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A National Soil Moisture Monitoring Capability

Volume I: Technical Results

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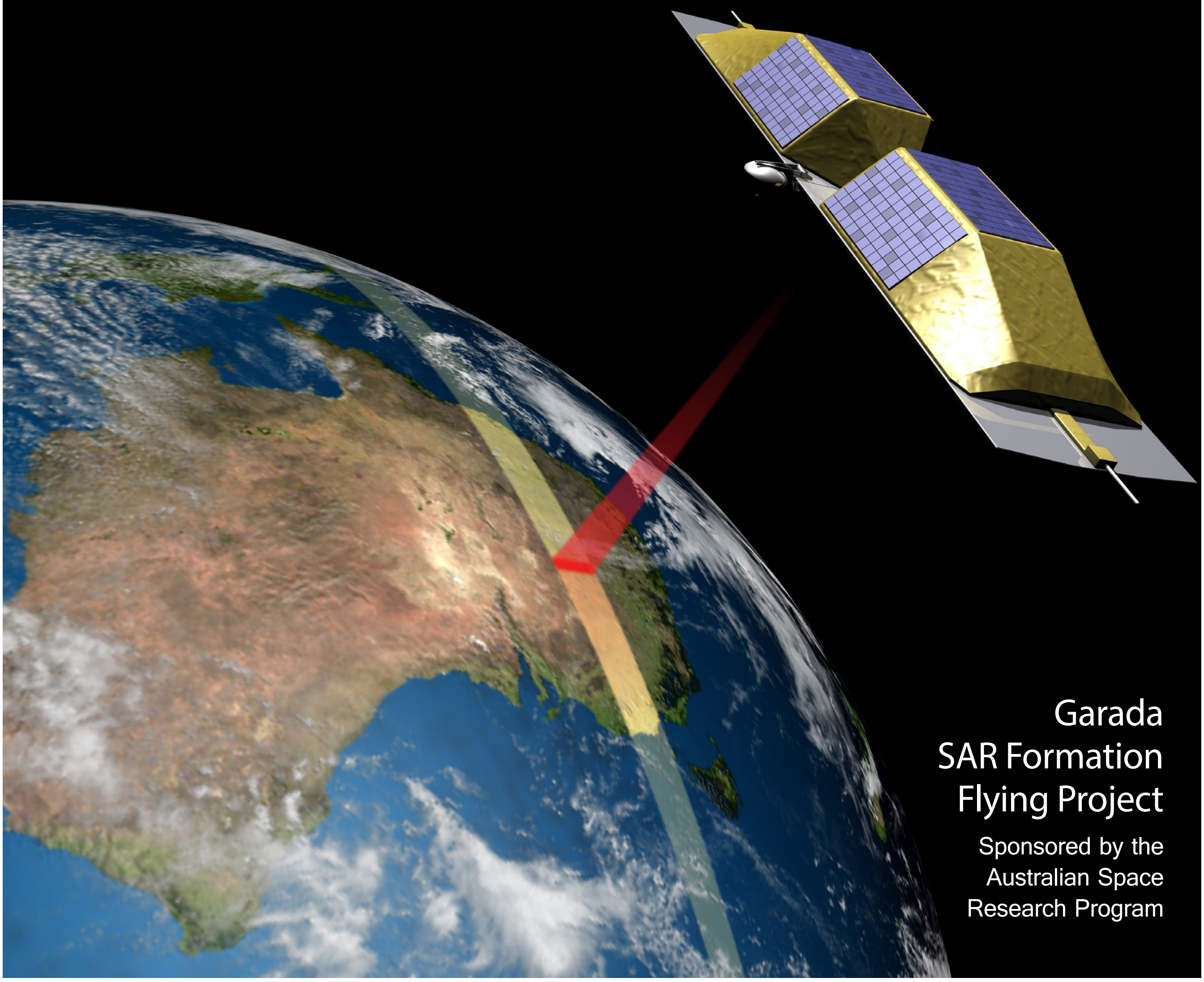

Garada
SAR Formation
Flying Project

Sponsored by the
Australian Space
Research Program

30th June 2013

SAR Formation Flying

Final Report: A National Soil Moisture Monitoring Capability

Volume I: Technical Results

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Prepared by: University of New South Wales

With input from:

- Astrium Limited
- BAE Systems Australia Limited
- Curtin University of Technology
- Delft University of Technology
- General Dynamics Corporation Limited

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CONTACT DETAILS

Professor Andrew Dempster
Director, Australian Centre for Space Engineering Research
University of New South Wales
Sydney, NSW, 2052
T: +61 (2) 9385 6890
F: +61 (2) 9385 7493
E: a.dempster@unsw.edu.au
W: www.acser.unsw.edu.au

Electronic copies of these reports can be found at: www.garada.unsw.edu.au

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PREFACE

This report “A National Soil Moisture Monitoring Capability – Volume I – Technical Results” is the first report of two released on completion of the Garada “Synthetic Aperture Radar (SAR) Formation Flying” Project. The Garada project was sponsored by the Australian Space Research Program (ASRP) and these reports were delivered as a requirement of that project.

