Aircraft Detection Experimental Results for GPS Bistatic Radar using Phased-array Receiver

Chow Yii Pui  
School of Electrical & Electronic Engineering, University of Adelaide  
Gate 5, Frome Rd, SA 5005  
Tel: +61 8 8313 8314  
Email: mpss@eleceng.adelaide.edu.au

Matthew Trinkle  
School of Electrical & Electronic Engineering, University of Adelaide  
Gate 5, Frome Rd, SA 5005  
Tel: +61 8 8303 4708  
Email: mtrinkle@eleceng.adelaide.edu.au

Brian Ng  
School of Electrical & Electronic Engineering, University of Adelaide  
Gate 5, Frome Rd, SA 5005  
Tel: +61 8 8303 5054  
Email: bwng@eleceng.adelaide.edu.au

ABSTRACT

Since the transmission power level of Global Positioning System (GPS) signal is weak, a passive bistatic radar that utilises GPS satellites as the illuminator of opportunity is only feasible for detecting large size targets such as aircrafts, assuming that the system utilises high sensitivity, large scale receiver antenna arrays and uses integration periods of sufficient length. A phased-array receiver that consists of 32 antenna elements is developed for the radar system to enhance the detection performance and search for aircraft reflections across all direction-of-arrival using conventional beamforming technique. An initial experiment was previously done to investigate techniques such as array orientation and channel phase calibration using GPS signals as the calibrating sources, and also direct path and multipath interference mitigation using Wiener filters. This paper reports on further experiments conducted to study the feasibility of using GPS signals for aircraft detection.

KEYWORDS: Passive Bistatic Radar, Phased-array, Aircraft Detection, Antenna Array Calibration
1. INTRODUCTION

The study of using GPS signals as the illuminator of opportunity for passive bistatic radar to detect aircraft has gained some interest recently. The interest in using GPS signals for such application is due to its global coverage. In fact, the presence of multiple GPS satellites at different locations makes this application potentially useful since such geometrical arrangements allow the receiver to capture reflections of target from different angles. The major challenge for using GPS signals in passive bistatic radar to detect targets is the low transmission power level. This mandates the use of high gain receivers in order for such an application to be feasible.

The investigation of feasibility for GPS bistatic radar in performing aircraft detection was exploited by Glennon and Dempster (2006). There have been studies that investigated the feasibility of GPS bistatic radar in detecting helicopters, such as Behar and Kabakchiev (2011) that compared the maximum range for GPS bistatic radar using the conventional bistatic and the forward scatter approach to detect various types of helicopters, and Clemente and Soraghan (2012) that demonstrated the possibility to detect helicopters based on the reflections of GPS signals from the rotor blades. All the abovementioned studies assume that the target of interest has a good radar cross-section (RCS) and the radar receiver has high gain in order to achieve a good maximum detection range.

The experiment performed for this paper extended the other experimental work that was carried by Pui and Trinkle (2011) to detect target at closer distance, such as a moving train using a 7-elements GPS phased array receiver. The detection procedure from previous experiment starts with performing a Doppler-range search on each element followed by applying a conventional beamforming method to search for the strongest return across all directions-of-arrival (DOA). However, the DOA information of the beamformer used in this experiment (where the antenna array is tilted vertically to face directly at the moving train) is defined as the direction of target relative to the plane of the antenna array, rather than the location of the receiver at ground level. Therefore, the DOA information of the target from the receiver must be determined by the position of the target that is located using the time-difference-of-arrival (TDOA) information between the target reflections and the direct signals from multiple satellites in this experiment.

This paper briefly describes the target Doppler shift and antenna array three-dimensional orientation error calibration aspects for aircraft detection experiment performed using a GPS phased-array receiver that utilises 32 antenna elements and also provides the analysis of the outcomes from the experiment. The feasibility of detecting an aircraft with RCS of 100m$^2$ that appears within 220 metres using the phased array receiver of such scale had been reported in our earlier paper (Pui and Trinkle 2013). The DOA information of the beamformer used in this experiment is defined as the direction of target relative to the location of the receiver at ground level, where the DOA of the aircraft from the receiver can be precisely determined and tracked.

