Design and Test of Altitude Measurement for Planetary Landing Radar

Tomohiko SAKAI1, Seisuke FUKUDA1, Teppei SATO2, Hideho TOMITA, and Takahide MIZUNO1,
ISAS/JAXA1, Tokyo University of Science2

Abstract
Institute of Space and Astronautical Science JAXA develops the radio altimeter and velocity meter (landing radar) that is one of mandatory navigation sensor for a planetary lander. The landing radar can measure its relative altitude and speed from planetary surface by C band (4.3[GHz]) pulse. The BBM with the function which can measure speed and altitude simultaneously was manufactured and the field experiment has been done by using helicopter that carried the BBM radar. From the result of the field experiment, the BBM radar realized the design performance and attained 5[%] of the required accuracy from the lander system. It was also able to evaluate the geographical feature dependability of measurement accuracy by comparing a natural surface with an ideal surface at the Airport. This paper introduces the BBM and the algorism of altimeter and describes the result of field experiment.

1. Introduction
The Institute of Space and Astronautical Science, Japan Exploration Agency, ISAS/J AXA, has been developing the landing radar for future lunar/planetary landing missions since 2001. While originally for the SELENE-B mission, it is considered to be an essential sensor for the future post-SELENE series. The landing radar can measure its relative altitude and speed from planetary surface by C band pulse. To do science observation satisfactorily, robust measurement is required even against the complicated surface, for example where altitude deviation is about 100 m. In the following, Section 2 overviews the system of the landing radar. In Section 3, the method of altitude measurement employed by the radar is explained in detail. The link budget based on the radar equation is shown in Section 4. Results of helicopter experiment with a bread board model, described in Section 5, are reviewed and discussed in Section 6. Section 7 gives conclusions.

2. Outline of landing radar
The landing radar measures altitude and velocity from the lunar/planetary surface. The
range of the measurement is from thousandths of meters from the surface to ten of meters just before landing. Required measurement accuracy is less than 5[%] for both altitude and velocity. In addition, since this radar is a navigation sensor for lunar/planetary spacecrafts, it is required to be a robust system even against unknown surfaces. The radar consists of five beams. Four beams with 15[deg] beam-width are used to measure velocity, inclining by 30[deg] from the explorer axis. The other beam with 40[deg] beam-width for altitude measurement is in the direction corresponding to the explorer axis. The concept of the beam configuration is shown in Fig.1. The wide beam used for the altitude measurement prevents attitude fluctuation of spacecrafts from biasing the altitude accuracy. The pulse sequence alternately transmits the vertical and slanted beams. The Pulse Repetition Interval (PRI) is 51.2 [usec]. The four slanted beams are switched in each 50[msec]. Therefore, it takes 204 [msec] to complete one sequence.

The landing radar has three measurement modes that depend on a distance from the surface: The Long, Middle, and Short mode. In Short mode, a width of a pulse is shorter than that of the Middle mode. Phase difference between transmission and reception clock can improve measurement resolution without increasing the frequency of A/D conversion. The resolution of 0.234[m] (1.56[nsec]) is obtained by making the phase difference of 16. In Long mode, the code compression is used to increase a measurement distance without reducing a resolution. The Minimum Peak Side lobe (MPS) code is used, and a gain of the code compression is obtained 14.5[dB] by using the pulse line of 28bit.

3. Principle of altitude measurement
As shown in Fig.2(a), the Gate Track Method employs four Gates: ED (Edge Detect), FD (Fault Detect), AGC (Auto Gain Control), and Noise Gate. The distance is measured with the ED Gate, which is settled so that the integrated value in the Gate becomes zero at the position of 1/2 of the peak of a reflected pulse. The gate width is equal to the pulse-width. FD Gate is located forward of ED Gate to prevent from false lock. It always tracks the first leading edge of the reflected pulse, even when there are some notches in the pulse. The width of AGC Gate changes in proportion to distance, and a lock judgment is done in the ratio to Noise Gate. In the Short mode, the width of each Gate become 1/10, because of the pulse-width changed 1/10. In the processing of the Gate Track Method, a DSP chip will be used. Its availability for space application, however, is not good, and radiation resistance is low.

