A Novel Method of Velocity Measurement for the Lunar/Planetary Landing Radar

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Abstract
A radar for navigation in future lunar/planetary landing missions is developed in the ISAS/JAXA. The C-band pulse radar provides not only altitude information but also relative velocity against the surface, so that the spacecrafts can perform soft landing safely. A novel method of velocity measurement is proposed in this paper. This method is based on the Doppler measurement at multiple points within a received pulse. While the Doppler frequency at each point also has a kind of ambiguity caused by restriction of range resolution corresponding to a pulse-width, the most probable velocity can be estimated by fitting the multi-point measurement with a theoretical curve in the plane of range time and the Doppler frequency. Additionally, in order to make the method robust, vertical altitude is swept over a range of its possible error and roughness of the target surface. Analytical results with data of helicopter-based field experiments as well as Monte Carlo simulations demonstrate that the proposed method is able to measure the velocity satisfactorily within required accuracy for the safe soft landing.

1. Introduction
The ability of pinpoint soft landing on lunar or planetary surfaces, where we want to examine, broadens the range of scientific and exploration missions. In order to perform the pinpoint landing, measurement of relative velocity against the surfaces is considered to be essential. The ISAS/JAXA has been developing a landing radar for future lunar and planetary missions, though originally for the SELENE-B mission. The C-band pulse radar provides not only altitude but also velocity information. The integrated configuration of the altimeter and the velocity meter is mainly because of restricted weight budget in expected missions. Required accuracy of the velocity measurement is less than 5% or 10 cm/s. In this paper, a novel method of the velocity measurement for the landing radar is presented (see [1] for the altitude measurement). First some problems around the velocity measurement are reviewed in Section 2. In Section 3, the newly proposed method based on utilization of Doppler frequencies at multiple time samples is described. The results applied to Monte Carlo simulations and experimental data using a helicopter are shown in Section 4 and 5. Finally, some concluding remarks are given in Section 6.

2. Problem Definition
The Doppler effect is of course used for the velocity measurement of the landing radar. In most pulse-type radars, the velocity (i.e., the Doppler frequency) is measured by phase rotation between
two received pulses. The range of the measurable velocity by these pulse-Doppler radars depends on carrier frequency and PRF (Pulse Repetition Frequency). The pulse-Doppler radar is familiar technology in the field of aircraft navigation. In a broad sense, the landing radar can be classified as the pulse-Doppler radar.

The Ku-band airborne radars can narrow the beam width with relatively small antennas. On the other hand, since our landing radar is employing C-band (4.3 GHz) due to the integrated configuration with the altimeter, the beam is as broad as 15 degrees; the value seems a kind of limit when considering the size of the antenna on the lunar or planetary landers. Furthermore, it has to be considered that attitude of the landers might fluctuate between ±15 degrees against the surface.

Every Doppler radar intrinsically measures the Doppler frequency in the line-of-sight direction. The properties of the landing radar give difficulties that the line-of-sight direction is not constant, because the received pulse is extended in the time domain corresponding to the beam width, or the line-of-sight is biased by the attitude fluctuation. In the early phase of the development, a method that regards the averaged Doppler frequency in a certain gate as the component from the center direction was investigated [2]. The above-mentioned difficulties, however, prevented the gate-based method from achieving the required accuracy.

Assuming that the surface is flat, a look angle, \( \theta \), corresponding to a time sample, \( t \), is easily calculated with altitude information, \( h \), such that

\[
\theta = \cos^{-1} \left( \frac{h}{ct/2} \right)
\]  

(1)

where \( c \) is the speed of light. Using the angle, horizontal velocity against the surface, \( v \), is obtained from the Doppler frequency, \( f_d \), at the time sample as

\[
v = \frac{\lambda f_d}{2 \sin \theta}
\]  

(2)

where \( \lambda \) denotes the carrier wavelength. The angle \( \theta \) is not necessarily the center of the beam as long as the S/N is enough there. This scheme is hereinafter called the single-point method, which uses only one time sample.

As depicted in Fig. 1, however, the received wave at a time instant is coherent summation of reflection from a part of the doughnut-shaped surface. So the Doppler frequency in (2) is distributed over the range \( \Delta f_d \) of (3). In (3) \( \tau \) is the pulse width. Accordingly, the single-point method suffers from ambiguity related to (3). While the ambiguity can be reduce by enhancing the range resolution, the width of the transmitted pulses is physically restricted to 10 ns or so.

Another problem concerning the single-point method is that it utilizes the altitude measurement \( h \), itself. The method, therefore, is directly affected by the altitude error (~5%) and the surface roughness.

