Radar Altimeter Processor Data Processing & Verification with GUI Development

Chandrayaan-2 Lander

Shloak Agarwal[1*], Ritesh Sharma[2], Sanjay Trivedi[2]

[1]Information and Communication Technology (ICT), School of Engineering and Applied Science, Ahmedabad University
[2]Microwave Sensor Data Acquisition and Processor Division (MSDPD), SAC, ISRO
*shloak.agwl@gmail.com

***Abstract*—Due to crater and boulder distribution on the surface of the moon, altitude and vertical velocity information often is difficult to obtain. Satellite radar altimeter has a potential to monitor height and velocity variation. Here, it is shown that the radar altimeter can successfully track the altitude and vertical velocity from the height 9.9 km to 2 m. For the landing of Chandrayaan-2 on the Lunar surface, the data obtained by radar altimeter is very crucial. This paper describes the altimeter operation principle, H/w data acquisition, ADC analysis, altitude and Vertical Velocity results.**

***Keywords*—Radar altimeter, altitude, vertical velocity, Chandrayaan-2, ENOB, SINAD, THD, SFDR, up-chirp and down-chirp**

I. Introduction

This article describes the development and implementation of altitude and vertical velocity of Chandrayaan-2 (Lunar-2) lander with the data provided by the radar altimeter. Chandrayaan 1 became the first successful mission of India to study the surface of the moon, similarly, ISRO has a planned another mission, Chandrayaan 2, on the lunar surface to gather information on the lunar region, mineralogy, elemental abundance, lunar exosphere and signature of hydroxyl and water [1]. During the Chandrayaan 1 mission, the Polar Satellite Launch Vehicle (PSLV) carried the satellite to the orbit of the moon but this time, a new fourth-generation vehicle, Geosynchronous Satellite Launch Vehicle Mark II (GSLV Mk II) will carry the module which consists of an orbiter, a rover and a lander to the moon. Chandrayaan-2 will reach lunar orbit after its launch within a month or two. On the arrival to the lunar orbit, the lander gets detached from the module and performs a soft landing near the south pole of the moon. According to ISRO, the rover is fixed on the lander and gets separates when reached to the surface. The rover has a battery which will provide power up to one lunar day (14 Earth days) on the moon surface and will hover about 500 m during the mission. Rover will study lunar surface and send images to Earth station via orbiter [2].

II. Planning

Chandrayaan 2 is planned with a circular orbit of 100 km altitude with orbiter and Lander together as a cluster. After separation from the orbiter, the Lander accomplishes autonomous soft landing with approach phase wherein it reaches an altitude of 10 km from the lunar surface followed by descent phase. One of the key elements essential for the safe landing is the Hazard Detection and Avoidance (HDA) system [3]. This system locates potential hazards in the planned landing site and provides alternate areas on a real time basis. The HDA system proposed, several sensors like Orbital High-Resolution Camera (OHRC) for characterization of predefined Landing Site, Camera for Horizontal velocity calculation, Camera for pattern matching and position estimation and microwave altimeter. The onboard data processing required for these HDA sensors are also supported by SAC. The scheme consists of the following components:

- Landing site identification prior to the mission
- Landing site characterization during orbital phase using OHRC data
- Horizontal Velocity Computation using Optical Images
- Pattern Matching and Position estimation (Reference path-based Guidance)

Chandrayaan 2 Landers most challenging task is to accomplish soft-landing. To achieve the same, gamut of sensors and actuators have been planned. One of the prime sensors is radar altimeter which will provide altitude and vertical velocity information for the Navigation, Guidance and Control (NGC) system of the Lander. Other than the above mention sensor, the Chandrayaan 2 also includes Lander Position Detection Camera (LPDC) and Lander Hazard Detection and Avoidance Camera (LHDAC). The sensors (Altimeter and LPDC) will come into operation at an altitude of 9.9 km, and the LHDAC cameras will be used during hovering (at 100m height) and descent phases. The height and vertical velocity information from Altimeter is required with an accuracy of 0.3m and