Therefore, as a method that does not use DSP, we propose the First Threshold Detection Method (FTD). As shown in Fig.2(b), the method detects a point that exceeds a threshold for the first time. The threshold is determined based on a noise level. Some sufficient numbers of pulses are integrated incoherently before the threshold detection. A relative large memory is necessary to sample the whole pulse. A threshold level is variable by the noise level to be constant in false alarm rate. In Long mode, the threshold level is calculated from the peak level in consideration of the code side lobe when S/N is high. In case that an error between
signal and tracking point is beyond a constant value, it doesn’t judge as a signal to prevent false detection. But, when the error from a tracking point is continuously exceeded, it judge as a correct signal. The characteristic of two methods are summarized in Table 2.

Table 3 shows estimate of link budget. The transmitter power is 1[W] at BBM model and 20[W] at FM model. The backscatter coefficient is grass on Aso (BBM) and rock on the moon (FM). On the surface of the moon, strength of reflection wave from vertical beam is strong and from the diagonal beam is weak compared with Aso. As a result of Table 3, the radar can measure up to 3500[m].

Table 2 Characteristics of two methods

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Gate Track Method</th>
<th>First Threshold Detection Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change of system response velocity according to reflected pulse forms</td>
<td>The influence of change of waves is small</td>
<td>Slightly long acquisition time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short acquisition time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small memory capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large memory capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Need DSP or CPU like command sets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relatively easy implementation on FPGA</td>
</tr>
</tbody>
</table>

4. Link budget

The radar equation is given below

\[ R^4 = \frac{P_t G_t \lambda^2 \sigma}{(4\pi)^3 k T_0 \frac{1}{\tau} (NF) \frac{(S_0/N_0)^2}{n} L_s (n) L_{other} L_p} \]  

(1)

- \( R \): Slant Range
- \( P_t \): Transmitter Power
- \( G_t \): Antenna Gain
- \( \lambda \): Wavelength
- \( NF \): Noise Figure
- \( (S_0/N_0) \): \( S/N \) of 1 pulse
- \( n \): Number of incoherent pulse integration
- \( L_s (n) \): Loss of incoherent pulse integration
- \( L_p \): Swinging loss by change of target
- \( L_{other} \): Transmission Loss

5. BBM (Bread Board Model)

The landing radar consists of a signal processing part, a RF part, and an antenna part (Fig.3). The signal processing part is divided into analog and digital signal processing parts. In the digital signal processing part, timing signal generation, removal of DC, AGC control, matched filter for 28bit MSL code, amplitude detection, the decision of the threshold, the detection of the tracking point are done (Fig.4 (a)). In the analog signal processing part, a phase control that controls sampling timing, quadrature demodulation, and A/D conversion are executed (Fig.4 (b)). RF part consists of a power amp for transmission, a 80[MHz] standard signal generator, 350[MHz], 3.95[GHz] synthesizer, up converter for transmission, down converter for reception, and a power supply. It carries out pulse generation of 1[W], signal generation to change the timing between transmission and reception, level control of transmission, up and down conversion of frequency. The antenna employs a patch array antenna of 8*8 elements that share for altitude and speed measurement (Fig.4(c)). For altitude measurement the beam with 42[deg] beam-width is formed by the four elements in the corner, and remaining 60
elements are used for speed measurement with 12[deg] beam-width. The beams are switched with PIN diode switches. A power distribution to the array feeds with Taylor distribution to suppress a side lobe level. The Wilkinson-type distribution circuit is used to maintain the isolation between arrays. As a result, the side lobe level is suppressed less than -23[dB] to the main beam (Fig.4 (d)).

6 Result of examination

6.1 Purpose of examination
We performed a field examination with a helicopter to check the landing radar that we designed the algorithm. As test sites, the Kumamoto Airport and the ranch zone around Mt. Aso are selected as an ideal flat surface and a natural rough surface. The field examination is divided into the experiment to evaluate precision for the flat surface and the experiment to check the operation for the natural surface.

