NovaSAR-S Low Cost Spaceborne SAR Payload Design, development and deployment of a new benchmark in spaceborne radar

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Abstract*— The NovaSAR-S Synthetic Aperture Radar (SAR) payload is the product of a UK national programme to establish a low cost radar system which enables affordable access to spaceborne microwave radar imaging. The S-band SAR payload provides highly capable, multi-mode SAR with a finest spatial resolution of 6m and incorporates a novel wide swath maritime surveillance mode. The payload features an active phased array with a markedly low phase centre count. The competiveness of this system has been achieved through the exploitation of new technology opportunities such as high efficiency Gallium Nitride solid-state power amplifiers, and working with a range of small UK companies to take advantage of developments from the commercial off-the-shelf domain. Also, the design and development approach has been a significant departure from previous SAR programmes with a strategy to maximise benefit from previous technology heritage, use generic flexible products, and employ a project structure centred on a small team with low overheads. The NovaSAR-S programme is based on the core principle of design-to-cost against aggressive mission price targets in order to address customers who are looking to enter into the SAR Earth Observation domain and who require the capabilities of an operational constellation, or demand a low cost of ownership. The capabilities of the S-band payload are well-suited to support a range of Earth Observation applications with specific emphasis on maritime surveillance and a range of land cover classification domains, particularly where constellation configurations providing frequent revisit is critical. The payload will be launched on the NovaSAR-S first mission in 2017 and has a nominal operational lifetime of 7 years. Follow-on S-band and X-band payloads are anticipated, and are being developed according to the same model as NovaSAR-S. The NovaSAR-S mission is a collaboration between Airbus Defence and Space (SAR payload and Image Processor) and Surrey Satellite Technology Limited (Satellite Platform). The first mission has been funded by a combination of UK government and internal Airbus Defence and Space investment.

Keywords—SAR; NovaSAR; S-band; NIA; Payload; Airbus

I. Design and Implementation

The NovaSAR-S Payload implementation [1] has been founded on low cost as the primary design driver, but also ensuring a SAR imaging capability that delivers good performance and flexibility. At the core of the design was a decision to develop the S-band radar because of the significant potential that it provided to realise an instrument architecture with a low hardware unit count and low equipment costs which together address the aggressive price and performance objectives.

After an extensive trade-off, the selected SAR instrument architecture comprises a low phase centre count phased array in which the peak power per phase centre is an order of magnitude larger than in traditional SAR phased arrays, but the number of phase centres is correspondingly reduced by an order of magnitude. This approach maintains power/aperture product, crucial to achieving good sensitivity, while reducing cost significantly, in this case by having 18 phase centres of 100W (peak RF) each, rather than 180 phase centres of 10W (peak RF) each. The grating lobe effects caused by reduced phase centre count are carefully managed to avoid excessive performance impacts. In particular, steer-off angles are limited so that grating lobes do not become too large. Nonetheless sufficient steering is available in elevation to enable a range of useful ScanSAR modes to be implemented.

The result for NovaSAR-S is an active phased array antenna with dimensions 2.74m x 0.96m and comprising 3 columns and 6 rows of phase centres. Each active row comprises two rows of radiating elements. Each active column comprises two 6-element subarrays. The antenna is dual-polar (Horizontal / Vertical) and the radiating subarrays are implemented using a foam/laminate sandwich microstrip patch construction which is both low cost and low mass, and achieves highly repeatable performance.

To keep cost to a minimum, only one receive channel is implemented. While this prevents simultaneous reception of H and V echoes, and hence prevents fully coherent polarimetry, incoherent polarimetric imagery can still be acquired through the alternating polarisation approach as used on ENVISAT's ASAR instrument [2], which is essentially a ScanSAR mode where different polarimetry combinations are used from burst to burst, rather than different sub-swaths. Furthermore, in general only HH and VV will be used since signal to noise ratio will be limited in the HV and VH cases. The exception to this is for ship detection at low incidence angles, where the ships are bright enough to be detected in cross-polar imagery and the use of cross-polar reduces sea clutter significantly enabling the ships to be detected.

This means that NovaSAR-S polarimetric applications potential lies somewhere between a single-polar SAR and a fully coherent Quad polar SAR.

