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Garada

SAR Formation Flying

Annex 2. Radar Concept

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Contents

1 Acknowledgements

I would like to acknowledge the work of Robert Middleton and Steven Tsitas in preparing the documents [Tsi11], [Mid11], [Mid12a] and [Mid12b] which aided me in the preparation of this report. The work of Thomas Cooney in [Coo12] is the basis of the RF front end design for Garada's phased array antenna and is summarised in this document. Thanks to Gordon Roesler for many helpful conversations.

2 Executive Summary

WP2 comprises the SAR solution, encompassing both the flight segment (in the design of the RF front end electronics) and the ground segment (in the description of the image formation processor). The SAR solution for the Garada mission is the joint work of ACSER (Steven Tsitas, Robert Middleton and Mauro Grassi) and Astrium (Andy Larkins, David Hall and Martin Cohen). The details of the RF front end electronics, a major part of the phased array antenna, were worked out in the thesis of Thomas Cooney, a graduate of UNSW.

There are five deliverable documents for WP2 excluding this final report. The design of the SAR solution depends on the users' applications of interest. For example, orbit determination is influenced by revisit requirements. The orbit period depends on the altitude, the altitude affects the peak transmission power and pulse repetition frequency and thus the SAR hardware and power subsystem.

The first deliverable report, titled: `TK2.1: User Requirements, Risk Analysis, Mission Baseline Report` ([Tsi11]) is a study of Australian users' applications to determine a baseline SAR solution. The applications considered include disaster monitoring (both fire and flood), oil slick detection, forest biomass mapping and soil moisture retrieval. Soil moisture retrieval is identified as the main application of interest and is the driver for all subsequent design decisions.

The next deliverable, titled: `TK2.2: SAR Hardware and Methods Description and Specification` ([Mid11]) is a determination of the hardware specifications as they relate to the SAR payload. Parameters such as incidence angle, noise equivalent sigma zero, range and azimuth resolution and carrier frequency are determined. It is fortuitous that soil moisture retrieval demands some of the most stringent conditions on the SAR payload, and thus other applications of interest will also be viable under the proposed design.

`TK2.4: SAR Hardware Description and Actual Specification` ([Mid12b]) describes the hardware specifications in detail, incorporating the work of Thomas Cooney in his thesis: `Electronic Circuits for L-Band Phased Array Synthetic Aperture Radar` ([Coo12]). The novel design using COTS (Commercial Off The Shelf) parts exclusively is there shown to be feasible. Using such parts guarantees cost reductions in the antenna subsystem. The prototype has been tested and shown to be capable of transmitting and receiving any polarisation, as well as providing an internal loop for calibration. The RF front end captures the backscattering from the earth and is downconverted to baseband and digitised. The resulting raw data is then downlinked to the ground station where further processing will occur. The report `TK2.3: SAR Processor Performance Requirements` lists the requirements on the image formation processor (IFP) for Garada, part of the ground segment.

The final deliverable `TK2.5: SAR Signal Processing Description and Actual Specification` ([Gra12b]) presents a signal model and details the signal processing steps required to take the raw SAR data to an image. The resulting image contains magnitude (reflectivity) information as well phase information and is an SLC (Single Look Complex) product. Since that image contains speckle noise (a grainy appearance that is due to the large number of scatterers contributing to each image pixel) a further product, an MLI (multi looked intensity) is obtained from the SLC using averaging. This eliminates speckle at the expense of spatial resolution. Once the image is obtained, other processes can be considered, including interferometry, which proceeds from two or more SLC images.

Overall, WP2 aims to detail the signal processing steps, as well as the hardware design, of the SAR payload. If Garada were to proceed beyond phase zero, an implementation of the IFP would need to be completed following the signal processing steps described in the documents above. In relation to the RF front end, the concept of using COTS parts has been proven.

3 Introduction

This is the final deliverable report for `WP2`, comprising Garada's SAR solution. It encompasses both the ground and flight segments and both software and hardware design.

Included is a description of the design and manufacture of a prototype T/R (Transmit Receive) module for the phased array antenna, achieved using COTS parts for cost savings and reliability due to industry heritage. There is also a brief synopsis of the evolution of the work package and the five deliverable reports which together present both the requirements on Garada's SAR payload and the specifications and implementation of the SAR solution. It is the comprehensive SAR solution that enables all the high-value applications, including the measurement of soil moisture and interferometric techniques allowing topographic and ionospheric mapping.

