and reflected signals separately or a single antenna is used to capture both the two signals.

The GNSS signals are always available, globally, and the signal structures are typically well known, except for those dedicated to military use. Furthermore, the GNSS signals have some distinctive characteristics which can be utilised for remote sensing purposes. Recently there has been an increase in such investigations by academia and research institutions, partly because this innovative use of GNSS signals has many potential applications. In particular, space agencies such as NASA and ESA have already funded, or are going to fund, a number of projects/missions which focus on the applications of GNSS reflectometry. The Cyclone Global Navigation Satellite System (CYGNSS) project is just one example [2], which aims to develop a system using a constellation of eight microsatellites to improve hurricane forecasting especially with regards to the storm intensity. Another example is the ESA’s Passive Reflectometry and Interferometry System (PARIS) project. PARIS can be used as a passive radar altimeter. Different from current radar altimeters, PARIS would measure multiple samples from different tracks and rapidly form images of mid-sized (mesoscale) phenomena such as ocean currents or tsunamis [3]. However, there are still many challenging problems to be resolved, especially when applying this reflectometry technique to a range of application scenarios.

There is a range of geophysical and geochemical parameters which can be measured using a GNSS-based reflectometry system, including soil moisture, salinity, sea surface height (SSH), sea surface wind speed, and biomass density [4-14]. A number of researchers have investigated GNSS-based ocean surface altimetry using measurements obtained by either mounting the receiver on an aircraft, or fixing it on the ground such as on a bridge [15, 16]. The Global Positioning System (GPS) coarse/acquisition (C/A) code or the GPS P(Y) code was employed to measure the sea surface height (SSH). The P(Y) code can be used to achieve accuracy which can be higher than that when using the C/A code alone; however, the P(Y) code structure is not known to the civilian community.

In this section the focus is on GNSS-based ocean surface altimetry. The known C/A code (also termed clean code) is employed. The direct and reflected signals are received via two different antennas and then processed separately. The code phase of the direct signal and that of the reflected signal are estimated using a correlation delay waveform, and then used to estimate the delay of the reflected signal relative to the direct signal. The relative delay (i.e. the time difference of arrival between the reflected and direct signals) is then used to estimate the SSH. Estimating the code phase of the direct signal is relatively easy; however, it may not be easy to estimate accurately the desired code phase of...
the reflected signal due to the rich multipath propagation resulting from the rough sea surface. The peak-power code phase of the reflected signal does not correspond to the time-of-arrival of the signal. Instead, there is an unknown offset between the peak power code phase and the desired code phase of the signal. A power-ratio method is proposed to deal with this challenging issue. Specifically, a parameter, power-ratio, is introduced to determine the desired unknown code phase of the reflected signal. Two different cost functions are proposed and the most suitable power-ratio is determined by minimising the cost function. Accordingly a sequence of SSH estimates is selected and the mean SSH estimate is determined. A key advantage of the proposed method is that it does not require any a priori knowledge of sea state information or any theoretical model. Thus, the proposed method is not affected by the modelling errors and uncertainties.

Digital complex intermediate-frequency (IF) samples of both direct and reflected signals were collected during a low-altitude airborne experiment conducted on 14 June 2011 using a UNSW-owned light aircraft. The digital samples were processed to generate delay waveforms associated with four satellites. A Lidar experiment was also conducted by the same aircraft at the same time. The mean SSH derived from the Lidar measurements is used as a reference for evaluating the performance of the proposed methods. Note that the ranging accuracy of the Lidar device used in the experiment is 2cm. The results demonstrate that the proposed power-ratio-based method can be used to determine accurately the desired code phase of the reflected signal associated with all four satellites. The mean SSH estimation error can be as small as decimetre.

The remainder of this section focuses on

- Describing how to calculate SSH using signal time arrival or code phase measurements
- Reviewing relative delay estimation methods
- Presenting a power-ratio-based method
- Describing the first airborne experiment
- Describing the processing of experimental data and generation of delay waveforms
- Showing statistics of Lidar-based wave height measurements and GNSS-based relative delay measurements
- Showing power ratio statistics and SSH estimation results

### 4.1.1 Sea Surface Height Calculation

As shown in Figure 1, SSH is calculated relative to the surface of the theoretical Earth ellipsoid in the WGS84 system, which has zero altitude. A two-loop iterative method for SSH calculation can be employed, which is described below. The SSH at a specific sea surface point is the distance from the point to the WGS84 Earth ellipsoid surface and the mean SSH is the average of all these distances.

Figure 2 shows the flowchart of how to calculate the SSH. Specifically, for a given tentative SSH, since both the GNSS satellite position \((x_s, y_s, z_s)\) and the receiver position estimate \((\hat{x}_r, \hat{y}_r, \hat{z}_r)\) are known, the specular point position (SPP) \((\tilde{x}_S, \tilde{y}_S, \tilde{z}_S)\) on the tentative sea surface can be readily determined. The SPP estimation is realised by minimising the total path length (TPL) from the satellite through the SPP and to the receiver, which is given by
Figure 1. Geometry of the receiver, WGS84 mean sea level (Earth ellipsoid surface), rough sea surface, direct and reflected signal paths.

\[ \tilde{R}_{SSr} = \tilde{R}_{Sr} + \tilde{R}_{Sr} \]  

(1)

where

\[ \tilde{R}_{Sr} = \sqrt{(x_S - \tilde{x}_S)^2 + (y_S - \tilde{y}_S)^2 + (z_S - \tilde{z}_S)^2} \]

\[ \tilde{R}_{Sr} = \sqrt{(\tilde{x}_S - \tilde{x}_r)^2 + (\tilde{y}_S - \tilde{y}_r)^2 + (\tilde{z}_S - \tilde{z}_r)^2} \]  

(2)

The minimisation can be simply achieved by using an iterative method and the SPP must be scaled.

The TPL can also be estimated using the propagation time of the direct signal and the relative delay (\( \tau_{rd} \)) of the reflected signal, i.e.,

\[ \hat{R}_{SSr} = \hat{R}_{sr} + c \hat{\tau}_{rd} \]  

(3)

where \( c \) is the speed of light, \( \hat{\tau}_{rd} \) is the estimated relative delay and

\[ \hat{R}_{sr} = \sqrt{(x_r - \tilde{x}_r)^2 + (y_r - \tilde{y}_r)^2 + (z_r - \tilde{z}_r)^2} \]  

(4)

where the satellite position is assumed error free, while the receiver position is an estimate. How to estimate the relative delay will be discussed later. Then, as indicated in Figure 2, the calculated TPL by (1) is compared with the measured TPL by (3) to determine whether the tentative sea surface height should be increased or decreased. The process is terminated once the difference between the two TPLs is smaller than the pre-defined threshold.

To reduce the computational complexity, a simpler technique may be used. For instance, if \( \tilde{R}_{Sr} > \tilde{R}_{Sr} \), the tentative surface height is increased by a relatively larger increment such as 40 metres. At the
next iteration of the outer loop if \( \tilde{R}_{\text{Sr}} < \tilde{R}_{\text{Sr}} \), the increment is decreased by half of the previous increment. In this way, the process will quickly converge to the steady state. Note that the specular reflection must satisfy Snell’s Law, i.e. the two angles (\( \theta_1 \) and \( \theta_2 \) in Figure 1) between the incoming wave and the reflected wave, separated by the surface normal must be equal or the difference is extremely small. Thus the results should be tested to see if this Law is satisfied.

\[ t_{\text{Sr}} \leq t_{\text{Sr}} R R \hat{\sim} \leq \delta_{\text{h}}, \text{ the increment is decreased by half of the previous increment.} \]

In this way, the process will quickly converge to the steady state. Note that the specular reflection must satisfy Snell’s Law, i.e. the two angles (\( \theta_1 \) and \( \theta_2 \) in Figure 1) between the incoming wave and the reflected wave, separated by the surface normal must be equal or the difference is extremely small. Thus the results should be tested to see if this Law is satisfied.

\[ \text{Note that the specular reflection must satisfy Snell’s Law, i.e. the two angles } (\theta_1 \text{ and } \theta_2 \text{ in Figure 1}) \text{ between the incoming wave and the reflected wave, separated by the surface normal must be equal or the difference is extremely small. Thus the results should be tested to see if this Law is satisfied.} \]

\[ \text{Figure 2. Flowchart for } SSH \text{ calculation. } \delta_{\text{h}} \text{ is a small positive number.} \]

From (1) the partial derivatives with respect to the coordinates of the specular point can be determined as

\[ \frac{\partial R_{\text{Sr}}}{\partial u_S} = \frac{u_S - x_r}{R_S} u_S + \frac{u_S - x_t}{R_S}, \quad u_S \in \{x_S, y_S, z_S\} \]

which can be rewritten in a vector form as

\[ dS = \frac{\tilde{R} - \tilde{S}}{R_S} + \frac{\tilde{T} - \tilde{S}}{R_T} \]

where \( \tilde{S}, \tilde{R}, \) and \( \tilde{T} \) are the position vectors of the specular point, the receiver and the transmitter, respectively. Equation (6) is used to generate an iterative solution to the minimum path length. That is, at time instant \( n+1 \) the specular point position is updated according to

\[ \tilde{S}_{n+1} = \tilde{S}_n + \kappa \cdot d\tilde{S} \]

where \( \kappa \) is a constant which typically should be set as a larger value as the flight altitude increases. The initial guess of the specular point can be simply the projection of the receiver position onto the surface. At each iteration, a constraint must be applied to restrain the specular point on the surface that is \( \tilde{e} \) metres above or below the WGS84 ellipsoid surface which has a zero altitude if \( \tilde{e} \) is a positive or negative number. That is, the specular point position is scaled according to

\[ \tilde{S}_{n+1} = (r_S + \tilde{e}) \frac{\tilde{S}_{n+1}}{|\tilde{S}_{n+1}|} \]

where the radius of the Earth at the specular point is calculated by
\[ r_S = a_{WGS84} \sqrt{\frac{1 - e_{WGS84}^2}{1 - e_{WGS84}^2 \cos^2 \lambda_S}}, \quad \lambda_S = \arcsin \left( \frac{z_S}{|S|} \right) \]

where \( e_{WGS84} = 0.08181919 \) and \( a_{WGS84} = 6378137 \) metres.

Since the altitude of the WGS84 Earth’s surface is zero, the WGS84 altitude of the specular point (point S) is equal to \( \ell \). Clearly, the altitude of a single specular point cannot be treated as the estimate of the mean sea surface height. However, a reasonable estimate of the mean surface height will be produced through the generation and subsequent processing of the altitude estimates of many specular points over a period of time.

### 4.1.2 Relative Delay Estimation Methods

From Figure 2 it can be seen that the SSH estimation accuracy is largely dependent on the performance of the TPL (transmitter-SPP-receiver) measurement, which is determined by (3). The measurement error associated with the first term in (3) comes from the receiver position estimation error. When the receiver is given, such an error is typically not reducible, although smoothing may improve the accuracy marginally. Thus, it is important to use a GNSS receiver which can achieve satisfactory position estimation accuracy. The measurement error related to the second term in (3) results from the estimation of the relative delay of the reflected signal. When an accurate receiver is used, the relative delay estimation error would be dominant. Therefore, it is vital to reduce this error. The relative delay is estimated by determining the code phase of the direct signal and that of the reflected signal. Basically, two different approaches can be used to estimate the relative delay. One is the delay waveform based approach and the other is the carrier phase based approach.

The carrier phase approach may be suitable for scenarios where the sea surface is relatively smooth and the receiver platform is land-based or on a low altitude aircraft. In the case where the sea surface is rather rough, obtaining the carrier phase of the reflected signal would be a rather challenging problem. It would be useful to conduct more investigations on this approach in the future.

There are two methods associated with the delay waveform based method. The first one makes use of the clean code (C/A code), while the second one utilises the interferometry technique. The clean code method deals with the direct signal and the reflected signal separately and only uses the C/A code to generate the delay waveform. In the interferometry technique, on the other hand, both signals are processed together. That is, the two signals are either received simultaneously via the same antenna or cross-correlated when they are received via two different antennas. The interferometry technique is intended to exploit the P(Y) code or military M-code to achieve an accuracy gain at the cost of high-gain and directional antenna, and that the P(Y) code or M-code signals may only be observed at some specific intervals. In addition, a high-bandwidth frontend/receiver is required.

In this section the focus is on the clean code method when the sea surface is rough. In the case where the zenith-looking antenna is high above the ground, especially when the receiver is mounted on a satellite or on an aircraft, the code phase of the direct GNSS signal can be readily estimated by determining the location of the peak power of the correlation waveform. On the other hand, it may not be easy to obtain an accurate estimate of the desired code phase of the reflected signal.
forwarded from a rough sea surface. The main reason is that the location of the peak power of the reflected signal would not be the desired code phase of the reflected signal since the peak power location is shifted due to rich multipath propagation. Clearly, using the peak power location to calculate the relative delay would produce a large bias error. The time shift or offset would depend on a number of factors including the surface roughness and the receiver altitude. The peak power location of the delay waveform derivative can be used as the desired code phase of the reflected signal, but the estimate would be biased [16]. It is observed that the desired code phase of the reflected signal is somewhere between the peak power location of the delay waveform and that of the waveform derivative. However, the exact location of the code phase is typically unknown.

For clarity, it is desirable to explain why the peak power location could shift when a flat sea surface is replaced with a rough sea surface. Figure 3 illustrates the idealised correlation diagram (correlogram) of a GNSS signal in the presence of multipath propagation. In the presence of a perfect smooth sea surface, the signal will only be reflected at the specular point and then travels to the receiver. In the presence of a rough sea surface, besides the first path signal, there will be multipath signals arriving at the receiver. Suppose that there are J multipath signals whose delays relative to the 1st path are less than the GNSS code chip width (r1; i.e. half of the correlogram triangle width). Then, the following result exists.

The peak correlation power location of the combined multipath signals will shift from the peak correlation power location of the first path signal provided that

\[ \sum_{j=2}^{J} P_j > P_1 \]  

where \( P_j \) is the peak correlation power of the \( j^{th} \) path signal.

**Proof:** Let \( C_j(t) \) denote the correlation power of the \( j^{th} \) path signal. At time \( r_1 \) the combined correlation power of all the paths is

\[ C(r_1) = \sum_{j=1}^{J} C_j(r_1) \]

At time \( r_1 + \delta r \) the combined correlation power becomes

\[ C(r_1 + \delta r) = \sum_{j=1}^{J} C_j(r_1) + \delta C \]

where by denoting the slope of the leading edge of the correlogram of the \( j^{th} \) path as \( k_j \), the correlation power increment over the small interval of \( \delta r \) is given by

\[ \delta C = \sum_{j=2}^{J} k_j \delta r - k_1 \delta r \]

\[ = \delta r \left\{ \sum_{j=2}^{J} k_j - k_1 \right\} \]

\[ = \delta r \left\{ \sum_{j=2}^{J} k_j (r_1 - r_1) - k_1 (r_1 - r_1) \right\} \]

\[ = \frac{\delta r}{r_1} \left\{ \sum_{j=2}^{J} P_j - P_1 \right\} \]
That is, if (10) is valid, then $\delta \tau$ is positive and thus the peak correlation power location shifts to the right hand side by at least $\delta \tau$. Since both the 1st path signal and signals of other paths are reflected signals, the signal power of the 2nd path and a number of following paths can be significant with respect to the 1st path. Thus, intuitively, (10) would always be valid with a rough sea surface.

It would be interesting to derive the theoretical formulas to describe the location difference and the sea state so that how much shift can be readily determined in the future. Note that the peak correlation power location ($\tau_1$) of the 1st path signal related to a rough sea surface can be different from that of the single path signal related to a smooth sea surface. However, the difference would be rather small.

![Figure 3. Illustration of multipath correlation diagram.](image)

### 4.1.3 Proposed SSH Estimation Methods

**Power-Ratio Concept**

As mentioned earlier, the desired code phase corresponding to the time of arrival of the reflected signal is an unknown parameter. A practical and effective approach is proposed here to estimate the unknown parameter. Specifically, the concept of power-ratio is introduced and defined as the ratio of the peak power of the reflected signal when the surface is perfectly smooth over the peak power of the reflected signal which is actually received. Figure 4 is an illustration of the delay waveform of the reflected signal in the presence of a rough surface. $C(\tau_m)$ is the peak power of the reflected signal received via the down-looking antenna where $\tau_m$ is the time point at which the peak power occurs, while $C(\tau_1)$ is the correlation power at the time point $\tau_1$ where the reflected signal peak power occurs when the surface is perfectly smooth. Since $C(\tau_m)$ can be measured, the time parameter $\tau_m$ can be estimated. On the other hand, neither $C(\tau_1)$ nor $\tau_1$ can be simply measured. The power-ratio is simply defined as

$$\eta = \frac{C(\tau_1)}{C(\tau_m)}$$

(14)
Clearly, in the case of a perfectly smooth sea surface, the power ratio is equal to unity. Otherwise it is less than one. Given a power ratio and the measured peak power, the power at the desired code phase ($\tau_1$) can be calculated using (10) and the measured delay waveform. Then, the desired code phase is calculated and then used to calculate the delay of the reflected signal relative to the direct signal. Finally, the SSH estimates are obtained using the method described earlier.

**Proposed SSH Estimation Method**

Suppose that a sequence of delay waveform is produced by processing the logged GNSS data such as digital IF samples. A number of power-ratio values are selected to cover the likely values of the actual power-ratio. Applying each of the given power-ratios to the sequence of delay waveforms produces a sequence of relative delay estimates and then a sequence of SSH estimates. That is, $N$ power-ratios yield $N$ sequences of SSH estimates.

Now the question is how to determine which power-ratio is the best so that the corresponding sequence of SSH estimates has the best performance. To answer this question, two different criteria are proposed. Specifically, in the first criterion the SSH estimation performance is measured by the cost function which is defined as

$$\psi(\eta) = \sum_{i=1}^{N} (m_i(\eta) - m_{\text{total}}(\eta))^2$$

(15)

where $N$ GNSS satellites are considered so that $N$ sequences of SSH estimates are available, $m_i$ is the mean of SSH estimates related to the $i$th satellite, and $m_{\text{total}}$ is the mean of the SSH estimates associated with all the $N$ satellites. If only selecting satellites whose elevation angles are greater than say 30deg, $N$ would be around five. Note that it is assumed that GNSS signals are captured via a receiver mounted in an aircraft flying at a low altitude, such as a few kilometres above the surface. The effective reflection area associated with the signals of the $N$ satellites would be a number of kilometres. Over such a relatively small sea surface area, the mean SSH can be considered the same. On the other hand, in the case of a LEO satellite platform at an altitude of several hundreds of kilometres, the effective reflection area can be hundreds of kilometres. In this case, the mean SSH of one specular point track can be significantly different from that of another track; thus, (15) cannot be used.
Note that \( N \) must be greater than one and this requirement is usually satisfied in practice. That is, the criterion is that the power-ratio which minimises the cost function in (15) is selected. Mathematically, this criterion is

\[
\hat{\eta} = \arg\min_{\eta} \psi(\eta)
\]  

(16)

The selection of such a cost function is based on the observation from processing the data that the best power-ratio associated with one satellite is very similar to that related to another satellite when the elevation angle is greater than 45deg. Lidar measurements were used to measure the mean SSH which was then used to calculate the time offset (i.e. \( \tau_m - \tau_1 \) in Figure 4) of the reflected signal. Next, a sequence of the power-ratio values and their mean were calculated. Using the mean power-ratio, the estimated mean SSH related to an individual satellite was very close to the estimated mean SSH associated with all the selected \( N \) satellites. When the selected mean power-ratio is significantly different from the calculated one, the estimated mean SSHs would be rather different from each other. Further discussion will be provided later.