TABLE I: Requirements

Parameter	Requirements
Altitude Estimation Range	9.9 km to touchdown (3 m)
Altitude Accuracy	0.3m or 0.01% of altitude (worst of both)
Vertical Velocity Accuracy	0.4m/s

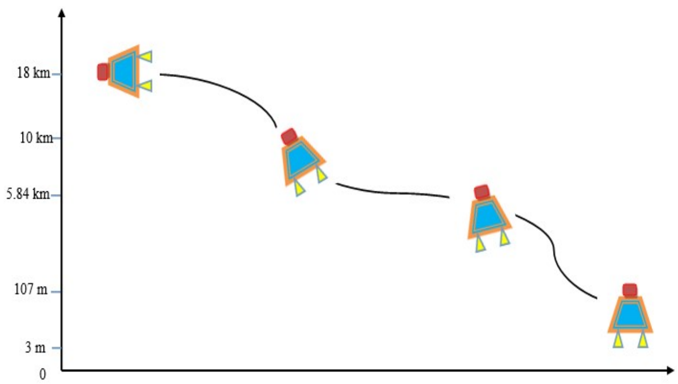

Fig. 1: Trajectory profile of Chandrayaan 2

0.4 m/s, respectively. Following are the requirements on the altimeter and HDA (Hazard Detection and Avoidance) cameras specified by the mission, that is shown in TABLE I [4]:

As you can see in the Fig. 1, the trajectory profile of Chandrayaan 2.

III. LITERATURE REVIEW

A. *Radar Altimeter*

- Purpose
  The main purpose of the radar altimeter is to estimate the instant altitude of the aircraft from the ground level.
- Basic Principle
  The basic principle of the radar altimeter is to measure the altitude using the radio ranging, that is, measuring the elapsed time between the transmission and reception of the Electromagnetic Waves after the reflection from the object. The altitude is given by half the product of the elapsed time and the speed of light [5].

  The Fig. 2 shows the lander and on its side the altimeter is fixed.

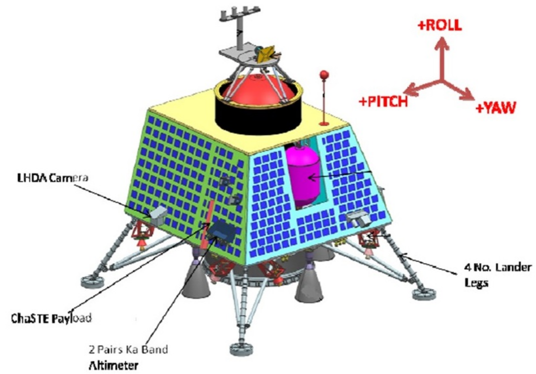

Fig. 2: Lander [4]

B. *Frequency Modulation Continues Wave (FMCW)*

- Principle of Operation
  A radar signal (Electromagnetic Waves of specific frequency) is emitted through an antenna, which gets reflected back from the object and received after a time T. The principle used is known as Frequency Modulated Continuous Wave (FMCW). The FMCW-radar transmits a high-frequency signal whose frequency increases linearly during the measurement phase (called the frequency beat) [6].
- Conventional FMCW
  In a conventional FMCW altimeter, the carrier frequency of 4200 MHz to 4400 MHz, is varied linearly, at a known rate, over the pre-defined range. Instead of measuring the time between the transmission and reception of the signal, the change in the carrier frequency is measured and is divided by the rate of change, giving the total travel time T. To measure the change in carrier frequency during the two-way travel time the echo is mixed with a sample of the signal being transmitted at the instant and the beat frequency is derived. The beat frequency is proportional to the altitude [7].

  The disadvantage of using simple continuous wave radar devices without frequency modulation is that it cannot determine the range, as it lacks the timing mark which is necessary for the system to measure the time difference between the transmitted signal and the received signal which is used to calculate range. In this method, the transmitted signal increases or decreases with respect to the frequency. In the received signal there is a change of frequency which gets delayed, t, similarly in the pulse radar technique. In the FMCW radar altimeter, the range is measured as the difference between the frequency of the transmitted signal to the received signal.

