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Business Under the Clouds

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ABSTRACT

Imaging at night time, or under the clouds has been the preserve of large powerful satellites until recent years, and now technological advances have finally made it possible to miniaturise Synthetic Aperture Radar missions in an affordable way. The NovaSAR-S spacecraft leverages a common small satellite bus coupled with a radar payload focused on a specific range of promising commercial applications. Through the inclusion of a novel wide-swath mode, and Automatic Identification of Ship receiver, a range of maritime applications are enabled. An innovative funding model was used in order to finance the mission, with a number of geographically spaced users each having fractional ownership of the spacecraft and payload tasking rights. The spacecraft can therefore look to individual owner-operators as their own spacecraft. NovaSAR-1 was launched in late 2018 and first results of this S-band SAR spacecraft with AIS ship detection are provided.

INTRODUCTION

Space borne radar systems provide an attractive means to observe the Earth from space at times where optical systems cannot be used efficiently, for instance at night time or in areas with poor lighting such as over the poles, or in areas with extensive cloud or haze. Space borne radar can also be used in some cases to penetrate foliage, soil or water which has been exploited for instance in archaeology [1]. Furthermore, radar can also provide some information about the properties of the illuminated target that can some-times not be established through other means, due to the reflection, absorption and scattering characteristics of the target which change with wavelength and polarization.

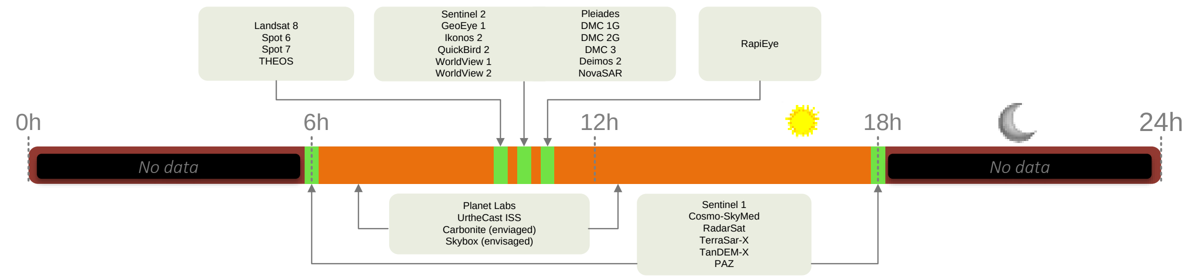

Figure 1: Existing EO missions tend to sample the Earth only at some specific times of day

The figure below shows that most optical and SAR satellites observe the Earth at some very narrowly defined time slots during the day. SAR imaging is not limited to any specific time, and therefore has the as yet unexploited opportunity for achieving higher temporal resolution by placing a number of SAR spacecraft in appropriate orbits.

Traditionally such space borne radar systems have required relatively large satellites. There are several reasons for this. Firstly, as an active Earth Observation system the amount of Radio Frequency transmission power is high in the kilowatt range leading to designs where that power is provided direct from solar panels. Secondly, spacecraft system design tends to drive solutions towards large area antennas. Until quite recently only major government agencies have developed such spacecraft. Their scientific or national needs have driven these missions to serve multiple applications, and as the expensive missions must serve all of the user community they include high levels of performance or features. Radar spacecraft system designs tend to lead to solutions in 6am-6pm sun-synchronous orbits where the power generation and thermal design are most easily dealt with. As there are not many other spacecraft that benefit from such an orbit, the only limitation to the size of the SAR spacecraft tends to be the size of the launch vehicle.

The table below shows that traditional SAR spacecraft have been "large" satellites with masses of around 800-4000kg. Two 300kg spacecraft have been the only small SAR spacecraft built by IAI to fit within the Shavit 300kg launch capability. In the past year however there have been a number of smaller SAR spacecraft launched, and most newly proposed systems are proposed as part of constellations providing commercial services.