In the second criterion, the cost function is simply defined as

\[
\psi(\eta) = \sigma(\eta)
\]

(17)

where \( \sigma \) is the standard deviation of all the \( N \) sequences of SSH estimates. That is, this criterion is to minimise the cost function in (17) to produce the desired power ratio. This criterion selection comes from the consideration that using the desired power ratio would yield estimates that have minimum variations.

Theoretically, the time difference between the desired code phase corresponding to the time of arrival of the reflected signal and the code phase of the peak correlation power may be determined using the sea state information such as the surface elevation standard deviation. When such a relationship is established, the relative delay of the reflected signal can be readily determined by measuring the code phases of the peak correlation power of the direct and reflected signals. However, it is inevitable that there are some uncertainties associated with such a theoretical model. Therefore, it would be useful to establish a model to describe the relationship between the peak power location shift of the reflected signal and the surface roughness as well as to analyse the effect of the model uncertainties in the future.

**Algorithm Complexity Reduction**

When the length of the sequence of power ratio evaluated is large, the computational complexity can be rather high. To reduce the complexity, a technique, similar to finding a minimum of a function using gradient descent method, is proposed as shown in Figure 5. Initially two tentative power ratios (\( \eta_1 \) and \( \eta_2 \) where \( \eta_2 > \eta_1 \)) are selected empirically and the difference between these two initial ratios should be such as greater than 0.02. Each of the two ratios is then used to obtain sequences of SSH estimates and calculate the cost functions as described in the preceding sub-section.
Next, the power-ratio value is updated as illustrated in Figure 6. Specifically, the next power-ratio update will be dependent on the position and value of the newly updated power ratios and corresponding cost functions. Initially, the ratio update is realised by

$$\eta_3 = \begin{cases} 
\eta_1 - \delta_2, & \psi_2 - \psi_1 > a \\
\eta_2 + \delta_2, & \psi_2 - \psi_1 < -a \\
\eta_1 + \delta_2 / 2, & |\psi_2 - \psi_1| < a 
\end{cases}$$  \quad (18)

where $a$ is a small positive number that is much smaller than the initial power-ratio increment which can be simply set to be

$$\delta_2 = \eta_2 - \eta_1$$  \quad (19)

Then sequences of the SSH estimates are produced and the corresponding cost function ($\psi_1$) is calculated. Also, the three cost function values are ranked as smallest ($\psi_{\text{min}}$), median, and largest. At the next iteration, the power ratio is updated according to

$$\eta_4 = \eta(\psi_{\text{min}}) + \delta_4$$  \quad (20)

The ratio increment ($\delta_4$) is determined as follows. If the power ratio with the smallest cost function ($\eta(\psi_{\text{min}})$) is the median of the three ratios and the power ratio related to the medium cost functions is the maximum, then the increment is updated by

$$\delta_4 = \delta_3 / 2$$  \quad (21)

Otherwise, if the power ratio related to the medium cost function is the smallest, then

$$\delta_4 = -\delta_3 / 2$$  \quad (22)
On the other hand, if \( \eta(\psi_{\text{min}}) \) is not the median ratio but the largest one, then

\[
\delta_4 = \delta_3
\]  

(23)

Further if \( \eta(\psi_{\text{min}}) \) is the smallest power ratio, then

\[
\delta_4 = -\delta_3
\]  

(24)

This process continues until the power-ratio increment is sufficiently small. Intuitively, such an iterative procedure would quickly approach the steady state and the power-ratio estimate approaches the desired one.

**Calibration**

Since the zenith-looking and nadir-looking antennas, the receiver, and the reference point are not in the same position, it is necessary to calibrate the relative delay measurements to remove the effect of these position differences. Note that the reference point may be set at the centre of the inertial measurement unit (IMU) provided that such a device is used. Figure 7 illustrates the configuration of the devices. The two antennas are connected to the receiver via two cables whose lengths are \( L_{CR} \) and \( L_{CD} \). The actual measurement of the relative delay of the reflected signal is given by

\[
L_{\text{measured}} = AS + SD + L_{DR} - (AU + L_{UR}) + \varepsilon
\]  

(25)

where \( \varepsilon \) is the measurement error. On the other hand, using the reference point position, the relative delay is calculated as

Figure 6. Iterative power-ratio updating.
where the theoretical and actual specular points are treated to be at the same position since their difference can be neglected. As described earlier, the SSH is estimated by comparing the measured and calculated relative delays. However, typically, there is an offset between the calculated and measured delays even in the absence of measurement error. That is,

$$\begin{align*}
L_{\text{offset}} &= L_{\text{measured}} - L_{\text{calculated}} \\
&= (SC - SD) + (AU - AC) + (L_{UR} - L_{DR})
\end{align*}$$

(27)

where the measurement error is ignored.

Therefore, the measured relative delay should be calibrated by subtracting the offset from itself. The lengths of the two cables can be readily measured in advance. In case where a LNA is used to amplify such as the signal, the path length from D to R or from U to R will be the sum of two cable lengths plus the distance between the two connection points of the LNA. The distance from U to C and that from D to C can be manually determined in advance. The positions of points U and C are estimated by the receiver and frame transformation; thus distances AC and AU can be readily calculated. Calculation of the distances SC and SD requires a knowledge of the SSH, which is unknown in advance. However, initial information about the SSH, or previous SSH estimation results, can be exploited. The uncertainty in the SSH estimate will affect the calculation of both SC and SD in a very similar way, so that a small SSH error will have a negligible impact. That is, distance CV can be estimated and distance SC can be calculated using elevation angle. Calculation of distance SD requires its orientation to determine the angle $\angle SD C$. In the case where the nadir-looking antenna is fixed directly beneath the reference point, the distance can be simply calculated by

$$SD = \sqrt{SC^2 + CD^2 - 2 \times SC \times CD \times \cos(90 - \phi)}$$

(28)

Once the distances and the cable lengths in (27) are known, the relative delay offset can be readily determined. For instance, suppose that points U and D are directly above and below point C respectively; $AC = 20000km$; satellite elevation angle is $50 \text{deg}$; $UC = 0.8m$; $CD = 0.4m$; $CV = 300m$; $L_{UR} = 1m$; and $L_{DR} = 0.6m$. Then, the unknown distances are obtained from some simple calculations: $AU = 19999.999387km$, $SD = 391.32m$, $SC = 391.62m$. As a result, the relative delay offset is calculated to be $0.094m$. The SSH estimation error caused by this relative delay offset can be approximated as

$$\delta \xi \approx \frac{L_{\text{offset}}}{2 \sin \phi} = 6.1 \text{cm}$$

(29)

Thus, when the configuration of the devices is arranged properly and the cable lengths are selected based on similar analysis, the SSH error caused by the device configuration will not be large. However, to achieve accurate altimetry, such an error must be compensated for.
4.1.4 Airborne Experiment

A low-altitude airborne experiment was conducted by a UNSW-owned light aircraft off the coast of Sydney between Narrabeen Beach and Palm Beach on the 14th of June 2011. The flight height above the sea was between 200m and 500m. These low flight altitudes were required by the Lidar experiment. Note that when preparing this GNSS-R experiment, the critical issue of flight height as mentioned earlier was not realised. The primary payload was for the Lidar experiment whose purpose was to monitor the Sydney coastal areas to provide information for future infrastructure development. The free host payload was for the GNSS signal reception and data logging. Totally, about 10 Gigabytes of binary raw IF data were logged over 21 minutes. Figure 8 shows the short flight track segment relative to the coastal area over the duration of about 60 seconds. The distances between the Waverider buoy and the two points A and B are $R_{AB} = 2.98$ km, $R_{AW} = 8.97$ km, and $R_{BW} = 9.54$ km, respectively.
Figure 9 shows the basic block diagram of the signal reception and data logging system. All the equipment was secured on stable structures in the aircraft. Figure 10 shows the light aircraft used for the experiment, which can accommodate four people. Figure 11 shows the GPS software receiver and the Lidar equipment secured in the aircraft. The Lidar device is a Riegl LMS-Q240i laser scanner and the laser wavelength is 905nm. This device is extremely rugged and thus ideally suited for airborne experiments. The maximum measurement range is around 650m and ranging accuracy is about 20mm.

The GPS data were logged using the NordNav software receiver, which has four front-ends so that the signals arriving at the LHCP and RHCP antennas were recorded simultaneously via two of the four front-ends. The direct signal was received via the normal zenith RHCP GNSS antenna as shown in Figure 12, which was also used for the Lidar experiment. The reflected GNSS signal was captured via the nadir-looking LHCP antenna mounted on the bottom of the aircraft as shown in Figure 13. This LHCP antenna is a passive L1/L2 GPS antenna with a 3dB-beamwidth of 114 degree in free space. The LNA of a fixed gain 20dB was connected between the LHCP antenna and the second front-end of the NordNav software receiver as shown Figure 14, amplifying the signals arriving at the LHCP antenna. The first front-end of the receiver receives the direct signal that was used to obtain the position and velocity of the satellite and the receiver. The IF and sampling frequency of the
software receiver are 4.1304MHz and 16.3676MHz respectively. The direct signal was also used to derive the code phase and Doppler frequency information. The raw IF GNSS signals from the output of the receiver were logged to a laptop as shown in Figure 15.

The wind data (provided by the Australian Bureau of Meteorology [17]) indicated that the wind speed was about 50km/h during the experiment. Also, the wave data (provided by Mark Kulmar from the Manly Hydraulics Laboratory (MHL), Sydney, New South Wales [18]) indicates that the sea surface during the experiment was rather rough with maximum wave height greater than 6m.

Figure 11. The software receiver (front left) is secured in the aircraft.

Figure 12. The RHCP antenna is secured on the top of the aircraft.
Figure 13. The LHCP antenna (white and round) is secured on the bottom of the aircraft.

Figure 14. The LNA is secured in the aircraft.

Figure 15. The laptops are secured in the aircraft.
4.1.5 Data Processing and Delay Waveform Generation

The collected IF data were processed to generate delay waveforms (correlation power versus C/A code phase). That is, the IF data were cross-correlated with a replica of a C/A code sequence associated with a specific satellite. Delay waveform is one of the two types of waveforms (the other one is the delay-Doppler waveform) which are the basis for most of the current GNSS-R remote sensing methods. In the approach reported in this section, delay waveforms associated with four GNSS satellites were generated. The coherent integration time is 1ms, while the incoherent integration time is 1sec. The spread of the correlation power on the trailing edge over time results from the roughness of the sea surface.

When the clean code (C/A code) is used and sampling frequency is low, interpolation of delay waveform is necessary to improve resolution of code phase estimation. For instance, Figure 16 shows the top of a measured delay waveform and the interpolated waveform. A software receiver was used to generate digital IF samples with a sampling frequency of 16.3676MHz. Clearly, the sampling period is equivalent to about 18m, which would be too large to achieve accurate altimetry. The smoothed/interpolated waveform would provide much more accurate timing information.

![Figure 16. Delay waveform interpolation.](image-url)
4.1.6 Lidar Data and GNSS Signal Relative Delay Estimation Error Statistics

Mean Sea Level and Wave Statistics

Figure 17 shows the results related to 3983 points on the sea surface from the processing of the Lidar data. The upper plot shows the WGS84 altitudes of the surface points and their mean (dashed straight line), while the lower plot shows the difference when the altitudes are subtracted by a value which is the mean of the altitudes. That is, the lower plot shows the surface elevation variation with respect to the measured MSL which is calculated as 23.44m. The standard deviation of the MSL estimate is 1.38m, mainly contributed to by the surface roughness. This MSL estimate can be employed as a reference when evaluating the performance of the GNSS-based altimetry. These samples were taken between 15:27:55 and 15:31:38 for duration of 3 min 43.3 sec. Figure 18 shows the wave heights derived from the Lidar surface points shown in Figure 17. A wave is defined as the portion of the water between two successive zero-up-crossings relative to the MSL. The wave height is simply calculated as the vertical displacement between the crest and the trough of the wave. Using the Lidar-based wave heights the wave statistics during this period can be calculated, which include the significant wave height (SWH), the root mean square (RMS) wave height, and the maximum wave height. Also, a nearby Waverider buoy continuously measures the wave height statistics and the relevant statistics were obtained from MHL. The wave statistics from Lidar and buoy measurements are listed in Table 1. From this table it can be seen that these Lidar-based statistics of the wave height measurements have good agreement with those of the Waverider buoy-based measurements. Note that the distance between the location of the Waverider buoy and the location where the presented data were collected is about 10km. Due to this location difference some small variations of the wave statistics are expected.

Figure 19 shows the cumulative distribution function (CDF) of the measured wave heights. It can be seen that the measured wave heights closely follow the Rayleigh distribution, whose CDF is given by \(1 - \exp(-x^2/(2\sigma^2))\) where the distribution parameter \(\sigma = 1.81 \text{ m}\) is calculated from the measured wave heights. This is in agreement with results reported in the literature [19, 20].
Figure 17. WGS84 altitudes of the sea surface points (top) and relative sea surface elevation (bottom) measured by Lidar.

Figure 18. Wave heights derived from the Lidar surface points.

Table 1. Measured wave statistics.

<table>
<thead>
<tr>
<th></th>
<th>SWH (m)</th>
<th>RMS WH (m)</th>
<th>Max WH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lidar</td>
<td>3.7</td>
<td>2.6</td>
<td>6.8</td>
</tr>
<tr>
<td>Buoy</td>
<td>4.0</td>
<td>2.7</td>
<td>6.4</td>
</tr>
</tbody>
</table>
Peak Power Based Relative Delay Measurements and Error Statistics

The delays of the reflected signal relative to the direct signal associated with four satellites are estimated. First the relative delay is estimated by determining the location of the peak power of the direct signal and that of the reflected signal. Second, the relative delay is determined under an idealised scenario where the sea surface is smooth and the SSH is equal to the Lidar-based mean SSH measurement. The four satellites that have the largest elevation angles are listed in Table 2. The selection of the satellites is based on the fact that the signal-to-noise ratio of the reflected signal typically increases as the elevation angle increases until the elevation angle reaches some specific value such as about 65deg [21, 22].

Table 2. Elevation and azimuth angles of four satellites.

<table>
<thead>
<tr>
<th>Satellite (PRN#)</th>
<th>22</th>
<th>18</th>
<th>6</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (deg)</td>
<td>62.67-62.99</td>
<td>58.14-57.41</td>
<td>50.89-50.92</td>
<td>48.57-47.95</td>
</tr>
<tr>
<td>Azimuth (deg)</td>
<td>238.19-240.29</td>
<td>148.82-149.94</td>
<td>266.29-268.22</td>
<td>78.87-79.93</td>
</tr>
</tbody>
</table>
Figure 20 shows the relative delay estimation results over a period of about 60 seconds. Clearly, although the shape of the peak power based estimates has a good match with that of the estimates using the Lidar-based mean SSH estimate, there is a relatively large offset between the two curves. As mentioned earlier, this offset is due to the roughness of the sea surface. When using the Lidar-based results as a reference, the relative delay estimation error of the peak power-based method can be calculated as shown in Figure 21. Table 3 shows the mean and STD of the estimation errors associated with individual satellites. It can be seen that the mean error varies significantly and the largest mean error difference is 1.37m. From this table it is difficult to tell how the estimation error is related to the satellite elevation and azimuth angles. However, if excluding satellite PRN#18, then the error in terms of mean or RMS increases as the elevation angle decreases. The reason why the error mean and STD related to satellite PRN#18 are relatively large may be due to the relationship between satellite azimuth angle (i.e. signal propagation direction) and the wave direction. As shown in Figure 22, during the data collection the wave direction was about 145 deg (southwest). That is, the reflected signal transmitted from satellite PRN#18 travelled virtually along the wave direction, while the signals from other three satellites basically travelled across the wave direction. It is not clear why the signal travelling along the wave direction produced a larger error than the other signals. It would be necessary to conduct more investigations to determine how the errors are related to the elevation and azimuth angles, wave direction, and other parameters.

![Figure 20](image_url)

Figure 20. Relative delay estimates using known MSL (23.44m) (dashed black curve); using the peak power code phase (blue dashed curve); and removing mean error (red solid curve).
Figure 21. Relative delay estimation errors of peak power-based method when the dashed black curve in Figure 20 is treated as true relative delay.

Table 3. Mean and standard deviation of measured relative delay errors associated with four satellites.

<table>
<thead>
<tr>
<th>Satellite (PRN#)</th>
<th>22</th>
<th>18</th>
<th>6</th>
<th>21</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (m)</td>
<td>22.29</td>
<td>23.43</td>
<td>22.98</td>
<td>23.66</td>
<td>23.09</td>
</tr>
<tr>
<td>STD (m)</td>
<td>1.96</td>
<td>2.16</td>
<td>1.63</td>
<td>1.45</td>
<td>1.89</td>
</tr>
<tr>
<td>RMS (m)</td>
<td>22.38</td>
<td>23.53</td>
<td>23.04</td>
<td>23.70</td>
<td>23.18</td>
</tr>
</tbody>
</table>
4.1.7 SSH Estimation Results

As mentioned earlier the receiver position coordinates, including altitude, are required to calculate the SSH. As shown in Figure 23, the aircraft flight height was measured by two different GNSS receivers, NordNav and Novatel, over the duration of about 1 minute. Taking the Novatel measurements as a reference, the NordNav measurement error mean is 2.5m and the error standard deviation is 2m. Since the Novatel measurements are much more accurate, its measurements of the receiver position including the altitudes were used in the SSH estimation. However, the NordNav receiver has four front-ends which are synchronised, hence the digital IF samples recorded through the NordNav receiver are used. Note that when processing the complex (IF) samples for generating delay waveforms, the coherent integration time is set at 1 millisecond. The 1ms delay waveforms are then accumulated over a period of 1 second to generate the final delay waveforms for code phase and SSH estimation.
Figure 23. Aircraft altitude measurements observed from two different GNSS receivers. The measurements are with respect to the WGS84 ellipsoid, not the sea surface.

