

# A CubeSat Train for Radar Sounding and Imaging of Antarctic Ice Sheet

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**Abstract**—In spite of more than 50 years of airborne radar soundings of Antarctic ice by the international community, there are still large gaps in ice thickness data. We propose a CubeSat satellite mission for complete sounding and imaging of Antarctica with 50 CubeSats integrated with a VHF radar system to sound the ice and image the ice-bed. One of the major challenges in orbital sounding of ice is off-vertical surface clutter that masks weak ice-bed echoes. We must obtain fine resolution both in the along track and cross track directions to reduce surface clutter. We can obtain fine resolution in the along track direction by synthesizing a large aperture by taking advantage of the forward motion of a satellite. However, we need a large antenna-array to obtain fine resolution in the cross track direction. We propose a train of 50 CubeSats with optimized offset position to obtain a 500-m long aperture and also coherently combine data from multiple passes of the train to obtain a very large aperture of 1-2 km in the cross track direction. Our initial analysis shows that we can obtain measurements with horizontal resolution of about 200 m and vertical resolution of about 20 m. The CubeSat will carry a transmitter and receiver with peak transmit power of about 50 W. We will synchronize all transmitters and receivers with a Ka-band system that serves as a communication link between the earth and Cubesats to downlink data and as command and control for the CubeSats.

**Keywords**—*CubeSat, Satellite formation, cryosphere, sounding, imaging, Antarctica*

## I. INTRODUCTION

Extensive satellite and airborne observations of large ice sheets in Greenland and Antarctic are showing both ice sheets are retreating and their contribution to sea level has been increasing over the last decade [1-2]. IPCC reported that sea level would increase between 26 and 96 cm over the next century under different warming scenarios [3]. Rahmstorf [4] and Jevrejeva et al., [5] used semi-empirical models and paleoclimate records to generate sea level rise estimates and reported that it could be as large as 2 m. Even modest sea level rise in heavily populated regions is a major problem particularly during storm surges as illustrated during recent super-storms Harvey and Irma. We need a more accurate estimate of sea level rise projections to develop coastal projections in a warming climate. In the next 3-4 years NASA will launch two satellite missions, ICESat-2 and NI-SAR to monitor polar regions. ICESat-2 will measure changes in surface elevations and determine the current mass balance of each ice sheet. The changes in surface elevation provide information to document mass loss or gain. One of the major objectives of the NI-SAR mission is to map surface velocities of glaciers to provide information on the speed-up or slow-

down of outlet glaciers. Additional information on ice-bed topography and basal conditions is required to develop ice-sheet models to generate more accurate estimates of sea level rise in a warming climate. Bed topography controls ice flow and basal conditions determine how fast ice flows.

Large gaps in ice thickness measurements still exist over Antarctica despite many years of airborne measurements. Fretwell et al. [7] generated a new bed map by compiling all data collected over Antarctica. In some areas, data points are separated by as much as 100-200 km. Also, ice thickness errors of up to a few hundred meters, greater than ten percent, are common in areas with significant topographic changes. Figure 1 shows a comparison of data collected by the Center for Remote Sensing of Ice Sheets (CREGIS) as a part of the NASA Operation IceBridge Mission (OIB) after the bed map was generated. The results clearly show that interpolation used to generate the new bedmap with very sparse sampling results in poor representation of peaks and troughs in bed topography. A satellite mission is the only way to effectively obtain complete ice thickness data for Antarctica. Bed topography and basal conditions generated from a satellite radar sounder/imager data would substantially enhance the scientific value of ICESat-2 and NI-SAR.

Airborne radars operating at frequencies between 60 and 300 MHz have been very effective in sounding and imaging ice [8-11]. A formation of 50 CubeSats with a radar sounder

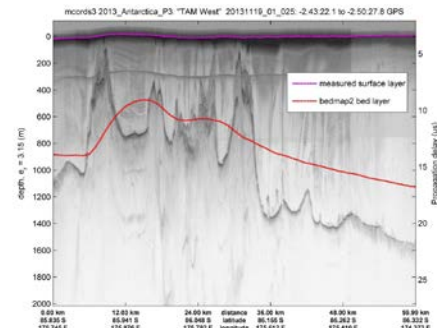


Figure 1: Comparison of interpolated bedmap with measurements in areas with significant topography [6].

operating at 150 MHz create a large synthetic aperture to obtain spatial resolutions of about 200 m both in along and cross track directions. The CubeSat formation will synthesize a large cross track aperture to reduce surface clutter that can mask bed returns and obtain the high sensitivity needed to

overcome high ice attenuation and spreading losses. A Ka-band system for each CubeSat will function as radar for precise measurement of distance and velocity between the CubeSats for accurate orbit determination, as a communication link to synchronize the distributed transmitter array, and as a down-link to transmit sounding and imaging data to a ground station.