For brevity and in order to avoid duplication, in cases where the work has been previously presented in one of the deliverables for this work package, we merely summarise the main results and guide the reader to the relevant documents.

4 Evolution of the Work Package

Garada's SAR solution is driven by user applications. As the project evolved, so did the applications and therefore the requirements and specification of the SAR solution. In this section, we give a brief overview of the evolution of the work package and how the previous five deliverable reports fit into the overall work package.

The applications originally conceived for the Garada mission include flood monitoring, oil spill incident detection and forensics, and forest mapping, as explained in deliverables `TK2.1` ([Tsi11]) and `TK2.2` ([Mid11]). These were derived through a study of users' requirements. To that end, the following personnel with broadly different interests were interviewed:

- **Soori Sooriyakumaran**: a supervisor at the Bureau of Meteorology in Melbourne who works in the flood warning section;
- **Felicia Andrews**: a GIS (Geographic Information System) Officer at the NSW State Emergency Services;
- **Mark Wallace**: a manager of GIS Operations and Capability Command at the Queensland Fire and Rescue Service;
- **John Arrowsmith**: a Principal Program Officer at Emergency Management Queensland; and
- **Paul Irving**: a Senior Scientific Coordinator of the Marine Environment Pollution Response, Marine Environment Division of the Australian Maritime Safety Authority;

As of `TK2.1`, the design concept was for a bistatic, formation flying, X-band SAR mission. Formation flying would allow advanced interferometric applications using coherent change detection. X-band was chosen for its advantages in resolution and antenna size, and hence in mass and cost.

As the project advanced, due to the strict revisit requirements of some of the applications envisaged by the above interviewees, by `TK2.2` it was changed to an L-band SAR mission, due to foreseeable difficulties in making a deployable X-band antenna (where the RMS height error of the antenna surface has a stricter tolerance requirement) and due to the fact that the applications did not require X-band per se and could in fact benefit from an L-band SAR. For example, it was observed that the time decorrelation at L-band for forest mapping could be in the weeks' time ([Mid11] pg. 5). Moreover, an L-band system was more feasibly implemented using low cost COTS parts for the RF front end (of which there are hundreds of T/R modules). This is due to the ubiquitous use of mobile phones and GPS receivers and hence the substantial industry experience with integrated circuits in the L-band part of the spectrum.

Furthermore, due to the recent failure of the Japanese earth observing satellite ALOS in April 2011, there is currently no L-band space borne SAR in orbit, although a few are planned and in the pipeline, including ALOS 2, SMAP [1] and SAOCOM 1A and 1B.

There are actually two documents pertaining to `TK2.3`. Both are requirements for the SAR IFP. This is the piece of software that converts a SAR raw image into an intelligible SLC product (that actually resembles the backscattering from earth).

[1] SMAP is specially designed for soil moisture measurements and its SAR is not a general purpose instrument.

By TK2.3 ([Mid12a]), the main application for Garada had been changed to soil moisture. The document [Gra12a] is an updated rewriting of that document.

While TK2.4 ([Mid12b]) deals with the SAR hardware description and specification, a more detailed description of the design of the RF front end is given in this current document. On the other hand, the details of the design of the IFP for Garada are presented in deliverable TK2.5 ([Gra12b]).

5 SAR Hardware Solution

The SAR hardware requirements for Garada are the topic of the `TK2.4` deliverable ([Mid12b]). The SAR hardware solution for Garada departs from those requirements and is detailed in deliverable `TK3.3` [Hal12] as well as in [Coo12], as part of that author's thesis.

The former work includes the design of the electronics for the SAR system, while the latter work proposes a novel design for the T/R modules. **Its main results are outlined in this section**. One of the main achievements of the thesis was to prove the concept of using exclusively COTS parts for the RF front end (ie. the T/R modules), a critical component in any SAR.

The type of SAR that we are considering in this document involves the use of a single antenna for both reception and transmission (ie. monostatic). The SAR hardware consists of a central electronics part and an array of T/R modules. The central electronics is responsible for generating the transmit waveform (a linear FM chirp) and also downconverting and digitising the received echoes.

The T/R modules each drive four small annular slot antennae that make up the phased array. The array is usually rectangular, although some are tapered at the ends to improve the ambiguity response [2]. What characterises a *phased* array is that the phase of each phase centre can be accurately controlled. A phased array antenna is often used as it is modular and it allows both beamforming and beamsteering, both essential for any spaceborne SAR.

