Doppler Radar for Planetary Safe Descent and Landing

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***Abstract*— This paper discusses some basic requirements for a Doppler Radar intended to provide critical measures to be used for safe descent and landing on planets. Some considerations are briefly developed in order to establish a preliminary design of such a radar.**

I. Introduction

In recent years, an increasing interest for robotic and human exploration of the Solar System has been shown by governmental agencies, scientific community and industrial entities. In particular, the capability of a safe descent and landing of large payloads on planets has risen as a critical aspect for a large number of planned missions. At this scope, the use of a Doppler Radar seems to be one of the most effective way to provide accurate measures of velocity vector and distance from the surface. These measures are needed to guide the landing module during the descent phase down to an altitude where a safe drop is feasible.

II. Basic Considerations

In the framework of planetary exploration, a Doppler Radar (DR), as well as any other equipment, shall encounter tight requirements in term of mass, size and power consumption. In order to satisfy such mechanical and electrical limitations, it is advisable to have a single transmitter and receiver for all the operations and to employ the same antenna in both directions implying the use of a pulsed approach.

From the performance point of view, it is foreseeable the necessity to operate under a very large envelope of conditions for altitude, velocity, attitude and relevant rates of change. Stability and accuracy of measures, especially at low altitude, will also be drivers for the design. TABLE I, summarize indicative ranges for some parameters in order to have a baseline for a preliminary design.

A pulsed radar is also preferred because of its flexibility in term of radar parameters (PRF, pulse width, etc.) [1]. The assumed large intervals of operations will require adjustment of radar parameters to avoid ambiguities, blind zones and meet accuracy requirements.

TABLE I
Operative Envelope

Parameter	Max	Min
Altitude	3000m	10m
Velocity	90m/s	0.1m/s
Off-nadir angle	+40deg	-40deg
Off-nadir angle change rate	30deg/s	0deg/s
Measure updating rate	50Hz	2Hz

Another important issue to be accounted for is the autonomy of the instrument and reliability of its measures. In fact, due to the short time of typical descent phase (arguably, in the order of hundreds of seconds) there is not place for complex scheme of failure detection and/or error reporting to higher instances in the platform. The current baseline is such that the DR shall communicate with its platform only to receive a start command and to provide a full set of measures (comprising one range measure and three scalar velocities) at a fixed rate to a system in charge of guidance and control.

A further defining issue for the radar is the request for a three-dimensional measure of velocity. It is well known that using the Doppler effect it is possible to measure a scalar velocity in the fixed direction connecting the radar and the target. In order to measure both magnitude and direction of the velocity vector, in a certain reference frame, three independent scalar measures are needed. This implies the necessity to have an antenna capable to generate at least three separate beams that will be not parallel with each other. Moreover, because of conflicting requirements on radar parameters, it is also difficult to extract information of range from the same echoed pulse used for velocity measure. The final proposed solution is to have an antenna providing four beams in the configuration sketched in Fig. 1. One of the beams will be dedicated to range measurement along the x-axis of the module reference frame. The other three beams will provide three velocity measures along corresponding pointing directions that shall be not parallel. To keep the symmetry of the whole structure, the three beams devoted to