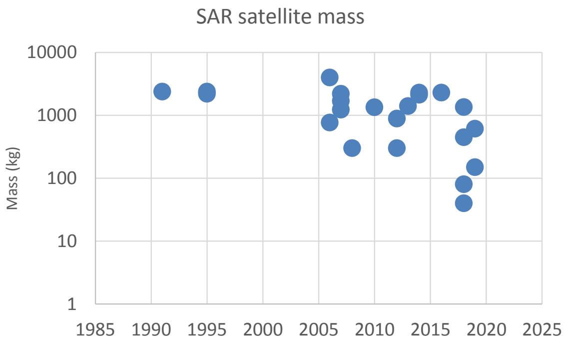

Figure 2: A selection of SAR missions and their mass

Table 1: SAR spacecraft and mass

SAR Mission	Year	Mass (kg)	Band
ERS-1	1991	2384	C
ERS-2	1995	2384	C
RadarSat-1	1995	2200	C
SARLupe	2006	770	X
ALOS-1	2006	4000	L
TerraSAR-X	2007	1230	X
RadarSAT-2	2007	2200	C
Cosmo-Skymed	2007	1700	X
TecSAR	2008	300	X
Tandem-X	2010	1340	X
HJ-1c	2012	890	S
RISAT-1	2012	300	X
KompSat-5	2013	1400	X
Sentinel-1a/b	2014	2300	C
ALOS-2	2014	2120	L
Sentinel-1a/b	2016	2300	C
IceEye-1	2018	80	X
NovaSAR-1	2018	450	S
Capella	2018	40	X
Paz	2018	1350	X
RiSAT-2B	2019	615	X
Harbinger	2019	150	X

SMALL SAR MARKET CHALLENGES

Like optical spacecraft, there are physical limitations on the size of spacecraft that can deliver a certain capability. References [2, 3, 4] have explored and analysed some of those trades, however the main sacrifices in making SAR spacecraft smaller and cheaper are in the amount of data return and orbital duty cycle that can be delivered from individual spacecraft.

The design of small SAR spacecraft is highly complex, and also challenging based on payload requirements and how those drive the spacecraft design. Although the physical limitations do not preclude the potential for microsatellite class (10-100kg) SAR spacecraft, the real questions is why you would develop those. Doubling the orbital duty cycle of a SAR spacecraft cycle does not double the size and cost of the overall spacecraft, and as such the only rationale for reducing the size of the spacecraft would be if working to a fixed budget, or in implementing a multi-satellite constellation.

Using an “off-the-shelf” bus to host a radar spacecraft is generally problematic, and most standard bus designs would require some modification to account for the specific power and attitude control imposed by a SAR payload. Furthermore, doubling the orbital duty cycle does not double the size and cost of the overall spacecraft, and as such the only rationale for reducing the size of the spacecraft would be if working to a fixed budget, or in implementing a multi-satellite constellation.

The market for SAR data is projected to be worth USD1.6b in revenues by 2027, with 2018 figures being just over half of that. Typical pricing for SAR data varies from around USD85-150/km^2 today, falling to around one third of that over the coming decade [2]. Using these figures, the current worldwide annual data sales can be estimated to be 8 million km^2. The value of SAR spacecraft and commercial data capacity far outstrips the market. Furthermore, some data is made available for free from the Sentinel-1 spacecraft, although the satellite is not available for casual tasking requests.

As such, any new SAR systems must differentiate their services from those currently available in order to generate value. Given the broad capabilities and scientific quality available from current SAR missions, it is likely that such new systems will need to use quite small spacecraft initially, in order to develop a suitable base of users.

Return-On-Investment from such spacecraft, whether in money or data terms, depends strongly on the amount of *useful* data and derived value that can be generated during the mission lifetime. Furthermore, many design choices are based on the specific application that is served.

Traditional SAR missions developed by governmental agencies tend to be designed to meet highly derived and rigid performance parameters. Systems designed to support a service and a business case may see a more iterative, rather than cascaded flow down, type of requirements development. Systems designed for surveillance type applications (e.g. security and environmental monitoring) will typically be driven by resolution and revisit where object detection and feature extraction, often relating to human activity, is required. Where classification of distributed targets is required (e.g. agricultural and environmental assessment) sensitivity and radiometric aspects are more important.

With the market in mind, NovaSAR was designed with a clear goal to achieve good potential for a Return-On-Investment, with a focus on good-enough performance and in addressing a promising set of applications of commercial value.

NOVASAR SPACECAFT

At the time of the NovaSAR project was started, it was the smallest SAR satellite planned to be economically sustainable in addressing commercial services [6]. In order to address a range of applications, the spacecraft was designed to operate in an unconventional SSO 10:30 orbit, to utilise S-band, to include an Automatic Identification of Ships (AIS) receiver, and to implement a number of modes including quad-polar capability. Although it can be used as a stand-alone spacecraft, it is designed with operation in constellations in mind. The applications considered having commercial value include (1) Ship detection and tracking (2) Oil spill monitoring, (3) Forestry management, (4) Resource monitoring, (5) Border monitoring, (6) Disaster management, (7) Land use and agriculture mapping, (8) Rice monitoring and (9) Soil moisture.

