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A Low SWaP-C Radar Altimeter Transceiver Design for Small Satellites

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Abstract— This paper discusses the design details of a high resolution, low "Size, Weight, Power and Cost" (SWaP-C) radar altimeter (RA) system. Operating frequency of the radar is chosen within the Ka-band to achieve the desired size and weight requirements, that are highly demanded for the small satellite missions in a cost-efficient way. We propose a system design such that, an intended radar altimeter can be built by using the Commercial off the Shelf (COTS) components. The simulation results show that the proposed RA has high potentiality for realization.

Keywords— Radar design, mission concept, radar altimeter

I. INTRODUCTION

A radar altimeter is known to be an elegant tool for estimation of the sea surface height, significant wave height, and wind speed. In the radar system engineering point of view, these parameters are corresponding to the measurement of range, the slope of the return signal and the strength of return signal respectively. Moreover, radar altimeters have great potential in obtaining the reliable knowledge of ocean currents, annual sea level rise, the kinetic energy of ocean circulation and the interaction between the ocean and the ice sheet and glaciers regions, which have been verified by different European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) spaceborne radar altimeters missions (e.g. SWOT, Cryosat-2 [1], Sentinel-3, etc ...).

The traditional altimeters are mostly operating in the Ku [2] and C bands [3]. It is easier to find COTS components operating in these bands. However, the size of the components like antenna and RF filters is much bigger, thus increase also the weight; for i.e., the weight of CryoSAT is 62 kg [4] that is quite a lot to be launched in a small cubesat. Increasing the operating frequency makes the antenna and RF circuitry smaller but unfortunately results in higher cost.

To the best of our knowledge, the highest operating frequency implemented for a radar altimeter is within W-band [5]. However in this case, the prices of the components are too high, and many components especially the power amplifiers are less likely to be found as COTS. Thus custom design of these components is required.

The Ka-band is a good compromise to achieve a low SWaP-C radar altimeter solution from a microwave design point of view. Additionally, this band has benefits to oceanic observations near coastal regions or near the regions between sea ice to inland water. Moreover, Ka-band is less affected by the ionospheric attenuation than the Ku-band.

There is a growing interest in the Ka band radar altimeters. To the best of our knowledge, there are at least three different Ka-band radar altimeter projects. Altika is a Nadir looking altimeter that is launched in 2013 [6] with the France and India collaboration. NASA/CNES wide-swath altimetry mission includes a Ka-band Radar Interferometer that is planned to be launched in 2020 [7]. Lastly, ESA has also plans for launching a Ka-band radar altimeter in the next Sentinel 6 mission in 2020 [8]. A comparison of different altimeters are presented in Table 1. The SAR missions are also within the area of interest of the radar altimeter missions [9].

There is an ongoing project at ESA about the investigation of a Cubesat altimeter constellation. A constellation is foreseen to greatly help in understanding the decorrelation times and the dynamic changing of the ocean mesoscale and sub-mesoscale processes, with the system's ultimate goal being a daily worldwide coverage. Instead of a single high power, huge and heavy satellite, low SWaP-C nodes are highly demanded to achieve multiple goals.

In this work, a Ka-band low SWaP-C radar altimeter RF transceiver that is demanded for a cubesat constellation is proposed. In the next section, the system specifications of the proposed radar will be presented. Then the system design will be explained in detail. The following sections discuss the onboard processing, results, and conclusion.

II. SYSTEM SPECIFICATIONS

The system-level parameters are given in Table 2. There will be two operational modes: Namely, the traditional mode where the pulse repetition frequency (PRF) is 4kHz and the SAR mode in which the PRF is 18.7kHz. It is wise to note that in the radar altimeter jargon "Delay-Doppler" term is used instead of unfocussed SAR [12]. In our design, the peak power is aimed to be 2W in the output of the transmitter. An antenna with a quite narrow beamwidth must be chosen to achieve a high gain (aimed 48dBi) with an antenna width of 1.15m. The bandwidth of the chirp is set to 320MHz which is comparable with the state of the art altimeters. The expected receiver signal power after the antenna is within -127dBm to -87dBm. This is a quite narrow dynamic range that relaxes the analog to digital conversion depth. The expected noise figure (NF) is less than 5dB. The antenna footprint will be less than 15km which results in a 76 meters scene length in range direction.