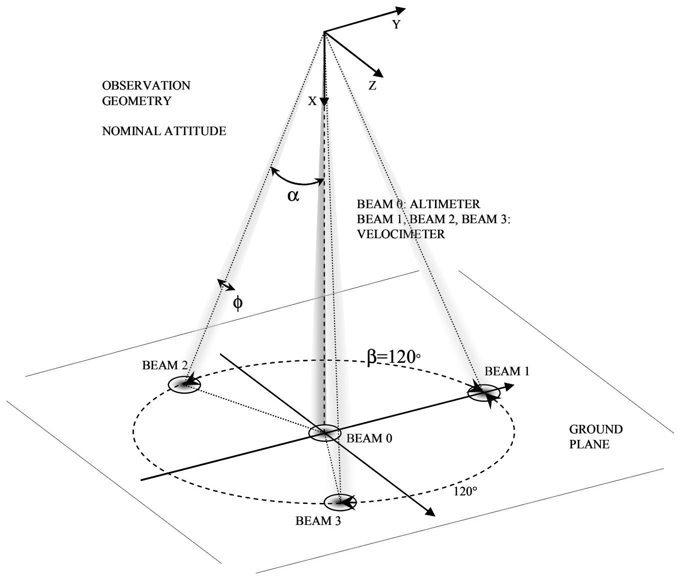

Fig. 1 Beam configuration

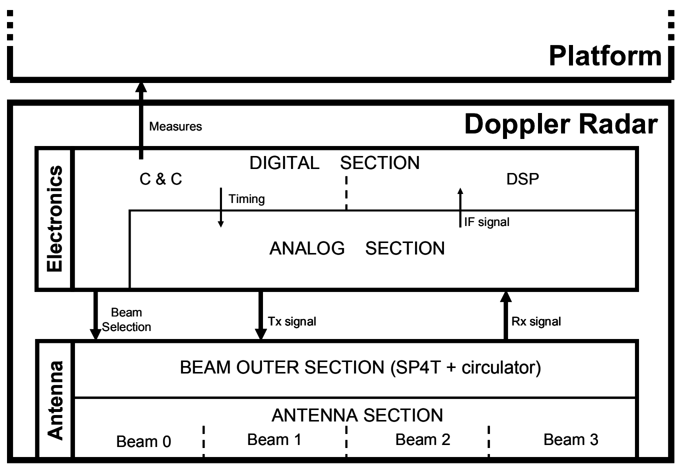

Fig. 2 Architectural diagram

velocity will point on a conical surface having the apex in the centre of gravity of the body and the axis coincident with the x-axis. The pointing angle α between the velocity beams and x-axis has been selected trading-off the following demands:

- Minimizing errors introduced by the transformation from the three velocities measured along the beams to the required velocity components in the reference frame.
- Minimizing echoes returning through a different beam.
- Worst-case angle of incidence on the surface given by the sum of the pointing angle and maximum off-nadir attitude of the landing module.

The first and second considerations favour greater pointing angle (but beam pattern is to be carefully evaluated in order to avoid echoes in the highest sidelobes). The third one limits the maximum pointing in order to still being able to receive echoes in most cases.

Another important consideration about the beam design is their aperture ϕ. It is envisaged to have pencil beams in order to keep cross-returns close to a minimum, to obtain higher directivity gain and to improve accuracy of the measures.

III. Carrier Frequency Selection

The selection of the carrier frequency is a major choice in the design of the DR. It impacts directly on size and mass as well as on performance. Size and mass considerations suggest using high frequencies (i.e. short wavelengths) in order to use smaller microwave components and to limit the antenna size needed to get the desired beam width. On the performance side, the main arguments to be introduced are:

- *the backscattering model of the terrain:*
  the minimum value for the terrain backscattering coefficient $\sigma 0$ and also its interval of variation are important parameters in the evaluation of the hardware requirements needed to meet the radar performance. Current models [2] foresee a smaller range of variation for $\sigma 0$ as frequency increases and also an higher absolute level for large incidence angles.
- *the need to have enough resolution in velocity measurement:*
  the selected approach to velocity measurement is to extract information by the Doppler-shift experienced by the radar signal as the landing module is moving in respect to the planet surface. It is well-known that the amount of Doppler-shift for a fixed velocity is a linear function of the carrier frequencies and, therefore, using high frequencies helps velocity measurement resolution and accuracy.
- *the beam aperture for a fixed antenna size:*
  beam aperture at higher frequencies shall be narrow in order to increase antenna gain and again to improve measurement accuracy.

All the factors briefly recalled above, push for a frequency carrier as high as possible (within a reasonable range). At the same time, availability and reliability for the hardware implementation, set an upper bound to frequencies usable for near-future missions. Taking into account both performance analysis and technological issues, the choice of a frequency within the Ka band seems to be the more promising.

An indicative block diagram of the whole Doppler Radar architecture (not including power section) is shown in Fig. 2. The DR is divided into two block namely Electronic Block and Antenna Block, each further divided into sections. The beam outer section routes the RF signals to the appropriate beam according to the command provided by the C&C part of the digital section. The Antenna Section will be constituted by different four slot arrays.

