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# A Novel Method for Achieving SAR Imaging with a Pair of Micro-Satellites by Means of a Bi-Static Configuration

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**Abstract:** There is increasing interest in the potential capabilities and applications of micro-satellites in the field of Earth-observation (EO). Passive optical imaging is now well established on such platforms, however, an active imaging payload - a synthetic aperture radar (SAR) - would appear to be insupportable, due to its size, complexity and high-power requirements.

A major driver of these requirements is that traditional SAR systems use backscatter - which is necessarily weak from most terrain types. If the forward scattered energy could be gathered, then the transmit-power requirements could drop significantly. We therefore propose a novel method by which two micro-satellites fly in formation to accomplish a SAR mission bi-statically. The transmitting satellite will be the "master", with the receiver satellite "slaved" off it by means of a synchronization signal. The satellites image a swath of 30 km, at a ground resolution of 30 m from 700 km altitude. Our constellation geometry can image anywhere in a pre-selected latitude band, and requires minimal orbit-control resources. The viewing configuration resolves the left-right ambiguity that occurs in near nadir pointing bi-static radar. Applications to a polar ice-monitoring mission are discussed, although with minor changes any location on Earth can be viewed.

## Introduction

Over the last 20 years, micro-satellites (that is satellites in the 10-100 kg mass range) have proven to be an effective means of reducing the cost of space missions, and of making space technology available to the wider community for a variety of applications. For example, micro-satellites are now routinely engaged in Earth Observation (EO) missions through the use of passive optical imaging payloads – that is payloads that produce images of the Earth by sensing reflected sunlight – operating mainly across the visible and near-infra-red spectrum.

Whilst such imaging satellites have many uses, active imaging satellites, i.e. satellites which carry their own illumination source, potentially have two great advantages: they can image at night, and, in the case of radar-based systems, they can image through clouds. The ability to image through clouds is useful as many parts of the world have significant cloud cover for much of the time, and similarly the ability to image at night has many uses – not least the ability to image high latitude areas during the long periods of darkness which occur during the winter months.

Thus, synthetic aperture radar (SAR) imaging is becoming an increasingly important EO tool. However, to-date, this technology has been limited primarily to the military, and to the major space agencies, due to the very high cost and complexity of such missions.

Much of this cost is due to the exacting requirements of the payloads, e.g. their large size (especially in terms of antenna size), their high transmit-power (typically requiring several kilowatts of electrical power), and their complexity (as typified by the high data-rates and advanced signal processing required).

A major driver of these requirements is that traditional SAR systems use backscatter - which is necessarily weak from most terrain types. Much of the radar energy is lost simply through being reflected in the forward direction. Thus, if the forward scattered energy could be gathered, then the transmit-power requirements could drop significantly – potentially making a SAR payload feasible for inclusion on a low-cost micro-satellite. However, in order to collect the forward scattered signal, a second satellite would be required, which would need a radar receiver synchronized to the transmitter on the first.

We therefore propose a novel method by which two micro-satellites fly in formation to accomplish a SAR mission bi-statically. The transmitting satellite will be the "master", with the receiver satellite "slaved" off it by means of a synchronization signal transmitted from the master.

To reduce the cost by a significant factor, we propose to base the mission on the micro-satellite technology pioneered over the last 20 years by the University of Surrey. In particular, our baseline satellite platform is the standard 100 kg "Constella" micro-satellite, currently in production at Surrey Satellite Technology Ltd. (SSTL).

The proposed mission architecture comprises a pair of satellites set up as a bi-static radar system operating at a frequency of approximately 2.4 GHz. This frequency was selected for the purposes of the study as it has a relatively long wavelength, which is useful when studying ice/water mixes, and experimental frequency allocations are available in this band.

Each satellite is of similar mass and cross-sectional area, so as to maintain the same ballistic coefficient. This is needed to allow for similar drag, thereby negating the need for excessive propellant mass for relative station keeping.

At the imaging latitude band, the satellites will be arranged to be in a side-by-side formation, with a cross-track baseline distance of approximately 60 km (as shown in Figure 1). From this position, the receiver will receive the forward-scattered signals from the transmitter.

We have chosen the polar-regions as the initial area of interest for the design, partly based on the potential commercial and scientific benefits of SAR imaging this region (which is difficult to monitor effectively by passive optical means), and partly based on the orbital dynamics needed to achieve the required baseline separation.