2. TARGET DETECTION ASPECTS

2.1 Doppler search

When reaching the ground receiver, the carrier frequency of GPS signal is always shifted by
the Doppler effect due to the motion of the satellites. Therefore, the GPS receiver is required to perform Doppler search for up to a range of 4 kHz to capture the GPS signal of direct path. To capture GPS signal reflections from an aircraft, Doppler search is required to be performed starting from the Doppler frequency of GPS direct signal and up to a certain range since the flight motion will result in an additional Doppler shift. The Doppler frequency of the reflections in a bistatic scenario, as illustrated in Figure 1, can be written in (1). Here, $V$ is the velocity of target and $\lambda$ is the wavelength of signal. So, bistatic angle, $\beta$ becomes a major factor in changing the Doppler frequency.

$$f_D = \left(\frac{2V}{\lambda}\right) \cos \delta \cos \left(\frac{\beta}{2}\right)$$

(1)

![Figure 1. Geometrical illustration of a GPS bistatic radar for aircraft detection](image)

When an air target aligns with the GPS direct path (also known as baseline), $R_D$, the angle $\beta$ will approach 180 degrees. The bistatic radar of this type of detection scenario is classified as the forward scatter radar. In that case, according to the Babinet’s principle, the target will create a shadow field and the signal is diffracted in a similar pattern to an aperture. Since the size of an aircraft is much higher than the wavelength of GPS signal (i.e. 19cm), the shadow field will be much less diffracted. Therefore in most of the cases, a vast area of the aircraft will be exposed, which means that the radar cross-section (RCS) of target appears at radar receiver will be large. However, such case will also result in little to no Doppler shift from the Doppler frequency of GPS direct path signal. As such, the Doppler search process can hardly discriminate target signature from the direct path signal. For this reason, the experiment performed for this paper uses conventional bistatic radar detection over the forward scattering approach. So, the target detection process used GPS signals broadcasted by satellites that make $\beta$ to be geometrically much smaller than 180 degree. The experimental results of the Doppler search process for target reflections are presented in Section 3.

2.2 Antenna Array Phase Error Calibration

A phased array receiver functions as a system that steers its beam across all directions to search for the target. When using the conventional beamforming approach, the incoming signals at a desired DOA will be improved by the factor of the number of elements in the receiver when appropriate phase shift that is determined from the spatial phase factor, $k$ is applied to each element. In reality, the electronic circuitries at each element would introduce phase errors to the system which causes misalignment in the phase of each element, so $k$ will no longer be the dominant phase shifting factor in the receiver. To achieve maximum array gain for an incoming signal at a desired direction, $s(t)$, the phase error at the $K^{th}$ element,
expressed as \( \hat{e} = [e_1, e_2 \ldots e_k]^T \), has to be cancelled. The output signal of phased-array receiver can be expressed in (2). Note that \( u_i \) is the coordinate of \( i^{th} \) element.

\[
y(k,t) = s(t) \sum_{i=1}^{K} \exp(-je_i)\exp(-jk^t u_i)
\]

Also, \( k = [\cos \theta \sin \phi \ \sin \theta \sin \phi \ \cos \phi] \) while \( \theta \) and \( \phi \) is are the azimuth and elevation steering angles from the receiver, respectively.

The system for the aircraft detection experiment performed on-site antenna array calibration using GPS satellites as the calibrating sources. This means that as the direction of each GPS satellite is applied in \( k \) and the phase information of GPS signals from all visible satellites at each array element are obtained using the cross-correlation technique, \( e_i \) can then be determined using least-squared estimation (LSE). This process is explicitly described by Trinkle et al. (2012). The orientation error problem is also considered in this literature and solution is provided by performing an exhaustive search across all possible azimuth angles offset, i.e. \( k \) changes by different \( \theta \) values in the LSE model and the one that corresponds to the smallest residual error will then be determined as the offset. This solution is however only able to resolve the two-dimensional orientation issue.