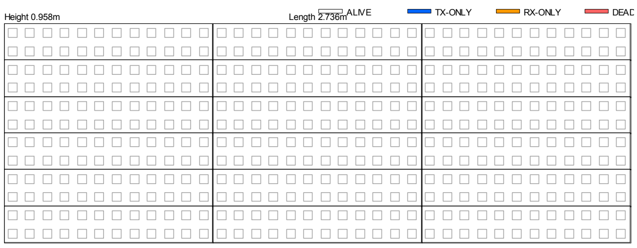

Fig. 1. NovaSAR-S Low Phase Centre Count Phased Array Configuration

The 3m² antenna area is relatively small for an S-Band SAR but is large enough to deliver good ambiguity ratio performance up to a moderate 31° incidence for traditional imaging (Stripmap and ScanSAR) modes.

The Back End comprises the Airbus Defence and Space 'New Instrument Architecture' (NIA) generic radar central electronics product, incorporating a highly flexible radar Chirp & Timing Generator (CTG) Module and a highly capable Digitiser module which includes a 12-bit A/C converter and all the receive chain digital signal processing and data handling that is required. This includes digital down-conversion, flexible L/M decimation filtering, data compression (2.5, 3, 3.5, 4, 4.5 and 5-bit Block Adaptive Quantisation), packetisation (to CCSDS standard) and datation (time stamp, PRI count, packet count, Mode ID, PRI ID etc...), buffering and output to a high rate data interface. The NIA Back End performs all instrument control functions yet uniquely requires no payload software or CPU module. Instead, configuration files that define the required operations are generated on the ground, uploaded to the spacecraft's on-board computer, and then copied to the SAR payload after payload power-up via write commands to registers in the FPGAs. The FPGAs then autonomously execute all the defined operations while enabling telemetry to be read back by the spacecraft on-board computer.

The NIA Back-End is implemented as a unit with a mass of 11kg and a DC power consumption of 50W. Two identical cold-redundant NIA units form the complete SAR Payload Back-End. Each is interfaced to the platform high-speed data recorders via a WizardLink interface.

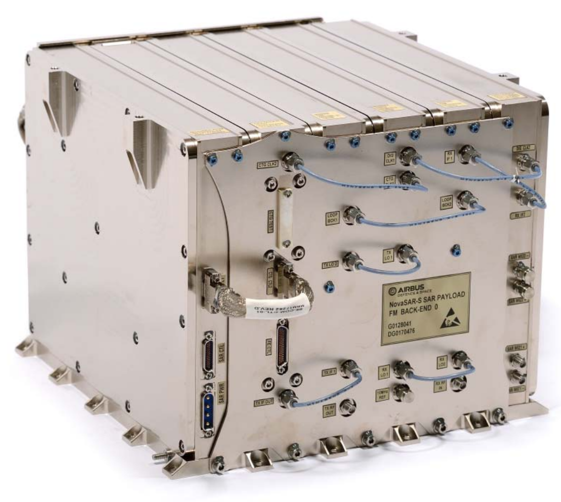

Fig. 2. NovaSAR-S 'NIA' Back-End Equipment

The Payload Front End / Antenna comprises 18 x 100 Watt peak phase centres in a 3-column by 6-row configuration. The architecture of a single phase centre is shown below.

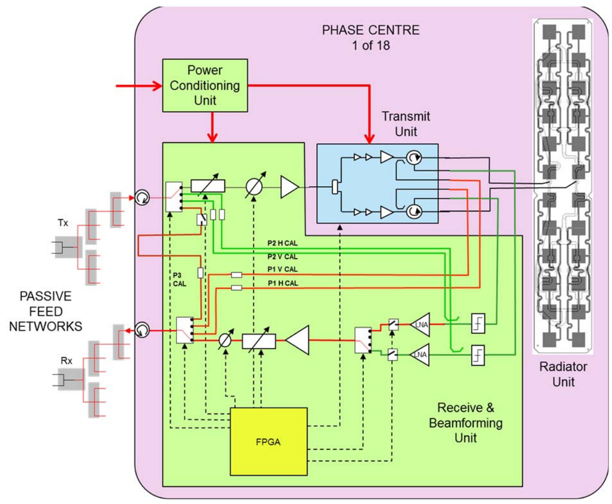

Fig. 3. NovaSAR-S Phase Centre Architecture

Beamforming components (digital phase shifters and digital attenuators) are included in both transmit and receive paths. Transmit is polarisation selectable from pulse to pulse between horizontal and vertical. Receive is also polarisation selectable between horizontal and vertical, but only one polarisation can be received at any one time.

Calibration paths are included based on a P1/P2/P3 calibration scheme as used on the ASAR instrument on

ESA's ENVISAT spacecraft [3]. The P1 calibration path includes all active transmit path components but omits all active receive path components in the phase centre. The P2 calibration path omits all active transmit path components but includes all active receive path components in the phase centre. The P3 calibration path omits all active components in the phase centre. Calibration is performed one phase centre at a time, and has multiple roles, including enabling range replica formation in the image processor, characterisation of any through-life variations occurring in the payload electronics, fault diagnostics and beamforming tuning.