3. Proposal of the multi-points method

Here, in order to overcome the problems in the previous section, a new method of the velocity measurement for the landing radar is proposed. It is based on an idea that the most probable curve is able to be determined from \( (t, f_d) \) plots in the plane of the range time and the Doppler frequency. It is referred as the multi-points method with some dozen of time samples. In this method, the Doppler frequencies at the multiple time samples, where the S/N is comparatively good without a notch of the level, are estimated through FFT or DFT. Though each Doppler frequency also has the ambiguity caused by the range resolution, an optimum velocity is derived by the least-squares regression (i.e., curve fitting)

\[
v = \frac{\lambda}{2} \cdot \frac{\sum_j f_{d,j} \sin \left\{ \cos^{-1} \left( \frac{h}{ct_j/2} \right) \right\}}{\sum_j \sin^2 \left\{ \cos^{-1} \left( \frac{h}{ct_j/2} \right) \right\}}.
\]  

(4)

Equation (4) contains the altitude \( h \). Hence, similar to the single-point method, the velocity would have to be influenced by the altitude error, if calculated straightforwardly. To avoid this, the altitude \( h \) is swept in a searching manner without using the immediate value in the multi-points method. The objective function is summation of the residual in the curve fitting as

\[
G(h) = \sum_j \left[ f_{d,j} - \frac{2\pi h}{\lambda} \sin \left\{ \cos^{-1} \left( \frac{h}{ct_j/2} \right) \right\} \right].
\]  

(5)
The velocity corresponding to the altitude that minimizes $G(h)$ is outputted.

4. Monte Carlo Simulations

The results of Monte Carlo simulations to ascertain that the multi-points method is superior to the single-point method are shown in this section. The input data of the simulations is multiple sets of $(t, f_d)$. The simulation conditions are summarized in Table 1.

Fig. 2 shows the result of both the single-point and the multi-points method with 15 and 50 ns pulse-width, respectively. From the figure, it can be seen that the multi-points method is able to satisfy the accuracy of 5 % by switching the pulse-width reasonably (e.g., the middle/short mode [1]). On the other hand, the accuracy of the single-point method exceeds 5 % in the low altitude of $h < 500$ m or so. No improvement of the accuracy can be seen even if the pulse-width is switched from 50 to 15 ns. In view of the fact that there is no difference of the accuracy between the 15 and 50 ns pulse at the altitude of $200 \sim 300$ m, it is supposed that the dominant error source is not the ambiguity accompanied with the pulse-width but the altitude error.

5. Application to Experimental Data

In March 2006, field experiments were done in Kumamoto Prefecture using the helicopter (MuPAL-ε [3]) equipped with the Bread Board Model (BBM) of the landing radar [1]. While then the single-point method was implemented on the BBM because of its simplicity, the baseband I/Q data was digitized and stored at 100 MHz sample rate. Evaluation of the multi-points method was carried out through application to this dataset.

The time samples of the multi-points method were provisionally selected as follows:

(i) Decide an amplitude threshold of a received pulse as $k \cdot [\text{peak level}];$
(ii) Divide the time range between the first and the last crossing of the threshold into $n$ samples equally;
(iii) Eliminate the samples where the amplitude level is below the threshold.

The parameters are settled as $k = 0.2$ and $n = 10$ in this paper.

The runway of the Kumanomoto Airport, which is an ideally flat surface, is appropriate for assessment of the velocity measurement. Fig. 3(a)–(c) illustrates the results at about 200, 300, and 500 m altitude. The helicopter flew at approximately constant velocity ($\sim 30 \text{ m/s}$). The reference data is DGPS/INS-based horizontal velocity provided by the onboard equipment [3]. As the BBM has a couple of beams inclining 30 degrees forward and backward from the perpendicular direction, averaged velocity of each measurement is plotted in Fig. 3. This is analogy with the JANUS configuration used in most airborne Doppler radars so as to cancel out effects of platform attitude such as a yaw angle.

$$\Delta f_d = \frac{2v}{\lambda} \left[ \sin \left\{ \cos^{-1} \left( \frac{h}{ct/2} \right) \right\} - \sin \left\{ \cos^{-1} \left( \frac{h}{c(t-\tau)/2} \right) \right\} \right]$$

bias error $= \left( \frac{\text{measurement} - \text{reference}}{\text{reference}} \right) \times 100 \, [%]$,

random error $= \left( \frac{\text{measurement} - \text{reference}}{\text{reference}} \right) \times 100 - \text{bias error} \times 100 \, [%]$. 

Table 1: Conditions of Monte Carlo simulations.