As described in a later section, in order to save on cost, both satellites are launched together on the same launch vehicle, and perform the required orbital manoeuvres using their own on-board propulsion systems. Our methodology requires moderate amounts of delta-V to attain the correct configuration for imaging a particular latitude band, with minimal delta-V thereafter to maintain the correct phasing.

A minor modification to the manoeuvres described would enable the satellites to image lower-latitude regions instead, and indeed, launching three or more pairs of satellites together could give global coverage.

Commercially, mapping of the polar-regions during both the summer and winter could provide shipping companies with information on viable polar routes, thus reducing the shipping costs and journey times.

Scientifically, the polar-regions are areas of great interest in studying the growth, motion and development of polar ice sheets, and noting their effect on climate change.

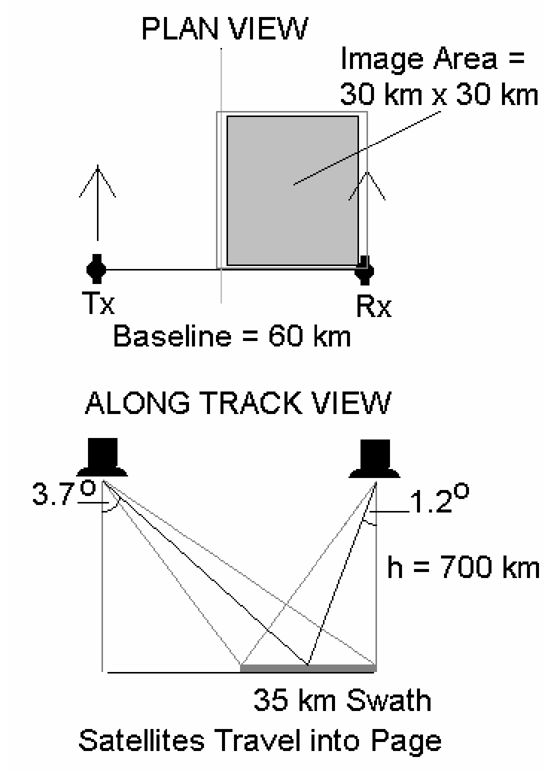


*Fig.1: System Geometry*

## General Theory

In any imaging system, there is a fundamental relationship between the ability to resolve the details of an imaged object and the size of the aperture of the system in comparison to the wavelength of the radiation involved. The problem with imaging at radio frequencies is that the wavelength of the radiation is relatively large compared to the physical size of aperture we could practically build. This severely limits the resolving power of so-called real-aperture radars.

In order to create a two-dimensional image of a scene at all, the radar needs to resolve the range to a scattering object (which is not so much of a problem), and to resolve its azimuth with respect to the radar (which is much less accurate). Initially, it was possible to create a finer resolution in real-aperture radars by simply using shorter radio pulses and increasing the physical size of the antenna to produce narrower beam widths. Then the advent of pulse compression techniques using signal processing enabled even finer resolution in the range, and yet, azimuth resolution was still limited by the physical factors of the aperture and radar platform.

The azimuth resolution problem was finally solved with the concept of synthetic aperture radar (SAR), which was first detailed in 1950 by Carl Wiley of the Goodyear Aircraft Corporation [1].

Wiley discovered that, when the radar was in motion relative to the target, the Doppler spread of the returning echo signals could be used to effectively synthesize a longer aperture by coherently adding multiple radar measurements using the Doppler shift.

This creates a single image with the same resolution as an aperture equal to the length of the travelled area (provided that the scattering object remains in view of the radar as it travels along). A large effective aperture can therefore be synthesized with accurately timed measurements and small physical apertures given the correct signal processing in the frequency domain.

Therefore, in the context of SAR imaging, the radar is set in motion with respect to the target (which is assumed to be stationary), and it "looks" to the side of the path or track being travelled in order to resolve the left-right ambiguity which would otherwise occur. The range to the scattering objects in the imaged scene is determined by the time-of-flight of the radar pulses to-and-from the scattering object, and the azimuth is determined by multiple samples of the object's returning echoes as the radar travels along its track – where each scattering object is identified by its unique Doppler history. The two dimensions of the image are therefore usually referred to as "range" for the cross-track direction and "azimuth" for the along-track direction.