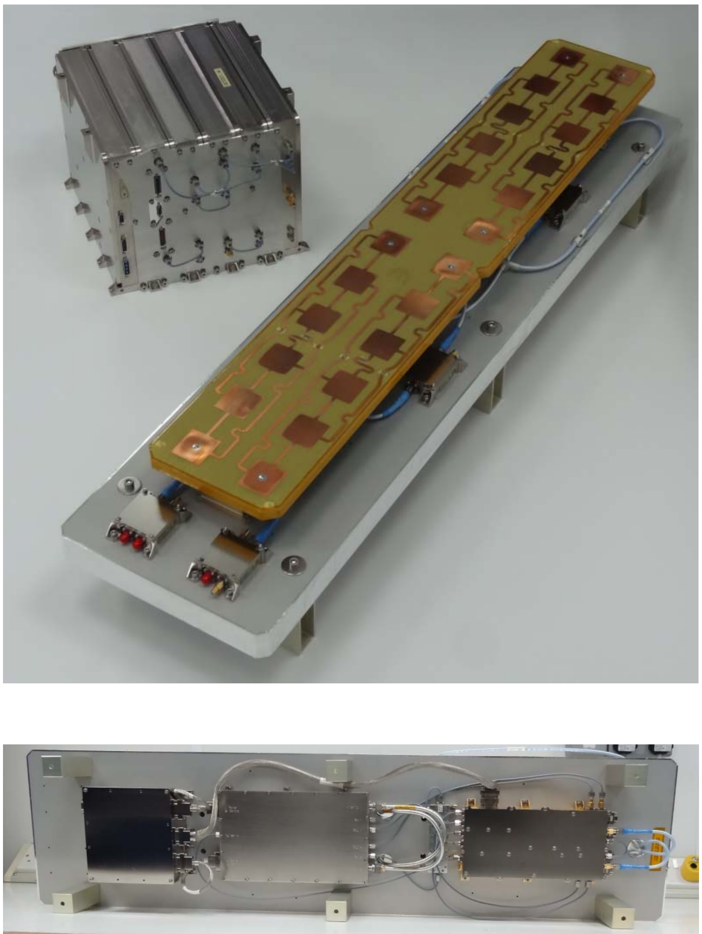

Fig. 4. NovaSAR-S Engineering Qualification Model Equipments (Back-End and Phase Centre)

The entire phased array has been characterised over temperature and a temperature compensation process is implemented within the NIA Back-End to correct for thermal and manufacturing variations and optimise the settings of the beamforming elements.

Antenna range testing has confirmed that good control of the beamforming is achieved in transmit and receive, in both polarisations, and for uniform as well as steered beam cases, as the example 'measured versus predicted' pattern comparison illustrates.

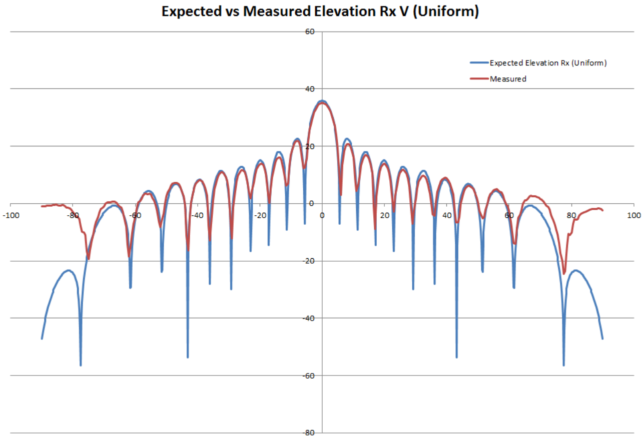

Fig. 5. Example Measured vs Predicted Beam pattern (Uniform Elevation V Beam on Boresight)

The active antenna electronic elements are the GaN based Transmit Unit (TxU), Receive & Beamforming Unit (RBU) and Power Conditioning Unit (PCU) building blocks (1 of each for each of the 18 phase centres). The PCUs include charge storage capacitance so that the platform sees low ripple current during radar operation.

The front-end units are mounted on a fixed honeycomb support panel thermally isolated from the spacecraft structure. Low power RF feed networks are mounted on the other side of the same panel, underneath the passive radiator units.