Table 1. Comparison of current altimeters that are installed in the last 30 years.

Name	PRF in Hz and Band	Pulse Width, us	Peak Power, W	Antenna Beamwidth, Degree	Bandwidth
ERS-1, 2	1020 (Ku)	20	50	1.3	330
Topex/Poseidon [10]	4200(Ku), 1220 (C)	102.4	237	1.1	320
Envisat	1795 (Ku), 449 (S)	20	161	1.29 (Ku), 5.5(S)	320
Jason-1, Poseidon 3	2060 (interlaced, Ku and C)	105	7	1.28 (Ku), 3.4 (C)	320
CryoSat-2 [11], SIRAL, Ku	1970 (LRM*), 17.8k (SAR, SARIn)	44.8	25	1.07 * 1.2	350
Sentinel-3	1920, Ku/C	20	-	-	-
SARAL/AltiKa [6]	3800, Ka	110	2	0.5	500
SWOT,Ka [7]	2 x 4420 Hz	4.5	1500	0.15*2.27	200
Proposed RA	4000, 18.7k (SAR) Ka	48	2	0.5	320

* LRM: Low Resolution Mode

Table 2. System Specifications

Parameter	Value	Unit
Bandwidth	320	MHz
Center Frequency	35.6	GHz
Pulse Width	48	us
PRF	4, 18.7(SAR)	kHz
Output Power	33	dBm
Rx input power	[-127,-87]	dBm
Rx Noise Figure	5	dB
IF Bandwidth after dechirping	7	MHz

The radar altimeter receivers use deramp (stretch) processing to reduce the ADC's bandwidth requirements since the duration of the pulse to scan the whole scene is much shorter than the pulse width. Stretch processing generates the beat frequency signal in the receiver which is selected less than 7MHz for the proposed design.

III. RF TRANSCEIVER DESIGN

The RF transceiver design is illustrated in Figure 1. The final RA will work as a pulsed radar that includes a circulator and a single antenna. However, to verify and validate the system in the laboratory and on-site where the range is quite short compared to the spaceborne geometry, the presented design includes two antennas instead of a circulator and a single antenna.

The waveform is generated by the Direct Digital Synthesizer (DDS). A two-channel DDS is selected to generate IQ channels without a hybrid splitter. To fulfill the 320MHz system bandwidth requirement, the DDS is chosen to be 500MSPS. The output of DDS is low pass filtered and given as IF input to the IQ (Inphase and Quadrature) mixer. The DDS-Filter-Mixer structure can be alternatively designed by using the DDS as a reference to the Phase Lock Loop (PLL) that drives a Voltage Controlled Oscillator (VCO). So in this case, IQ mixer (MIX IF) and the low pass filter will be no more required. In the final version of the altimeter, this option will be implemented. However, to support also the Arbitrary Waveform Generators (AWG) that can be used for various experiments, the current design will be implemented for the laboratory tests.

The center of the intermediate frequency (IF) is chosen as 2GHz. The selection of IF is a compromise between sideband

suppression and the availability of the components. The Local Oscillator (LO) input of the second mixer is 33.6GHz. So a bandpass filter is required to have a center frequency of 35.6 GHz and a stopband at 31.6 GHz; yielding a reasonable Q-factor. The output of the first mixer is given as input to the variable attenuator to fine-tune the transmitted signal power in order not to saturate the successive amplifier. The IF amplifier is used to provide sufficient power to the local oscillator (LO) of the receiver mixer (MIX IF Rx).

The selected RF mixer (MIX RF) is IQ. A radar altimeter is not required to have an IQ mixer as the beat frequency is always positive. An important disadvantage of the IQ mixer is the need for higher power in the LO input comparing with the LO requirement of a single channel one. For the Ka band mixer in this design, the required LO power is 18dBm, which is quite high. However, to achieve a high-quality sideband suppression capability, the mixer is chosen to be IQ. To generate this power, at least one additional amplifier (RA LO2) is inserted as it is seen at the bottom of Figure 1.