In a traditional SAR mission, a single satellite looks to one side of its own track across the Earth, and receives echoes via backscatter. Thus, the rougher the surface is with respect to the wavelength of the radiation, the stronger the resultant backscattered signal (i.e. a perfectly smooth surface on the scale of the wavelength would give no backscatter). The timing synchronisation between transmitted and received pulses is simplified as the transmitter and receiver are mounted on the same platform and can therefore share a master clock timing reference.

In bi-static SAR, the principles are similar, except that in this case the imaged area must be to one side of the line which bi-sects the baseline between the transmitting and receiving spacecraft. Also, the receiver must know its relative position with respect to the transmitter, as well as knowing the precise time that the pulses were transmitted. This is made more difficult by the fact that the transmitter and receiver are physically separated.

In the bi-static case, a smooth surface would give a strong signal, and so the image is in some sense the "negative" of that achieved with traditional SAR.

## SAR System Design

### *Sea Ice Properties*

Our example mission involves SAR imaging of the polar-regions (>60$^o$ latitude) for scientific and/or commercial purposes - both of which require knowledge of the thickness of the sea ice, the distribution of that thickness, the extent of ice coverage, and the thawing and freezing cycles of the area. It is possible to determine these characteristics by the radar scatter from the ice, characterized by its age and composition. Further information may be derived by use of different polarisations on the transmitter and receiver.

Table 1 offers a summary of the radar cross-section (RCS) for sea ice at 2.4 GHz at a representative 4$^o$ inclination angle (measured to the vertical).

New or "grey" ice, is typically 1-20 cm in thickness and has a high salinity content, with a surface temperature of 0$^o$C or slightly lower [2]. It has a high dielectric constant, but a low absorption constant due to, often, large concentrations of liquid water mixed within the ice. Thick first year (FY) ice, has a lower surface temperature and a rougher surface texture, typically covered with snow or a brine slush, which decreases the vertical scattering coefficient. Multi-year (MY) ice can be divided into two parts, the upper part, characterized by low density and large air bubble size, and a lower part, with a high density and a high concentration of melt ponds.

*Table 1: Sea Ice Radar Cross Section (dB)*

| | Winter/ Spring | Late Spring | Summer | Autumn |
|---|---|---|---|---|
| MY | -6.7$\pm$2.2 | -4.3$\pm$2.1 | -9.3$\pm$1.1 | -6.1$\pm$2.4 |
| Thick FY | -9.0$\pm$2.1 | -8.0$\pm$1.4 | -9.3$\pm$1.1 | -8.7$\pm$2.4 |
| Thin FY | -4.3$\pm$1.2 | -5.2$\pm$1.6 | -5.6$\pm$1.4 | -4.8$\pm$1.9 |

### *Power Requirements*

Given the characteristics of the RCS of sea ice, it is possible to model the bi-static radar to determine the required power of the transmitted signal for a given signal to noise ratio (SNR). As the minimum RCS in the table is -10.4 dB, we take –15 dB as a reasonable estimate for the minimum RCS we would wish to record in the image.

As the satellites are only 60 km apart, the range to the target is approximately equal to the satellites' altitude, i.e. ~700 km, giving a round-trip range of ~1400 km. We estimate system losses to be ~15 dB over an above efficiency losses estimated separately. We assume a moderate DC-to-RF conversion efficiency of 20% in the transmitter, with an antenna illumination efficiency of 30% at both the transmitter and the receiver. Thus, a simple 2.5m parabolic dish will give ~30dB gain on both satellites.

The effective transmitter power requirement is further reduced by use of a linear-frequency modulated chirped pulse of 34 µs duration operating at a 6 kHz (167 µs period) pulse-repetition frequency (PRF).

The total imaging time is ~4 seconds to produce a scene 30km x 30km at 30m range and azimuth resolution.

Figure 2 shows the peak DC power required in the system as a function of signal-to-noise ratio.

Assuming a realistic 100W DC power availability from the spacecraft over the imaging time, a –15 dB RCS target can be detected at a signal-to-noise ratio of ~14 dB after multiple-look processing. Thus, the required power levels are well within the scope of those available on a micro-satellite.