Key factors in making NovaSAR possible have been to leverage the latest high-efficiency semiconductors to reduce the needed on-board power, the choice of S-band as the transmission band, and the approach to defining modes of operation to serve a range of applications. Coupled with this, NovaSAR-1 was the first to include AIS within the radar spacecraft design, and employs a novel funding model allowing geographically disparate users to each act as owner-operator sharing the mission costs.

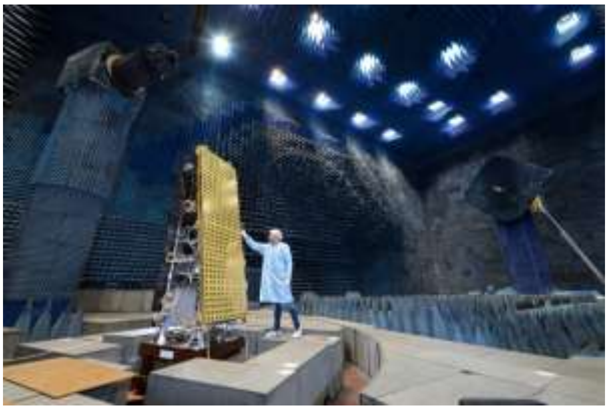

Figure 4: NovaSAR in antenna test chamber at Airbus UK.

NovaSAR level-1 image products are radiometrically corrected and available in either slant range or ground range projection. In addition, stripmap products can be detected or single look complex. For land applications stripmap offers high resolution for monitoring urban development and disasters. ScanSAR modes offer wider swaths for agricultural and environmental applications. Swaths up to 195km have been implemented using lower than normal incidence angles down to 11deg, the utility of which will be established through the mission.

Table 2: NovaSAR summary specification

Parameter	Value
Imaging frequency band	3.1-3.3 GHz
SAR Antenna	Microstrip patch phased array (3x1 m)
No. of phase centres	18
Peak RF power	1.8 kW
Polarisations	HH, HV, VH, VV
Imaging polarisation	Single, dual, tri or quad-polar
AIS Antenna	2 orthogonal mounted monopole antennas per receiver
Design life for operations	7 years
Design Mass	<440 kg
Optimum orbit	580 km SSO (LTAN 10:30)
Propulsion system	Xenon
Payload data memory	2xHSDR (32 GBytes) + 2xFMMU (512 Gbytes)
Downlink rate	500 Mbps
TT&C frequency band	S-band (2025-2110 MHz, 2200-2290 MHz)
Downlink frequency band	X-band (8.025-8.4 GHz)

The NovaSAR-1 spacecraft specification and modes are tabulated in Table 3 below.

Figure 4: NovaSAR designed for constellation launch

Table 3: NovaSAR summary of modes

Type	Resolution	Swath	Polarisation
Stripmap	6m	13-20km	HH or VV
Stripmap (wide swath)	6m	18-25km	HH
Stripmap (x-pol)	6x10m	20km	HV
Maritime (scanSAR)	6x14m	400km	HH
ScanSAR	20m	50-100km	HH or VV
ScanSAR	30m	55-150km	HH or VV
ScanSAR	33m	195km	HH
Dual pol	20m	50-60km	HH+VV
Dual pol	20m	20-30km	HH+HV
Dual pol	40m	195km	HH+HV
Dual pol	45m	195km	HH+HV
Tri-pol	30m	50-56km	HH+VV+HV
Tri-pol	35m	100km	HH+VV+HV

NOVASAR-1 FIRST YEAR OF OPERATIONS

NovaSAR-1 launch was arranged after a minimum number of users had been secured. The satellite employs a novel “fractionated satellite” model with several users sharing the satellite over different geographic regions. Each user has full access to task the satellite with priority access to their specific areas of interest.

NovaSAR-1 was launched on PSLV C42 from India on the 16th September 2018. First images were taken within weeks and a range of early images were subsequently published during commissioning [7]. The spacecraft has started pilot service ahead of full commercial service. The first year in-orbit has mostly been concerned with commissioning and execution of the demonstration phase of the mission during which mission partners will start to exploit the system.

Launch and Early Operations (LEOP) activities in the few days after launch went smoothly with no anomalies encountered. Once tracking of the satellite and platform communications were established, a de-tumble mode was implemented to achieve nominal nadir pointing. There followed a period of platform checkout and on the 8th October 2018 the first image was acquired. The satellite was tasked to image West Africa and download the data to Guildford in the ascending half of the same orbit.

The first image turned out to be a fortuitous anomaly and there followed a period of fixing bugs in mode definitions, tasking software, on board computer software and ground data processing. In parallel, commissioning activities, relating to both space segment and ground segment, progressed. The NovaSAR radar antenna is a planar phased array. Although the aperture is small for this type of system it has sufficient phase centres to support flexible modes of operation. A number of modes have been implemented and modes will be added through the mission at the request of mission partners. The following mode in Table 3 have so far been implemented and functionally tested.