Beamforming allows a definite antenna pattern to be synthesised from an array of phase centres by carefully varying the phase offsets and amplitudes of each, allowing the emitted electromagnetic radiation to constructively and destructively interfere to form a sharply focused beam. A sharply focused beam is essential for obtaining good spatial resolution. A typical two-way antenna pattern follows a sinc-squared function and has a good impulse response width, peak sidelobe ratio and integrated sidelobe ratio, all three crucial in obtaining a finely resolved image.

Beamsteering is a form of beamforming where the beam can be electronically steered so that its footprint on the earth is changed. Beamsteering is essential for implementing imaging modes other than Stripmap, where the illuminated swath can be increased at the expense of azimuth resolution (ScanSAR or TOPSAR modes) or vice-versa, where the azimuth resolution is improved while the swath is decreased (Spotlight mode).

The antenna itself is driven by an array of 22 by 22 T/R modules. There are therefore a total of 484 modules that comprise the antenna, each T/R module will control four annular slot antennae (designed by Astrium) [Hal12] (pgs. 62-63).

The stated design targets for [Coo12] are mainly driven by cost. Minimising the cost of the RF front end, as well as its mass, is especially important for an L-band radar where the antenna is one of the costliest and more massive of parts. Below are the stated design goals of [Coo12] (pg. 19):

- High efficiency
- Low Noise Receiver
- Temperature Stability in Phase and Gain
- Low Mass
- Low-cost COTS parts, heritage design

[2] For the purposes of this report, the array can be considered to be rectangular.

Much of the novelty in [Coo12] is in fulfilling the last requirement above, thus leveraging industry experience in mobile phones and GPS receivers, which use similar microwave frequencies ([Coo12], pg. 19). A thorough and logical development of the requirements and their implications was undertaken. Note that the design is at the T/R module level. There is no thought given to how the different modules will fit together - that is strictly speaking part of the system design. Typical SAR systems employ an analogue feed network, where the distance of cable to each T/R module is kept the same. The usual implementation uses coaxial cable. This works for transmit and receive, in the latter case, it ensures that the signals are collected coherently. While it is conceivable to replace this analogue feed network with a digital one, the data volume on receive would be considerably larger (for eg, there are typically hundreds of modules comprising the antenna). Such so-called SMART antennae belong to the next generation of SAR missions.

The hardware design incorporates both arbitrary transmit polarisation as well as simultaneous receive in a linear basis, compatible with the SAR system requirements. This full polarimetric design is vital for measuring soil moisture, as well as for properly calibrating the instrument and implementing advanced polarimetric techniques, including polarimetric interferometry.

Faraday rotation is a rotation of the polarisation of an electromagnetic wave as it travels through the ionosphere (approx. 80km to 1000km altitude). While Faraday rotation can be corrected using a fully polarimetric mode (ie. quad polarisation), this increases the PRF (Pulse Repetition Frequency) and the antenna size, which directly impact cost. Astrium's patented system for online real time correction of Faraday rotation can be implemented as long as the RF front end electronics are capable of full phase, amplitude and polarisation control.

The main requirements for the T/R modules were as follows:

- **Carrier Frequency**: the centre frequency will be 1.2575 GHz, with a bandwidth of 85 MHz. This maximises the range resolution whilst complying with international standards on spectrum use (ITU International Telecommunications Union, L-band allocation for earth observation from space);

- **Operating Temperature**: complying with industrial temperature range between $-40°$C and 85°C;

- **Receive Path Gain**: at least 30 dB gain, selectable in 64 steps (6 bit control);

- **Receive Path Phase Control**: shift the whole 360° range, in 64 steps;

- **Transmit Path Input Power**: up to 10 mW input to each T/R module;

- **Transmit Path Gain**: at least 32 dB gain on transmit;

- **Transmit Path Phase Control**: shift the whole 360° range, in 64 steps;

- **Transmit Module Power**: each T/R module shall be able to deliver 16 W.

- **Polarisation Control**: each T/R module will be able to transmit in any polarisation and receive in a 45° and 135° linear basis;

- **Reconfigurable within a PRI**: each T/R module shall be fully reconfigurable within the PRI (Pulse Repetition Interval), the reciprocal of the PRF;

The requirement that the T/R module be reconfigurable within the PRI time is essential both for full polarimetric operation (where the transmission switches between two orthogonal directions) and for beamsteering (which makes possible both spotlight modes and wide swath modes such as ScanSAR and TOPSAR).