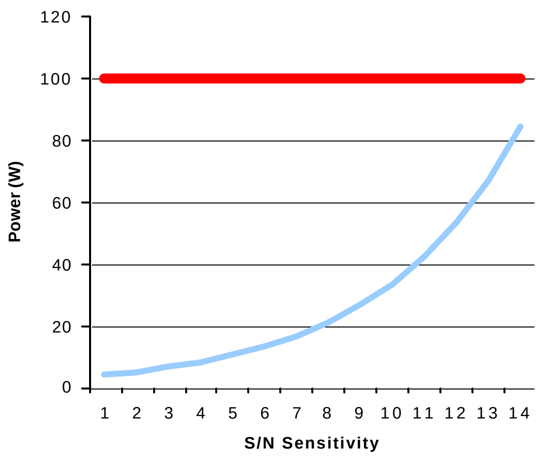


*Fig. 2: SNR vs. DC Power Requirement for -15 dB RCS (100 W DC = Specified System Limit)*

### *Transmitting and Receiving Subsystems*

The transmitter for this system will need to generate coherent, rectangular 34 µs duration pulses with a linear frequency modulation (i.e. a chirped pulse) at a nominal centre frequency of 2.4 GHz, and a 100 MHz bandwidth. Any errors in the frequency, phase, and amplitude of the transmitted signal will result in defocusing and measurement errors in the final image.

The transmitter needs to have good short-term relative stability, within 2.5 $\times 10^{-10}$ over the 4.7 ms propagation time (transmitter-to-ground-to-receiver) with no more than 1$^{o}$ phase error. This value is well within the current technological possibilities [1]. The error margin for the modulation scheme is 3 MHz, or 3%, in the bandwidth value for each pulse.

The role of the space-borne receiver will be to simply receive the echoed signals, and down-convert this to an intermediate frequency (IF), before digitising and storing the resultant data. The receiver's bandwidth, must be sufficient to detect the transmitted pulses including the Doppler shift which can be up to 120 kHz for the proposed mission. The receiver must have low-noise components so that it does not hide any of the target responses. Also, the receiver must be able to reproduce an adequate representation of the transmitted signal in order to correctly de-chirp the received signal., therefore it has the same frequency and phase stability requirements as the transmitter.

Synchronisation between the transmitting and receiving satellite is achieved through the use of a GPS receiver and inter-satellite link on both satellites, which provide accurate, synchronised clock sources and also provide a means to derive relative position data. The baseline distance needs to be known to an accuracy of 15m absolute, and the internal clocks must be stable to 2 parts in $10^{9}$ to maintain adequate phase control over the 4 second imaging period.

All these RF and synchronisation requirements are within the scope of current technology.

To maintain a low cost system and to help relax these high stability requirements, the use of a direct digitally synthesized (DDS) exciter is a possibility. First proposed by W.D. Gallaway in the 1988 National Radar Conference, this exciter achieves near theoretical performance values [3]. This would also allow for better synchronization between the transmitting and receiving subsystems, as each could hold an identical copy of the DDS waveform.

### *On-Board Data Handling*

The characteristics of the radar system lead to high performance constraints on the signal processing. Given a chirped pulse length of 34 µs and a compressed pulse of 10 ns, the frequency excursion of the chirped signal is 100 MHz. The sampling rate required is therefore twice this frequency (200 MHz), which needs to be applied to both the in-phase and quadrature-phase (I and Q) signals. Sampling both signals separately at this rate is sufficient to reconstruct the original signal with only a small error.

The processor must be able to write to memory at this speed multiplied by the number of bits of each sample, and the process must be continued for each pulse which occurs within the 4 seconds it takes the satellite to fly the 30 km ground track distance, giving a total of 24000 pulses each of 34 µs duration.

*Table 2: Data Handling Requirements*

| 200 Msps | 8 bits | 6 bits | 3 bits |
|---|---|---|---|
| Memory Speed | 1600 Mbps | 1200 Mbps | 600 Mbps |
| Channel Size | 1690 Mbits | 1267 Mbits | 634 Mbits |
| Image Size | 3380 Mbits | 2534 Mbits | 1268 Mbits |

Thus, with 8-bit samples, a 512 Mbyte data recorder would be able to hold the raw image. This is quite feasible, however the more challenging aspect will be sampling and storing data at 200 Msps (see Table 2).

Due to the large amount of data generated, data compression is needed to truly make it feasible for implementation on a LEO micro-satellite – especially in terms of the limited downlink bandwidth and limited pass time (typically ~10 minutes). Thus, a Block Adaptive Quantisation (BAQ) compression algorithm was chosen which estimates the statistics of the source data and attempts to match the quantiser to the observed statistics. The amplitude and phase of the returned echoes are statistically independent of each other and of other scatterers within the scene, so we may assume the data are uncorrelated and have a Gaussian distribution [4].