C. *Ka-Band*

Ka-band system has been chosen mainly to minimize mass and volume of the system. As per Recommendation, 35.500 GHz to 36.000 GHz has been identified as a frequency band for Active Remote Sensing in the Lunar Region. Hence, centre-frequency of 35.75 GHz and bandwidth of 240 MHz has been chosen for this altimeter [4].

D. Running Moving Average

Moving average, also known as rolling average or running average, is used to calculate data points, by creating an average of a small subset, form full data set. It is also called as Moving Mean (MM) or Rolling Mean. It is a type of finite impulse response filter.

The working algorithm is simple. From the given series of numbers, a fixed subset size is chosen. The first moving average element is obtained by taking the average of the first finite subset size numbers from the series. The second element is calculated by shifting forward that is, removing the first number from the series and including the next number in the subset.

If the size of the original series is N and let the subset size chosen for the moving average is a, then the new series has N-a elements.

E. Chirp

A chirp is known as a signal which increases (up-chirp) or decreases (down-chirp) the frequency linearly with respect to time. The term chirp is also used with sweep time. The common chirp signal application is in sonar and radar and as well as in spread-spectrum communications.

F. Signal-to-noise ratio (SNR)

Signal-to-noise ratio (SNR or S/N) is a common term used in science, engineering and communication field. As the name says, it is the ratio of the desired signal to the background noise. It also defined as the ratio of the signal power to the noise power. The unit of SNR is decibel, dB. If the ration is greater than 1, it indicates that there is more signal than noise.

G. Signal-to-noise and distortion ratio (SINAD)

SINAD is a measurement useful in radio communication. Basically, the SINAD looks at the degradation of the signal by unwanted signals, mainly, noise and distortion. The definition of SINAD is quite simple, it measures the ratio of total power level (Signal + Noise + Distortion) of the signal to unwanted signal power (Noise + Distortion). The higher the value of SINAD, better is the quality of the signal. The unit of SINAD is decibel, dB, and can be determined from the equation 1 [11].

$$SINAD = 10\log_{10}\frac{SND}{ND} \tag{1}$$

where,

SND = notional permeability factor

ND = number of waves

H. Effective number of bits (ENOB)

ENOB is a unique way to specify the quality of an analog signal to digital signal conversion. Higher the value of ENOB means that the voltage levels indicated in the analog to digital conversion are more accurate.

The ideal analog to digital converter has a linear characteristic and simply specify the incoming signal. This process introduces quantization noise. Using the signal power and the noise power, it is possible to derive a signal to noise ratio (SNR) for the signal after the analog to digital conversion. If the full-scale sine-wave is used as the input, then the SNR can be written as,

$$SNR = 1.5 \times 2^B \tag{2}$$

The term B denotes the number of bits of the ADC. Expressing the equation in dB results in,

$$SNR = 1.5 + 6.02B \quad dB \tag{3}$$

Rearranging the equation to solve for B results in,

$$B = \frac{SNR - 1.76}{6.02} \tag{4}$$

Equation 4 shows how much the number of bits can be derived from the signal to noise ratio and provides the basis for calculating the ENOB. In the ideal ADC, the results for B will always be positive real integers. In the non-ideal ADCs, B can be any positive real number [8].

I. Total harmonic distortion (THD)

THD is the distortion of the voltage or the current due to the harmonics in the signal. THD application is in the audio, communication and the power system and should typically, but not always, low as possible. Lower the THD value in power systems means higher the power factor, lower the peak current and higher the efficiency [9].

J. Spurious-free dynamic range (SFDR)

SFDR application is to characterize the dynamic performance of a signal generator. SFDR shows the relationship between the amplitude of the fundamental frequency being generated and the amplitude of the most prominent harmonic. Ideally, the frequency domain of an analog signal has all power cumulative at the desired frequency. However, due to noise and the nonlinearity of components, even the best signal generated also generates a frequency content at harmonics (or multiples) of the desired tone. The dynamic range between the fundamental tone and the largest spur is called Spurious-Free Dynamic Range (SFDR). SFDR is the ratio between the fundamental signal and the largest harmonically or non-harmonically related spur from DC to half of the sampling rate. Using decibels, it is easy to calculate SFDR [10]:

$$\begin{aligned} SFDR = {} & Amplitude\ of\ Fundamental\ (dB) - \\ & Amplitude\ of\ largest\ Spur\ (dB) \end{aligned} \tag{5}$$

IV. IMPLEMENTATION

For the implementation of altitude and vertical velocity, I have followed a simple flowchart as shown in Fig. 3 and in Fig. 4.