In the next section, we outline the process by which the design of the T/R modules was achieved.

6 Hardware RF Front End Design

In this section, we summarise the design tasks and decisions made in building the prototype T/R module, for more details consult [Coo12]. The design begins with the block diagram as shown in Figure 1 (pg. 12). Note that in reality, each T/R module will control four annular slot antennae, whilst the figure shows only one.

The transmit path consists of a 6-bit configurable phase shifter (360° in 64 steps) which is connected to a quarter-wavelength hybrid with its isolation port grounded (through a series 50Ω resistor). In this configuration it acts as a power splitter, where the incoming RF power is split evenly between the two output ports, which also subtend a 90° relative phase difference. The two outputs at -3dB enter driver amplifiers before passing through two configurable 6-bit phase shifters. Each output enters another driver amplifier before passing through a high power amplifier and finally through another quarter-wave coupled hybrid and onto the switches that lead eventually to the annular slot antennae. The phase shifters allow both arbitrary phase and arbitrary transmit polarisation.

The receive path consists of a driver amplifier, followed by a low noise amplifier. The amplified RF echo then passes through a programmable phase shifter and attenuator. RF switches can form a path where the transmitter is connected to the receiving electronics through a bank of attenuators. This can be used for calibration purposes.

Departing from the overall block design, a signal flow calculation of power was first performed, using insertion losses at worst case and providing conservative margins for return loss and transmission line attenuation. While at the system level, the isolation between transmit and receive paths is ensured using circulators, at the T/R module level it is achieved using configurable RF switches.

Separate signal flow calculations were made for both the receive and the transmit path. A further separate calculation was performed for the calibration path, as the T/R module can either receive backscattering from the earth and transmit the high power linear FM pulse, as well as being configured in a calibration loop mode where the transmitter is connected through a bank of heavy attenuators directly to the receiver.

Selection of the appropriate components is performed according to the above signal flow calculations and ease of availability. Preference is given to cost effective parts. Once the parts are selected, the all important design of the PCB (Printed Circuit Board) was begun, with an initial plan of using four distinct layers.

The more layers a PCB has the more expensive it is to manufacture. But by having at least four layers, the routing of the signal tracks between the components is made simpler. Thus, it was decided to use a four layer PCB with the following layers, in order from top to bottom; routing the RF, GND, VCC and thermal layers.

The RF layer carries all the radio frequency energy, while the GND (ground) and VCC (voltage collector-collector) carry the power to the active components. A range of different voltage nets are used. Each is derived using a linear voltage regulator. Finally, the bottom-most layer is used for thermal dissipation, especially important for the high power amplifier and voltage regulators.

Once the range of voltages was known, a tentative power distribution map was designed. Linear regulators offer lower noise at the expense of lower power efficiency compared to switchmode regulators. The current draw of each voltage zone, and therefore the required power to be delivered by each voltage regulator is computed and each regulator's specifications were checked against the requirements. Also, the dropout voltages of the regulators were checked to ensure compliance with specifications.