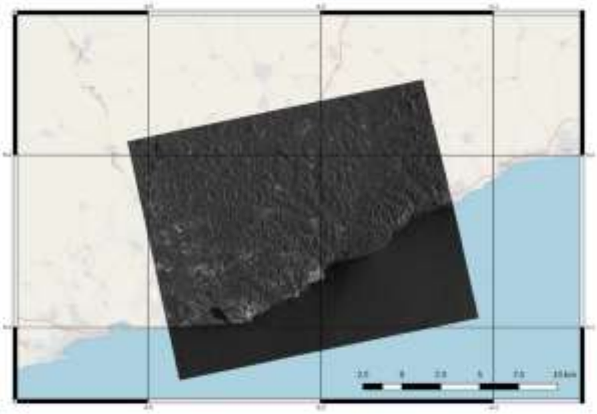

Figure 5: NovaSAR first image

Being S-band the NovaSAR payload provides data in an underutilised frequency band. With a wavelength between L- and C-band there is interest in seeing how much information is available relating to vegetation penetration and soil moisture. Proper studies are required to quantify these effects. To the eye images look information rich and multipolar examples in particular suggest there is plenty of information content to be exploited by classification techniques.

From images captured so far there is good potential for exploitation by ocean applications (Figures 10, 13, 14, 15). Wave structure, bathymetry and sea ice all show up well (figure 16). Responses from ships and ship wakes suggest a direct read across of ship detection techniques developed on other data. The darkness of calm sea areas suggests good potential for oil spill identification.

A unique feature built into the NovaSAR payload is the ability to support long pulse durations. The bulk capacitance associated with the SSPA in each phase centre of the antenna array has been oversized to support low pulse repetition frequencies with long duration pulses. Although not useful for normal SAR imaging, wider swaths can be captured at the expense of along-track ambiguities. When imaging open ocean areas in this mode NESZ exceeds ocean backscatter levels. Hence, if SAR focusing is applied to the data ships are represented as bright responses with ambiguities against a background which is the noise floor of the instrument modified by scalloping from radiometric correction. Tests to date have produced expected results. Since the resultant level 1 data is somewhat unique there are currently no bespoke ship detection algorithms but it is hoped mission partners will develop techniques to exploit this mode.

Figure 6: NovaSAR ship detection mode

As well as the primary SAR payload NovaSAR also carries a secondary AIS payload. To make data handling convenient the AIS will capture AIS messages and store a separate file for each hour it is operational. AIS antennas are omnidirectional and transmissions are received anywhere within line of sight of the satellite. Analysis of data indicates many thousands of AIS transmissions are captured per hour, although many of these are coastal stations and static facilities. It is also apparent from lat/longs outside line of sight of the orbit that there are many erroneous or malicious rogue transmissions.

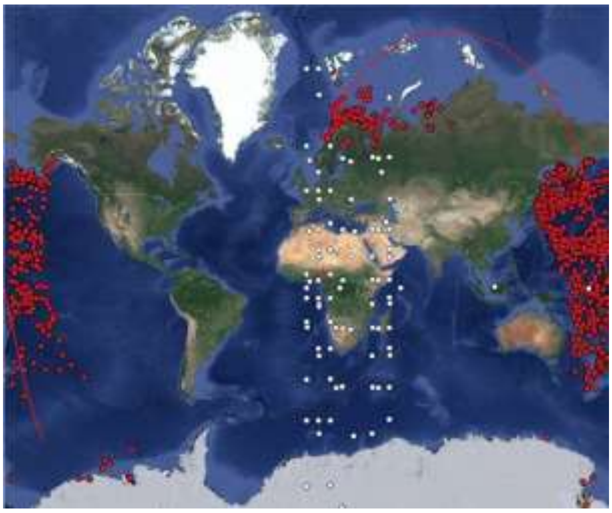

Figure 7: NovaSAR AIS data showing "suspect" transmissions (white)

Figure 8: NovaSAR AIS data in Sydney Harbour

An obvious advantage of having both SAR and AIS payloads on the same space borne platform is the potential to associate the two types of data. An initial attempt shows that a close correlation can be achieved if the time delta is favourable. In the example the offset between the ship response in the SAR image and the lat/long pair of the AIS messages is consistent highlighting an error in the geo-referencing of the SAR data. Since the data was captured near a port the ships' AIS transceivers are transmitting every few seconds. Hence, multiple successive lat/long pairs are captured for each ship showing a nice correlation with the direction indicated by the shape of the ship response in the SAR image.