In previous experiment performed by Pui and Trinkle (2013), the antenna array panel is flatly placed on ground surface at a random azimuth orientation as shown in Figure 2a. However, it is discovered that if the array panel is tilted at an unknown angle shown in Figure 2b to get a better reception for capturing signal reflections from aircraft that appear at some distance from the receiver, then the orientation error becomes a three-dimensional problem. Therefore, the solution to resolve the three-dimensional orientation problem is to perform exhaustive search for \( \theta \) and \( \phi \) across all possible angles such that \( u_i \) is changing in the LSE model.

![Figure 2a. Antenna array panel placed flatly on ground surface (Left)](image1)
![Figure 2b. Antenna array tilted at a certain angle (Right)](image2)

To determine \( u_i \), the problem must be solved first by considering the antenna array panel to be rotated about \( x \) or \( y \)-axis. In the case of this experiment, the antenna array is rotated around the \( y \)-axis. By referring to Figure 3, when changing \( u_i \) by \( \phi \), the new coordinate of an antenna element becomes \( [x_2 \ y_2 \ z_2] = [\sqrt{x_1^2 + z_1^2} \cos \phi \ \ y_1 \ \sqrt{x_1^2 + z_1^2} \sin \phi] \). Then when orientating the antenna array panel by \( \theta \), it will be rotated about the \( z \)-axis. This will change the final coordinates of the antenna element to become \( [x_3 \ y_3 \ z_3] = [\sqrt{x_2^2 + y_1^2} \cos \theta \ \sqrt{x_2^2 + y_1^2} \sin \phi \ z_2] \).
In the experiment, the $y$-axis of antenna array panel is facing close to the southern direction and tilted at an unknown angle facing to the West. As the North direction is the reference $y$-axis direction, the azimuth orientation error of the antenna array panel is expected to be around 180 degree and elevation orientation error is expected to be some negative angles. The deployment of the radar receiver panel during the experiment is illustrated in Figure 4.

From the estimation of LSE shown in Figure 5, the largest inverse sum of residual errors of all channels are found to be $\theta_{\text{err}} = -176.5^\circ$ and $\phi_{\text{err}} = -42.5^\circ$ as shown in Figure 5. This estimation satisfies the aforementioned experiment scenario. The phased-array receiver can also be used to search for the DOA of air target accurately once the phase errors at the antenna array are properly calibrated.

---

**Figure 3.** Translations of antenna coordinate by $\theta$ and $\phi$

**Figure 4.** The satellite view of the experimental site and the orientation of the antenna array

**Figure 5.** The Inverse sum of residual errors of all channels estimated from LSE model
3. RADAR RECEIVER MODEL

3.1 Structure of receiver

The radar receiver used in this experiment is formed by 4 sub-array panels (see Figure 2) that consist of 8 dual-polarised (i.e. vertical and horizontal) elements per panel. The configuration of the antenna elements of the sub-array is illustrated in Figure 6. These 4 panels are configured in a 2x2 planar array and utilised to capture both direct and reflected GPS signals. As illustrated in Figure 7, the direct and reflected GPS signals that are captured by the phased array are down converted by the IQ front-ends at intermediate frequency of 420 kHz and sampled at 4.167 MHz by a digitizer using a common local oscillator. Then a snapshot of digital data of around 960 milliseconds is stored into a personal computer (PC) via an FPGA, which are then analysed and post-processed using MATLAB.