**Measured Power Ratio Statistics**

Using the known mean SSH measured by the Lidar device, the power-ratio statistics can be calculated as shown in Figure 24 and the procedure can be described as follows. Given the known mean SSH and using the known satellite position and the measured receiver position, the SPP on the mean sea surface can be determined as described earlier. Accordingly, the TPL can be calculated, and hence the relative delay of the reflected signal can be determined. Then, using the code phase of the direct signal, the desired code phase of the reflected signal can be calculated. As a result, the correlation power of the reflected signal at this code phase can be determined using the delay waveform. Finally, the ratio of this correlation power over the peak power of the reflected signal can be readily calculated. This is just to evaluate the statistics of the power-ratio calculated over a time series and related to four individual satellites.

The procedure of the power-ratio calculation can be repeated for a significant number of delay waveforms obtained over a time interval. For instance, if a delay waveform is produced by accumulating waveforms over a period of 1 second without overlapping, then 1 minute measurements would produce 60 delay waveforms associated with a specific satellite, resulting in 60 power-ratio values. If four satellites are considered, 240 power-ratio values would be produced. Then, the MPR is calculated.

Next, the procedure runs backwards. That is, given the MPR, the correlation power of the reflected signal at the desired code phase can be readily calculated. Then, one locates the point on the delay waveform whose power value equals the calculated power. Note that typically there are two such points on the waveform with one on each side of the peak power point, but only the left-hand-side one is the desired one. The corresponding code phase (i.e. the desired code phase) of this
correlation power is then obtained. As a consequence, the relative delay of the reflected signal can be calculated and the SSH is estimated according to the two-loop iterative method described earlier.

Figure 25 shows the discrete power-ratios calculated using the above procedure. The mean and standard deviation of the power-ratios associated with the four individual satellites are listed in Table 4. The overall MPR is 0.9666 and the overall standard deviation is 0.0049. It can be seen that the four MPRs are very similar and the largest difference is only 0.0017 which is 0.18% of the overall MPR. That is, a single MPR can be used to approximate the MPRs related to the individual satellites for a given sea state.

![Diagram](image)

Figure 24. Calculation of power ratio of reflected signal when SSH is given. DS: direct signal, RS: reflected signal.

The MPR (0.9666) is then used to calculate the desired code phases and the relative delays of the reflected signal associated with each satellite. Finally four sequences of SSH estimates are obtained as shown in Figure 26. It can be seen that the mean of the SSH estimates associated with each satellite is very close to the Lidar-derived mean SSH estimate. Table 5 shows the error mean and standard STD associated with individual satellites when taking the Lidar measurement (23.44m) as the error-free mean SSH estimate. The overall error mean and STD are 4.5cm and 1.08m, respectively. That is, if the desired MPR can be retrieved, accurate mean SSH estimation can be obtained.
Figure 25. Calculated power ratios related to four satellites.

Table 4. Mean and standard deviation of calculated power-ratios associated with four satellites.

<table>
<thead>
<tr>
<th>Satellite (PRN#)</th>
<th>22</th>
<th>18</th>
<th>6</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.9674</td>
<td>0.9657</td>
<td>0.9664</td>
<td>0.9670</td>
</tr>
<tr>
<td>STD</td>
<td>0.0050</td>
<td>0.0063</td>
<td>0.0042</td>
<td>0.0035</td>
</tr>
</tbody>
</table>

Figure 26. SSH estimates using a single MPR. Power-ratio-based mean SSH estimate (black dashed), power-ratio-based SSH estimates (red dashed), and Lidar-derived mean SSH measurement (blue solid).
Table 5. Power-ratio-based SSH estimation error mean and STD associated with individual satellites.

<table>
<thead>
<tr>
<th>Satellite (PRN#)</th>
<th>22</th>
<th>18</th>
<th>6</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (m)</td>
<td>0.181</td>
<td>-0.090</td>
<td>-0.023</td>
<td>0.112</td>
</tr>
<tr>
<td>STD (m)</td>
<td>0.996</td>
<td>1.409</td>
<td>0.959</td>
<td>0.872</td>
</tr>
</tbody>
</table>

Joint Power-Ratio and SSH Estimation

Figure 27 shows the effect of varying the MPR on the SSH estimation error mean when all four satellites are considered. Varying the MPR by 2% would result in a mean SSH error of either -5m or 3.83m. That is, the performance is rather sensitive to the MPR selection. Figure 28 shows how the MPR affects the cost function defined by (15) when all four satellites are considered. Clearly, when ignoring the small variations from sample to sample, the overall cost function behaves as a convex function. That is, it is possible to search for the MPR at which the cost function achieves the minimum to obtain the desirable SSH estimate. In this case, the minimum cost function occurs when the MPR is equal to 0.9650. From Figure 26, this MPR produces a SSH error mean of 0.39m.

Figure 29 shows the STD of SSH estimation errors associated with all four satellites. In this case the cost function is the STD which reaches the minimum when the MPR is equal to 0.9672. Using this MPR produces a mean SSH estimate whose error is -0.08m. Figures 30 and 31 show the estimation results when three satellites are considered as well as the two different cost functions are used. There are four different combinations when choosing three from four satellites. Table 6 shows the MPRs and the mean SSH errors associated with the four combinations using the two different cost functions. Note that CF1 denotes for cost function defined by (15) while CF2 denotes for the one defined by (17). Clearly, when the worst combination is selected, the mean SSH error are 0.97m and 1.51m for the two different cost functions, respectively. On the other hand, if the best combination in each case is selected, the error would be 0.26m and -0.08m, respectively. That is, the performance is also rather sensitive to the satellite selection.

Table 7 shows the average of the estimated MPRs and RMS of the mean SSH errors when the number of satellites ranges from two to four. For instance, in the case of three satellites the overall error of the four different combinations shown in Table 6 is calculated in terms of RMS. As expected, the performance improves as the number of satellites increases. It can also be observed from the table that the first cost function is more suited for the case of two or three satellites, while the second cost function is best used for the case of four satellites. The poor performance associated with the second cost function in the case of two satellites may be due to the limited number of samples. It would be interesting to do more data processing to generate more samples to see if the performance can be improved. In Table 7 the average of the mean SSH estimation errors is also listed. In the case of multiple combinations the performance is improved by averaging. In particular the mean SSH error is only 0.18m for the first cost function with two-satellite combinations. Due to the error randomness, averaging would typically cancel the errors with each other to some degree so that an estimation accuracy gain can be achieved as indicated by the results in the table. As for the first cost function,
the error with two-satellite combinations is even smaller than that with three- or four-satellite combination. This may be a coincidence since the large errors nearly completely cancel each other.

Figure 27. Effect of MPR on mean SSH estimation error.

Figure 28. Cost function defined by (15) versus MPR (four satellites).
Figure 29. Cost function (SSH error STD) versus MPR. Data related to four satellites are used.

Figure 30. Cost function defined by (15) versus MPR. Data related to three satellites are used.
Table 6. Estimated MPRs and mean SSH error when combinations of three satellites are considered.

<table>
<thead>
<tr>
<th>Satellite PRN#</th>
<th>18,6,21</th>
<th>22,6,21</th>
<th>22,18,21</th>
<th>22,18,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPR (CF1)</td>
<td>0.9682</td>
<td>0.9648</td>
<td>0.9656</td>
<td>0.9622</td>
</tr>
<tr>
<td>MPR (CF2)</td>
<td>0.9686</td>
<td>0.9596</td>
<td>0.9672</td>
<td>0.9672</td>
</tr>
<tr>
<td>Mean SSH Error(m) (CF1)</td>
<td>-0.31</td>
<td>0.44</td>
<td>0.26</td>
<td>0.97</td>
</tr>
<tr>
<td>Mean SSH Error(m) (CF2)</td>
<td>-0.40</td>
<td>1.51</td>
<td>-0.08</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

Table 7. Average of estimated MPRs and mean SSH error when using different numbers of satellites.

<table>
<thead>
<tr>
<th>Number of Satellites</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Averaged MPR (CF1)</td>
<td>0.9659</td>
<td>0.9652</td>
<td>0.9650</td>
</tr>
<tr>
<td>Averaged MPR (CF2)</td>
<td>0.9683</td>
<td>0.9657</td>
<td>0.9672</td>
</tr>
<tr>
<td>RMS of mean SSH errors (m) (CF1)</td>
<td>0.78</td>
<td>0.57</td>
<td>0.39</td>
</tr>
<tr>
<td>RMS of mean SSH errors (m) (CF2)</td>
<td>2.87</td>
<td>0.78</td>
<td>0.08</td>
</tr>
<tr>
<td>Average of mean SSH errors (m) (CF1)</td>
<td>0.1841</td>
<td>0.3385</td>
<td>0.3947</td>
</tr>
<tr>
<td>Average of mean SSH errors (m) (CF2)</td>
<td>-0.6</td>
<td>0.24</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

Figure 31. Cost function (SSH error STD) versus MPR. Data related to three satellites are used.
4.1.8 Concluding Remarks

In this section sea surface altimetry is investigated using low-altitude airborne experimental data collected when the sea surface wind speed was 50km/h and the significant wave height was about 4 metres. The SSH estimation was performed using the GPS C/A code and delay of reflected signal relative to direct signal. The power-ratio concept was proposed and a power-ratio-based method was developed to estimate the desired code phase of the reflected signal. This method is based on the observation that the MPRs associated with a group of satellites are almost the same. Therefore, a single power-ratio constant can be used to estimate the code phase and the relative delay of the reflected signal and hence the SSH. By selecting a number of power-ratio values, sequences of SSH estimates are obtained using the measured delay waveforms of the reflected signal. Two different cost functions were defined to evaluate the performance related to each power-ratio. The power-ratio with the minimum cost function is selected and the corresponding mean SSH estimate is treated as the desired estimate. The results demonstrate that using the proposed method the mean SSH estimation error can be at the sub-decimetre-level in the presence of SWH of about four metres. The developed method does not require any theoretical model or any a priori information about the sea state. The main disadvantage of this proposed method is that the computational complexity is increased.

In the future it would be useful to conduct more investigations on establishing a theoretical model to describe the relationship between code phase shift of reflected signal and surface roughness, as well as on how the modelling error affects the estimation accuracy.
4.2 Second Airborne Experiment and Sea Surface Wind Speed Estimation

The idea of using GNSS signals to remotely sense geophysical parameters was originally proposed by Martin-Neira [1]. Since then, different methods and techniques have been proposed for GNSS-based earth observation. In particular, the sea surface wind speed estimation has been investigated by many researchers [4, 5, 8, 23-25]. Information about the sea surface conditions is very useful for a range of services. For instance, the safety of ocean transport and ocean fishery can be enhanced so that tragic ferry/ship accidents can be avoided or greatly reduced. Also, with accurate information about the sea state appropriate measures can be taken to significantly reduce the economic loss due to flooding, especially in coastal areas.

Surface wind and sea state are two different concepts. One of the sea surface characteristics is the surface mean square slope (MSS) which is closely related to surface wind, especially when the surface slope is generated by local wind. However, the most important parameter associated with the sea state may be the significant wave height (SWH) which is defined as the average height of the one-third highest waves. Alternatively, the standard deviation of the surface elevation is a sea state parameter, which can be more readily handled mathematically. Note that surface elevation and wave height are two different concepts/parameters, although the latter is determined from the former. Surface elevation time series can be divided into individual waves. Typically a wave is defined as the portion of the water between two successive zero up-crossings relative to the still water surface. Wave height is the difference between the maximum and the minimum surface elevations and there is only one zero down-crossing between them. Surface elevation of random waves can be described as a zero-mean Gaussian random variable with a standard deviation (STD) denoted by $\sigma_z$ [26]. On the other hand, the distribution of wave height can be rather different from that of surface elevation. Based on theoretical studies and field measurements it has been shown that wave height is a random variable that follows the Rayleigh distribution [19, 20]. The two random variables can be connected to each other through associating the SWH with the surface elevation STD by the simple relationship

$$SWH = 4\sigma_z$$

(30)

Studies have demonstrated that for deep water waves the SWH calculated as above has good agreement with that determined by the one-third highest wave heights. In the case of intermediate and shallow water depths the SWH determined by the above equation would be less than the average height of the one-third highest waves [27]. Nevertheless, this relationship is commonly accepted for calculating the SWH in wave height analysis.

The focus of this section is on the basis of the sea surface modelling, the second low-altitude airborne experiment, and near sea surface wind speed estimation. Next subsection investigates the sea wave spectrum, the surface scattering and the theoretical formulas for calculating the reflected signal power, followed by report on the airborne experiment conducted on a UNSW-owned light aircraft. Then, the delay waveforms and delay-Doppler waveforms through processing of the logged data are generated and the near sea surface wind speed estimation is performed, and finally some estimation results are presented.
4.2.1 Modelling and Theoretical Waveforms

Nearly all the existing methods for sea state and wind retrieval are related to the modelling of sea waves and sea surface scattering directly or indirectly. In this subsection, the details of the modelling are investigated, including the sea wave spectrum, sea surface scattering, and the formula for calculating the power of the reflected signal entering the nadir-looking LHCP antenna.

Sea Wave Spectrum

Sea surface undulation is a complex process and sea wave heights change randomly in time and space. Sea surface roughness can be described by a number of parameters including significant wave height (SWH) and significant wave period (SWP). SWH is defined as the average height of the one-third highest waves and SWP is defined as average period of the waves used to calculate the SWH. Alternatively, wave height spectrum and wave direction spectrum can be used to describe the surface roughness. Among the wave height spectral models, the Pierson-Moskowitz model, the JONSWAP model, and the Elfouhaily model are widely studied [28, 29].

The Elfouhaily model that describes the wind-driven wave height spectrum is defined as

\[ W(\kappa, \phi) = \frac{\kappa^{-4}}{2\pi}(B_r(\kappa) + B_h(\kappa))(1 + \Delta(\kappa) \cos(2(\phi - \phi_0))) \]  \hspace{1cm} (31)

where \( \kappa \) is the wave number, \( \phi \) is the azimuth angle, and \( \phi_0 \) is the wind direction. The long wave curvature spectrum \( B_r(\kappa) \) is defined as

\[ B_r(\kappa) = \frac{3 \times 10^{-3}U_{10}}{c \sqrt{\Omega}} \exp\left( -\frac{\Omega}{\sqrt{10}} \left( \frac{\kappa}{\kappa_p} \right)^2 \right) \exp\left( -\frac{5}{4} \left( \frac{\kappa_p}{\kappa} \right)^2 \right) \gamma^\Gamma \]  \hspace{1cm} (32)

where \( U_{10} \) is the wind speed at a height of 10m above the sea. Note that the wind speed at a height of 19.5m above the sea is related to \( U_{10} \) by \( U_{19.5} = 1.026U_{10} \), showing little difference between wind speeds within the vicinity of these heights. \( \Omega \) is the inverse wave age which is equal to 0.84 for a well-developed sea (driven by wind). \( \kappa_p \) is the wave number of the dominant waves defined as

\[ \kappa_p = \frac{g\Omega^2}{U_{10}^2} \]  \hspace{1cm} (33)

where \( g \) is the gravity. The other three parameters in (32) are defined as

\[ \tilde{c} = \sqrt{g(1 + (\kappa / \kappa_m)^2)} / \kappa, \quad \kappa_m = 370 \]

\[ \Gamma = \begin{cases} 1.7, & 0.83 < \Omega < 1 \\ 1.7 + 6 \log(\Omega), & 1 < \Omega < 5 \end{cases} \]

\[ \gamma = \exp\left( -\frac{1}{2\delta^2} \left( \frac{\kappa}{\kappa_p} - 1 \right)^2 \right), \quad \delta = 0.08(1 + 4\Omega^{-3}) \]  \hspace{1cm} (34)
In [4], $B_i(\kappa)$ is defined as

$$B_i(\kappa) = 0.003 \left[ \frac{\kappa \Omega}{\kappa_p} \right] \exp \left( -\frac{\Omega}{\sqrt{10}} \left( \frac{\kappa}{\kappa_p} \right) - 1 \right) \exp \left( -\frac{5}{4} \left( \frac{\kappa_p}{\kappa} \right)^2 \right) \gamma^T$$

(35)

which is slightly different from the one defined by (32).

The short wave curvature spectrum $B_h(\kappa)$ in the Elfouhaily model is defined as

$$B_h(\kappa) = \frac{c_m \alpha_m}{2c} \exp \left( -\frac{1}{4} \left( \frac{\kappa}{\kappa_m} - 1 \right)^2 \right)$$

(36)

where $c_m = 0.23$ and the parameter $\alpha_m$ is determined by

$$\alpha_m = \begin{cases} 10^2 (1 + \ln(u_f / c_m)), & u_f < c_m \\ 10^2 (1 + 3 \ln(u_f / c_m)), & u_f \geq c_m \end{cases}$$

(37)

where $u_f$ is the friction velocity which can be iteratively computed by

$$u_f = 0.4 U_{10} \left( \ln \left( \frac{10}{b(u_f)} \right) \right)^{-1}, \quad b(u_f) = 0.11 \times 14 \times 10^{-6} u_f^{-1} + \frac{0.48 u_f^{3} \Omega}{g U_{10}}$$

(38)

The initial value may be chosen as $\sqrt{10^{-3}(0.81 + 0.065U_{10}U_{10})}$.