## II. ORBITAL RADAR SOUNDING AND SURFACE CLUTTER

Orbital radar must have high sensitivity to overcome large ice attenuation and spreading loss of operation at an orbit of 400 km or higher and minimize off-vertical surface clutter that masks weak ice-bed returns. Radar must have a large power-aperture product to provide the necessary sensitivity and spatial resolution. A peak transmit power a few kilowatts or higher is needed to combat both the spreading and ice loss to sound the ice-bed with a reasonable signal-to-noise ratio (SNR). A large antenna aperture is also essential to provide a narrow beamwidth for fine spatial resolution and suppressing surface clutter. Signals scattered by the rough ice surface, referred to as surface clutter, can mask weak echoes from the ice-bed interface. Surface clutter is a major issue in high-altitude and orbital sub-surface sounding because the ice surface is illuminated at small incidence angles. While SAR processing can be used to reduce the along track antenna beamwidth to filter out surface clutter coming along the flight direction, advanced array processing techniques must be used to reduce clutter in the cross track direction. An orbital radar operating at an altitude of 400 km; the surface scattering from incidence angles of 7.5° and 12° can mask returns from ice-beds covered with 2 and 5 km thick ice, respectively. If the two-way attenuation rate is assumed to be 15 dB/km, clutter must be reduced by ~60 dB to obtain discernable echoes from the ice-bed interface covered with 5 km of ice. A link budget for the radar system is given in Table 1.

Table 1: Link Budget

Transmit Power	56.00	dBm
Antenna/Array Processing Gain	25.00	dB
Wavelength Effect, ( $\lambda = 2\text{cm}$ )	6.02	dBm <sup>2</sup>
Two way power transmission coeff.	-0.69	dB
Loss for 5 km thick ice (15 dB/km)	-75.00	dB
Pulse compression gain, CI	20.00	dB
Integration gain	29.61	dB
Total Spreading loss term	-130.22	dB
Noise power (Bandwidth = 10MHz)	-100	dBm
Reflection coefficient at the bottom	-10.00	dB
Signal-to-noise ratio	10.71	dB

Li et al. [12] developed coherent and incoherent clutter reduction, as well as a technique to reduce cross track clutter, and applied the coherent clutter reduction technique to data collected with a radar on the NASA DC-8 aircraft from a height of about 10,000 m above the surface [13]. Figure 2 shows SAR- and array-processed results. The left echograms show results after SAR processing the data combined with a sum-delay beamformer with Hanning weights. The ice-bed echoes are masked by the cross track surface clutter. The right shows the results from a Minimum Variance Distortionless Response (MVDR) beamformer; the bed echoes are clearly discernable. To adapt the technique to a spaceborne ice

sounder we estimate that a cross track antenna array of 40-50 m long is required. A 50 m long antenna aperture at 150 MHz provides an antenna beamwidth of about 4° after weighting, which is required to reduce antenna-array sidelobes to suppress clutter. With advanced signal processing using multiple passes, we can obtain ice thickness measurements with a vertical resolution of 20 m and horizontal resolution of 200 m to satisfy most of the major glaciology and geology science requirements.

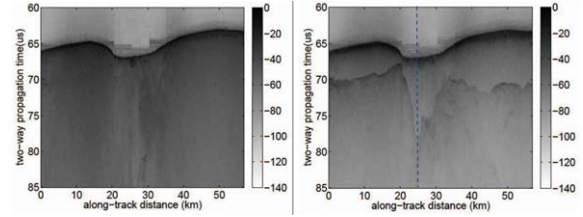


Figure 2. Bed returns recovered after surface clutter suppression [14]. Top and bottom echograms are before and after array processing, respectively.

## III. SATELLITE FORMATION

50 CubeSats spaced 50 m in the along track and 1 m spacing in the cross track direction will synthesize a large cross track array using the Earth's rotation [14]. The cross track array sample spacing is determined by the offset distance between adjacent CubeSats for a single pass. We can combine multiple passes to synthesize a very large aperture to obtain fine spatial resolution in the cross track direction.