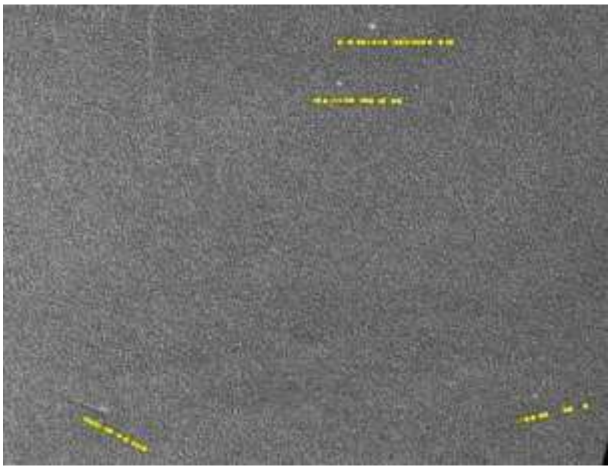

Figure 9: Coincident SAR and AIS data

Post launch commissioning activities have included a calibration campaign on the SAR payload to optimise and characterise its performance. Typical measurements using passive targets where carried out: corner reflectors for known radar cross section point targets; rain forest for wide area homogenous targets; calm water, salt flats and airport runways for low backscatter dark targets. Radiometric stability looks good with a standard deviation of <0.4dB. The mission requirement for geolocation error is 50m. When a correction is made to account for the difference between the ellipsoid height used to generate the level 1 product and the actual terrain height the geolocation requirement is easily achieved and is typically <10m.

FUTURE PLANS - CARBSAR

Based on experience with NovaSAR, and leveraging improvements in technology, SSTL has developed a follow-on SAR spacecraft product. ”CarbSAR” is an ultra-low cost SAR satellite intended for operation in SAR or mixed service Earth Observation constellations, providing very high resolution across relatively small scenes with the potential for high temporal resolution. CarbSAR utilises the platform heritage of the Carbonite optical satellite series and combines it with an innovative deployable X-band SAR antenna and payload.

Table 3: CarbSAR specifications

Parameter	Specification
GSD	0.5m
Swath	4km
Spectral bands	X-Band (9.6GHz)
Throughput	180GByte per day 45 spotlight mode images per day
Reference orbit	525km SSO with 10:30 LTAN
Mission lifetime	5 Years
Launch mass	140kg
Data storage	512GByte
Downlink	500Mbps

Figure 9: CarbSAR is part of a series of small EO spacecraft

Although capable of stripmap operation, its primary utility is anticipated to come from sub-metre resolution repeat visit applications in Spotlight mode.

CONCLUSION

As SAR systems become more popular with commercial companies supporting data analytics applications, there is significant room for a variety of systems that utilize small SAR spacecraft in order to address some specific markets. These system require low-cost SAR systems with payload characteristics matched to the specific market, rather than the general purpose SAR spacecraft launched under some national and space agency projects. Such small SAR spacecraft may need to be deployed into multi-plane constellations in order to observe targets at different times of the day.

NovaSAR-1, and its follow-on SAR concept CarbSAR address two particular variants of small SAR spacecraft addressing very specific applications, and have been presented as examples of how small SAR missions can help address specific markets and end-users. NovaSAR-1 results from the first year of operations show significant promise in the use of S-band radar for a range of commercial applications including maritime surveillance.

References

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Table 4: NovaSAR modes

Mode	Ground range resolution	Incidence angles	Swath width (across track)	Sensitivity (NESZ)	Azimuth ambiguity ratio (DTAR)	Range ambiguity ratio (DTAR)	No. of looks
0 Calibration	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1a ScanSAR	20m	15.8-25.38°	100 km	<-18.5 dB	<-17 dB	<-17 dB	4
1b ScanSAR	20m	25-29.4°	50 km	<-20 dB	<-17.5 dB	<-16.5 dB	4
2 Maritime	6m range 13.7m azimuth	34.5-57.3°	400 km	<-11.4dB	N/A	<-18 dB	1
3a Stripmap	6m	16-25.38°	20 km	<-19.5 dB	<-20 dB	<-18 dB	3
3b Stripmap	6m	21.83-31.2°	13-20 km	<-18.5 dB	<-17 dB	<-16.5 dB	3
3c Stripmap	10m	13.4-27.4°	20km	<-19 dB	<-15dB	<-15dB	5
4a ScanSAR Wide	30m	14-27.39°	140 km	<-19 dB	<-17 dB	<-15.5 dB	4
4b ScanSAR Wide	30m	27.35-32.01°	55 km	<-19.5 dB	<-17.5 dB	<-15.5 dB	4