The variable attenuator (Var ATTN RF) at the output of the RF mixer is used to guarantee the succeeding amplifiers not to be saturated and also to compensate the power. The technology for driver amplifier and the power amplifier are chosen as solid-state. The power amplifier is selected to have a P1dB of higher than 33dBm to achieve the required output power. The bandpass filter, (BPF RF) is used for suppression of the sidebands of the mixer and harmonics of the amplifiers.

The transmitted signal is coupled to the receive path for the calibration of the system. This calibration aims to extract the impulse response of the transceiver. In this path, the transmitted signal is delayed and attenuated to inject a simulated target to the receive path. There is also a power detector in the calibration path to control the output power and fine-tune the variable attenuator.

The receiver chain includes a limiter, BPF, LNA and a second BPF. By doubling the filters, the NF can be decreased more with the cost of a bigger size of the PCB. The mixer (MIX RF) is the same as the one in the transmitter. The output signal is combined with a hybrid combiner (HYB COMB) and given as input to the amplifier. This amplifier before the mixer has also a positive impact on the final NF. The remaining part of the receiver is conversion to baseband of the I and Q channels, low pass filtering and amplification of the signal to

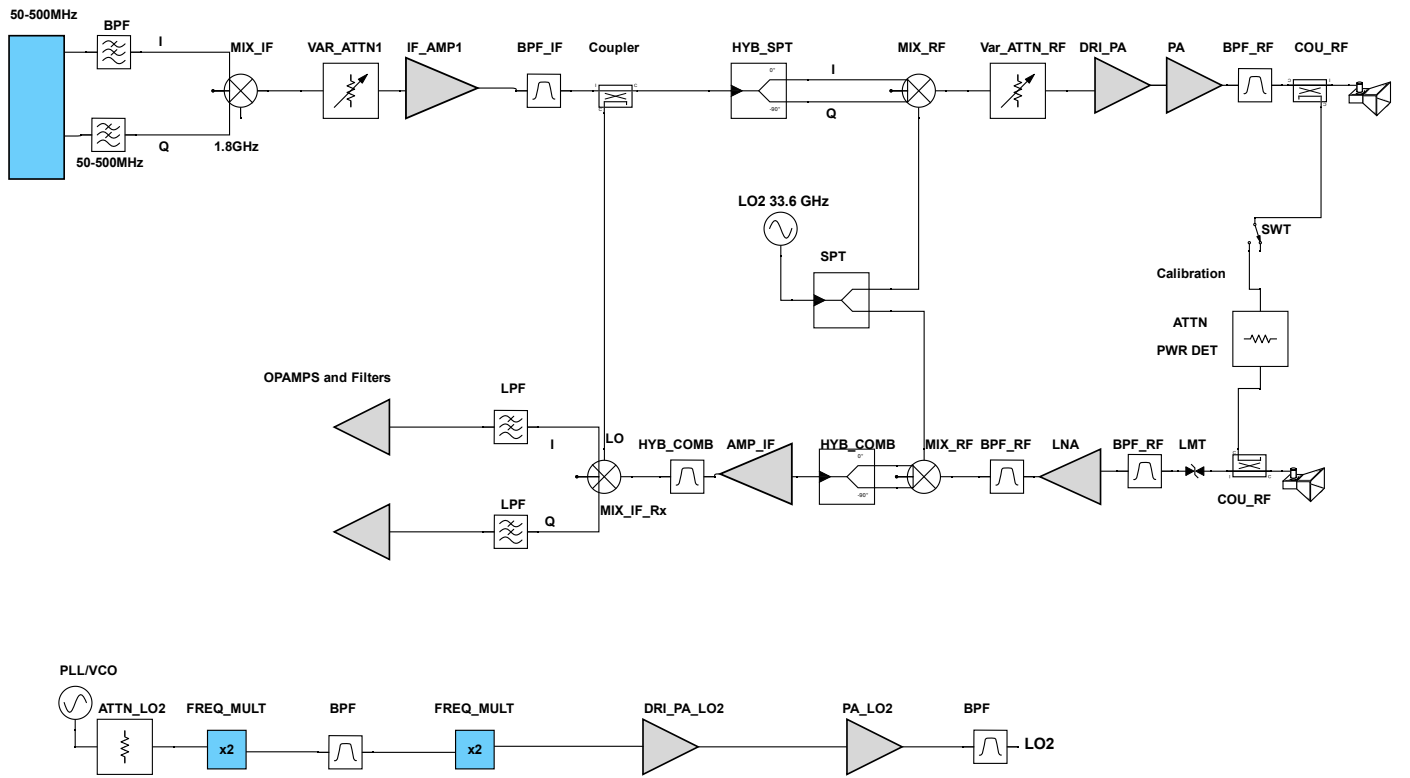


Fig. 1. Radar Altimeter Transceiver Design

achieve the required ADC dynamic range.

The expected size of the PCB for the RF transceiver and the signal processing board will be less than 4 by 10cm*10cm. The PCB's can be realized as multilayer that results in shorter heights. The weight of the PCB and the electromagnetic shields will be less than 2 kg. The power required during transmission for the PA is 12W, for the other RF amplifiers is 6W where the duty cycle is 5%. The power required for the whole radar is expected to be less than 30 W. The cost of the PCBs and the all components are estimated to be less than 20k Euro. Hence, the proposed design can be defined as low SWaP-C.

The space qualification of the RF transceivers is under discussion. To the best of our knowledge, there is no consensus on if COTS products are needed to be selected as space-qualified to develop a space-qualified product. In the proposed system, the RF amplifiers (DRI PA, PA, LNA) are chosen as space-qualified. Besides, most of the COTS products have specifications that fit the extreme conditions of the space.