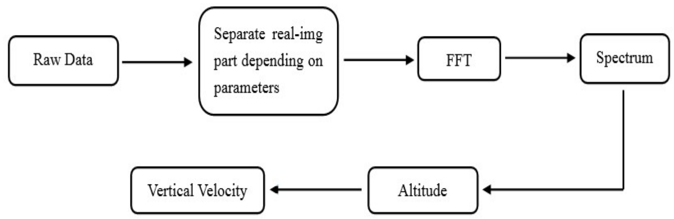

Fig. 3: Flow Chart of Algorithm

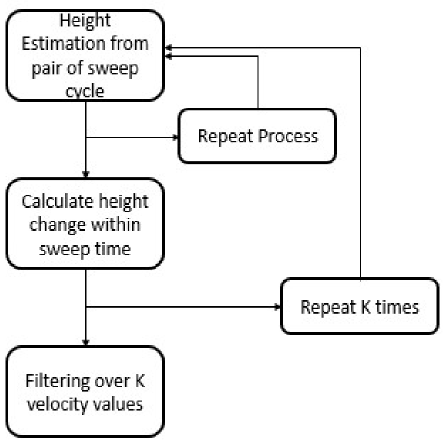

Fig. 4: Typical vertical velocity estimation flow

First, the raw data provided by the radar altimeter is separated into different segments according to the mission requirements, depicted in Fig. 5 and in Fig. 6.

129,610,528	b5	53	53	8d	8d	98	97	4d	4e	b3	b2	64	65	75	75	ab
129,610,544	aa	49	4a	a6	a5	7c	7c	5e	5f	b5	b3	50	51	92	91	94
129,610,561	93	f8	dd	42	59	3d	7f	fc	0b	ed	0f	78	c4	98	a9	14
129,610,576	52	03	d3	00	35	ce	43	00	35	9a	de	00	2b	01	22	a4
129,610,592	a3	49	4b	ac	ab	72	73	67	67	b2	b1	4c	4d	9b	9a	8a
129,610,608	8a	54	56	b6	b5	59	5a	83	83	a0	a0	4a	4b	af	ae	6d
129,610,624	6e	6b	6b	b0	af	4b	4c	9e	9e	85	86	58	58	b5	b5	56
129,610,640	57	88	88	9c	9c	4c	4d	b1	b0	68	69	70	70	ae	ad	49

Fig. 5: Raw Data with the data format

Frame Sync Word (FSW)	Frame Count	Control Signal	Altitude Value (cm)	Maximum location	Vertical Velocity (cm/sec)	MGC Threshold	PRI time stamping count	Altitude time stamping count	Vertical Velocity time stamping count	Sensor (Video) Data
4 Byte	1 Byte	4 Byte	3 Byte	2 Byte	2 Byte	2 Byte	4 Byte	4 Byte	4Byte	Word n

Fig. 6: Ka-band Radar Altimeter Payload Data Format

According to the Imaging model selection in the control signal, particular window size, shown in Table II, sensor (video) data is selected.

As the altitude estimation has to be carried out for very short target distances, pulsed-radars are not suitable and the FMCW based system is an appropriate choice. Hence, the altimeter has been configured for FMCW operation.

The implementation of the algorithm is done in LabVIEW with GUI development for ADC performance.