With this compression technique, and assuming 8-bit samples, the compressed data requirements are 850 Mbits per image instead of 3380 Mbits. This is easily storable in a 128 Mbyte solid-state data recorder, and can be transmitted via a standard 2 Mbps S-band downlink to the ground station, where the SAR image processing will occur. It should also be noted that traditional SAR systems often use less than 8 bits per sample with little loss information.

## Mission Design

### *Satellite Platform*

The satellite bus chosen for the project is based on SSTL's "Constella" micro-satellite platform, which is a low-cost, readily available system. The modular design enables it to easily accommodate the proposed SAR payload, and to provide the required system resources.

The design consists of a truncated pyramidal structure with a 1 m x 1 m base, a height of 0.6 m, and a mass of 100 kg, 60% of which is available for the payload and antenna [5].

The shape of the spacecraft is designed to optimise the power production of the body-mounted solar panels, but it also provides an extended base for the mounting of the 2.5m diameter antenna, which itself comprises four petals, which fold-up during launch, and deploy once in orbit.

Outwardly, the transmitter and receiver spacecraft would look identical (see Figure 3) Their mass would be arranged to be the same, with as much commonality of systems as possible. If not prohibitive in terms of cost, and mass, each spacecraft could be equipped with the transmitter and receiver part of the SAR payload. This would then give a degree of redundancy in orbit.

### *Power Subsystem*

The satellite has 4 body mounted Gallium Arsenide (GaAs) solar panels, which each produce an average of 100 W, respectively, with a peak power of 140 W. The Nickel Cadmium batteries provide 200 Whr capacity at 28 V.

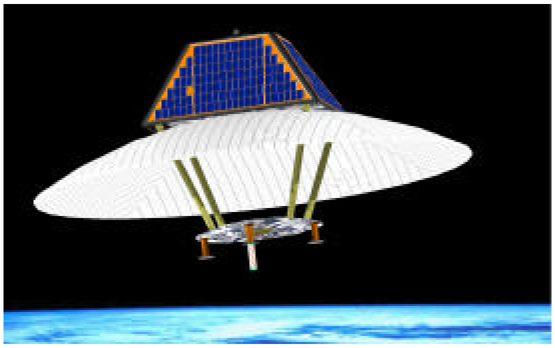

*Fig. 3: Bi-Static Radar Imaging Technology Satellite (BRITSAT) Concept (one of a pair)*

### *Attitude determination and Control System*

The Attitude Determination and Control System (ADCS) sensor suite comprises a three-axis flux-gate magnetometer, two-axis Sun sensors and an infra-red Earth-horizon sensor. The accuracy of the basic magnetometer and Sun-sensors is $0.5^o$ ($3\sigma$). The horizon sensor is used to provide further attitude knowledge, with a resolution of $0.06^o$ within a $\pm 5^o$ angle off the horizon.

The main actuator available for the ADCS is a pitch-axis momentum wheel, but a four-reaction wheel system could be substituted, to provide for full 3-axis stabilization. These actuators provide control of $0.25^o$ on the roll axis, $0.4^o$ in the pitch axis and $0.5^o$ in the yaw axis. Surrey is also currently developing a 4 wheel Control Moment Gyro, which would provide additional control and stability.

Any errors in the roll, pitch or yaw angle of the satellite will cause errors in the final image. The effect of small roll-pointing errors (say within half a degree), have a negligible effect on the image [6]. However, pitch and yaw errors cause a distortion in the Doppler frequency shift. An error in the yaw knowledge of the system causes a displacement of the antenna beam footprint around the non-zero Doppler line, and pitch error displaces the footprint forward and backwards. As it stands, the basic ADCS for the satellite provides a yaw error of less than $0.5^o$, which is acceptable. The attitude accuracy of the satellite is $0.4^o$ in pitch, leading to a Doppler frequency error of up to 350 Hz. It will therefore be necessary to correct this error in the ground image processing.

### *Downlink Communications Subsystem*

The S-band downlink transmitter will have a 2 Mbps data rate at a power output of 4 W, modulated using quadrature-phase-shift keying (QPSK). This meets the mission requirement of being able to download the compressed SAR data from the receiving satellite in a typical 10-minute pass over a single ground-station. Note: the SAR payload on the transmitting spacecraft will not be actively transmitting at this time so as to avoid any mutual interference.