The mean square slopes of the surface in the upwind direction and in the cross-wind direction are then respectively calculated by

$$mss_x = \int_{0-\pi} \kappa^2 \cos^2 \varphi W(\kappa, \phi) \kappa d\varphi d\kappa, \quad mss_y = \int_{0-\pi} \kappa^2 \sin^2 \varphi W(\kappa, \phi) \kappa d\varphi d\kappa$$

(39)

where the wave number cutoff $\kappa_*$ can be calculated according to

$$\kappa_* = \frac{2\pi}{3\lambda}$$

(40)

where $\lambda$ is the wavelength (0.1904m for the GPS L1 signal). In [5] the wave number cutoff is modified as

$$\kappa_* = \frac{2\pi \sin(\theta)}{3\lambda}$$

(41)

where $\theta$ is the incidence angle (complementary to the elevation angle of the satellite). More details about this model can be found in [2, 29, 30].
Sea Surface Scattering

As the GNSS signals arrive at the sea surface some of the signal energy is absorbed by the sea water, while the other energy is reflected. The reflected signals that travel towards the receiver will be captured by the nadir-looking antenna. Let the positions of the transmitter (on the GNSS satellite) and the receiver (on an aircraft, LEO satellite, or land-based) be \((x_t, y_t, z_t)\) and \((x_r, y_r, z_r)\) respectively. Also define the position of the scattering point on the sea surface as \((x_s, y_s, z_s)\). Then the distance from the transmitter through the scattering point to the receiver is given by

\[
d_{tsr}(x_s, y_s, z_s) = \sqrt{(x_t - x_s)^2 + (y_t - y_s)^2 + (z_t - z_s)^2} + \sqrt{(x_r - x_s)^2 + (y_r - y_s)^2 + (z_r - z_s)^2}
\]  (42)

The specular point is the scattering point \((x_{SP}, y_{SP}, z_{SP})\) on the surface where the distance \(d_{tsr}\) is minimal. With respect to the signal reflected at the specular point, the signals reflected at other scattering points arrive at the receiver with a delay given by

\[
\delta\tau = d_{tsr}(x_s, y_s, z_s) / c - \tau_c
\]  (43)

where \(c\) is the speed of light and \(\tau_c = d_{tsr}(x_{SP}, y_{SP}, z_{SP}) / c\). Given the transmitter and receiver positions and the delay \(\delta\tau\), the scattering points define an ellipse on the surface. That is, at each specific delay the signals reflected on the ellipse will arrive at the receiver at the same time, supposing that they travel towards the nadir-looking antenna. Due to the relative movement between the transmitter and the receiver, Doppler frequencies are produced, resulting in the increase or decrease of the signal carrier frequency. Let the velocity vectors of the transmitter and the receiver be \(\vec{V}_t\) and \(\vec{V}_r\) respectively. The Doppler frequency is determined by

\[
f_D = (\vec{V}_t \cdot \vec{m} - \vec{V}_r \cdot \vec{n}) / \lambda
\]  (44)

where \(\vec{m}\) and \(\vec{n}\) are the unit vectors of the incident wave and the reflected wave respectively, and “\(\cdot\)” denotes the vector dot product. For a given Doppler frequency, equation (44) represents a hyperbola. That is, the signals reflected on such a hyperbola will have the same Doppler frequency. The intersection of the iso-delay lines and the iso-Doppler lines forms a network of grids which will be used to determine the power of the reflected signals arriving at the receiver. Figure 32 and Figure 33 show an example of the iso-Doppler map and the iso-delay map, respectively, when the satellite elevation angle is 63°. The three components of the velocity of the aircraft are \(21.166946\text{m/s}\), \(-52.149224\text{m/s}\), and \(-2.527502\text{m/s}\), and the receiver position is \((-33.693117°, 151.2745950°, 508.0884\text{m})\). The satellite position is \((-52.3194°, 162.2910°, 1.9903\times10^7\text{m})\) and the velocity vector is \((-131.75275, -2727.07856, -573.77554)\text{m/s})\).
Reflected Signal Power

The reflected signals received via the nadir-looking antenna are first down-converted to IF signals. The code phase offset and the Doppler frequency associated with the satellite of interest can be estimated based on processing the direct signal received via the zenith-looking antenna through code acquisition and tracking. The carrier frequency of the IF signals is then compensated for and
the resulting baseband signal is correlated with a replica of the PRN code related to a specific satellite. At the central Doppler frequency the cross-correlation with a sequence of code phases produces a delay waveform (correlation power versus code phase). A delay-Doppler waveform is produced when both a sequence of Doppler frequencies and a sequence of code phases are considered.

Theoretically, the signal power with respect to code phase and Doppler frequency can be computed by [2]

\[ Y(\tau, f_D) = \frac{T_i^2 \lambda^2 P \eta}{(4\pi)^2} \sum \frac{G G_{\prime} \sigma_0}{R_t^2 R_{\prime}^2} \Lambda^2(\tau - \tau_{\prime}) \text{sinc}^2((f_D - f_{\prime}) T_i) dA \]  

(45)

where \( T_i \) is the coherent integration time, \( P_i \) is the transmit power, \( \eta \) is the atmospheric attenuation, \( G_i \) and \( G_{\prime} \) are the antenna gains of the transmitting and receiving antennas respectively, \( R_t \) and \( R_{\prime} \) are the distance from the transmitter to the scattering point and the distance from the scattering point to the receiver respectively, \( \Lambda(\tau - \tau_{\prime}) \) is the triangle correlation function of the PRN code with \( \tau \) the delay of the replica code and \( \tau_{\prime} \) the delay of the received code, \( \text{sinc}(\cdot) \) is the sinc function representing the attenuation caused by Doppler misalignment with \( f_D \) the Doppler frequency of the replica signal and \( f_{\prime} \) the Doppler frequency of the received signal, \( A \) is the effective scattering surface area, and the bistatic radar cross section (BRCS) \( \sigma_0 \) can be calculated according to

\[ \sigma_0 = \frac{\pi |\rho|^2}{(\hat{q}_i \hat{q}_z)^4} p\left(\frac{\hat{q}_z}{\hat{q}_i}\right) \]  

(46)

where \( \rho \) is the polarisation-dependent Fresnel reflection coefficient, \( \hat{q} \) is the scattering unit vector that bisects the incident vector and the reflection vector, \( \hat{q}_i \) and \( \hat{q}_z \) are the horizontal and vertical components of \( \hat{q} \) respectively, and \( p(\cdot) \) is the probability density function (PDF) of the surface slope, which may be simply assumed as omni-directional Gaussian distribution. When performing the double integration in equation (45) the size of the effective scattering area should be appropriately selected. As the flight height increases, the scattering area increases accordingly. Nevertheless, it is not necessary to make the area dimensions too large. The contribution of the reflected signals beyond the effective scattering area will be negligible due to the limited antenna beamwidth and the fact that the power is inversely proportional to the squared distance between the GNSS satellite and the scattering point and between the scattering point and the receiver.

Figure 34 shows the decibel delay waveforms based on the theoretical models studied above. Six curves correspond to the six different wind speeds (4, 7, 10, 13, 16, and 19m/s). Four different flight heights were tested: 0.5, 2, 5, and 10km. In the case of 0.5km altitude, the six curves are nearly identical and the spread versus time is rather small. Since the wave forms are insensitive to the wind variation when the flight altitude is less than 0.5km, it would be inappropriate to use the trailing edge to perform any sea state or wind retrieval. As the flight altitude increases, the signal spread increases and the waveforms distinguish from each other better. Thus more accurate parameter estimates would be expected.
Figure 34. Normalised correlation powers in decibel of the simulated reflected signals using the Elfouhaily wave elevation model with four different flight heights and five different wind speeds (4, 7, 10, 13, 16, and 19m/s).

4.2.2 Second Low-Altitude Airborne Experiment

Similar to the first airborne experiment that was reported in the first section of this Annex; this second airborne experiment was carried out by the same UNSW-owned light aircraft flying off the coast of Sydney near Palm Beach on 4 November 2011. Figure 35 shows the experiment site and the flight trajectory of the aircraft. There are two nearby coastal weather observation stations where wind speed is measured and recorded, serving as the wind speed reference. Unlike the first experiment with two payloads, the only payload was the GNSS signal reception and data logging system. In total, about 46 Gigabytes of binary raw IF data of the direct and reflected signals were logged over one and half hours. The maximum flight height was 3.2km and the aircraft flew at this height for about 35min as shown in Figure 36. The aircraft speed, i.e. the receiver platform moving speed, over the duration of the experiment is shown in Figure 37. The speed is basically between 60m/s and 90m/s when the aircraft flew above the sea. The wind speed and gust observed at the North Head Station, which is the closest station to the experiment field are shown in Figure 38. These data were provided by the Bureau of Meteorology and the latest wind speed and gust data over the past three days can be found at the website [30]. The wind direction was basically east southeast (ESE). The data logging started at 15:48:21 and stopped at 17:27:13. From Figure 38 it can be seen that during the data logging the wind speed ranged between 4.95m/s and 5.65m/s, while the wind gust ranged between 6.5m/s and 7.7m/s. The sea surface can be treated as well-developed since the wind had blown the surface continuously for a few hours and the variation of the wind speed was not very large. As a result the corresponding theory can be employed to perform the wind parameter estimation.
Figure 35. Experiment location and aircraft flight track segment. The picture was generated using GPS Visualizer and Google Earth.

Figure 36. Aircraft flight height over the duration of the experiment.
4.2.3 Data Processing

In this subsection a problem with the software receiver is first investigated and some data bits of the original data are corrected. Then the two-dimensional delay waveforms and three-dimensional delay-Doppler waveforms are generated.
Problem with the Software Receiver

It has been observed that there was a problem with the four front-ends of the NordNav software receiver that has been used for the data logging during the experiment. The problem was associated with the encoding of the GPS IF signals. The 2-bit quantisation scheme was used so that the output data bits are within {3, 1, -1, -3}. Also, the distribution of the data bits should basically follow some specific pattern such as the one shown in Figure 39 where the 4-bit 16-level quantisation is used. The envelope of the histogram is approximately symmetric with the bins in the middle having the maximal numbers. However, the original data bits collected via this software receiver had an unexpected bit distribution pattern as shown in Figure 40. Clearly, the encoding of the two data bits {-1} and {-3} must have been swapped in the receiver. Such a 2-bit quantisation encoding scheme is actually equivalent to a 1.5-bit quantisation scheme. As a result, certain performance degradation would be incurred although the degradation may be minor in some cases. Figure 41 shows the corresponding results of Figure 40 after the {-1} bits are swapped with the {-3} bits.

![Time domain plot and Histogram](image.png)

Figure 39. An example of IF data bits statistics when using 4-bit quantisation.
To evaluate the impact of the wrong encoding process in the receiver, the delay waveforms of the reflected signal associated with one specific GPS satellite (PRN#8) were used as shown in Figures 42 and 43. When the correlation powers were normalised so that the maximal correlation power is zero dB as seen in Figure 43, it can be clearly observed that the performance improved after swapping the {-1} bits with the {-3} bits. The noise floor in this case was reduced by about 0.8 dB,
approximately 7% of the maximal signal power. From such a decrease in the noise floor, it may be predicted that the decrease in the noise floor or the increase in the signal-to-noise ratio would be more significant when a higher-level quantisation, such as the 3-bit or 4-bit quantisation is used. As a consequence a performance gain would be achieved. Further investigation would be needed if one wants to determine the accurate relationship between the quantisation level and the performance. Also, it can be seen from Figure 43 that the two delay waveforms are nearly identical when the signal power is above -8 dB. That is, in the case where only the waveform with a power greater than -8 dB is used, the swapping of the {-1} bits and {-3} bits will actually not produce any impact on the sea state and wind parameter estimation provided that only the waveform shape is employed. On the other hand, when the whole waveform shape or correlation power is exploited for the parameter estimation, the effect might not be negligible. In the remainder of this report, the results were produced after the original collected data were corrected by swapping the {-1} bits with the {-3} bits.

![Figure 42. Example of impact of swapping the {-1} and {-3} bits of the IF signals.](image)
Figure 43. Example of impact of swapping the {-1} and {-3} bits of the IF signals when the correlation powers are normalised.

Delay Waveform and Delay-Doppler Waveform

Via the zenith-looking antenna, the receiver received the signals transmitted from 12 GPS satellites when the aircraft was above the sea. Figures 44 and 45 show the delay-Doppler waveforms and the delay waveforms of the direct signals associated with four satellites (PRN#10, PRN#19, PRN#28 and PRN#3), respectively. As expected the delay-Doppler waveforms are symmetric with respect to both the Doppler frequency and the code phase. Also, in the delay waveforms the leading edge and the trailing edge are symmetric with respect to the code phase at the peak of the correlation power when the power is above the noise floor. The coherent integration time is set at 1 millisecond and the non-coherent integration time is equal to 0.5 seconds. That is, the results are produced by averaging 500 waveforms of 1 millisecond. From the delay waveforms it can be seen that the peak powers of the reflected signals can be significantly different from each other. Many factors will affect the reflected signals power, including the configuration of the specific satellite and the receiver and the transmitted signal power, in addition to the surface roughness and the receiving antenna gain. Further it is observed that over the period of 0.5 seconds the code phase of the signals can vary significantly up to by 16 samples equivalent to one code chip. Thus, when performing the non-coherent integration, the phase variation must be taken into account. Variation in the Doppler frequency is also observed but it is negligible over a period of a few seconds.

The nadir-looking antenna captured the reflected signals associated with ten satellites. Figures 46 and 47 show the delay-Doppler waveforms of the reflected signals associated with eight GPS satellites (PRN#13, PRN#7, PRN#8, PRN#23, PRN#10, PRN#19, PRN#28, and PRN #3). Reflected signals associated with the other two satellites (PRN#5 and PRN#6) were also captured via the nadir-looking antenna. However, the related results are not presented since they are too noisy and distorted due to the rather small elevation angles and the limited antenna beamwidth. It may be
difficult to obtain useful information from such noisy and distorted waveforms. The elevation angles and azimuth angles of the eight satellites are shown in Table 8, which were used in the generation of the theoretical waveforms.

Table 8. Elevation angles of the eight GPS satellites.

<table>
<thead>
<tr>
<th>Satellite Number</th>
<th>13</th>
<th>7</th>
<th>8</th>
<th>23</th>
<th>10</th>
<th>19</th>
<th>28</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation Angle</td>
<td>65.42</td>
<td>60.51</td>
<td>44.89</td>
<td>35.94</td>
<td>35.35</td>
<td>34.78</td>
<td>26.30</td>
<td>23.55</td>
</tr>
<tr>
<td>Azimuth Angle</td>
<td>54.62</td>
<td>186.46</td>
<td>233.02</td>
<td>43.03</td>
<td>284.17</td>
<td>90.35</td>
<td>313.09</td>
<td>126.46</td>
</tr>
</tbody>
</table>

Through comparing the results in Figures 46 and 47 with the results in Figure 44, it can be seen that the delay-Doppler waveforms of the reflected signals are not symmetric with respect to a specific code phase that corresponds to the maximal power. Instead, on the top of the delay-Doppler waveforms the signals are spread over two or more code chips, resulting from the roughness of the sea surface. The spreading of the signals over time can be more clearly observed from the delay waveforms as shown in Figures 48 and 49. Further, Figure 50 shows the delay waveforms of the direct and reflected signals associated with satellite PRN#19. It can be seen that both the leading edge and the trailing edge of the reflected signal are affected by the sea surface roughness. In this case the impact on the trailing edge is much more significant. It is this factor that allows the sea surface wind information to be retrieved as described in the next subsection.

Figure 44. Delay-Doppler waveforms of direct signals associated with four GPS satellites.
Figure 45. Delay waveforms of direct signals associated with four GPS satellites.

Figure 46. Delay-Doppler waveforms of reflected signals associated with four GPS satellites.
Figure 47. Delay-Doppler waveforms of reflected signals associated with four GPS satellites.

Figure 48. Delay waveforms of reflected signals associated with four GPS satellites.
4.2.4 Near Sea Surface Wind Speed Retrieval

The wind speed estimation is based on the model fitting method using the model derived in [2]. Figure 51 shows the five theoretical delay waveforms corresponding to five different wind speeds (3, 4, 5, 6, and 7 m/s) and the measured delay waveform associated with satellite PRN#13 which has the largest elevation angle. The measured waveform is produced through coherent integration of 1 millisecond IF signals and then non-coherent integration of 1000 such 1 millisecond waveforms. It can be seen that the measured waveform has a good match with the theoretical waveform of wind
speed 4m/s, producing the wind speed estimate of 4m/s, which is a good estimate of the real wind speed.

![Figure 51. Wind speed estimation through matching the waveforms.](image)

This is just an illustrative example to show how the wind speed is estimated. In practice, a mathematical approach will be employed to automatically produce estimation solutions. Regarding this model-matching approach, a certain number of theoretical waveforms are produced and a cost function is defined. The theoretical waveform with the minimal cost function is then selected and the corresponding wind speed is the estimate of the real wind speed. The cost function can be defined as the sum of the squared difference between the theoretical and measured waveforms. However, this method requires the alignment of the two waveforms so that the difference between the two waveforms is minimised. Alternatively, a slope-based method proposed in [2] can be employed. However, as observed in Figure 51, it is rather difficult to distinguish the slopes of neighbouring curves related to different wind speeds. Here a multi-step procedure is proposed to perform the waveform fitting to estimate the wind speed:

1) interpolating both the measured and theoretical waveforms without changing the original data
2) selecting the cut-off correlation power to retain the waveform above certain power lever so that the slope of the trailing edge does not change abruptly
3) calculating the areas of the interpolated waveforms above the cut-off power and calculating the area difference between the measured waveform and each of the theoretical waveforms
4) selecting the theoretical waveform that produces the minimum area difference and taking the corresponding wind speed as the estimate. Note that when using Matlab the library function ‘INTERP’ can be directly used to perform the interpolation.

Figure 52 shows the individual wind speed estimates using signals related to the eight satellites. The data were collected at Point A and one second of the data were processed to generate the results. The horizontal axis corresponds to the eight satellites and the first satellite (PRN#13) has the largest elevation angle, while the eighth satellite (PRN#3) has the smallest one. The average of the eight
wind speed estimates is 4.04 m/s, which is close to the wind speed at the Norah Head Observation Station. It is difficult to see the relationship between the estimation performance and the elevation angles from such a small number of samples. Many more samples are needed to obtain useful observations.

Figure 52. Wind speed estimates using signals transmitted at eight satellites.

In the above four-step waveform matching method, the matching rule is based on the difference between the area size of the measured waveform and that of the theoretical waveforms associated with different wind speeds. The theoretical waveform producing the minimal area size difference is selected and the corresponding wind speed is chosen to be the wind speed estimate. An alternative method is based on the least-squares fitting method. Specifically, as shown in Figure 53, both the measured and theoretical waveforms are normalised to have the same peak value, and they are truncated to keep their minimum value above a threshold which can be selected based on the shape of the measured waveform. The theoretical waveform is aligned with the measured waveform so that they have the best match in the sense of least-squares fitting. That is, the error function

\[ Er = \sum_{i=1}^{L} (f_i^{(th)} - f_i^{(m)})^2 \]  

(47)

is minimised through adjusting the relative positions of the two waveforms. Here, \( f_i^{(th)} \) and \( f_i^{(m)} \) are the theoretical and measured waveform values, respectively. There are \( L \) time points between the first and last samples of the two waveforms. In the interval between the two first samples and that between the last two samples of the two truncated waveforms, one of the two waveforms does not have specified values due to truncation. In these cases they are assigned the minimum value, i.e. the threshold value, of the power level. For instance, the dashed, instead of the dotted, theoretical waveform has a best match with the measured one. Thus, for each theoretical waveform associated with a wind speed, there is an error function value which is the minimum, referred to as the residual for convenience. Among all the theoretical waveforms corresponding to a range of wind speeds, the theoretical waveforms with the smallest residual is selected and the corresponding theoretical wind speed is the estimate of wind speed at the experiment site.
Using the data associated with a specific satellite, a sequence of wind speed estimates over time can be produced. The data collected when the aircraft flew from Point A to Point B in Figure 35 were employed. During this period of 100 seconds there were eight satellites whose elevation angles were greater than 20 degrees. A wind speed estimate is produced using data collected over duration of 1 second, so that a sequence of 100 wind speed estimates is produced with respect to each satellite. Figures 54 and 55 show the estimation results associated with the eight satellites. For comparison, the wind speeds measured by the two closest coastal observation stations (Norah Head and North Head) were also plotted.