TABLE II: Window Size

Img_Model_Sel	Up(leave)	Dn(leave)	No of Samples (take)
0	1	1	12
1	2	2	26
2	3	3	54
3	6	6	108
4	8	8	164
5	12	12	246
6	19	19	382
7	28	28	590
8	49	49	1028
9	89	89	1880
10	151	151	3198
11	274	274	5806
12	531	3354	8192
13	962	12927	8192
14	1824	32073	8192

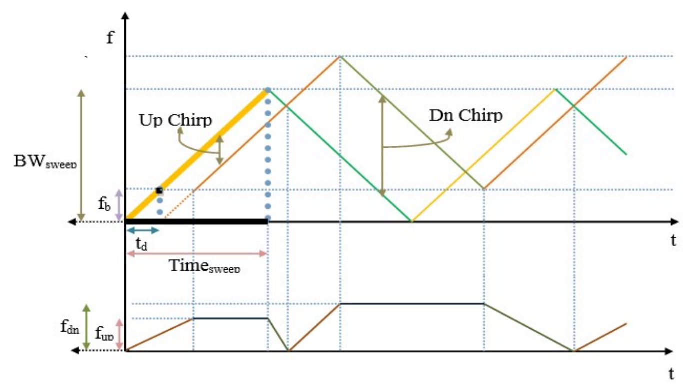

Fig. 7: FMCW with beat frequency up and down

FMCW radar transmits a signal continuously but varies the frequency linearly. At any time, the receive echo frequency and the signal fed to transmit antenna will be different. The farther the target is, the greater is the difference between the frequency of the received echo and the frequency being transmitted. The rate of change of frequency along with measured frequency difference at any time between transmit and receive frequency will provide altitude information. Because of relative motion between platform and terrain, there will also be Doppler shift which needs to be corrected. The effect of Doppler can be corrected by using frequency sweep of opposite slope in alternate sweep cycles.

Due to Doppler Effect, there are two beat frequencies generated that is, f_{dn} and f_{up}.

$$f_{up} = f_b - f_d \tag{6}$$

$$f_{dn} = f_b + f_d \tag{7}$$

Adding the above equations to get beat frequency (f_b),

$$2f_b = f_{up} + f_{dn} \tag{8}$$

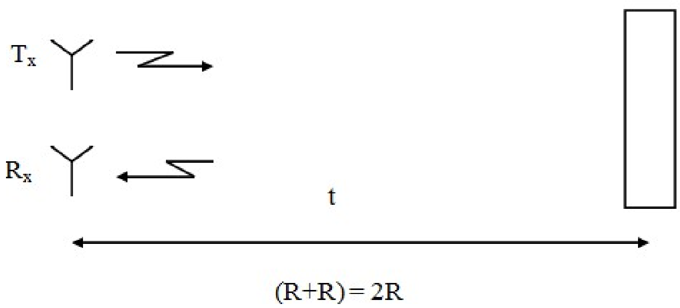

Fig. 8: Range Calculation

To calculate the altitude, first, we look at the basic.

Suppose transmitter transmits an e.m wave, which gets reflected back when struck to the object and received by the receiver as shown in Fig. 8.

Since the wave have to travel from the transmitter to object and back from the object to receiver, the wave travels 2D distance. In the Fig. 8 the wave travels 2R distance. So, by the velocity formula,

$$Velocity = \frac{Distance}{Time} \tag{9}$$

$$2R = t \times c \tag{10}$$

where,
t is the time taken to travel by wave
c is the speed of the light

If R=3 meter then T will be 2×10^8 second.

From Fig. 7, using Properties of Similar Triangles and can imply

$$\frac{BW_{sweep}}{T_{sweep}} = \frac{f_b}{t_b} = \frac{f_b \times c}{2R} \tag{11}$$

Rearranging the above equation,

$$R = \frac{f_b \times c \times T_{sweep}}{2 \times BW_{sweep}} \quad = (\frac{f_{up} + f_{dn}}{2}) \times (\frac{c \times T_{sweep}}{2 \times BW_{sweep}}) \tag{12}$$

For the vertical velocity calculation, we take the difference in the consecutive height (altitude) divided by the time sweep, as discussed in the Fig. 4.

With the help of the altitude and vertical velocity signal, SNR, SINAD, THD, ENOB and SFDR is calculated.

V. Results

After the window is applied the raw is converted to the readable form for visualization, as shown in Fig. 9 and Fig. 10.