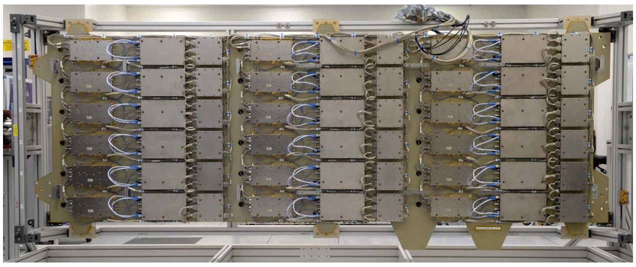

Fig. 6. Front-End Panel (Back Side) on Handling Frame

The total payload mass is around 140kg. Payload DC power during imaging operations is approximately 1850W and between 2 and 4 minutes of imagery will be acquired per orbit. These design parameters enable compatibility, in both technical and price terms, with the small satellite platform provided by SSTL.

The Payload is complemented by an Image Formation Processor also developed by Airbus DS (UK) which takes the raw data and converts it into a defined and calibrated image whilst removing instrument dependent features. Airbus DS (UK) has additionally created a product reader that will enable NovaSAR-S processed data to be read by the

ESA Sentinel-1 Tool Box (S1TBX) [4] enabling the data to be further processed as required by exploitation partners.

II. Technology

The use of high-speed re-programmable FPGAs in the central electronics was chosen to enable the more complex modules to be re-used for a range of other missions in the future without needing to re-design the hardware. The space grade Xilinx Virtex 5 device is used in both the Chirp & Timing Generator module and the Digitiser module. Qualification of the use of this FPGA has represented a key milestone and advantage to the realisation of NovaSAR-S Payload architecture.

The advent of high-efficiency Gallium Nitride-based Solid State Power Amplifier devices at S-Band has had a key influence on the payload architecture through the ability to deliver higher peak RF power per phase centre, thereby reducing the number of antenna phase centres whilst still delivering sufficient beam steering capability.

Airbus DS (UK) has also designed and developed the in-house S-band radiating subarray technology that supports generation of the elevation and azimuth antenna patterns with the required polarimetric performances.

These and other device-level or module-level technologies have contributed to a high performance to cost ratio solution with building blocks that will have application on follow-on SAR missions at S-Band as well as other radar bands.

III. Performance

The baseline operations provided by the payload are facilitated by the electronic beam steering capabilities of the phased array. This provides for flexible imaging in either high resolution or high coverage modes, as a function of the user applications requirements, including the following performance from the nominal 580km orbit altitude for the NovaSAR first mission:

- Stripmap: 6m resolution, 15-20km swath width, access over 16-31° incidence angle range
- ScanSAR: 20-30m resolution, 100-140km swath, 14-32° incidence
- Maritime: >400km swath, 34-57° incidence

Range ambiguity ratio is typically < -18dB is all modes. Azimuth ambiguity ratio is typically < -18dB in all modes except Maritime Mode, which is deliberately highly azimuth ambiguous.

Pulse Repetition rates vary between 5000 and 7000Hz in regular modes, and between 1000 and 1800Hz in Maritime mode.

Pulse duty ratio is 20% in all cases except the 6m Stripmap mode, which uses 25%.

Nominal pulse bandwidths vary between 20MHz and 90MHz depending on spatial resolution and incidence angle. The instrument has been designed to operate with up to 200MHz bandwidth (3100-3300MHz). Transmit pulses are always centred on 3200MHz. A linear FM up-chirp is nominally used in all cases.

Sidelobe weighting will be applied to suppress Impulse Response Function sidelobes. The system is expected to achieve better than -20dB peak sidelobe ratio.

The Maritime surveillance mode [7] is a low pulse repetition frequency mode which is specifically intended for detecting ships on the open ocean. Through the use of 6 subswaths at higher incidence angles a 400km swath is achieved with single-look spatial resolution cells of 13.7 x 6m. Range azimuth ambiguity performance is good but high azimuth ambiguities are generated. However these can be identified via a range of analytical techniques and eliminated as 'false' targets. Maritime mode 'images' will comprise ships (and their azimuth ambiguities) on a background of noise, rather than sea clutter, and will enable detection of medium to large vessels with a good probability and a low false alarm rate (less than 1 in 10^7). The presence of 'clusters' of bright pixels from single vessels significantly longer than 6m will further improve detection probability and false alarm rates.

Around-orbit operational duty cycle is constrained by DC power and thermal control to between 2 and 4 minutes per orbit, but this still enables of the order of 1,000,000 km^2 of image product acquisitions per day through a combination of different modes.