Creating the synthetic aperture requires coordinated autonomous operation using the Ka-band device for phase-locked operation of the VHF radar. A highly inclined orbit using the argument of perigee to create phasing was chosen. The five satellites in Figure 3 are an example of the PICS (Polar Inclined CubeSats) formation.

Over the Antarctic coordinated autonomous operation of the VHF radar is required. Each CubeSat carrying a 150 MHz radar can be considered a single transmit and receive center. Operation of the VHF radar will be phase-locked by using the Ka-band device. The device will provide the range and range-rate of each spacecraft's neighbors. GPS differenced measurements will provide additional positional and velocity knowledge. SAR formed by multiple small spacecraft has not been operationally achieved [15]. The best formation flying spacecraft mission to-date is the CanX-4&5 mission; successfully demonstrating autonomous formation flight with sub-meter control error and centimeter-level relative position knowledge with the closest controlled range of 50 m during formation flight [16]. For perspective, the closest controlled range a CubeSat in PICS will experience is 49 m. The 1 m cross track distance will drive the propulsion choices and the return from the Ka-band prototype will drive the ADCS selection.

### A. PICS Formation and Operations

PICS varies the argument of perigee to separate the CubeSats in the along track direction. The inclination of each orbit is varied slightly to achieve the 1 m cross track separation

over Antarctica. The phasing distance, relative position information from the Ka-band device, and absolute position information from differenced GPS when equipped with a cold-gas thruster will provide sufficient capability to achieve the desired offset position and maintain a safe separation. Each CubeSat will have an identifier to distinguish it from its compatriots as it changes position in the formation.

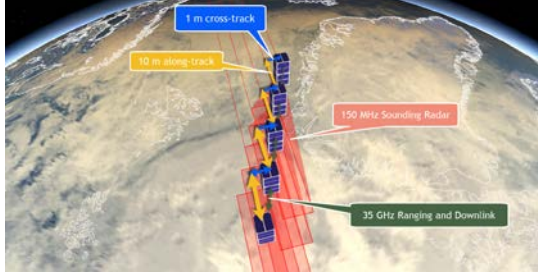


Figure 3: Five CubeSats creating a synthetic aperture through separation of 1 m in the cross track and 10 m in the along track.

Each CubeSat will consist of a radar transmitter and receiver operating in the Ka band to provide local navigation and communication within the formation. The transmitter on each CubeSat will generate a complementary coded chirp digitally. The chirp will be amplified to the required power level with a driver and power amplifier chain and coupled to the antenna through a transmit/receive (T/R) switch. The coding will allow us to isolate and process signals from each CubeSat before combining signals from all CubeSats to synthesize large apertures both in the along track and cross track directions. Table 1 shows our preliminary link budget for the radar. We can sound close to 5-km thick low-loss ice in Antarctica with our CubeSats train.

Data quality critically depends on the antenna aperture synthesized by the PICS formation. The Ka-band device will provide precise ranging, velocity and high-speed downlink capabilities for each CubeSat. We have chosen a FMCW radar architecture for ranging and relative velocity measurements, similar to commercially available automotive radars. The proposed FMCW radar not only has the common advantage of low peak power requirement, but the continuous-wave signal can also be used to synchronize the local oscillators used in the ice sounders on different CubeSats.

It is possible to optimize the along track separation by varying the eccentricity vector to change the along track distance as the formation passes over a targeted latitude using the cold-gas thruster in a nadir orientation. Cross track separation can be varied through inclination changes or taking advantage of natural nodal regression. PICS, taking advantage of the precession of the line of nodes, can vary the cross track distance in less than 7 days. Orbital altitude will be maintained by periodic drag make up maneuvers. A cold-gas thruster will be sufficient for small attitude and up-keep maneuvers to fine-tune the formation. Other formations have taken advantage of specially designed orbits to maintain formation position [17]. Using differenced GPS, IMUs, and the Ka-band device we can expect centimeter-level relative positional knowledge and millimeter-level precision. The sub-meter control error will

need to be addressed in order to maintain 1 m cross track separation efficiently.