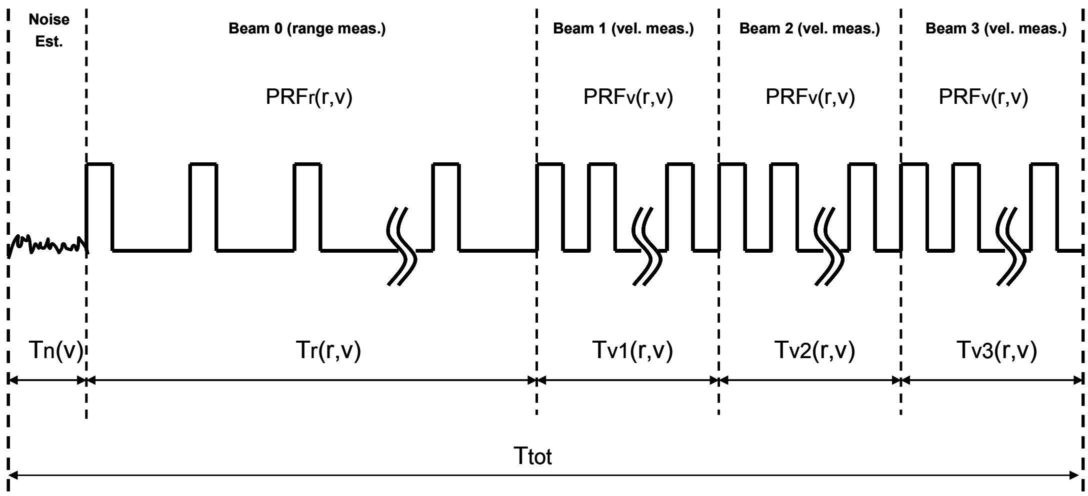

Fig. 3 Example of timeline

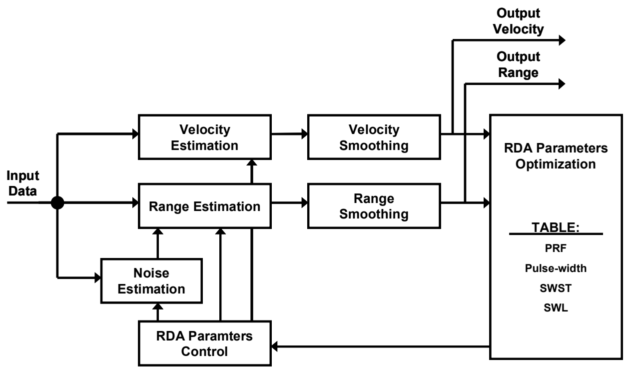

Fig. 4 Control loop philosophy

IV. Radar Parameter and Internal Control Loops

As stated before, a DR for planetary landing is likely to operate autonomously. The foreseeable short time of mission (e.g. from start of operation to airbags inflation before final drop) does not allow for any intervention for recovery from malfunctioning or for reaction of a higher instance to anomalous behaviour. Moreover, from an engineering point of view, it would be useful to have the DR as much as possible as a stand-alone unit. Therefore, even during normal operation, no information exchange apart from providing measures together with a validity flag is foreseen. For these reasons all instrument control and timing will be in charge of a computer internal to the DR.

A qualitative timeline is showed in Fig. 3 where the time available to acquire a set of measure is parted into separate time-slot devoted to different measures. Basic considerations in respect to ambiguity of both the altitude and velocity measures show the impossibility to select a fixed PRF value to be used for all the beams and for the entire mission range. Moreover, the required time of observation for velocity measure is inversely proportional to the velocity and will vary significantly during the descent phase. For this reason, the time-slot allocated for each beam within a cycle of acquisition of a new set of measure will be adapted.

Another important issue is relevant to the pulse length. The limited availability of transmitted power for the given technology, requires to have a certain pulse length to reach a sufficient signal-to-noise ratio. While the module is approaching the surface, the round-trip time becomes smaller and the pulse length is to be reduced in order to avoid superposition of sampling window with transmitting phase.

All the above considerations lead to the necessity to design internal control loops to adapt PRF, pulse length, sampling window and observation times according appropriate functions of altitude and velocity. The philosophy of the control is outlined in Fig. 4.

A. Information Extraction

1) Range

The extraction of information will be done digitally after RF downconversion to a low-IF and direct final baseband conversion and I/Q demodulation through digitisation at a rate 4 times the IF.

The information of range will be extracted measuring the round-trip time of the pulses. The leading edge of the returning echo will be detected. The range estimation process starts with the integration of the received echoes along the time-slot dedicated to range to improve signal-to-noise ratio. Then, the square of the modulus will be extracted and its value will be compared with a threshold to detect the crossing time. The threshold will be set according to the last noise estimation available. The crossing time will be converted to a delay in respect of the start of transmission and eventually to range estimation.

2) Velocity

Velocity estimation relies on the well-known Doppler's law that relate the radial velocity between radar and target with the frequency-shift experienced by the signal travelling from radar to target and back. The information of velocity will be extracted using a "pulse-pair" algorithm [3, 4] that is time-domain-based. In this way the computational effort needed to get the frequency-domain information is avoided.

Basically the pulse-pair algorithm consists in the computation of the phase of the autocorrelation function of the received signal. It can be shown that this phase is proportional to the velocity to be estimated. The two digitised baseband components of the received signal are low-pass filtered and decimated up to retain one sample per PRI then the pulse-pair algorithm is applied. The sequence will be repeated for the three velocity beams.

Finally a geometrical transformation to be applied to the measures is required in order to provide the velocity vector in the descent module reference frame.

V. Conclusions

This paper has given an overview of preliminary design for a Radar Doppler/Altimeter for safe planetary landing. A baseline has been derived according foreseeable mission needs, then consequent basic design choices and architecture of the Radar Doppler/Altimeter have been presented. Detailed design will be tailored to the specific mission requirements as available.

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