Figure 54. Sequences of wind speed estimates associated with satellites PRN 3, 7, 8, and 10. Dashed line and dotted line are for the wind speeds at Norah Head Station and North Head Station respectively.
As mentioned earlier, since the experiment was conducted near two coastal weather observation stations an accurate independent estimate of the wind speed can be used as a reference. Suppose that the wind speed varied from 4.2 m/s at Norah Head Station to 4.7 m/s at North Head Station at a constant rate. Then, the true surface wind speed between Points A and B on the flight route can be approximated as 4.33 m/s. Thus the wind speed estimation errors can be determined. First, each sequence of estimation errors was dealt with independently and the corresponding error statistics were determined. Then the error characteristics were determined using all the estimation errors associated with all the eight satellites.

Figures 56 and 57 show the sequences of wind speed estimation errors associated with the eight satellites. The estimation results are consistent over the duration of 100 seconds. The mean, standard deviation (STD) and root mean square (RMS) of the estimation errors are listed in Table 9. In particular, the RMS error ranges between 0.3 m/s and 0.94 m/s, better than 1 m/s. Except for the relatively large error variation associated with satellite PRN#3 which has the smallest elevation angle; it is difficult to set up a relationship between the error statistics and the elevation angles. Further investigations are needed to investigate how the error statistics are related to some other specific parameters.
Figure 56. Wind speed estimation errors related to satellites PRN# 3, 7, 8, and 10.

Figure 57. Wind speed estimation errors related to satellites PRN# 13, 19, 23, and 28.

<table>
<thead>
<tr>
<th>PRN#</th>
<th>13</th>
<th>7</th>
<th>8</th>
<th>23</th>
<th>10</th>
<th>19</th>
<th>28</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eleva (deg)</td>
<td>65.4</td>
<td>60.5</td>
<td>44.9</td>
<td>35.9</td>
<td>35.4</td>
<td>34.8</td>
<td>26.3</td>
<td>23.6</td>
</tr>
<tr>
<td>Mean (m/s)</td>
<td>-0.22</td>
<td>0.70</td>
<td>-0.69</td>
<td>0.84</td>
<td>-0.26</td>
<td>-0.30</td>
<td>-0.15</td>
<td>0.56</td>
</tr>
<tr>
<td>STD(m/s)</td>
<td>0.19</td>
<td>0.23</td>
<td>0.13</td>
<td>0.25</td>
<td>0.23</td>
<td>0.21</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>RMS(m/s)</td>
<td>0.29</td>
<td>0.73</td>
<td>0.70</td>
<td>0.86</td>
<td>0.35</td>
<td>0.36</td>
<td>0.24</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Figure 58 shows the average of wind speed estimates associated with eight satellites when sixteen different wind directions are assumed. One observation is that although the mean wind speed estimate varies with the assumed direction, the variation is limited between 4.25m/s and 4.78m/s. Figure 59 shows the STD of the wind speed estimation versus the assumed wind directions. The STD ranges from 0.52m/s to 0.9m/s. The true wind speed is about 110 deg, so this STD plot provides some useful information about the wind direction. That is, the wind direction with the smallest STDs may be treated as the actual wind direction. However, there exists an ambiguity of 180 deg.
4.2.5 Summary

This section reported on the second airborne experiment conducted by the UNSW-owned light aircraft. A problem of wrongly encoding the two bits {-1} and {-3} in the NordNav software receiver was investigated. This encoding error would decrease the signal-to-noise ratio to some degree. This fact also tells us that a higher-level quantisation scheme may be needed in order to achieve a better estimation performance. Through the generation of the delay waveforms and delay-Doppler waveforms it was observed that the reflected signals of up to ten GPS satellites can be received via the nadir-looking antenna. The reflected signals of eight GPS satellites can be employed to reliably estimate the near sea surface wind speed. The wind speed estimation was performed by comparing the measured delay waveform and the theoretical waveforms. The theoretical waveform with the best match was selected and the corresponding wind speed was chosen to be as the estimate of the real wind speed. The results demonstrated that using the model-matching approach accurate wind speed estimation can be achieved with an estimation error of around 1m/s.

Figure 59. Wind speed estimation STD versus assumed wind direction.
4.3 Third Airborne Experiment and Forest Abnormal Condition Detection

In the first section of this Annex the authors investigated GNSS-based sea surface height estimation; some of the results were presented in 2012 ISPRS [13], 2012 GNSS Reflectometry Workshop [14], and in a journal paper [32]. In the second section of this Annex and [11, 12] the authors investigated GNSS-based sea state estimation with a focus on sea surface wind speed estimation. In addition to sea state estimation and sea level altimetry, GNSS signals can be utilised for other Earth observation applications including land surface classification, land deforestation, and soil moisture measurement. This section focuses on forest abnormal condition detection, while the next section will discuss soil moisture parameter retrieval.

In the literature there are a significant number of reports on soil moisture measurement and forest emission modelling which are often jointly investigated [33-40]. This is due to the fact that soil moisture measurement is affected by forest emission, while modelling forest emission needs to, in general, take soil moisture content into account. A large part of the relevant literature is associated with the ESA SMOS (soil moisture and ocean salinity) mission. A PhD thesis written by Rahmoun [41] is a good reference covering many topics related to soil moisture measurement and forest emission modelling.

Surface/terrain classification is one of the applications of GNSS reflectometry. In [42] GPS reflected signals are used for terrain classification. The moisture-sensitive GPS reflected signal allows clear distinguishing of water bodies from heavy vegetation (forests) and light vegetation (cultivated fields). A similar outcome was observed in [43]. That is, as the specular point crosses a river within a forest, the power of the reflected signal increases dramatically. In [44] GPS reflected signal strength is used to derive terrain/landcover features. By combining with visible wavelength imagery the terrain classification accuracy can be improved significantly regardless of the soil moisture level, or of the amount of precipitation received prior to data acquisition.

This section reports on the third airborne bistatic experiment conducted on the 19th of September, 2012. Unlike the previous two airborne experiments, this experiment was intended to collect data by flying the aircraft over land areas with different surface characteristics. In particular, the data may be exploited to infer land surface characteristics especially information about forest conditions and deforestation. At this stage, only limited preliminary results have been produced. However, the results demonstrate that the reflected GNSS signal power can be reliably to identify the change of surface/terrain characteristics in a forest.
4.3.1 Third Low-Altitude Airborne Experiment

As mentioned earlier, the third airborne experiment was designed to collect both direct and reflected GNSS signals by flying the aircraft over land areas. Unlike the first two airborne experiments which were designed and conducted for sea state estimation, this experiment was intended to investigate the monitoring of land deforestation and the measurement of soil moisture.

A team of four people participated in the experiment. Professor Jason Middleton was the pilot, flying the aircraft along the designed flight route. The flight route was selected by Jason and Kegen after a number of discussions. Mr. Greg Nippard was the engineer, assembling and disassembling the equipment. Dr. Bo Yang was the operator, flying with the pilot and operating the laptop to log data. The fourth person was Dr Kegen Yu, the coordinator of the experiment.

The aircraft and the equipment (GNSS software receiver, LHCP antenna, RHCP antenna, and low noise amplifier) used for this experiment were the same as those used in the previous two experiments. In addition, an extra small rugged sports camera (GoPro hero2) as shown in Figure 60 was also used to take photographs of the ground surfaces. Although Google Earth pictures can be used to determine land surface characteristics, those images may have been taken several years ago so that the current surface characteristics may be significantly different from the Google Earth images. For instance, during the interval of several years, a significant part of a forest may be cut down for timber. In this case the photographs from the camera would provide more accurate information. The viewing angle of the camera was around 90 degree so that the width or length of each photograph would be twice the flight height. The photographs were taken at a frequency of 0.2 Hz, i.e., one photograph every five seconds. This frequency was selected with consideration of the flight height and the aircraft speed. Figure 61 through Figure 64 show four representative photographs of the ground surfaces (grassland, forest, lake, and residential area) taken by the camera. The camera images and those provided by Google Earth can be jointly used to provide some basic information about the surface conditions when analysing the characteristics of specific ground surfaces using the logged data of the direct and reflected GNSS signals.

The reflectivity of normal land surfaces such as grasslands and forests is much less than that of sea/lake water. The LHCP antenna which is used for receiving the reflected signals during the experiment is a passive antenna and has a relative large beamwidth, i.e. 114 degree. Also, the aircraft is typically not allowed to fly high in the Sydney basin. Thus, the flight height was selected to be around 400m above the ground topography.
Figure 60. A typical camera used for taking pictures of ground surfaces.

Figure 61. Representative image of a grassland taken by the camera.
Figure 62. Representative image of a forest taken by the camera.

Figure 63. Representative image of a land taken by the camera.
Figure 64. Representative image of residential area taken by the camera.

The experiment was conducted on the 19th of September, 2012. Based on the latest weather forecast and the actual weather conditions, it was decided to start the flight late morning. The aircraft took off at 11:00am from Bankstown Airport, west of Sydney, and it returned to the same airport at 12:38pm. During the flight, the weather was sunny and there were a few clouds. The wind had a speed of around 6 knots.

Figure 65 shows the aircraft altitude (WGS84 system) during the flight. The altitude measurements were determined by the NordNav receiver which has an estimated accuracy of about three metres. Such accuracy might not be sufficient for precise positioning; however, it is not a serious issue when the received signal power and the correlation waveform (either delay waveform or delay-Doppler waveform) are the main focus. The flight altitude varied from time to time and it was greater than 400m most of the time. It can be seen that over the whole flight duration there are three breaks in the flight altitude curve. During these three short periods of time, no data were logged on the laptop via the receiver because some unexpected errors occurred.
Figure 65. Actual aircraft altitude during the experiment.

Figure 66 shows the flight route and the surrounding ground surfaces with the images provided by Google Earth. The flight route was clamped to the ground instead of floating in the air for clarity. It can be seen that the flight route is on the southwest of Sydney and northwest of Wollongong. The aircraft flew over a range of different surfaces including forests, residential areas, grasslands, and lakes/reservoirs. The ground surface elevations are shown in the upper plot of Figure 67. These elevations are produced by Google Earth using the latitudes and longitudes of the aircraft positions along the route. They were produced by dividing the Earth’s surface into grids which have dimensions of 90m by 90m; and each grid was assigned one elevation value. Clearly, over each grid of surface area, the elevation of one surface point can be significantly different from that of another point, depending on the surface topography. Thus, these ground elevations can only be used as an approximate reference. Nevertheless, it can be seen that the surface elevations in this region varies dramatically with the elevation difference up to around 800 metres. The lower plot of Figure 67 shows the flight height relative to the ground surface. The relative flight height was between 200m and 600m most of the time.
Figure 66. Aircraft flight route during the experiment. The picture was generated using GPS Visualizer and Google Earth.

Figure 67. Ground elevation and aircraft flight height relative to ground surface.
4.3.2 Data Processing and Preliminary Results

The logged digital IF samples of the direct and reflected GPS signals were processed to generate delay waveforms (correlation power versus code delay). The coherent integration time for correlating the complex IF signal (in-phase and quadrature components) is 1 millisecond and the non-coherent integration time for the accumulation of the signal power is 0.5 second. Due to the computational complexity, only two data segments were processed, which are associated with flight track segment AB and segment CD as shown in Figure 66. The lengths of track AB and track CD are 11.41km and 12.94km, respectively. The flight duration over each of the two tracks is 3 minutes. Table 10 shows the elevation angles and azimuth angles of four satellites over the two time periods. Satellite 31 has the largest elevation angle and all the results presented in this report are associated with this satellite.

Table 10. Elevation and azimuth angles of four satellites.

<table>
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<tr>
<th>Satellite</th>
<th>Track AB</th>
<th>Track CD</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Elev (deg)</td>
<td>Az (deg)</td>
</tr>
<tr>
<td>31</td>
<td>66.7~67.3</td>
<td>56.7~67.3</td>
</tr>
<tr>
<td>1</td>
<td>49.2~50.0</td>
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</tr>
<tr>
<td>11</td>
<td>45.4~45.2</td>
<td>276.7~278.8</td>
</tr>
</tbody>
</table>

Received Signal Power

One important parameter of the received GPS signals is the correlation peak power which would be related to ground surface reflectivity. Figure 68 shows the correlation peak power of the direct signal captured when flying the aircraft on the track AB, while Figure 69 shows the peak power of the direct signal received when the aircraft flew from Point C to Point D. The variation of the received direct signal power is within a few decibels. The variation would mainly come from the aircraft movement and thus the orientation of the antenna. It is also likely that the transmitted signal power is not exactly constant and that the power loss due to the atmosphere would also be different from time to time.

The variation of the direct signal peak power can be used to normalise the peak power of the reflected signal. That is, the peak power of the reflected signal is divided by the peak power of the direct signal at the same time instant. Of course, the division becomes a subtraction when the power unit is decibel. Note that the direct signal peak power is normalised so that their maximum value is unity. Such reflected signal power normalisation is valid and necessary under the assumption that similar variation would occur to both the direct signal and the reflected signal. By removing the impact of these unrelated factors, the peak power variation of the reflected signal would be mostly related to the ground surface characteristics. However, the direct signal may be corrupted by multipath interference, so it may not be appropriate to do the normalisation without removing the multipath interference. One basic technique to reduce multipath effect is smoothing the measured
direct signal. There are many different smoothing techniques such as the moving average and polynomial smoothing. When using moving average, the length of moving window should be long enough. In the case of polynomial smoothing, third-order polynomial may be used. Here, the reflected signals power is not normalised in this report. Further investigation on such normalisation is required.

Figure 68. Correlation peak power of the direct GPS signal associated with satellite PRN#31. The corresponding flight track segment (AB) is shown in Figure 66.

Figure 69. Correlation peak power of the direct GPS signal associated with satellite PRN#31. The corresponding flight track segment (CD) is shown in Figure 66.
Figure 70 shows the peak power of the reflected signal when the aircraft flew on route AB. For clarity, Figure 71 shows the enlarged picture of the area around ground flight track segment AB. The corresponding specular reflection track of the signal is shown, which is also colourised according to the peak power values of the reflected signal. In the colourised track, the minimum value of the peak power is drawn in red and the maximum is drawn in magenta/violet. The medium values are drawn in yellow, green, and blue, as the peak power value increases. For better clarity, a colour bar is added on to the Google Earth picture. Also, it is worth noting that the reflect track is usually different from the flight ground track, although they are very close to each other due to the low flight height and that the satellites with the largest elevation angles are considered.

Basically, along the track AB, there are three surfaces which have low radio reflectivity, while the other three surfaces have much higher reflectivity. It can be seen that the first high reflectivity surface is in an area (roughly rectangular) where the trees were almost completely removed. The second high reflectivity surface corresponds to an area where there are only a few isolated trees and a large part of the area is barren. The third high-reflectivity surface is the water surface of Lake Burragorang. The three low reflectivity surfaces are covered by forests. Therefore, the peak power variation of the reflected signal can be used to monitor the conditions of a forest. It can be seen that the peak power values related to the first low reflectivity forest surface is higher than those of the other two low reflectivity forest surfaces. Such a difference may be related to the forest density, the flight height, or the surface topography. It is useful to do more investigation to determine the reason for this.

![Figure 70. Correlation peak power of the reflected GPS signal associated with satellite PRN#31. The corresponding flight track segment (AB) is shown in Figure 66.](image-url)
Figure 71. Ground reflection track associated with flight track AB and related ground surfaces. The picture was generated using GPS Visualizer and Google Earth.

Figure 72 shows the peak power values of the reflected signal associated with the track CD, while Figure 73 shows the colourised track (according to the peak values) and the surrounding surfaces. Clearly, the peak power variation is not as dramatic as that in Figure 70. However, if the forest surfaces are treated as normal surface while all other surfaces are considered as outliers, then a number of outliers can be identified from the peak power distribution. For instance, if an outlier is defined as any surface whose maximum peak power value is greater than 2dB, then there are six such outliers. Starting from Point C, the first outlier is actually a long and narrow corridor which separates the forest into two areas. The second outlier and the third one are very close to each other so that they may be considered as one outlier. This surface is on the edge of a small town and is covered by trees and fields. The fourth outlier is also a field surface which is connected to the third one on one side but separated by part of a forest along the track. The fifth outlier is a narrow corridor which separates two forests and where there are no trees but some grass. The final outlier is the fields next to the forest. If the power threshold is set to be 1dB, then a few more extra outliers can be identified to provide more information about the surface conditions. That is, the peak power values are a good indicator of the change of surface characteristics and abnormality in a forest.
Figure 72. Correlation peak power (normalised by direct signal peak power) of the reflected GPS signal associated with satellite PRN#31. The corresponding flight track segment (CD) is shown in Figure 66.

Figure 73. Ground reflection track associated with flight track AB and related ground surfaces. The picture was generated using GPS Visualizer and Google Earth.
As observed, the variation of the reflected signal peak power can be utilised to identify the change of the surface characteristics and abnormal areas in a forest. However, it may still be a challenging problem to identify the specific types of the ground surfaces simply based on the signal peak power. To achieve the goal, accurate signal models are required to describe the reflected signal power when the signal is reflected over different surfaces. The modelling is complicated even for one type of surface such as forests. For instance, the reflectivity of a forest depends on the type, the density, and the age of the trees. In the literature the radio reflectivity of a range of surfaces/materials is known with respect to some signal frequencies. However, more work is required to investigate modelling of the power of radio signal reflected by forests.

Now let us have a look at some segments of interest on track AB. Basically, along the track AB there are three main surfaces which have low radio reflectivity, while the other three surfaces have much higher reflectivity. It can be seen that the first high reflectivity surface is in an area (roughly rectangular) where the trees were almost completely removed. The second high reflectivity surface corresponds to an area where there are only a few isolated trees and a large part of the area is barren. The third high-reflectivity surface is the water surface of Lake Burragorang. The three low-reflectivity surfaces are covered by forests. Figure 74 shows the enlarged three areas which have the highest reflectivity along track AB. When setting one power level threshold at 3dB, it can be seen from the figures that the abnormal conditions in the forest are clearly identified. Figure 75 shows the specular reflection tracks related to four satellites (PRN#1, PRN#11, PRN#31, and PRN#32). Compared to the signal reflection track shown in Figure 71, multiple reflection tracks provides more information about the ground surface characteristics.
Figure 74. Enlarged three reflection track segments associated with three flight ground track segments on track AB. The picture was generated using GPS Visualizer and Google Earth.
Figure 75. Ground reflection tracks associated with four GPS satellites. The picture was generated using GPS Visualizer and Google Earth.