6.2 Result of altitude measurement
There are two purposes of the field examination, one is to evaluate precision for the flat surface and the other is to check the operation for the natural surface. Accuracy of altitude measurement is evaluated in comparison with GPS equipped with the helicopter in Airport. Result of altitude measurement in Airport appears in Fig.5 (a) when the helicopter flew above about 230[m] on Airport at a fixed velocity. An altitude reference is used a value that subtract the geoid and the surface altitude from the GPS altitude. The surface altitude data is used the 10[m] mesh DEM (Digital Elevation Models). Both First Threshold Detection and Gate Track Method measure precisely. The result of altitude measurement accuracy is shown in Table.4. The measurement error is within 2[%] and it was confirmed to satisfy request precision sufficiently. It doesn't make much difference between two methods in accuracy. In the Gate Track Method, an acquisition time is proportional to an altitude because of a method to sweep from a short distance. The acquisition time takes 0.3[sec] at 1[km] and 1.1[sec] at 3.5[km]. The stability of the track falls with increasing a sweep speed, so it is difficult to improve the acquisition time. On the other hand, in First Threshold Detection Method, it takes constantly 50[usec] to judge at each reflected pulse. It is possible to track again at once, even if the radar loses the reflected wave while descending.

Fig.5 (b) shows the result of altitude measurement to descend from 1000[m] to 300[m]. An attitude of the helicopter has inclined 15[deg] at maximum owing to do a nosedive. However, it
doesn’t affect the tracking point. The error is within 3\%. Beam-width is so wide that the change of the attitude is absorbed.

The result of altitude measurement in the natural surface is shown in Fig.5(c). In this area, there are ups and downs of about 100[m] (Fig.6). The evaluation is difficult in natural geographical features because the measurement principle is different from GPS. The altitude measured with the radar is a distance with a shortest point in beam-width 42[deg]. In a valley, the radar tracks a rim of the valley as the shortest distance. On the other hand, GPS calculates height from the GPS base level and fixes altitude from the topographical map of 10m mesh. Therefore, it becomes a distance from the right under of the helicopter. If beam-width expands, it becomes robust structure to the change of the posture. If it makes beam-width wide too much, a probability to measure the distance from the right under of the helicopter become low, because the radar measures the shortest distance. Relation between beam-width and effect of the topography are trade-off.

In this way, it is possible to measure for the complicated natural geographical features too. However it is necessary to evaluate geographical features before landing.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>FTD</th>
<th>Error[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1.8</td>
<td>1.36</td>
</tr>
<tr>
<td>300</td>
<td>0.52</td>
<td>1.04</td>
</tr>
<tr>
<td>500</td>
<td>0.33</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Relation between beam-width and effect of the topography are trade-off.

In this way, it is possible to measure for the complicated natural geographical features too. However it is necessary to evaluate geographical features before landing.

**Table 4 Result of measurement accuracy**

<table>
<thead>
<tr>
<th>Altitude</th>
<th>FTD</th>
<th>Error[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1.8</td>
<td>1.36</td>
</tr>
<tr>
<td>300</td>
<td>0.52</td>
<td>1.04</td>
</tr>
<tr>
<td>500</td>
<td>0.33</td>
<td>0.66</td>
</tr>
</tbody>
</table>

6.3 Receive level

Fig.7 shows the result of receive level in Aso. Both the altitude and the velocity receive level correspond with the theoretical curve. They are proportion to cubed. The link budget is proper from this result. On the surface of the moon, the backscatter coefficient and the transmitter power are different from Aso (BBM), but it is possible to measure up to 3500[m].
7. Conclusion
The field experiment using BBM of the landing radar was carried out, and the performance and the function of the radar were evaluated. The field experiment evaluated Gate Tracking Method and First Threshold Detection Method. As a result, it became clear that both of the algorithms had attained required accuracy. In addition, the measurement for a natural feature like a pasture is also possible. When the airframe inclines, it doesn't influence the measurement. The pulse acquisition time of First Threshold Detection Method is only 51.2[usec]. All the functions of the landing radar about altitude measurement is well, and it is necessary to evaluate about the influence of geographical features before landing.

References