<table>
<thead>
<tr>
<th>Velocity</th>
<th>30 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler ambiguity</td>
<td>Gaussian random number $N(0.0, 29.4^2) \text{ Hz}^*$</td>
</tr>
<tr>
<td>Altitude error</td>
<td>Gaussian random number $N(3.0, 7.7^2) \text{ m}^*$</td>
</tr>
<tr>
<td>Number of samples**</td>
<td>10</td>
</tr>
<tr>
<td>Sweep of altitude**</td>
<td>immediate value ±25 m, 1 m interval</td>
</tr>
</tbody>
</table>

* Based on the FY16 field experiments
**Only for the multi-points method
Fig. 3 indicates that both methods agree with the reference data as the time trend of the measurement. The fluctuation of the measurement by the multi-points method is obviously less than that by the single-point method. For more quantitative investigation, Table 2 makes a summary of the bias and random errors defined as (6) and (7). The accuracy (i.e., random error) in the table is almost consistent with the results of the simulations in Fig. 2. The proposed multi-points method has realized the accuracy of less than 2%.

Fig. 4 shows the results of a ‘speed-up’ test from hovering to 50 m/s at about 300 m altitude. It is notable that the fluctuation of the multi-points method is independent of the velocity. That of the single-point method, however, increases with the velocity because the Doppler ambiguity $\Delta f_d$ in (3) is a function of $v$. Fig. 4 suggests that in the multi-points method the idea of the curve fitting in the $(t, f_d)$-plane works satisfactorily.

For the purpose of surveying the measurement performance against natural surfaces, the helicopter was flown over the ranch field around Mt. Aso. The test site is composed of a series of local rough hilly terrains as shown in Fig. 5. The results at about 500 m altitude are shown in Fig. 6(a). The velocity is also around 30 m/s. In the figure, some burst errors appear among the measured velocity by the multi-points method. This is because the sweep range of the altitude is not enough for the surface roughness; the range is ±20 m in Fig. 6(a) as well as in Fig. 3 and 4. The errors are considerably suppressed in Fig. 6(b) with the sweep range of ±100 m.

Even in Fig. 6(b), the measurement by the multi-points method, of course also by the single-point method, exhibits different variation from the reference data time by time. It is important to understand that, for the rough terrains, the horizontal velocity against the surface provided by the multi-points method and the GPS-based velocity are not identical in themselves like Fig. 7. And thus more sophisticated techniques to evaluate the results over the natural surfaces are left for future work. Needless to say, as the altitude increases, the local roughness is averaged within the irradiated spot so that the time trend of the measurement becomes close to the reference (Fig. 8: the results at about 1000 m altitude).

### 6. Conclusion

In this paper, a novel method of velocity measurement for the lunar/planetary landing radar has been presented. It is based on utilization of Doppler frequencies at multiple time samples. While each Doppler frequency contains ambiguity due to restriction of range resolution, an optimum velocity can be estimated by curve fitting with theoretical functions. Analytical results with data of helicopter-based field experiments as well as Monte Carlo simulations demonstrate that the proposed method is able to measure the velocity satisfactorily within required accuracy.

At present, the method is being implemented on the BBM of the landing radar as FPGA logic. Feasibility about the gate size and throughput has been already confirmed. Some refinements to facilitate the H/W implementation are being tried around the selection of time samples, etc. The final BBM-based field experiments using the helicopter are planed at the end of this FY.

### Acknowledgment

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### References


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Table 2: Summary of errors of velocity measurement over the runway of the Kumamoto Airport.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>single-point</th>
<th>multi-points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bias random</td>
<td>bias random</td>
</tr>
<tr>
<td>~200 m</td>
<td>-3.66 % 7.82%</td>
<td>-1.27 % 1.26%</td>
</tr>
<tr>
<td>~300 m</td>
<td>+0.36 % 6.60%</td>
<td>-0.55 % 1.93%</td>
</tr>
<tr>
<td>~500 m</td>
<td>-0.71 % 7.09%</td>
<td>-0.50 % 1.35%</td>
</tr>
</tbody>
</table>
Fig. 3: Application to experimental data over the runway of the Kumamoto Airport (velocity $\sim 30$ m/s).

(a) altitude $\sim 200$ m

(b) altitude $\sim 300$ m

(c) altitude $\sim 500$ m

Fig. 4: Application to experimental data over the runway of the Kumamoto Airport (velocity $\sim 0\rightarrow50$ m/s).

Fig. 5: Ranch field around Mt. Aso.
(a) sweep range of altitude: ±20 m

(b) sweep range of altitude: ±100 m

Fig. 6: Application to experimental data over the ranch field around Mt. Aso (altitude ~ 500 m, velocity ~ 30 m/s).

Fig. 7: Difference of measured velocity between the multi-points method and GPS.

Fig. 8: Application to experimental data over the ranch field around Mt. Aso (altitude ~ 1000 m, velocity ~ 30 m/s, sweep range of altitude: ±100 m).