### 4.3.3 Summary

In this section some details of the third airborne bistatic experiment conducted in September 2012 are presented. Unlike the previous two airborne experiments, this experiment was carried out by flying the aircraft over the inland areas instead of over the ocean surface. It was intended to make use of GNSS signals for applications including deforestation monitoring and soil moisture measurement. Data collected over two 3-minute periods and associated with one specific satellite were processed. The results demonstrated that the change of surface characteristics can be reliably detected by using the reflected signal peak power. Thus, it is feasible to monitor land deforestation based on GNSS reflectometry.

In the future it would be interesting to process more of the logged data and investigate on the use of the delay waveform as another possible measure for surface change detection and land deforestation. Also, it would be useful to investigate feasibility of using GNSS-R to monitor the long-term slow change in forests.
4.4 Fourth Airborne Experiment for Soil Moisture Estimation

The main theme of the Garada project is the development of a spaceborne SAR and investigation of SAR formation flying to enhance earth observation performance. The key target application of this spaceborne SAR is the global monitoring of land soil moisture which is the key factor associated with a range of phenomena and natural processes on the globe. Thus, this reflectometry focus also needs to address the major application of the project. In particular, it is envisaged that the measurements from a “GNSS reflectometer” can be combined both SAR measurements to improve geophysical parameter estimation. In this section an overview of GNSS-based soil moisture estimation is first presented. Then, the focus is on the design and conduct of the fourth airborne experiment. The purpose of the experiment is to collected GNSS data over land areas to investigate soil moisture estimation using GNSS signals. Finally, preliminary results from processing the collected data are presented. The results demonstrate that the variation pattern of the signal-to-noise ratio (SNR) of the reflected GNSS signal has good match with that of the ground surface/field change. Ongoing work will focus on process more of the collected data to realise soil moisture estimation.

4.4.1 Overview of GNSS-Based Soil Moisture Estimation

When using low frequencies (less than 3GHz) microwave radiometry is an effective technique for remotely sensing soil moisture [45]. To achieve a good resolution, a large antenna is required when such a low frequency is used. In the case of spaceborne microwave remote sensing, a retractable/expandable antenna is required [46]. GNSS reflectometry is an alternative technique for soil moisture measurement. This is because the GNSS L-band frequencies (such as 1.5GHz) are among the frequencies which have the highest sensitivity to soil moisture. That is, GNSS signals can be used to effectively perform soil moisture measurement. Using GPS signals for soil moisture measurement was originally investigated by a number of researchers [47, 48]. In these initial investigations the basic observation was that the reflected signal power varies as surface soil moisture changes.

The soil moisture experiment 2002 (SMEX02) is the first experiment in which both GPS reflected signals from land and in-situ data were collected throughout the state of Iowa, USA in June-July 2002. There were 32 data sampling sites: 21 corn fields, 10 soybean fields, and one grass field. Many scientists and engineers from various agencies and institutes participated in the experiment. One of the main objectives of the experiment was the development and verification of soil moisture retrieval algorithms in challenging vegetation conditions and the evaluation of new instrument technologies, including the GNSS reflectometer, for soil moisture remote sensing. The U.S. National Snow and Ice Data Center (NSIDC) web site provides the complete data acquired during the SMEX02 [49]. The SMEX02 data have been used by researchers to investigate soil moisture retrieval based on GNSS reflectometry. In [50] calibration of the reflected GPS signals was investigated for soil reflection and dielectric constant estimation. When using an aircraft platform, the zenith-looking antenna is typically mounted on the top of an aircraft and the antenna face is nearly on the same level of the top surface of the aircraft in general. That is, it is inevitable that the received direct GPS signals would be affected by the multipath propagation. Although a third–order polynomial fitting was then used to reduce the multipath effect, further investigation may be needed to find out if there are techniques that perform better. Reflectivity calibration was also performed by flying the
aircraft over water (assuming smooth lake surface). The obtained water reflectivity was scaled to the value of 63 percent so that the soil reflectivity can be readily determined based on the measured power of the reflected signal over soil surfaces.

There are a range of models proposed to simulate the emission characteristics of a rough surface including the geometric optics model, optical physical model, small disturbance model, integration model, and advanced integration model [51-53]. That is, the forward scattering coefficient can be calculated when the input parameters are given, which include the surface roughness and the signal incidence angle. As shown in [54], the simulated forward scattering coefficient varies significantly with both the incidence angle and the surface roughness. When giving a specific incidence angle and surface roughness, a linear relationship between forward scattering coefficient and soil moisture can be established. Such a linear relationship is also applicable to the measurements from the SMEX02 mission when individual sites/fields were covered with specific vegetation. The fitness between the measurements and the model can be tested by calculating the correlation coefficient. A good fitness corresponds to a correlation coefficient which is close to unity. The forward scattering coefficient and the soil moisture in a number of different sites with different crops can also be modelled as linear; however, the fitness is rather poor since the correlation coefficient is quite small such as less than 0.7.

A number of research groups at different institutes conducted ground-based experiments for investigating soil moisture estimation using a GNSS reflectometer. Although the soil moisture variation can be found through observing the changes in the reflected signal power or SNR during a certain period of time, it is a challenge to precisely estimate the soil moisture content due to the diversity of the surface roughness and vegetation variation. In [55] the Interference Pattern Technique (IPT) method was developed to estimate soil moisture in bare soil fields. This ground-based method uses a single vertically-polarised antenna to capture both the direct and reflected GNSS signals at the same time. The interference power of the two signals is continuously measured for a few hours over which the elevation angle of a specific satellite varies by tens of degrees. At one specific elevation angle, the measured power is minimal and this power notch position corresponds to the Brewster’s angle at which the signal refraction is the maximum. There is a unique relationship between the notch position and the soil moisture content, and the notch position is independent of the surface roughness. Thus, the notch position can be used to reliably retrieve the soil moisture. In [56] this IPT approach is used to estimate topography, soil moisture, and vegetation height in vegetation-covered soils. Unlike bare soil fields, there are multiple notches in the measured power time series. The number of notches is related to the vegetation height which can thus be estimated. To make a ground-truth soil moisture map over a large area, a large number of such receivers/systems are needed. Also, this is a ground-based method and significant modifications might be required to adopt it for a space platform. Further, as pointed out by Gleason [57] in the case of a space platform, the measurement resolution is a significant issue and the very large glistening zones of Earth-reflected GPS signals needs to be narrowed into usable measurement cells.

In the literature the random surface roughness is typically assumed and its effect is then investigated. In [58] the authors investigated how tillage orientation affects soil surface emissivity. Experiments were conducted over a period of one week using both an L-band radiometer and a GNSS reflectometer which were mounted on a tower of about 5.5m in height. Three bare fields with different tillage were examined: (1) no tillage; (2) transverse tillage; and (3) longitudinal tillage. It was observed that in the case of no tillage both H- and V-polarisation were less sensitive to variation of soil moisture than in the case of tillage. H-polarisation is more sensitive to changes in soil
moisture and roughness than V-polarisation. In addition, H-polarisation is less sensitive to soil moisture when the antenna scan is perpendicular to the tillage direction, whereas V-polarisation is slightly more sensitive when the antenna scan is perpendicular to the tillage direction. Such a phenomenon needs more investigation, especially because variation of the tested soil moisture is only about 0.1 m$^3$/m$^3$.

Interestingly, in [59] and [60] the authors intended to make use of the GPS receivers installed primarily for geophysical and geodetic applications to estimate near surface soil moisture. In the United States alone, there are thousands of such GPS receivers. This is a useful resource, and if it is exploited effectively, these receivers may provide a global network for soil moisture monitoring. The antennas of these GPS receivers are zenith-looking. However, the reflected signals at low elevation angles can also be captured by these antennas. This is because of the antenna gain patterns of these receivers; there is a sizable gain at negative elevation angles. In [61, 62] carrier phase is employed for soil moisture retrieval.

### 4.4.2 Airborne Experiment Design

Based on our experience of conducting three airborne experiments (two in 2011 and one in 2012) and the experiments reported in the literature, a new airborne experiment design is proposed in this section.

**SMAP and SMAPEx**

Soil Moisture Active Passive (SMAP) is a mission recommended by the U.S. National Research Council Committee on Earth Science and Applications from Space in 2007 [63]. A radiometer and a synthetic aperture radar (SAR) are the main SMAP instruments to measure surface emission and backscatter to sense soil conditions. SMAP has successfully completed its Critical Design Review. System Integration Review is scheduled in April 2013 and System Integration and Test is scheduled to begin in May 2013. It is currently scheduled to launch SMAP satellites in October 2014. SMAP will provide measurements of soil moisture and its freeze/thaw state globally, which have both high science value and high application value. SMAP has a range of application areas, including weather and climate forecasting, drought, floods and landslides, agricultural productivity, and human health. There are reasons for mentioning the SMAP mission. The first is simply to emphasise the importance of making soil moisture measurements; while the second is that the proposed experiment is indirectly connected to the SMAP mission.

The Soil Moisture Active Passive Experiments (SMAPEx) are the pre-launch SMAP validation campaigns in Australia, which consist of a series of three aircraft and field experiments specifically designed to contribute to the development of soil moisture retrieval algorithms from radar and radiometer for the SMAP mission [64]. Prof. Jeff Walker from the Department of Civil Engineering, Monash University led a research group to work on the SMAPEx. The three experiments were conducted on 5-10 July 2010, 4-8 December 2010 and 5-23 September 2011. The experiment site is located in the Yanco study area, a semi-arid agricultural area in the Murrumbidgee Catchment, about 530 km west of Sydney, as shown in Figure 76. Concurrently with each flight, supporting ground data on soil moister, soil temperature, and surface roughness were collected at intensive monitoring sites. In the ground SMAPEx network there are 24 surface monitoring stations (0-5 cm) and profile monitoring stations (0-90 cm) which are unevenly distributed over an area of 36 km x 38 km as shown in Figure 77. These monitoring stations/sites were established in 2009 and denoted by small squares. Also, between 2001 and 2005, thirteen stations were established in the Yanco...
study area, denoted by stars. The WGS84 positions of these SMAPEX stations are listed in Table 11. Listed are also the station ID and the year when the station was established. These data were provided by Dr. Alessandra Monerris and Prof. Jeff Walker. Note that seven monitoring stations were established in the Murrumbidgee catchment in 2001, and five stations in the Adelong Catchment in 2001, but their details are not presented.

Figure 76. SMAPEX Yanco study area (provided by Dr. Alessandra Monerris-Belda at Monash University).

Figure 77. Station distribution in Yanco study area. The picture was generated using GPS Visualizer and Google Earth.
Table 11. Positions of 24 monitoring stations: “Y” for Yanco Region.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Established</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
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<td>146.079365</td>
<td>131</td>
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<tr>
<td>YA4b</td>
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<td>146.105287</td>
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<td>130</td>
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Experimental Site Selection

This next Garada airborne experiment is intended to collect data for investigation on soil moisture estimation using GNSS reflectometry. As mentioned earlier, soil moisture is very important to a range of applications and sciences, including agricultural application since it is one of the key factors limiting crop production. Therefore, it is desirable to conduct the airborne experiment in agricultural fields. Since a small UNSW-owned aircraft will be used, the experimental site should not be too far away from Bankstown Airport, west Sydney, where the aircraft is parked. In addition, to evaluate the performance of the GNSS-based technique, an independent validation technique is required to provide the ground-truth reference. Clearly, the Yanco study area is an excellent candidate for the experimental site.
Figures 78 and 79 show the enlarged “YA” area and “YB” area in the Yanco region. The distances between every pair of stations are listed in Table 12 and Table 13 for these two areas, respectively. The shortest distance between a pair of stations is 1.13km, while the longest distance is 10.28km. The dimensions of the whole area shown in Figures 78 and 79 are about 8.96km (width) x 11.13km (height) and 9.0km x 8.1km, respectively.

To cover most of the stations in the Yanco “YA” and “YB” areas, the aircraft would fly over the areas in a zigzag pattern as shown by the dashed blue lines in Figures 78 and 79. Specifically, the stations are covered in the order: YA3 -> YA1 -> YA4a -> YA4d -> YA7a -> YA7d -> YA7e -> YA7b -> YA4e -> YA4b -> YA4c -> YA5 -> YA9 in Yanco YA area; YB1 -> YB3 -> YB5b -> YB5a -> YB7a -> YB7d -> YB7e -> YB9 -> YB5e -> YB7b/YB5d -> YB7c in Yanco YB area; The aircraft would not exactly follow these trajectories, but along the suggested directions, and the aircraft would fly on smooth trajectories. The flight direction selection is made by considering ease of flying of the aircraft as well as minimisation of flight time, whilst ensuring aircraft safety.

Figure 78. Enlarged “YA” area in Yanco study region. The picture was generated using GPS Visualizer and Google Earth.
Figure 79. Enlarged “YB” area in Yanco study region. The picture was generated using GPS Visualizer and Google Earth.

Table 12. Distance (km) between each pair of stations in YA area

<table>
<thead>
<tr>
<th></th>
<th>YA3</th>
<th>YA4a</th>
<th>YA4b</th>
<th>YA4c</th>
<th>YA4d</th>
<th>YA4e</th>
<th>YA5</th>
<th>YA7a</th>
<th>YA7b</th>
<th>YA7d</th>
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Table 13. Distance (km) between each pair of stations in YB area

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<th>YB5b</th>
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<th>YB5e</th>
<th>YB7a</th>
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<th>YB7d</th>
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<td></td>
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</tr>
</tbody>
</table>

4.4.3 Airborne Experiment

The fourth airborne experiment was conducted on the 9th of May 2013. The weather conditions were good; sunny and calm. Professor Jason Middleton, Head of Department of Aviation, UNSW, was the pilot for this experiment as well as the three previous airborne experiments. Mr Greg Nippard, the engineer, did the assembling and disassembling of the equipment for this experiment (as well as the three previous experiments). Mr Scott O’Brien, a PhD student from ACSER, operated the laptop to log data in the aircraft.

Before landing at Narrandera Airport for refuelling, the aircraft flew over the Lake Coolah (about 8km northeast of the Airport) to collect data for reflectivity calibration. According to the original plan, there should be one flight over the Lake at one flight height before flying over the stations and another flight over the same Lake at another flight height after the flight over the stations. However, the two flights over the Lake were completed one followed by the other for convenience. Note that it would be best to have the flights over the Lake immediately before or after the flights over the YA and YB stations. Figure 80 shows the ground tracks of the aircraft of the two flights and the dimensions of the plot are about 5.66km (width) x 9.20km (height). Track segment AB is associated with the first flight, while track segment CD is related to the second flight. The flight altitude and speed are shown in Figure 81. The flight speed was around 70m/s, and the speed variation was not significant, just about a few metres per second. The lake surface elevation is about 150m, so the relative flight height of the first and second flights was about 400m and 200m respectively. Table 14 lists the elevation and azimuth angles of a group of satellites which have the largest elevation angles. Over each of the two tracks, the variation in the elevation is less than one degree, hence the elevation can be treated as a constant.
Figure 80. Aircraft/receiver ground track when flying over Lake Coolah. AB = 5.84km, CD = 6.57km. The picture was generated using GPS Visualizer and Google Earth.

Figure 81. Aircraft flight altitude and speed in Lake Coolah area.
Table 14. Satellite elevation and azimuth angles (degree) related to ground track AB and CD.

<table>
<thead>
<tr>
<th>Track</th>
<th>Satellite</th>
<th>25</th>
<th>12</th>
<th>5</th>
<th>2</th>
<th>29</th>
<th>10</th>
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<tbody>
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<td>70.3-69.5</td>
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<td>41.3-40.8</td>
<td>37.7-38.1</td>
<td>25.6-25.4</td>
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<tr>
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<td>Azimuth</td>
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<td>25.5-24.9</td>
<td>62.9-63.7</td>
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<td>CD</td>
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<td>71.8-72.3</td>
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<td>47.7-48.1</td>
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<td></td>
<td>Azimuth</td>
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<td>65.0-66.1</td>
<td>134.7-134.6</td>
<td>237.0-236.3</td>
<td>125.8-126.5</td>
</tr>
</tbody>
</table>

After refuelling, the aircraft flew over the Yanco YA stations twice and then the YB stations twice. Figures 82 and 83 show the flight speed and altitude in YA and YB areas respectively. Although there are some variations, the speed was around 60m/s. Since the elevation of all the stations is about 130m, the relative flight height is about 400m for the first flight and 200m for the second flight, similar to those flight heights over Lake Coolah. The purpose of using two different flight heights is to investigate the effect of flight height on the parameter such as soil moisture estimation.

The ground tracks of the aircraft are shown in Figures 84 and 85 respectively. Also shown are the locations of the in-situ stations. It can be seen that nearly all the stations are very close to the ground tracks at some specific points. Tables 15 and 16 show the shortest distance between each station and either one of the two ground tracks. The mean distance of YA stations to the two tracks is 36m and 44m, respectively, while that of YB stations to the other two tracks is 38m and 57m, respectively. The minimum of the shortest distance is 5m and 7m in these two areas respectively, while the maximum is 129m and 210m respectively. Tables 17 and 18 list the elevation and azimuth angle of six satellites in YA area and seven satellites in YB area, respectively. During the flight over the individual tracks, the elevation angle variation can be greater than eight degree. Such a variation may have no trivial effect on the ground parameter (e.g. soil moisture) retrieval.

Figures 86 and 87 show the specular reflection tracks in YA and YB area, respectively. Since the flight height relative to the ground is not high, either around 200m or about 400, the specular reflection tracks will not greatly deviate from the aircraft ground tracks. Thus, at the closest points, the reflection tracks will also be close to the in-situ stations. The shortest distance from the stations to reflection tracks are listed in Tables 16 and 17 for satellite PRN#29. The mean shortest distance in Table 16 is 96m and 51m, respectively; and that in Table 17 is 64m and 65m, respectively. Interestingly, there are five stations which have a shortest distance of less than 10m to one of the reflection tracks.
Figure 82. Aircraft flight speed over Yanco areas.

Figure 83. Aircraft flight height over Yanco areas.
Figure 84. Flight ground track in Yanco YA area. The picture was generated using GPS Visualizer and Google Earth.

Figure 85. Specular reflection track in Yanco YA area. The picture was generated using GPS Visualizer and Google Earth.
Table 15. Shortest distance (metre) from each station to the two aircraft ground tracks in YA area.