FCnt	SD	ST	AVF	VVF	IM	PS	BF	Mup	Mdn	AGU	AGD	AGR	OPM	MGI	MGQ	RES
8	0	0	1	0	14	1	1	0	0	0	0	0	2	63	63	0
9	1	0	1	0	14	3	1	0	0	0	0	0	2	63	63	0
10	0	0	1	0	14	4	1	0	0	0	0	0	2	63	63	0
11	1	0	1	0	14	1	1	0	0	0	0	0	2	63	63	0
12	0	0	1	0	14	1	1	0	0	0	0	0	2	63	63	0
13	1	0	1	0	14	3	1	0	0	0	0	0	2	63	63	0
14	0	0	1	0	14	4	1	0	0	0	0	0	2	63	63	0
15	1	0	1	0	14	1	1	0	0	0	0	0	2	63	63	0
16	0	0	1	0	14	1	1	0	0	0	0	0	2	63	63	0

Fig. 9: Raw Data converted into the readable form

ALT	MDC	MaxU	MaxD	MaxS	Thr	Cnt	Vv	PTS	ATS	VTS
539342	2	0	0	3358	979	589430	0	0.0284941	0.0122131	0
539342	2	0	0	3358	979	673634	0	0.0325636	0.0122131	0
539342	0	1679	0	0	979	757838	0	0.0366347	0.0122131	0
539342	2	0	0	3358	979	842042	0	0.0407042	0.0284941	0
539342	2	0	0	3358	979	926246	0	0.0447752	0.0284941	0
539342	2	0	0	3358	979	1010450	0	0.0488447	0.0284941	0
539342	0	1679	0	0	979	1094654	0	0.0529157	0.0284941	0
539181	2	0	0	3357	979	1178858	0	0.0569852	0.0447752	0
539181	2	0	0	3357	979	1263062	0	0.0610562	0.0447752	0
539181	2	0	0	3357	979	1347266	0	0.0651257	0.0447752	0
539181	0	1678	0	0	979	1431470	0	0.0691968	0.0447752	0
539021	2	0	0	3356	979	1515674	0	0.0732662	0.0610562	0
539021	2	0	0	3356	979	1599878	0	0.0773373	0.0610562	0
539021	2	0	0	3356	979	1684082	0	0.0814068	0.0610562	0
539021	0	1678	0	0	979	1768286	0	0.0854778	0.0610562	0

Fig. 10: Raw Data converted into the readable form

After selecting the proper number of bits, depending upon the chirp up or chirp down as well as data input, complex number is formed and its Fast Fourier Transform (FFT) of 8k samples is taken.

Running Moving Average algorithm is applied to get f_{dn} and f_{up}.

According to each PRI the value of the f_{dn} and f_{up} yields the altitude.

As discussed above, the difference between the consecutive

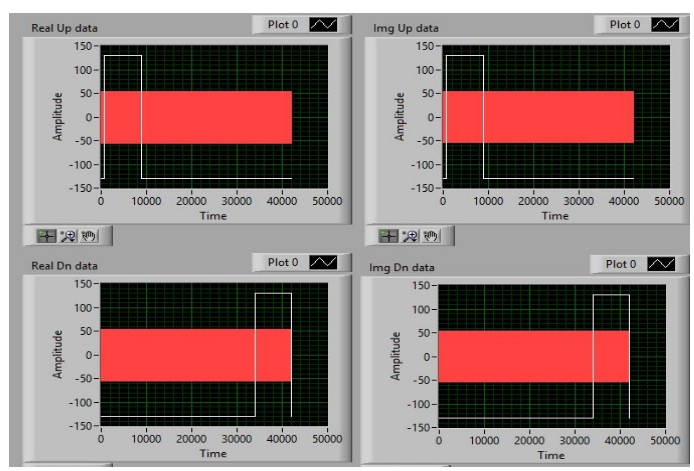

Fig. 11: Number of samples selected after windowing. The images show (clockwise) real data of up chirp, imaginary data of up chirp, imaginary data of down chirp and real data of down chirp