IV. Development and QUALIFICATION

No development model was built. Instead the first build was an Engineering Qualification Model (EQM). The design took heritage from earlier developments, including elements from the Airbus Airborne SAR demonstrator system [9]. An approach starting with an EQM accelerated the development and reduced overall cost while managing a reasonable amount of risk. The EQM programme was undertaken in 2013 and included functional, vibration, thermal vacuum and EMC testing of a single Back-End and a single antenna phase centre. Additional activities were carried out to qualify the attachment process for the Virtex 5 FPGA.

A payload flight model (FM) programme was then initiated in Q1 2014 and completed in July 2015. Following satellite-level integration the payload has been subject to vibration testing and antenna pattern characterisation testing at Airbus DS facilities in Portsmouth, UK and thermal vacuum testing at Rutherford Appleton Laboratory in Harwell, UK. Finally antenna pattern testing was completed, also at spacecraft level.

Fig. 8. NovaSAR-S SAR Payload and the NovaSAR-S Team

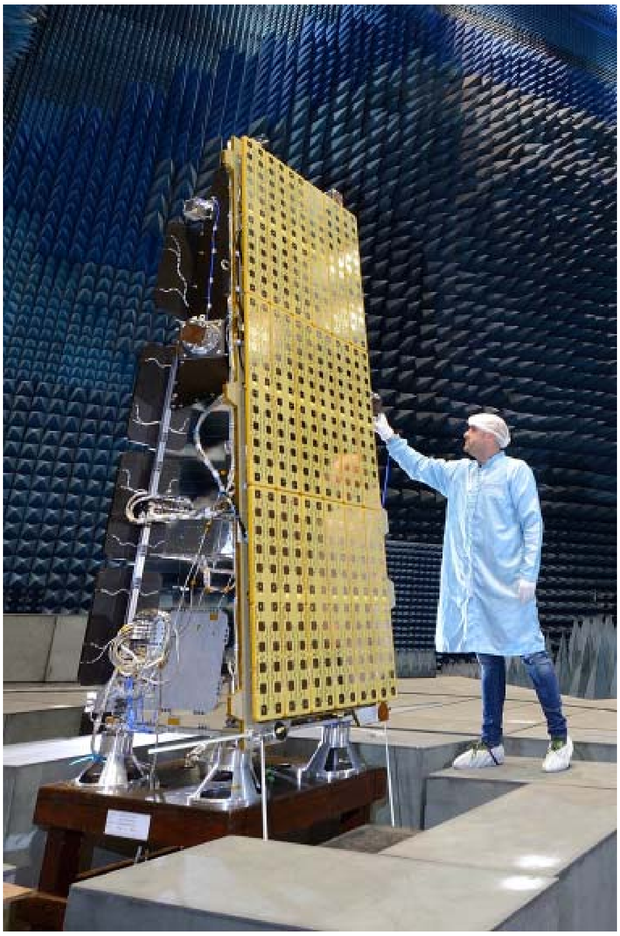

Fig. 9. NovaSAR-S Spacecraft during EMC testing

The NovaSAR-S Payload is hosted on an SSTL-300 platform with standard avionics and a bespoke structure to facilitate the antenna to be accommodated in a fixed, non-deploying configuration. The platform offers the capability for the satellite to be rolled in an axis about the flight direction such that the Payload can image either side of the nadir track, increasing the operational flexibility provided by the mission.

The NovaSAR-S first mission will be deployed into a polar Sun-synchronous orbit. The launch is anticipated in the summer of 2017. The system will be operated and tasked from a UK Spacecraft Operations Centre (at SSTL). Acquired data will be downloaded to local ground stations of each partner including a UK-based receiving station and data processing facility.

V. Business Model

Operationally utilisation of the NovaSAR-S capacity will be shared between government access (15%) and commercial exploitation (remaining 85%) by partners. Share of the payload data acquisition capability and tasking will be on the basis of funding contributions by partners or affiliates, be they the launch partners or third party organisations.

The total mission cost of NovaSAR-S is less than £50M including the space and ground segment, launch and operations – funding secured by a combination of investment by the UK government, Airbus DS (UK) and launch/commercial partners. The price of the Payload element of this system is considered to be highly competitive such that future NIA SAR Payloads will be at a more affordable price point than any system offering similar performance.

It is anticipated that the NovaSAR-S capability and approach will foster commercial exploitation, facilitate export opportunities and encourage government and business partnerships. The goal is to significantly expand the utilisation of S-band radar data in order to develop value-adding SAR-derived information products. It is asserted that the mission cost and product generation capability that is afforded by the NovaSAR-S Payload, and NIA SAR Payloads to follow including at X-Band [5,6], will represent a new benchmark in spaceborne Earth Observation by SAR.

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