<table>
<thead>
<tr>
<th></th>
<th>YA1</th>
<th>YA3</th>
<th>YA4a</th>
<th>YA4b</th>
<th>YA4c</th>
<th>YA4d</th>
<th>YA4e</th>
<th>YA5</th>
<th>YA7a</th>
<th>YA7b</th>
<th>YA7d</th>
<th>YA7e</th>
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<td>43</td>
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<tr>
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<td>24</td>
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<td>56</td>
<td>45</td>
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Table 16. Shortest distance (metre) from each station to the two aircraft ground tracks in YB area.

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<th>YB5a</th>
<th>YB5b</th>
<th>YB5d/YB7b</th>
<th>YB5e</th>
<th>YB7a</th>
<th>YB7c</th>
<th>YB7d</th>
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Table 17. Satellite elevation and azimuth angles (degree) in YA area.

<table>
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<th>12</th>
<th>21</th>
<th>2</th>
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</thead>
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<td>14.6-13.7</td>
<td>286.7-281.9</td>
<td>123.6-120.6</td>
</tr>
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</table>

| 2nd track | Elevation | 63.1-68.7 | 57.4-48.3 | 45.8-40.2 | 29.8-21.2 | 30.5-36.5 | 11.8-6.1 |
| Azimuth   | 197.1-181.0 | 342.6-347.4 | 118.8-126.8 | 13.7-12.9 | 281.9-274.1 | 120.6-116.0 |

Table 18. Satellite elevation and azimuth angles (degree) in YB area.

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<th>5</th>
<th>21</th>
<th>15</th>
<th>26</th>
<th>12</th>
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<td>12.2-15.7</td>
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<td>84.6-91.5</td>
<td>12.7-12.8</td>
</tr>
</tbody>
</table>

| 2nd track | Elevation | 75.0-73.0 | 30.9-23.0 | 27.2-20.6 | 47.6-52.4 | 21.5-26.6 | 17.4-19.6 | 27.5-35.3 |
| Azimuth   | 126.0-95.0 | 352.6-354.6 | 134.9-136.4 | 255.9-245.2 | 52.4-58.5 | 96.1-103.7 | 331.8-329.0 |
Figure 86. Flight ground track in Yanco YB area. The picture was generated using GPS Visualizer and Google Earth.

Figure 87. Specular reflection track in Yanco YB area. The picture was generated using GPS Visualizer and Google Earth.
Table 19. Shortest distance (metre) from each station to the two specular reflection tracks in YA area.

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<th>YA4d</th>
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<td>30</td>
<td>50</td>
<td>41</td>
<td>28</td>
<td>109</td>
<td>80</td>
<td>59</td>
<td>60</td>
<td>102</td>
<td>15</td>
<td>7</td>
<td>69</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 20. Shortest distance (metre) from each station to the two specular reflection tracks in YB area.

<table>
<thead>
<tr>
<th></th>
<th>YB1</th>
<th>YB3</th>
<th>YB5a</th>
<th>YB5b</th>
<th>YB5d/YB7b</th>
<th>YB5e</th>
<th>YB7a</th>
<th>YB7c</th>
<th>YB7d</th>
<th>YB7e</th>
<th>YB9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st track</td>
<td>117</td>
<td>84</td>
<td>54</td>
<td>23</td>
<td>35</td>
<td>34</td>
<td>16</td>
<td>73</td>
<td>55</td>
<td>131</td>
<td>86</td>
</tr>
<tr>
<td>2nd track</td>
<td>213</td>
<td>7</td>
<td>56</td>
<td>11</td>
<td>38</td>
<td>9</td>
<td>55</td>
<td>76</td>
<td>130</td>
<td>82</td>
<td>34</td>
</tr>
</tbody>
</table>

### 4.4.4 Initial Data Processing Results

Using the shortest distance points on the ground reflection tracks, a short reflection track segment is selected associated with each station and flight. That is, there are two track segments related to an individual station. The data length for each of the track segments is 30 seconds, equivalent to about 1.8km, and the shortest distance point is around the middle of the track segment. The logged data are processed to generate a delay waveform by coherently integrating 1 millisecond IF samples. These delay waveforms are then non-coherently accumulated over 250 milliseconds and the peak power is obtained. The noise magnitude is calculated by averaging the delay waveform data of one chip duration (16 samples) which is nine chips away from the peak power location on the left-hand side and another one on the right-hand side. Over these regions on the waveform, there would be no signals but noise.

The preliminary results generated are the SNR of the reflected signal collected when flying over the track segments close to four YA stations (YA4b, YA5, YA7a, and YA7d) and four YB stations (YB1, YB2, YB5e, and YB7e) as shown in Figures 88 and 89. The SNR magnitude variation over time/location attribute to the surface characteristics. Figures 90 and 91 show the ground surfaces where the reflection tracks are located. Also shown are the reflection tracks colourised by the SNR magnitude. The SNR variation can be clearly observed when the track goes from one field to another in three areas shown in Figure 88 and one in Figure 89. The variation could be contributed to by the different crops in these fields as well as the difference in soil moisture and surface roughness. In the other four areas there are no such obvious variations in SNR with specific patterns since the surfaces are basically grasslands.

Table 21 shows the start time instants in local time for the period of 30 seconds related to each of the eight 30 second track segments. Tables 22 and 23 show the in-situ soil moisture measurements observed at the eight stations on the flight day. These stations continuously measure the soil moisture.
moisture every 20 min and the data are downloaded from the stations in the field manually or they are forwarded wirelessly so that the data can directly be downloaded in the laboratory at Monash University. From the tables it can be seen that the soil moisture measurement at each station is nearly constant over the period. In fact the soil moisture typically does not change significantly during a day provided that there are no significant weather changes, such as from sunny to raining or vice versa. However, the soil moisture can vary dramatically from one location to another.

These in-situ station measurements can be used as a reference when the GNSS measurements are employed to estimate the soil moisture. However, one needs to be cautious when using these data since the reflection tracks do not exactly cross the station locations. The minimum distance from the station to the reflection track is between 7m and 213m as shown in Tables 19 and 20. The in-situ measurements can be used as an approximate reference only when the surface conditions at the station location and the reflection track area are quite similar.

Figure 88. SNR measurements of reflected signals over reflection track segments closest to four stations in YA area.
Figure 89. SNR measurements of reflected signals over reflection track segments closest to four stations in YB area.
Figure 90. Reflection tracks colourised by SNR around the in-situ stations in YA area. The picture was generated using GPS Visualizer and Google Earth.

Figure 91. Reflection tracks colourised by SNR around the in-situ stations in YB area. The picture was generated using GPS Visualizer and Google Earth.
Table 21. Start time instants for each of the eight 30-second data collected on 9 May 2013.

<table>
<thead>
<tr>
<th></th>
<th>YA4b</th>
<th>YA5</th>
<th>YA7a</th>
<th>YA7d</th>
<th>YB1</th>
<th>YB3</th>
<th>YB5e</th>
<th>YB7e</th>
</tr>
</thead>
</table>

Table 22. In-situ soil moisture measurements (%vol) versus local time (hour: minute) at YA stations on 9 May 2013 (data provided by Dr. Alessandra Monerris-Belda at Monash University).

<table>
<thead>
<tr>
<th>Time-&gt;</th>
<th>10:00</th>
<th>10:20</th>
<th>10:40</th>
<th>11:00</th>
<th>11:20</th>
<th>11:40</th>
<th>12:00</th>
<th>12:20</th>
<th>12:40</th>
<th>13:00</th>
<th>13:20</th>
</tr>
</thead>
<tbody>
<tr>
<td>YA4a</td>
<td>6.65</td>
<td>5.81</td>
<td>6.66</td>
<td>5.97</td>
<td>6.32</td>
<td>6.98</td>
<td>6.49</td>
<td></td>
<td></td>
<td></td>
<td>6.61</td>
</tr>
<tr>
<td>YA4b</td>
<td>24.26</td>
<td>25.76</td>
<td>26.97</td>
<td>27.99</td>
<td>29.25</td>
<td>30.89</td>
<td>31.43</td>
<td>32.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YA5</td>
<td>7.1</td>
<td>7.37</td>
<td>7.25</td>
<td>7.67</td>
<td>7.39</td>
<td>7.67</td>
<td>7.54</td>
<td>8.11</td>
<td>7.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YA7a</td>
<td>4.08</td>
<td>4.40</td>
<td>3.96</td>
<td>4.27</td>
<td>4.09</td>
<td>4.36</td>
<td>4.15</td>
<td>4.16</td>
<td>4.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YA7d</td>
<td>7.15</td>
<td>6.58</td>
<td>6.85</td>
<td>6.93</td>
<td>6.52</td>
<td>6.79</td>
<td>7.15</td>
<td>7.17</td>
<td>7.19</td>
<td>7.19</td>
<td>7.28</td>
</tr>
<tr>
<td>YA7e</td>
<td>6.42</td>
<td>5.80</td>
<td>6.08</td>
<td>6.10</td>
<td>5.70</td>
<td>5.79</td>
<td>6.28</td>
<td>6.13</td>
<td>5.92</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 23. In-situ soil moisture measurements (%vol) versus local time (hour: minute) at YB stations on 9 May 2013 (data provided by Dr. Alessandra Monerris-Belda at Monash University).

<table>
<thead>
<tr>
<th>Time-&gt;</th>
<th>10:40</th>
<th>11:00</th>
<th>11:20</th>
<th>11:40</th>
<th>12:00</th>
<th>12:20</th>
<th>12:40</th>
<th>13:00</th>
<th>13:20</th>
<th>13:40</th>
<th>14:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>YB1</td>
<td>11.42</td>
<td>11.50</td>
<td>11.79</td>
<td>11.88</td>
<td>11.52</td>
<td>11.89</td>
<td>11.42</td>
<td>12.42</td>
<td>12.23</td>
<td>12.25</td>
<td>11.85</td>
</tr>
<tr>
<td>YB3</td>
<td>6.93</td>
<td>7.20</td>
<td>7.04</td>
<td>7.35</td>
<td>7.46</td>
<td>7.50</td>
<td>7.40</td>
<td>7.22</td>
<td>7.84</td>
<td>7.87</td>
<td></td>
</tr>
<tr>
<td>YB5a</td>
<td>5.47</td>
<td>6.17</td>
<td>6.14</td>
<td>6.03</td>
<td>6.52</td>
<td>6.64</td>
<td>6.52</td>
<td>6.63</td>
<td>6.49</td>
<td>6.78</td>
<td>6.82</td>
</tr>
<tr>
<td>YB5b</td>
<td>5.68</td>
<td>5.51</td>
<td>6.51</td>
<td>5.66</td>
<td>6.22</td>
<td>6.05</td>
<td>6.05</td>
<td>6.33</td>
<td>6.05</td>
<td>6.51</td>
<td>5.76</td>
</tr>
<tr>
<td>YB5e</td>
<td>4.00</td>
<td>4.09</td>
<td>3.84</td>
<td>3.93</td>
<td>4.25</td>
<td>4.28</td>
<td>4.06</td>
<td>4.08</td>
<td>4.40</td>
<td>4.18</td>
<td>4.18</td>
</tr>
<tr>
<td>YB7a</td>
<td>6.01</td>
<td>6.13</td>
<td>6.25</td>
<td>6.15</td>
<td>6.33</td>
<td>6.63</td>
<td>6.75</td>
<td>7.05</td>
<td>7.17</td>
<td>7.29</td>
<td>7.16</td>
</tr>
<tr>
<td>YB7c</td>
<td>7.51</td>
<td>7.42</td>
<td>7.21</td>
<td>7.52</td>
<td>7.64</td>
<td>7.76</td>
<td>8.21</td>
<td>7.74</td>
<td>7.97</td>
<td>8.47</td>
<td>8.17</td>
</tr>
<tr>
<td>YB7d</td>
<td>7.05</td>
<td>6.94</td>
<td>7.47</td>
<td>7.36</td>
<td>7.24</td>
<td>7.34</td>
<td>7.45</td>
<td>7.88</td>
<td>7.33</td>
<td>7.81</td>
<td>7.43</td>
</tr>
<tr>
<td>YB7e</td>
<td>1.95</td>
<td>2.32</td>
<td>2.69</td>
<td>2.73</td>
<td>2.46</td>
<td>2.85</td>
<td>2.88</td>
<td>2.6</td>
<td>2.98</td>
<td>2.99</td>
<td>2.64</td>
</tr>
</tbody>
</table>

4.4.5 Summary

In this section the airborne experiment conducted in May 2013 was described. This experiment was intended to collect data for investigation of soil moisture estimation using GNSS reflectometry. The aircraft flew over different land surfaces where in-situ stations are located so that the ground soil moisture measurements can be used as a reference. Through processing the logged data the SNR measurements of the reflected signal captured over eight different track segments were obtained. These preliminary results demonstrate that the SNR variation pattern has good agreement with the surface/crop field change. Future work will focus on processing more data including the direct signals to investigate the ground reflectivity, top surface layer dielectric constant, and soil moisture content.
4.5. Initial Design of GNSS Bistatic Receiver

Originally, GNSS reflectometry (GNSS-R) experiments were conducted using software receivers which have multiple RF front-ends. At the present time, software receivers are still often used for research in GNSS-R. The front-ends process the received signals to produce IF signals. By sampling the analogue signal followed by quantization during the analogue-to-digital conversion (ADC), the raw IF data bits are stored typically on a laptop. There are many different software receivers; for instance, nine different software receivers are listed in [65]. Another different software receiver, the NordNav receiver, which has four front-ends, has been used in the experiments for the Garada Project. After the experiments, the raw IF data are processed through cross-correlating the raw data with the local signal replica of GNSS pseudorandom noise codes and using dedicated software. As a result, samples of cross-correlation function are produced over a range of Doppler frequencies and a number of code chips (i.e. a waveform is produced). Clearly, such a procedure requires intensive cross-correlation computation which involves the use of software routines, good knowledge on how to use the software to process the raw data, and a lot of time to run these routines to generate the results. These waveform data are just the basis for further analysis to remotely sense geophysical parameters. That is, prior to the analysis of the observed data, significant amount of computer time has already been consumed.

To resolve such issues a better instrument, based on a hardware receiver, needs to be developed so that the cross-correlation can be performed in real time. As a consequence, the scientific end users and industry can directly analyse the data obtained from either airborne or spaceborne experiments or missions to infer the geophysical or geochemical parameters. Due to the importance of such a hardware receiver, a number of universities and research institutions have been developing hardware receivers. They include the instruments developed by NASA Langley Research Center [5], CSIC-IEEC [65], SSTL [66], UPC [67], and Beihang [68]. The initial design of the bistatic receiver reported in this section is based on the information of these existing hardware receivers. The focus of this section is first on the basic description of the bistatic receiver, the architecture and signal processing of the back-end of the receiver. Also, detailed discussions on the number of front-ends and the utilisation of multi-frequency and multi-GNSS constellations are provided. The key point is that the UNSW-designed Namuru receivers [69] should be used as the basis to save time and reduce resource consumption. In addition, the multi-frequency schemes and the multi-GNSS constellations should be leveraged to achieve a performance gain in both accuracy and coverage. The issue of antenna selection is also discussed for the sake of system simplicity as well as good performance.

4.5.1 Brief Description of the Hardware Receiver

Figure 92 shows the block diagram of the first scheme of the hardware receiver. It consists of two main parts, the multiple RF front-ends and the signal processing back-end. Typically, external antennas are required to receive the GNSS signals. That is, the RHCP antenna is used to receive the direct GNSS signals, whereas the LHCP antenna is used to receive the reflected GNSS signals. Although there is a LNA or even more in the RF front-ends, an external LNA is usually necessary to amplify both the direct and reflected signals when passive antennas are used. In the case of a spaceborne receiver, to reliably detect the really weak reflected signal, some special strategies are
required. One strategy is to utilise a high-gain antenna. The RF front-end consists of two identical front-ends which would be similar to most of the existing front-ends. These front-ends produce analogue IF signals with a specific central frequency which can be selected to be around 20 MHz. Digital IF signals are produced by sampling the analogue signals at a frequency of around 40 MHz through an ADC. In some hardware receiver designs, the resolution of the ADC is significantly different from others. For instance, one receiver uses 1-bit ADC, whereas another uses 8-bit ADC. Clearly, the computational complexity is a minimum when using the 1-bit ADC. As the resolution (i.e. the number of bits) increases, the computational complexity increases. On the other hand, the SNR of the waveform produced by the signal processor will improve with the number of bits as observed in [70]. However, the improvement would be negligible when the number of bits is greater than some value. At the moment, an ADC with 3-6 bits can be considered optimal although the most suitable value still needs to be determined. These digital samples from the ADC are the input to the signal processor to generate the two-dimensional delay waveform or three-dimensional delay-Doppler waveform.

A reference oscillator is used to maintain synchronisation between the GNSS receiver clock, the signal processor clock, and the local oscillators in the two RF front-ends. This system reference oscillator operates at a frequency of around 40 MHz, which may also be adjustable. An oven controlled crystal oscillator (OCXO) can be used as the reference oscillator. The accuracy of the OCXO is high; for instance, the accuracy of a 5-10 MHz OCXO is 20 ppb (parts per billion), whereas the long-term (e.g. 10 years) stability is around 20-200 ppb per year (according to Wikipedia). The GPS receiver can be a commercial GPS receiver card which takes the direct signal received by the RHCP antenna as input to calculate the navigation solution which is then forwarded to the signal processor. Since UNSW has built a number of Namuru GNSS receivers, the GNSS receiver can be replaced by one of the Namuru receivers [69]. USB interface is required to output the waveform data (preferably, and the navigation data as well) to an external device such as a laptop where the data are logged for further processing, or a flash drive as a buffer in order to forward the data to the ground through a wireless downlink channel. Only two front-ends are considered in the initial design of the receiver; however, such a design can be extended to the case of more than two front-ends such as four front-ends to capture signals from two different GNSSs (e.g. GPS and GLONASS) or different frequency bands (e.g. GPS L1 and L2).

The second design scheme is shown in Figure 93. It can be seen that the extra GNSS receiver is removed. In this scheme the front-end (or front-ends) of the Namuru receiver can be used as the front-ends of the hardware receiver subject to some modifications. In particular, new facilities and features need to be added to the existing Namuru platform to realise the function of delay-Doppler map (DDM) generation. The digital IF data bits from the ADC connected to front-end 1 are used to track the code phase and the carrier frequency of the direct signal as well as to decode the navigation message. The navigation message retrieval, the code and frequency tracking, as well as the cross-correlation computation are all realised in the signal processor.