IV. ON BOARD PROCESSING

The onboard processing aims to control the transceiver, to digitize IQ signal and to achieve the DSP functionality. The control of the transceiver includes the fine-tuning of the waveform duration to achieve the beat frequency within the bandwidth. For this purpose, the received signal is firstly digitized. The required minimum number of samples to cover the 150m range is 320 that is between 256 and 512. A 512 sample complex FFT at the PRF is required to be performed and the squares of I and Q must be summed up to compute

the signal amplitude. The input of the tracking algorithm is the detection results over the averaged signal amplitude and the Digital Elevation Model of the scene. The tracked range is given as input for chirp duration estimation so that the height measurement will be in the middle of the range window.

The onboard processing will also include the control mechanisms for the states of the system. The calibration will be the initial state of the system. In this state the transmitted power will be detected, the PLL lock signals will be checked and the system impulse response will be measured. The next stage is the search state in which, the height will be measured with a narrow band chirp. Once the height is estimated roughly, the band will be increased in a loop like focusing a telescope in a stepwise manner. The height accuracy can be increased by interpolation techniques [13]. Once the highest bandwidth is achieved, the system will be in the lock state. If there is an inconsistency of the system, the lock state will convert back to the search state. In order to achieve the onboard functionality, space proven FPGAs will be used.

V. SIMULATION RESULTS

In this section, the simulation results of the RA system will be discussed. The system is simulated by using the AWR Microwave circuit design tool. In Figure 2 the transmitter chain signal power analysis is presented. The brown line that has the lowest values represents the power of the transmitted signal, the pink line is P1dB and the blue line is the IP3. As it is seen the transmitted signal is always lower than the others and is the same with P1dB only at the output of the transceiver. The