Figure 10: NovaSAR multi-polar images Mississippi Delta and gulf of Mexico (left), Suez Canal and red Sea 30m resolution Alt-Pol scanSAR with HH green, VV blue, HV red (Right)

Figure 11: NovaSAR AIS tracking around the Cape of Good Hope

Figure 12: Calgary, Canada 6m resolution stripmap

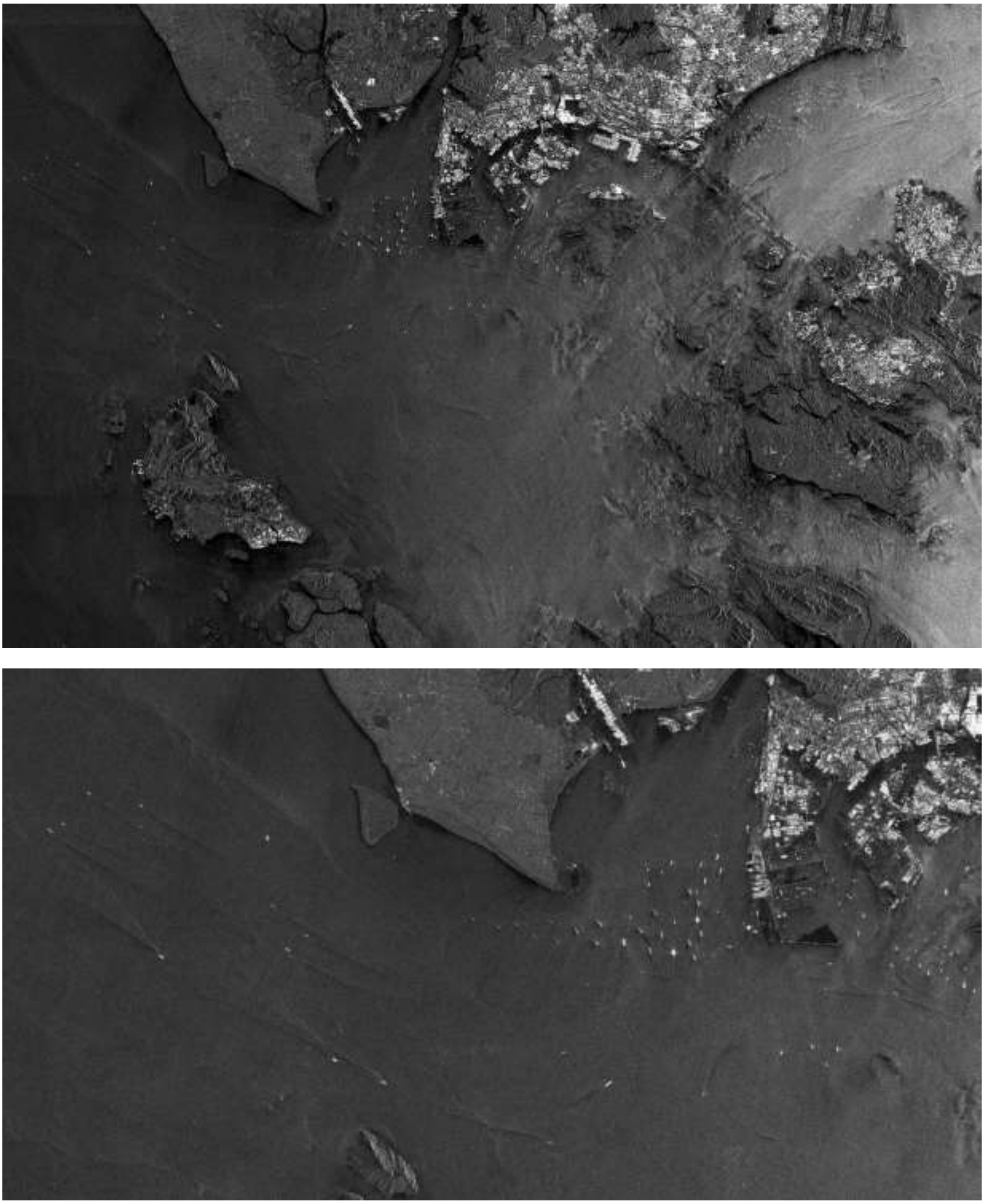

Figure 13: **Singapore 20m resolution scanSAR showing anchored and moving ships.**