![Figure 6. Layout of sub-array panel with dual-polarised elements (in cm)](image)

![Figure 7. Block diagram of the current radar hardware](image)

3.2 Signal Processing Module

This section briefly outlines the post-processing part of the captured signals. Initially, one of the elements in the array is selected to perform Doppler search for the GPS direct path signal. When the time domain information (i.e. C/A codes and 50 Hz modulation) is obtained, it will be correlated with the data at every element, such that the phase of GPS direct signal can be acquired to solve the phase and geometrical orientation errors of the receiver. Next, the receiver will perform Doppler-range search at each channel. This process initiates Doppler...
search from the Doppler frequency of GPS direct signal, which is obtained at the beginning of the process and scans up to 1.5 kHz range. The range search works as delay-shifting the digital data at every element in time from 0 to 3 samples. Instead of performing integration for the whole data snapshot of 960ms, the data is partitioned into 10 time frames, which means that the correlation process is performed between these data and C/A codes for 96ms at every frame. The reason of taking such consideration will be brought out in Section 3. The correlation values of all elements will finally be brought into the conventional beamformer and direction finding will be made across all possible DOA to search for signature of target.

3. EXPERIMENT SCENARIO

The experiment is performed nearby Adelaide airport. The radar receiver is deployed at about 600 metres away from the airstrip and very close to the landing flight path of airliner. Notice that the reference of azimuth angle used in this experiment defines 0 degree as East, 90 degree as North, -90 degree as South and ±180 degree as West while the reference of elevation angle defines 0 degree as grazing angle and 90 degree as horizon. The antenna array panel is facing westward, which implies that the azimuth angle of an approaching landing aircraft that was chosen as the target relative to the receiver is expected to appear initially at around -180 degree and then increasing by time while the elevation angle should be gradually increasing. This aircraft is expected to fly at extremely low altitude and constant velocity of around 75m/s. In that case, the distance of an aircraft would appear to be around 100 metres away from the receiver such that the receiver can be capable of capturing the signature of target. However, the receiver would expect a rapid change of Doppler frequency of reflections due to the close distance, which means the angle of the target relative to radar receiver will be significantly changed within 960ms. Therefore, using long integration periods for increasing the gain of signals is not recommended since the Doppler change will reduce the power level of reflections.

Figure 8. The flight path (shown in yellow line) of an approach landing aircraft
4. EXPERIMENTAL OUTCOME

After applying Doppler-range search and taking the maximum output of the beamformer, the Doppler-range maps (Figure 9) that was generated using the correlation technique between the digital data at the 3rd time frame and C/A codes of four GPS satellites received positive returns at their corresponding Doppler offsets. The ephemeris information of these satellites regarding of their PRN group and DOA relative to the receiver as provided by “JSatTrak” are listed in Table 1.

<table>
<thead>
<tr>
<th>PRN #</th>
<th>Azimuth angle (degree)</th>
<th>Elevation angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>52.12</td>
<td>26.56</td>
</tr>
<tr>
<td>4</td>
<td>-22.43</td>
<td>39.90</td>
</tr>
<tr>
<td>12</td>
<td>-124.5</td>
<td>38.35</td>
</tr>
<tr>
<td>24</td>
<td>137.4</td>
<td>25.79</td>
</tr>
</tbody>
</table>

Table 1. DOA of GPS satellites that receive positive returns from signature of target

It can be noticed that the Doppler offsets that correspond to all satellites are distinct from each other. In fact, there are multiple returns from each PRN at various Doppler offsets. These returns are suspected to be the reflections of GPS signals from different part of the aircraft body. The DOA information of these returns can be obtained from the beamformer to verify such hypothesis. Hence, the strongest return of each PRN is selected and their DOAs are obtained using the conventional beamforming approach (Figure 10). Note that for PRN12, the
returns that appear above -50 Hz at the Doppler-range map are excluded from analysis since they correspond to the GPS direct path signal (i.e. Doppler offset = 0Hz for PRN12 in Figure 9). Although the direct path signal were attempted to be removed from the data based on the estimation using Wiener filter as demonstrated by Pui & Trinkle (2013), their presence still appear to be much stronger than the reflections. Table 2 shows the Doppler offset and DOA information of the strongest returns for each satellite.