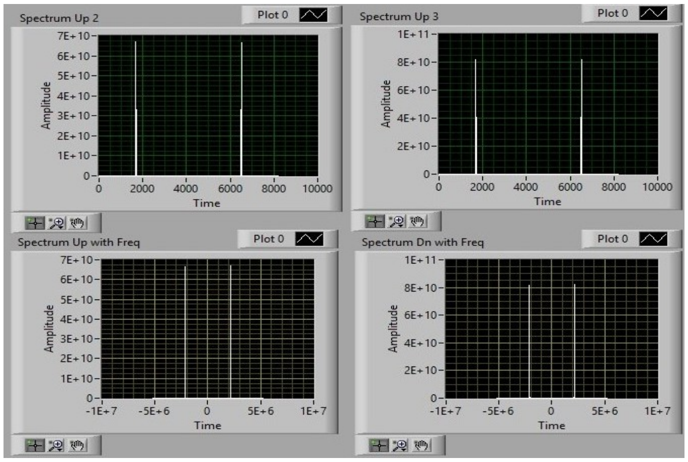

Fig. 12: Spectrum of the chirp up and chirp down. The images show chirp up fft, chirp down fft, chirp up spectrum and chirp down spectrum

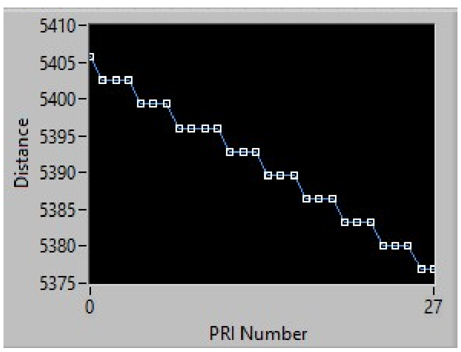

Fig. 13: Altitude computed. Showing how the lander will descend

heights according to PRI number by the time between them gives the vertical velocity of lander.

Every signal includes some kind of distortion or the noise. So how good is the quality of the signal is determined by SINAD, THD, SNR, ENOB and SFDR.

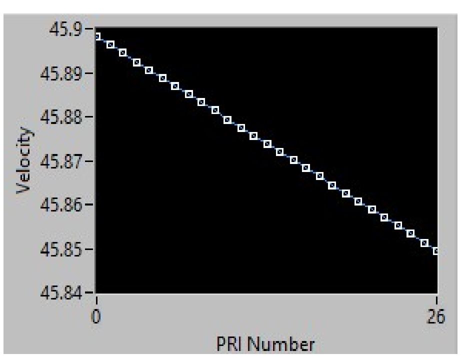

Fig. 14: Vertical Velocity computed. Showing at what speed the lander will descend