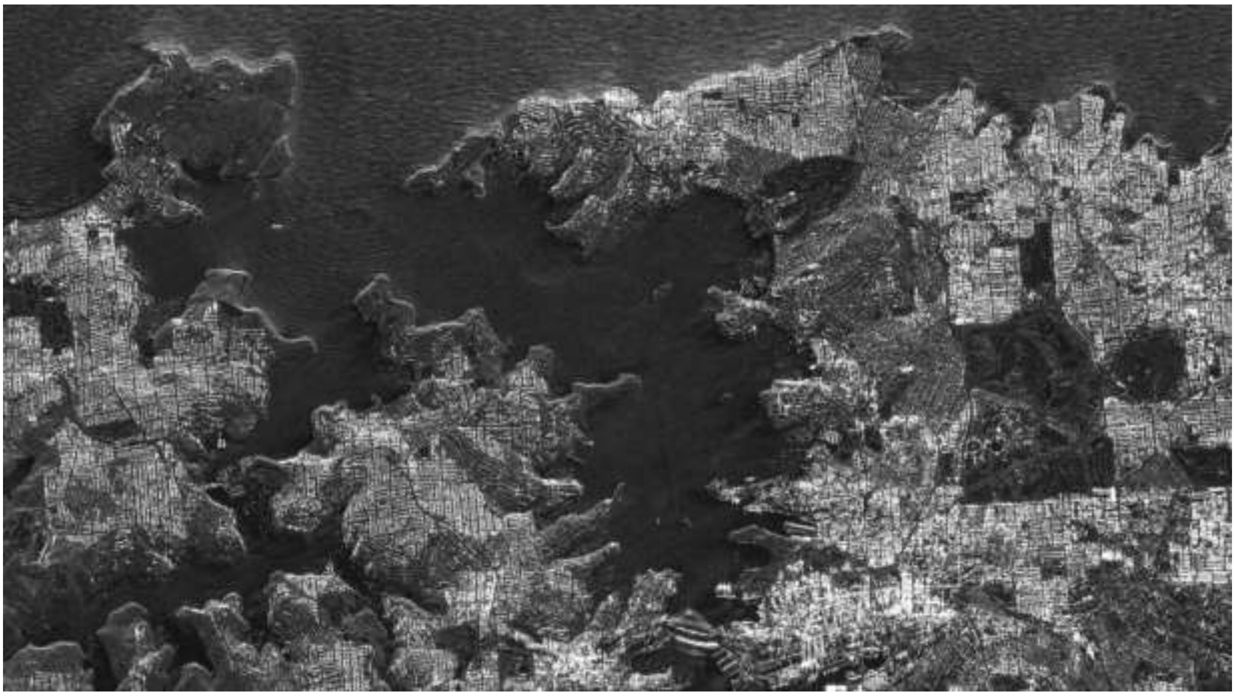

Figure 14: Sydney Harbour 6m resolution stripmap.

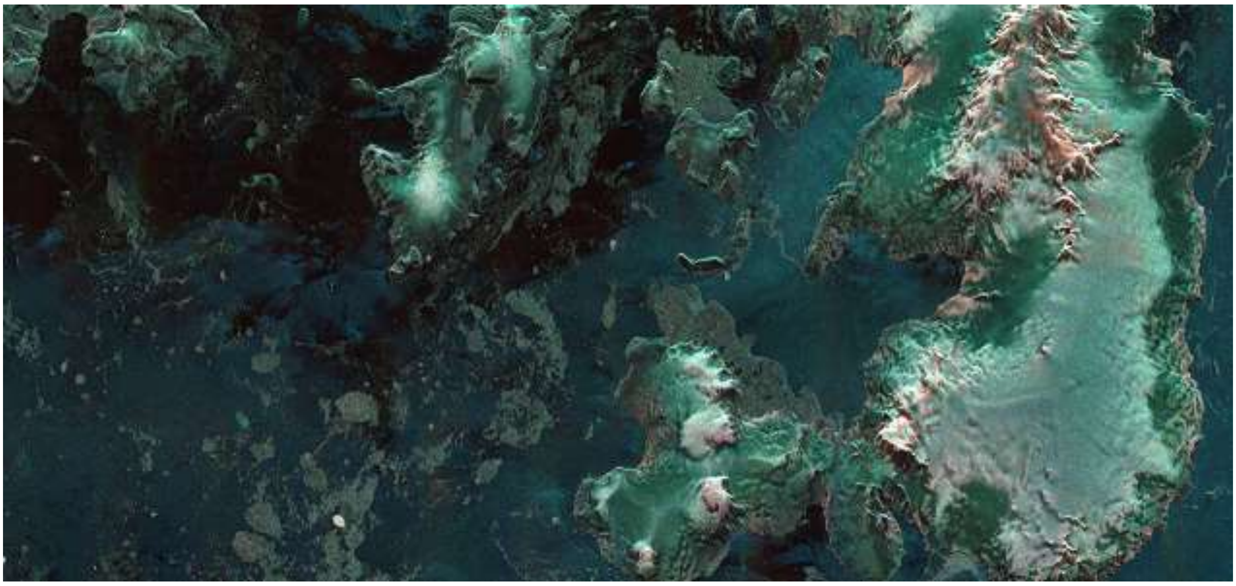

Figure 15: Duse Bay and Antartic Sea ice 30m resolution Alt-Pol scanSAR (HH green, VV blue, HV red)