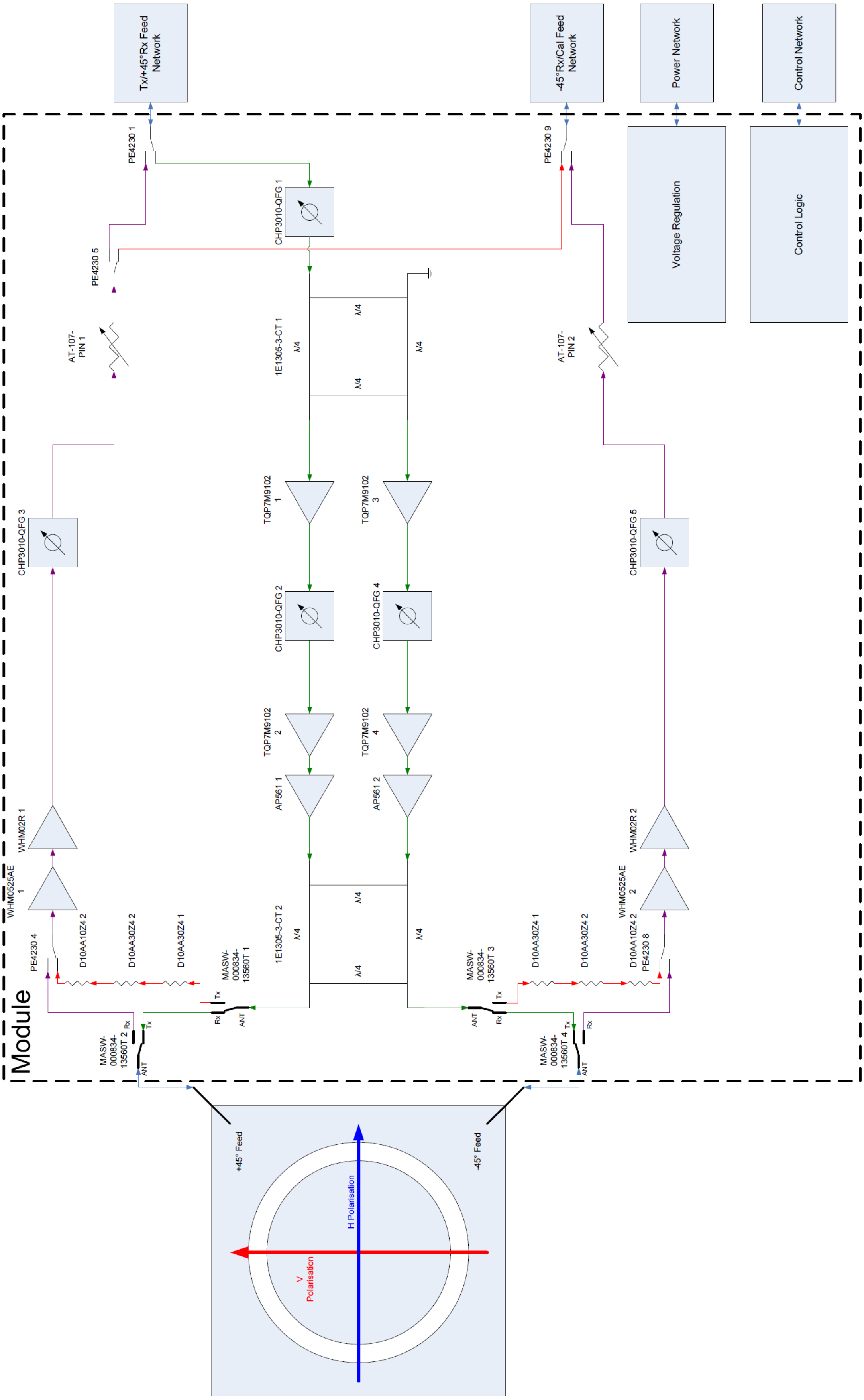

Figure 1: Overall T/R Module Design, see [Coo12]

A detailed design of the PCB was begun. Transmission lines are of 50Ω characteristic impedance and implemented as microstrip transmission lines (copper track and ground plane separated by substrate with a known dielectric constant). Support components for each MMIC (Monolithic Microwave Integrated Circuit) were chosen according to the required specifications, such as decoupling capacitors, RF chokes, inductors and resistors. All were surface mount parts soldered to the PCB by the manufacturer.

There are a number of amplifiers that comprise the RF front end, including the LNA (low noise amplifiers) in the receive path and the high power amplifiers in the transmit path - stability analyses were performed for each using S-parameters (scattering Parameters). The circuit was modified slightly to achieve unconditional stability (see [Coo12], pg. 51).

Next, matching networks for each stage were designed. This is required to minimise losses, so the impedance of each section is matched to the next. The resulting receive and transmit paths are modelled using SPICE [3] and their performance was characterised. Smith chart diagrams of the performance of the chains are included in the thesis (see [Coo12], pgs. 63 and 67). An FPGA development board was used for controlling the phase shifters, switches, amplifier gain and digital attenuators through two 40-way ribbon cables connected to IDL headers.

Once the final schematic and PC board design were finished, the board was sent for manufacture. Then, extensive testing of the design was completed using a VNA (Vector Network Analyser).

The results were consistent with the design goals, except for one non-compliance in the transmit power specifications [4]. See [Coo12], pg. 155 for a comprehensive summary of the test results as compared with the requirements.

[3] Software for simulating the behaviour of circuits.