The advantage of the first scheme is that any modification of the two RF front-ends and the two ADCs will not affect the GNSS receiver. That is, the two parts can be treated independently. As a result, such a scheme is more flexible. The disadvantage of the scheme is that an extra GNSS receiver is required. On the other hand, the advantage of the second scheme is the avoidance of the extra GNSS receiver. However, in the presence of any modifications in the front-ends or in the ADCs, both the navigation message detector and the cross-correlator in the signal processor may need to be
modified accordingly. At the moment the second scheme is preferred due to its lower system complexity.

Figure 92. Block diagram of the first scheme of the hardware receiver

Figure 93. Block diagram of the second scheme of the hardware receiver
4.5.2 Signal Processor

As mentioned earlier there are two main parts in the hardware receiver, the RF front-end and the signal processing back-end. Since the Namuru front-end will be used as the front-end of the hardware receiver, subject to some modifications, the focus of the design is on the signal processing back-end. In this subsection the key hardware components, the architecture, the flow of the signal processor are described. Also, the selection of the DDM parameters is discussed.

Architecture of Signal Processor

Figure 94 shows the block diagram of the signal processor. The processor board consists of two main chips, the FPGA (field-programmable gate array) chip and the DSP (digital signal processing) chip. The functions implemented on a FPGA chip include the acquisition of the code phase and carrier frequency of the direct signal, the local code and carrier generation, the cross-correlation of the reflected signal with the local replica, the waveform data and other data buffer, and the control functions. Note that the functions of the DSP chip can also be realised on a FPGA chip. The FPGA chip can be selected from the Altera FPGA series such as the Cyclone II & Cyclone IV FPGA chips [71]. These two FPGA chips have been used in the earlier versions of Namuru receiver, while Namuru 3.2 used the Actel FPGA chips. The DSP chip performs functions including code and carrier tracking, and navigation data/message decoding. The DSP design can be implemented in a DSP chip which can be selected from the TI (Texas Instruments) processor series [72]. Namuru v3.3 has a Cyclone IV FPGA and retains the use of the NIOS-2 softcore processor, although future versions may switch to Cyclone V, which includes hard-coded ARM Cortex cores on board. The FPGA and DSP communicate via an interface. More details about the signal processor are provided in the following subsections.

Figure 94. Signal-processor block diagram.
Principle of the Signal Processor

Figure 95 shows the structure of the signal processor with a detailed illustration of the waveform-generation correlator array. Although a number of different functions are performed in the processor, the key product of this signal processor is the delay-Doppler waveform of the reflected signal. Note that the waveform of the direct signal is not of interest since it does not provide any useful information about the characteristics of the scattering surface. Nevertheless, the processing of the direct signal provides the estimates of the code phase and Doppler frequency of the direct signal, which are used to infer those of the reflected signal. It is also worth mentioning that the GNSS receiver of interest is actually equivalent to a reflectometric sensor where the direct and reflected signals are received and processed separately. In the case of a GNSS interferometer, the direct signal and the reflected signal are received by one antenna simultaneously so that the two signals are superimposed. Alternatively, the two signals are received by different antennas (the antenna for receiving the reflected signal must have a high gain), but the two signals are then cross-correlated for a certain period of time; the amplitude is squared and then accumulated over a number of samples [73]. The advantage of interferometric processing is that accurate estimation of the relative delay can be obtained without the need to generate any replica of the modulating codes onboard. Also, all embedded codes in a given GNSS frequency band would contribute to the cross-correlation shape, including the high-chip rate restricted access codes such as the GPS P(Y) code which can be used to improve the ranging performance. The detection of these embedded codes may require the use of a high-gain nadir-looking antenna. However, more discussions about a GNSS interferometer and its design are beyond the scope of this Annex.

Since the aim of the signal processor is to generate a 3-D DDM, a range of code delays and a range of Doppler frequencies need to be defined. With the aid of the acquisition and tracking of the direct signal, the estimates of the central Doppler frequency and the code phase of the reflected signal at the specular reflection point can be obtained and thus the ranges of the code phases and Doppler frequencies can be selected. Note that the specular reflection point is the point where the total path length of the reflected signal travelling from the transmitter to the receiver is the minimum. As shown in Figure 95, there are \((m+n+1)\) code phases, ranging between \(-m\delta\tau\) and \(n\delta\tau\) where \(m\) and \(n\) are positive integers and \(\delta\tau\) is the code phase spacing. A zero code phase corresponds to the code phase of the signal reflected at the specular reflection point. The Doppler frequency ranges between \(-\ell\Delta f\) and \(\ell\Delta f\) where \(\ell\) is an integer and \(\Delta f\) is the Doppler frequency spacing. Each Doppler frequency corresponds to a specific carrier frequency of a carrier generated by a multi-carrier generator. More discussion about these code phase and frequency parameters will be provided later. For each pair of a Doppler frequency and code phase, there is a pair of correlators for cross-correlating the in-phase and the quadrature components of the reflected signal with those of the modelled signal. The amplitude of the correlation output of the in-phase component and that of the quadrature one are squared and then added, followed by non-coherent summation.

The code sequences with different code phases can be generated by using a serial-in and parallel-out shift register which is driven by a clock as shown in Figure 96. There are \(N\) parallel outputs from the shift register at each sampling instant, resulting in \((N+1)\) C/A code sequences. Note that, to match the number of code phases in Figure 94, \(N = m+n\). The sampling period of the clock is equal to the code phase spacing or resolution, i.e. \(\delta\tau\). The generation of different Doppler frequencies is realised using a multi-carrier generator with each carrier corresponding to a specific Doppler frequency. Each
of the carriers is generated using a Numerically Controlled Oscillator (NCO) and thus the implementation of such a multi-carrier generator is not a difficult issue.

In addition to the code phase and Doppler frequency parameters to be discussed later, two other correlation-related parameters, the coherent integration time and the non-coherent integration time, need to be selected. For a spaceborne receiver, the coherent integration is typically set at 1 millisecond which is the GPS C/A code chip length. For a receiver dedicated to airborne experiments, the coherent integration can be selected to be equal to or greater than 1 millisecond. The selection of the non-coherent integration time may be more flexible, but typically greater than 1 second. Due to the divergent selection of these two parameters, they should be readily adjustable so that the user can conveniently select the parameter values of their interest. For convenience the default values of the coherent and non-coherent times can be specified as 1 millisecond and 1 second, respectively.

Each of the dashed boxes in Figure 95 corresponds to the generation of waveform data related to a specific Doppler frequency. That is, a delay waveform is produced by each of the boxes. In each dashed box, there are $2(m+n+1)$ parallel correlators. Since there are $2(\ell+1)$ Doppler frequencies, there are totally $4(\ell+1)(m+n+1)$ parallel correlators.

Although in some cases only the two-dimensional delay waveform is used to remotely sense the geophysical parameters, the generation of three-dimensional waveforms should be attempted. This is because the 3-D waveform contains more information than the 2-D waveform. However the use of 3-D waveform or 2-D waveform is the choice of the user. The 2-D waveform is simply a part of the 3-D waveform when the Doppler frequency is set at its central value.
Figure 95. Architecture of the signal processing back-end.
Signal Processing Flow Chart

Figure 97 shows the signal processing flow chart in the signal processor which uses both the direct digital signal and the reflected digital signal to generate the delay-Doppler waveform. Specifically, the processor consists of two parts, the direct signal channel (DSC) and the reflected signal channel (RSC). The DSC generates both the reference Doppler frequency and the reference code phase for the RSC. In fact the DSC performs the functions of a typical software receiver, as described below. The acquisition and tracking is first realised to estimate the code phase and Doppler frequency of the direct signals associated with specific GNSS satellites. The navigation data decoding and extraction are then carried out to generate the code phase and Doppler frequency of the reflected signal with respect to the direct signal. Next, the code phase \( \delta\tau \) of the reflected signal are used to estimate the code phase of the reflected signal using the formulas

\[
CP_R = CP_D + \delta\tau_R
\]

where

\[
\delta\tau_R \approx 2h \sin(\theta)
\]

where \( h \) is the altitude of the receiver and \( \theta \) is the elevation angle of the GNSS satellite. Since the Doppler frequency of the reflected signal is very similar to that of the direct signal, both the code phase and Doppler frequency of the reflected signal can be estimated and the accuracy is sufficiently good for the generation of the delay-Doppler waveform. The RSC makes use of these Doppler and code phase estimates to perform 2-D cross-correlation to produce the delay-Doppler waveform.

It is expected that a certain processing time will be consumed in generating the reference code phase and Doppler frequency estimates of the reflected signal even though the processing is hardware-based. However, such a processing delay is negligible when considering the code phase and Doppler frequency variation over such a delay. Airborne experimental results have demonstrated that the variation of the Doppler frequency over duration of one second is rather small, just up to a few dozen Hertz. The variation of the code phase in one second is between a few samples and around 40 samples. Note that the sampling frequency is 16.3676MHz and there are

![Diagram of Signal Processing Flow Chart](image-url)
about 16 samples per code chip. Except that at the starting point, dozens of 1 millisecond data are required to perform signal acquisition, the update period of the code and frequency tracking would be of the order of milliseconds. Also, at the starting point a delay of 30 seconds is inevitable in order to detect the navigation message to obtain the GNSS satellite data.

![Signal processing flow chart](image)

**Figure 97. Illustration of signal processing flow chart.**

**Selection of DDM Parameters**

As mentioned in earlier four important parameters associated with the DDM need to be defined in the design of the bistatic receiver. They are the DDM size (i.e. number of code pixels and number of Doppler pixels), code phase resolution or spacing (\(\delta \tau\)), and the Doppler frequency resolution (\(\Delta f\)). The knowledge of these parameters is required to determine the total number of correlators which will be implemented on the FPGA chip. It is important to appropriately choose these parameters so that the observed DDMs can be utilised to reliably retrieve the geophysical parameters. To enable the accuracy requirement, the code phase and Doppler frequency spacing should not be large and the DDM size should not be small. On the other hand, to reduce system complexity and speed up the DDM generation, the DDM size should not be large. Thus, a trade-off is required. In [67] each DDM has \(24 \times 32\) complex points and the resolutions are configurable with \((\Delta f_{\min} = 20\, \text{Hz}, \ \delta \tau_{\min} = 0.05\, \text{chips})\). In addition, the coherent time (minimum = 1 millisecond, maximum = 100 millisecond) and non-coherent integration time (minimum of one coherent integration time period and maximum unlimited but typically less than 1 second) are selectable. Such a design was focused on building a GNSS receiver for conducting airborne experiments. In [66] the design objective was to build a receiver suited for a spaceborne platform. The implemented DDM processor has 52 Doppler frequencies by 128 code delays and the resolution can be configurable. It is a fact that the spread over both time and frequency of the reflected signal received via a spaceborne receiver is much larger than that of the signal received via a land-based or an airborne receiver. Thus, the DDM size for a spaceborne receiver should typically be larger than that of an airborne receiver.
Based on the above discussions and the consideration of a receiver suited for both airborne and spaceborne applications, the DDM parameters of the bistatic receiver of interest are initially specified in Table 24.

### Table 24. Initial specification of DDM parameters.

<table>
<thead>
<tr>
<th>parameter</th>
<th>min</th>
<th>max</th>
<th>characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay resolution</td>
<td>0.03125 chips</td>
<td>Less than 0.5 chips</td>
<td>Configurable</td>
</tr>
<tr>
<td>Doppler resolution</td>
<td>15.625 Hz</td>
<td>Less than 2 kHz</td>
<td>Configurable</td>
</tr>
<tr>
<td>Number of code delays</td>
<td>64</td>
<td>128</td>
<td>Fixed</td>
</tr>
<tr>
<td>Number of Doppler frequencies</td>
<td>20</td>
<td>60</td>
<td>Fixed</td>
</tr>
<tr>
<td>Coherent Integration time</td>
<td>1 millisecond</td>
<td>Less than 0.1 second</td>
<td>Selectable</td>
</tr>
<tr>
<td>Non-coherent Integration time</td>
<td>Larger than coherent integration time</td>
<td>Unlimited but typically Less than 10 seconds</td>
<td>Selectable</td>
</tr>
</tbody>
</table>

### Issues Related to Front-ends

In the preceding subsections although the receiver structure and signal processing back-end parameters were defined, a number of issues were not mentioned. In this subsection the issues of number of front-ends, multiple frequencies and multi-GNSS systems are discussed.

Since this receiver is supposed to be based on the UNSW-developed Namuru receivers, it will have the facility support for multiple GNSSs. Currently, the 2-frontends Namuru receiver is designed to acquire and track the GPS L1 and L5 signals and the Galileo E1 and E5 signals with one front-end for handling the L1/E1 signals and the other front-end for the L5/E5 signals. In fact the recent design of GNSS receivers typically considers using multiple front-ends and multiple frequencies. The reason for using such a GNSS receiver structure is rather obvious. Currently there are four different operational or planned GNSSs, namely U.S.’s GPS, EU’s Galileo, Russia’s GLONASS, and China’s BeiDou. Although only GPS and GLONASS are fully operational, the others will be operational by the end of the decade. Furthermore, a number of different frequencies are used by these systems, including L1/E1, L2/L2C, L5/E5, E6, G1, and G2. It is desirable to make use of the multi-frequency and multi-constellation to achieve a diversity gain in estimating the geophysical parameters with regards to both estimation accuracy and coverage.

Based on the above considerations a number of different options of the bistatic receiver front-ends and frequencies are proposed as shown in Figure 98. In terms of the number of front-ends there are four different options: three, four, five and six. The 3-front-end structure is the simplest one with one front-end for dealing with the direct signal captured via the zenith-looking RHCP antenna, another front-end for the reflected signal received via the nadir-looking LHCP antenna, and the third
front-end for the reflected signal via the nadir-looking RHCP antenna. In this case both dual constellations and dual polarisation are exploited.

The second option is that there are four front-ends with two front-ends for L1/E1 signals and the other two for L5/E5 signals. A pair of L1/E1 and L5/E5 front-ends is connected for dealing with the direct signal, while the other pair for the reflected signals. The downward antenna is assumed to have the left hand circular polarisation unless the surface has a better sensitivity or higher reflectivity to the RHCP signals. This option is under the assumption that the frequency diversity gain is greater than the polarisation gain. In the literature there are no reports on the diversity gains associated with different parameters. Therefore it is desirable to carry out investigations for comparing the performance gain achieved by using multiple polarisations and the gain obtained by using multiple constellations or multiple frequencies. Of course, for a fair comparison, the performance of the system should be evaluated when using two polarisations and two constellations or two frequencies.

In the option of five front-ends, the only difference to the option of four front-ends is that the additional front-end can be used for handling either L1/E1 or L5/E5 signals but not both. The selection would depend on which signals have a better sensitivity and/or higher reflectivity to the surface of interest. If the additional front-end is L1/E1, then a pair of L1/E1 front-ends would be used to handle the reflected signals via the LHCP antenna and the RHCP one, respectively. In the option of six front-ends the simple combinations would be three L1/E1 front-ends and three L5/E5 front-ends. A pair of L1/E1 and L5/E5 front-ends is used for processing the direct signal, while the other four front-ends for handling the reflected signals via a L1/E1 RHCP, a L1/E1 LHCP, a L5/E5 RHCP, and a L5/E5 LHCP antenna, respectively. Alternatively, three front-ends may be used to receive the direct signal with the third one for a third satellite constellation of either GLONASS or BeiDou. The three other front-ends are assigned to process the reflected signals of the three different constellations. In this case, only the LHCP antennas are used to capture the reflected signals. The advantage of such an option is that the spatial coverage is increased since the elevation or azimuth angles of the satellites of a constellation typically would not be the same as those of the satellites of another constellation. Further analysis and evaluation are required to make a final decision on which of the above options will be used when implementing the design and building the bistatic receiver.

Another issue is that the bistatic receiver should provide users with the flexibility that they can obtain the raw IF digital data, the delay-Doppler map data, or both. That is, the receiver should be able to output both digital IF data and the processed DDM data. As mentioned earlier using the DDM data will save the end-users much time in retrieving the geophysical parameters. On the other hand, in addition to DDM data, some end-users may be interested in using the digital IF samples to extract more useful information.

Finally, it is worth mentioning one more issue related to antennas. A number of off-the-shelf multi-GNSS antennas are available. For instance, the 3G+C antenna built by Navxperience is able to capture nearly all the GNSS signals. However, only RHCP polarisation is used and the dimensions are relatively large, 72mmx172mm. More information about this antenna can be found in [73]. Thus, a single multi-GNSS antenna can be used to capture the signals from the different constellations. On the front panel of the receiver, only one input connection may be used to a nadir-looking multi-GNSS RHCP antenna, but an internal splitter is needed to forward the signal to different front-ends. Otherwise, an external splitter is required to split the signal to different ports on the receiver front panel. In the absence of a multi-GNSS LHCP antenna, multiple individual LHCP antennas are needed.
to receive the reflected signals related to different constellations. Another point is that it is desirable to use high-gain antennas especially for capturing the reflected signals.

<table>
<thead>
<tr>
<th>Frontend</th>
<th>Direct Signal</th>
<th>Reflected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>2nd</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>3rd</td>
<td>L1/E1</td>
<td>LHCP antenna</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>Frontend</th>
<th>Direct Signal</th>
<th>Reflected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>2nd</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
<tr>
<td>3rd</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>4th</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Frontend</th>
<th>Direct Signal</th>
<th>Reflected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>2nd</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
<tr>
<td>3rd</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>4th</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
<tr>
<td>5th</td>
<td>L1/E1 or L5/E5</td>
<td>RHCP antenna</td>
</tr>
</tbody>
</table>

(c)

<table>
<thead>
<tr>
<th>Frontend</th>
<th>Direct Signal</th>
<th>Reflected Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>2nd</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
<tr>
<td>3rd</td>
<td>L1/E1</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>4th</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
<tr>
<td>5th</td>
<td>L5/E5</td>
<td>RHCP antenna</td>
</tr>
<tr>
<td>6th</td>
<td>L5/E5</td>
<td>LHCP antenna</td>
</tr>
</tbody>
</table>

(d)

Figure 98. Options of number of front-ends and frequencies.
4.5.3 Summary

In this section a preliminary specification of the bistatic receiver was provided, especially with a focus on the signal processor and the number of front-ends. In contrast to standard GNSS receivers, the bistatic receiver has a signal-processing back-end which generates the DDMs in real time. It was considered that this signal processing back-end mainly consists of two chips, a FPGA chip and a DSP chip, jointly performing all the required functions. Some detailed information about this back-end was presented and a number of parameters including those associated with the DDM size were initially specified. The issues of exploiting multiple frequencies and multiple constellations were also considered. In addition, the issue of antenna selection was also briefly discussed. It is suggested that a significant part of the UNSW-built Namuru receiver will be used, subject to some modifications, as the basis for the bistatic receiver.
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