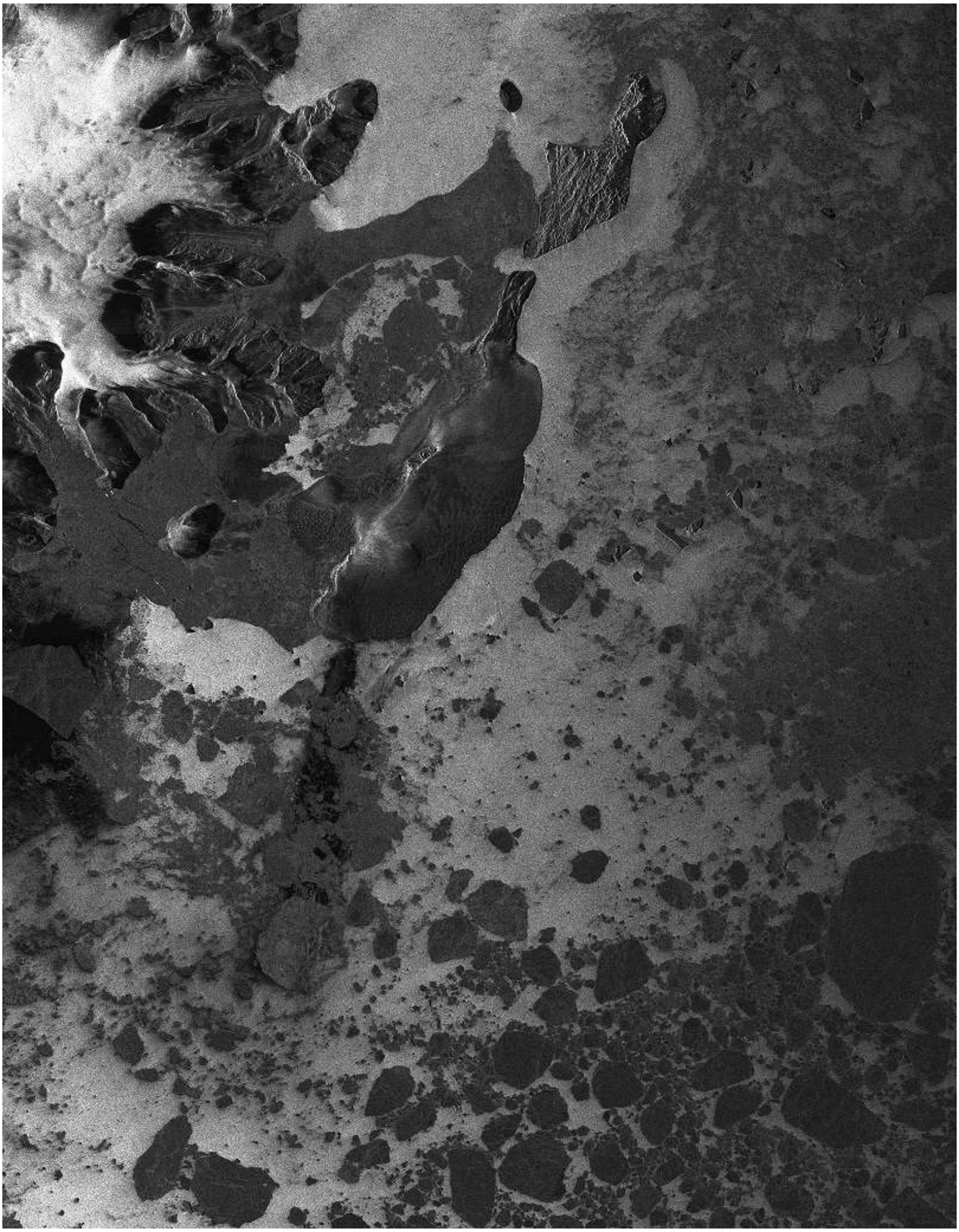

Figure 16: James Ross Island and Antartic sea ice 30m resolution scanSAR .