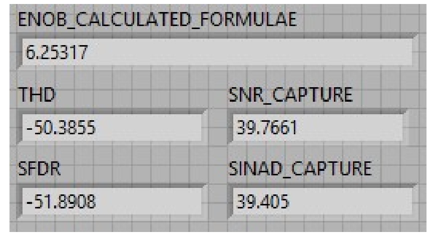

Fig. 15: Values of ENOB, THD, SNR, SFDR, SINAD of a particular PRI

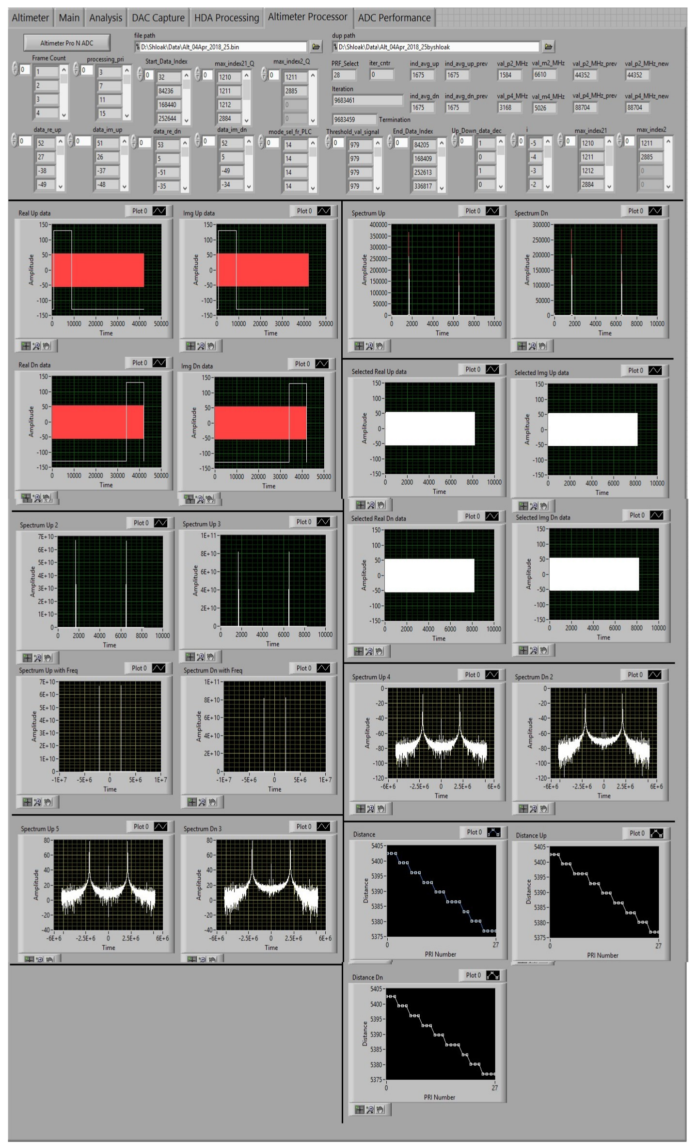

Fig. 16: GUI of Altimeter Processor

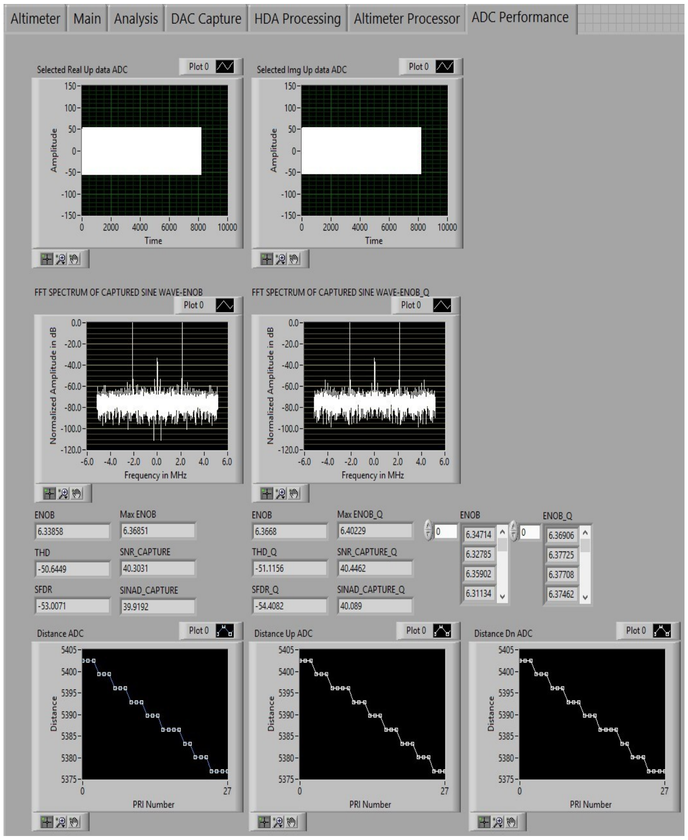

Fig. 17: GUI of ADC Performance

VI. CONCLUSION

To achieve the soft landing of the Chandrayaan 2, altitude and vertical velocity is the key factor. The radar altimeter data with single tone acquired to calculate ENOB, SINAD, THD and SFDR values. These calculations will help in the landing operations of Chandrayaan 2. The algorithms helped in calculating altitude and vertical velocity of the lander. Successful in-orbit operation of altimeter will offer the lander craft to land safely and softly on Lunar Surface.

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