<table>
<thead>
<tr>
<th>PRN #</th>
<th>Doppler offset (Hz)</th>
<th>Azimuth angle (degree)</th>
<th>Elevation angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-500</td>
<td>-157</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>-433</td>
<td>-158</td>
<td>61</td>
</tr>
<tr>
<td>12</td>
<td>-66</td>
<td>-157</td>
<td>62</td>
</tr>
<tr>
<td>24</td>
<td>-285</td>
<td>-149</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 2. DOA of the strongest target signature for each satellite

From the above analysis, it can be observed that the returns from all satellites are very close to each other. The azimuth angle of return for PRN24 however varies by about 10 degree from the others. Further investigation has been made by observing the DOA of third strongest signature (i.e. -328 Hz) for PRN24 at the beamformer. From Figure 11, the peak beampower of this signature appear at azimuth and elevation angle of -156 and 65 degree respectively, which is much closer to the DOA of signatures from other satellite. Such observation can explain the hypothesis which is mentioned earlier in this section.
Another observation is made by further investigate how Doppler offset and DOA of target signature varies across the whole timeline of 960ms. Recall that partition has been made for the captured data into 10 frames, where each frame performs integration of data for 96ms. The target signature of PRN02 is chosen for the observation.

From analysis earlier in this section, the target signature usually appeared between the first and second range bin. The range bin is expressed by each sample of data propagated in time, which is equivalent to a distance of $\frac{c}{f_S} = 72$ metres. Such condition satisfies with the experiment scenario as the aircraft appeared to be less than 100 metres from the receiver. Also, the distance that an approaching landing aircraft can travel in nearly a second is about 75 metres, which means that the target signature will be shifted no more than two samples within 960ms. Therefore, the Doppler-time map for PRN02 at 2nd range bin is studied. As shown in Figure 12, it can be observed that the target signature appeared initially at -490 Hz and gradually decreased to -530 Hz towards the end of the timeline. This can explain the rapid change of Doppler offset for a target that is very close to the receiver as a result of varying $\beta$.

The Doppler offsets that correspond to the strongest return azimuth and elevations from the consecutive time frames of the Doppler-time map for PRN02 at 2nd range bin along with their DOA information shown in Figure 13 are recorded in Table 3 and these results show the
azimuth and elevation angles increased gradually with time and this satisfies with the changing of position of the aircraft along the flight path in this detection scenario as previously mentioned in Section 3.

<table>
<thead>
<tr>
<th>Time frame</th>
<th>Doppler offset (Hz)</th>
<th>Azimuth angle (degree)</th>
<th>Elevation angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-490</td>
<td>-160</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>-500</td>
<td>-157</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>-505</td>
<td>-156</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>-520</td>
<td>-153</td>
<td>68</td>
</tr>
<tr>
<td>7</td>
<td>-525</td>
<td>-153</td>
<td>71</td>
</tr>
<tr>
<td>8</td>
<td>-535</td>
<td>-149</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 3. Doppler offsets and DOA of target signature for PRN02 at different time

Figure 13. Doppler offset and DOA of target signature for PRN02 at varying time frame
5. CONCLUSION

This paper has presented the results of GPS bistatic radar system that performed aircraft detection using phased array receiver. The results indicated that with sufficient array gain and integration periods of appropriate length, the receiver of this kind of passive bistatic radar is able to detect and track a moving target, particularly aircraft. The multiple numbers of satellites also demonstrated the flexibility of choosing transmitting sources to compensate the disadvantages of passive bistatic radar where target detection are restricted by the geometrical issue and the lack of direct control to the transmitting sources. This paper also shows the capability and convenience of performing phase and orientation errors calibration for the GPS phased array receiver with the aid of GPS signals. Additional work will be carried on for GPS bistatic radar, such as to locate the position of target and getting a better approach in suppressing the GPS direct path signal that might affect target detection.

ACKNOWLEDGEMENTS

The authors are grateful for the help of Dr. Abraham du Plooy from Opt-Osl Systems for the design and manufacture of the high gain dual-polarised GPS antenna array used in this experiment. Opt-Osl Systems is a RF company in South Australia specialising in research design and manufacture of RF and Microwave systems (http://www.optosl.com).

REFERENCES