### B. Synthetic Aperture Acquisition

Our high resolution polar mapping leverages both the natural synthetic aperture characteristics of the radar array formation and the variation in orbital revisits. Figure 4 conceptually illustrates the cross track synthetic aperture width for a single orbit and the track separation for subsequent orbits. The cross track synthetic aperture width is length of the total formation ground track. The track separation (spatial resolution) takes advantage of the Earth's natural rotation and precession of the orbital plane, which creates a natural variation in inbound and outbound orbit angles (i.e. apparent crosshatching in the tracks in Figure 4). Element track separation is achieved by the PICS formation cross track separation. The proposed PICS formation design is driven by the need to form a synthesized aperture with minimum cross track grating lobe levels. The element track separation is 1 m (seen in Figure 3 and 4). For the 50 CubeSat formation, the synthetic aperture width will be about 500 m.

Our mission altitude, 400 km, gives a  $92.6 \pm 1.67^\circ$  min orbit in which the Earth rotates by approximately  $23.2 \pm 0.06^\circ$ . Revisit coverage depends on the target location and mission duration. The pole receives multiple revisits early on because of the highly inclined orbits ( $85^\circ \leq i \leq 95^\circ$ ). Other locations will receive no early revisits because of their latitude or inclination. By day ten of the mission, all ground targets have seen at least one revisit. The variation in inbound and outbound ground paths create iso-latitude rings of at least 2 passes over the same ground target at day ten. Figure 5 illustrates the revisit coverage at 400 days. Coverage is not

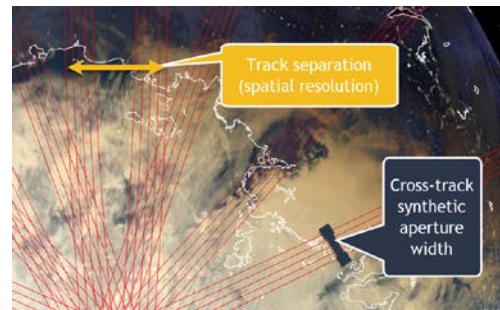


Figure 4: Ground track separation of array

uniformly spaced with bands in specific radii and angles. Flight correction/maneuvers on-orbit have the potential to provide more detailed scanning in targeted areas.

### C. Effect of Ka-band Device PICS Operations

The 35 GHz device serves three purposes: ranging radar, downlink, and phase-lock for VHF sounding radar. When functioning as a ranging radar the device will provide range and range-rate information to each CubeSat. The on-board autonomous command will determine orbit correction maneuvers to maintain the synthetic aperture. The SNR will



drive the Attitude Determination and Control System (ADCS) selection. Maryland Aerospace currently provides ADCS with a  $0.007^\circ$  pointing capability at a technology research level (TRL) 6 [18, 19]. There is a negative correlation between the SNR level and the resolution required of the ADCS; see an example in Figure 5.

When operating as a downlink, the spacecraft will slew as it passes over the target ground station. The CubeSats will be unable to rely on the ranging radar capability at this point in the

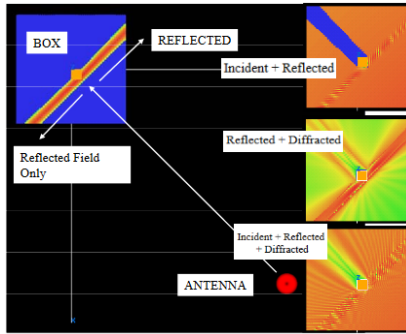


Figure 5: RCS affects SNR adversely requiring a higher resolution from the ADCS, [20].

flight. Position and velocity updates will be provided by differenced GPS measurements and an on-board IMU. The ADCS and the CubeSat bus will have to be able to slew at the rate required to keep pointing the highly directional beam at the ground station. The required slew rate is proportional to the inverse of the half beam width,  $\theta$ . At 400 km for an infinitely-thin beam, the spacecraft would need to slew at  $\sim 0.567^\circ/\text{sec}$  if it does not use electronic steering of the beam.

#### IV. SUMMARY

In the paper we presented a preliminary concept for a CubeSat train-base radar sounder/imager to map Antarctica completely. A formation of 50 CubeSats with a radar sounder operating at 150 MHz create a large synthetic aperture to obtain spatial resolutions of about 200 m both in along and cross track directions. Both 144 MHz and 225 MHz are approved for radar use. The CubeSat formation will synthesize a large cross track aperture to reduce surface clutter that can mask bed returns and obtain the high sensitivity needed to overcome high ice attenuation and spreading losses. A Ka-band system for each CubeSat will relative positions, serve as a communication link to synchronize the distributed transmitter array, and as a down-link to transmit sounding and imaging data to a ground station.

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