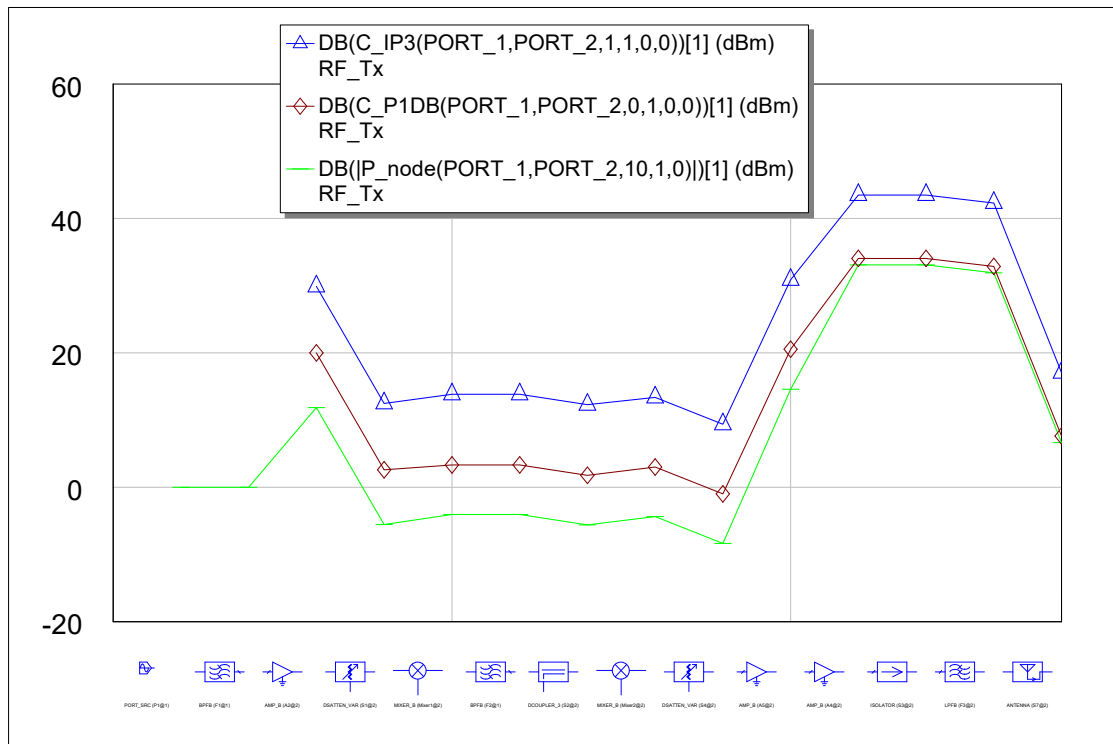


Fig. 2. Transmitter chain RF budget analysis. (dBm)

output power is 34.4dBm that is 1.4dB higher than the system requirement.

In Figure 3 the NF of the receiver chain is presented. The NF requirement was 5dB, and it is seen that 1dB is saved. The bandpass filter after the LNA and the amplifier after the mixer are inserted to the chain to keep the NF in these lower values. This is a compromise between the size, power and NF.

VI. CONCLUSION

This paper presents a Ka-band RA transceiver design and discusses the design choices in each stage. All the components are selected as COTS, which can be easily found in the market, to achieve not only a low SWaP but also a low-cost solution. The simulation results show that the design fulfills the system-level requirements. The next step is to implement and validate the design by laboratory and cite tests.

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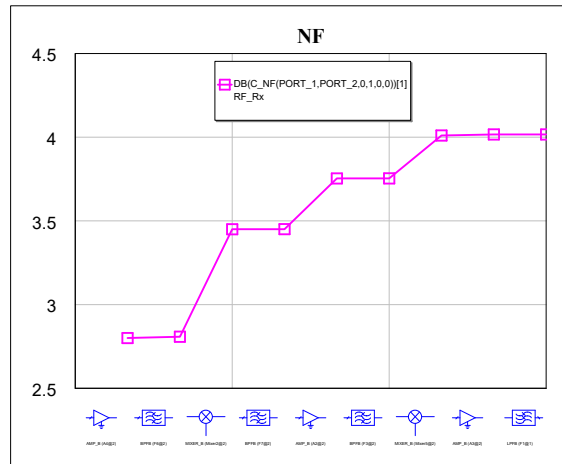


Fig. 3. Receiver chain Noise figure. (dB)

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