[4] Note that the power requirements were increased during the development of the prototype.

7 SAR Software Solution

The final deliverable `TK2.5: SAR Signal Processing Description and Actual Specification` **([Gra12b]) describes in detail the SAR software solution for Garada. This section merely summarises some of the results of that document.**

The SAR software solution is strictly speaking part of the ground segment. It encompasses the reception of digital payload data, which is uncompressed, decrypted and error-corrected to produce the raw SAR data.

Once the SAR raw data is extracted, the IFP is applied to it to produce an SLC image. The SLC image is the starting point for all applications. That is, all applications begin with one or more SLC images, interferometry usually begins with a number of SLC images of the target area. This allows topographic maps, subsidence studies with sub-cm accuracy, as well as atmospheric mappings to be undertaken.

Speckle gives SAR images a characteristically grainy appearance, and occurs because in each resolution cell there are many scatterers and the resulting phase of the echoes is uniformly distributed. Speckle can be effectively eliminated by incoherent averaging, producing a so-called MLI (Multilook Intensity) product at the expense of reduced azimuth resolution.

In order to describe the steps necessary to implement a full IFP, it is necessary to understand and model the raw SAR data. The raw SAR data is digitised onboard in two independent channels (H and V, or any other basis) and each of which has two components, an I (in-phase) and Q (quadrature) component. Each of the components can be modelled as independent, zero mean Gaussian with variance proportional to received power.

Preprocessing of the data is necessary for a number of reasons. Firstly, DC-bias correction is accomplished, as the onboard BAQ compression can introduce a small non-zero offset. Furthermore, temperature effects can also introduce an unwanted offset. As the I and Q channels are obtained by onboard mixing of the incoming RF signal with known signals, and since those signals will exhibit small deviations from the ideal signal case, it is also necessary to correct the gain of I and Q channels and to correct their phase.

There are a number of known image formation algorithms for SAR imaging. The range Doppler algorithm is one of the oldest and most effective image formation algorithms. It offers a good compromise between image quality and computational efficiency. It benefits from efficiently implementing RCMC (Range Cell Migration Correction) in the range Doppler (ie, range time, azimuth frequency) domain, so that targets at the same slant range of nearest approach share the same migration trajectory in signal memory.

In order to properly focus an image using the range Doppler algorithm, it is necessary to compute the Doppler centroid, which is defined to be the average Doppler shift of the scene. The echoes will have a frequency different to the transmitted signal due to the Doppler effect, where the relative velocity of the platform and target introduces a frequency shift.

There are many methods for estimating the Doppler centroid. We note that the Doppler centroid is non zero when there is squint, which needs to be considered in all cases. Also, the onboard attitude sensor information that determines the viewing geometry is usually not accurate enough for the IFP's requirements. Therefore the Doppler centroid is estimated more accurately from the raw SAR data itself. There is the added complication that the rotation of the earth is equivalent to an antenna yaw and varies with latitude, thus introducing more squint.

Range compression is achieved by convolving the received range line echo with a time reversed complex conjugate of a chirp replica (usually recorded in the transmission echo or using a modelled chirp). This minimises the noise contribution (as the noise will be uncorrelated to the transmitted chirp) as well as allowing better range resolution inversely proportional to the bandwidth of the chirp.

An azimuth DFT (Discrete Fourier Transform) is used to efficiently bring the signal space to the range Doppler domain, where RCMC can be efficiently carried out. RCMC is essential to obtain a well focused image. Failure at this stage will almost invariably guarantee an unusable image, that will be poorly focused and smudged. Finally, the azimuth compression is achieved in a similar way to the range compression, by correlating the azimuth columns with a chirp apparent in azimuth. Its FM rate can be estimated from the data.

The resulting SLC image can then be geocoded using telemetry information, and/or incoherently averaged to obtain the MLI product.

8 Conclusion

WP2 has specified a comprehensive SAR solution for the Garada mission. It is geared towards the main application of interest, soil moisture, but the design also enables all other known SAR applications, including disaster monitoring. The design of the SAR hardware is detailed as to the T/R modules, as well as to the central SAR electronics. A novel T/R module design was proven that could lead to substantial cost savings. The SAR software solution, in terms of the specification of the image formation processor was also detailed in the two deliverable documents [Gra12b] and [Gra12a].

Further work would involve implementing the IFP software as well as evolving the T/R module design beyond the prototype stage.

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