If the ground-station was at high latitude, an image could be returned on every orbit (~14 per day). With more than one ground-station, more images could be acquired – for example covering both poles.

### *Constellation Design*

The orbits for the formation have been chosen to be Sun-synchronous, near circular, low-Earth orbits (LEO), with an altitude of 700 km. The period of the orbit is 98.8 minutes, giving approximately 14.5 orbits per day.

Given a basic two-body (Keplerian) model, the optimal constellation for the satellite would be two orbits, one inclined $0.2^o$ relative to the other to give the correct cross-track spatial separation near the poles. However, in reality, the presence of perturbations, specifically the $J_2$ perturbation, will cause the relative orientation of the two orbits to change, and the satellites will drift apart by $0.024\ ^o$/day due to a difference in the rates of change of the Right Ascension of the Ascending Node (RAAN) of the orbits.

If, on the other hand, the satellites were to have the same inclination but be separated by a $1.8^o$ in RAAN, the separation would be correct and the relative drift would be zero. However, this would require two separate launches which increases the expense.

Instead, we propose that the satellites are launched from the same vehicle, and that the transmitting satellite executes a small plane-change manoeuvre to alter its relative inclination by $0.2^o$. This configuration is propagated forward in time until the differential nodal drift has caused the relative RAAN to build up to $3.5^o$ (this takes approximately 75 days or 1088 orbits). Then, the receiving spacecraft changes its inclination by $0.2^o$, to match the inclination of the transmitting satellite. Note: by this means both spacecraft share the same delta-V ($\Delta V$) requirements, helping them to maintain the same ballistic ratio

The two orbits will now have the same nodal drift, and be separated by 60 km at the time of imaging.

The polar-imaging constellation design requires each satellite to have a $\Delta V$ budget of 66.4 m/s over a 5 year mission lifetime—65.4 m/s for the inclination change and only 1 m/s for station-keeping requirements – well within the 100 m/s capability already available on the proposed micro-satellite bus.

Similar manoeuvres can be carried out for pairs of satellites to image different latitude bands, and our modelling shows that a minimum of three pairs of satellites could cover the whole Earth. Further satellites could be added to the constellation to provide multiple look-angles and or different SAR frequencies, which could give further information on the nature of the surfaces being probed.

## Conclusion

The results of this study have indicated the basic feasibility of creating a micro-satellite-based SAR system for imaging specific latitude bands. The system requires a pair of satellites to "fly" side-by-side 60 km apart during image acquisition, so that, by means of bi-static SAR principles, it is possible for the receiver to collect the forward-scattered element of the ground response, greatly reducing the power requirement of the transmitted signal. Our orbit design achieves this with reasonable propulsion requirements, whilst enabling the satellites to be launched together on a single launch-vehicle.

The SAR system consists of a transmitting satellite, operating at 2.4 GHz, transmitting a chirped pulse of 34 µs duration with a bandwidth of 100 MHz at a power level of 20W RF output, into a 30 dB gain, 2.5m dish antenna. The receiving satellite has a similar dish, and provides sufficient on-board processing to down-convert the signal for compression and storage. All further SAR processing (image forming, focussing, etc.) will occur at the ground station.

The payload requirements fit comfortably within the capabilities of SSTL's existing 100 kg micro-satellite platform.

## Acknowledgements

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## References

[1] Curlander, J. and R. McDonough, Synthetic Aperture Radar Systems and Signal Processing, John Wiley & Sons, Inc., New York. 1991. pp. 126-152.

[2] Carsey, F.D. [ed], Microwave Remote Sensing of Sea Ice, Geophysical Monograph Series, Washington DC. 1992. pp. 9-47.

[3] Gallaway, W., K. Luckscheiter, E. Cowen, and J. Wilhelm, "A Direct Digitally Synthesized Exciter Achieving Near Theoretical Performance for an Operational SAR System", IEEE National Radar Conference. 1988. pp. 22-27.

[4] Kwok, R. and W. T. K. Johnson. "Block Adaptive Quantization of Magellan SAR Data", IEEE Transactions on Geoscience and Remote Sensing, Vol. 27, No. 4. July 1989. pg. 375-383.

[5] Wicks, A. "Constella Satellite Design Factsheet", SSTL Commercial Document. 2001.

[6] Elachi, C. Introduction to the Physics and Techniques of Remote Sensing. John Wiley & Sons, Inc., New York. 1987. pp. 161-218.