Volume I – Technical Results is a comprehensive technical report which introduces the ASRP and the Garada project. It contains extensive analyses that demonstrate the suitability of the Garada space-based radar system to address Australia’s water resource monitoring needs. It provides detailed design studies, fundamental research reports, and engineering reports resulting from the project. It includes a discussion of technical steps that should follow in order to implement the capability, in order to move forward.

Volume II – Implementation Case is the second report, a companion to Volume I that concentrates on the implementation implications of the Garada program. It summarises the Garada program findings concerning Australia’s water resources monitoring needs. It deals with key points only and focuses on the critical nature of data that could be produced by the proposed Garada system. It shows how such data could be used to make better water resource decisions, and discusses programmatic approaches for implementing the proposed system.

EXECUTIVE SUMMARY

The Garada SAR Formation Flying Spacecraft program was a 2 ½ year project to evaluate the feasibility of synthetic aperture radar spacecraft to address Australian needs for Earth observation, and to advance the use of Global Navigation Satellite Systems (GNSS) for space applications. The program was one of fifteen funded by the Australian Space Research Program and administered by the Space Policy Unit of the Australian Government. The program lead organisation was the Australian Centre for Space Engineering Research at the University of New South Wales. The other team members were Curtin University, BAE Systems Australia, EADS Astrium (UK), TU Delft (Netherlands) and General Dynamics (New Zealand).

The extensive series of studies in the program led to the conclusion that a synthetic aperture radar satellite is a highly feasible approach for measuring critical environmental parameters on the Australian continent. In particular, the satellite and sensor design were assessed as highly suitable for measurements of soil moisture, flooding, and forest change detection. They are also capable of a wide range of other measurement modes, such as interferometry, coherent change detection, medium resolution radar imaging, and maritime surveillance.

A major effort within the program was the development of a GNSS receiver system for space applications. This project was highly successful, and resulted in the development of three complete GNSS receivers of increasing capability suitable for spaceflight. These receivers have a number of unique features and are the first of their type made for space. Integrating such receivers onto the SAR spacecraft will result in greatly enhanced measurement accuracy, due to the improved absolute and relative position knowledge of the satellite compared to ground tracking approaches. One of the receivers passed an extensive series of functional and environmental tests and was provided to the United States Air Force for integration into one of its experimental satellites. This international effort was conducted in coordination with the Defence Science and Technology Organisation (DSTO).

At the beginning of the program, an extensive series of interviews was undertaken to identify compelling uses for the SAR spacecraft, and to derive from those uses the appropriate system parameters. The soil moisture measurement application was found to provide sufficient specificity to proceed with a detailed analysis of spacecraft and sensor requirements, and also to address a large number of critical environmental and economic concerns on the Australian continent. A User Advisory Group, consisting of experts in soil moisture measurement, SAR operation, and calibration, was added to the team, in order to represent the requirements of likely users, and to provide a detailed analysis of algorithmic approaches for soil moisture measurement. The program developed a detailed requirements baseline for the system, using best aerospace engineering practices. Postulated user requirements were translated into over 1,000 requirements defining system, space segment and ground segment functional performance.

A series of analyses of the mission performance requirements led to a detailed study of the required sensor characteristics, the number of spacecraft, and the orbital geometry. The sensor design that emerged will provide soil moisture measurements of unprecedented high resolution. The mission baseline evolved to incorporate two spacecraft in the same orbit, one-half orbit apart, each carrying a large SAR sensor. A unique structure for the spacecraft was proposed, to enable safe launch of the very large radar, precise planarity when in operation, and adequate volume for supporting subsystems. Computer simulation of the structure under launch conditions showed all stresses and

deflections were within required limits. Special antenna elements were designed to enable precise control of the radar signal polarisation, when transmitted and when received. A circuit to control the radar antenna elements, composed of commercial electronic components, was developed. Testing confirmed that the objectives for radar performance could be achieved using that circuit, suggesting a low-cost approach to implementing the radar on a spacecraft. Calculations of thermal performance on orbit showed that the spacecraft's mission would not be severely limited by thermal considerations, and that standard methods for thermal control would be sufficient.

Applications considered early in the program were those that could be performed by SAR satellites flying in formation. One example was precision flood monitoring. In that case, to meet user requirements, a very large constellation of very low cost satellites would have been required. Our advisors insisted that such a mission would be difficult to argue from a political point of view. However, it threw up many interesting research challenges, which were then pursued as part of the project, while the core application changed to be more palatable. It would be entirely possible to demonstrate a formation flying capability as part of the proposed SAR multi-spacecraft mission, given the success of this research.

The program also investigated a second method of characterizing the Earth's surface other than radar, namely, using GNSS signals reflected from the ground. A series of data collection tests using an airborne GNSS receiver demonstrated clear responses of the received signal to changes in ground and sea characteristics. Receiver modifications were designed to optimise this method of Earth sensing.

An accurate orbit configuration was developed to provide a complete soil moisture map of the agriculturally important Murray-Darling Basin every three days, and in fact the system would be able to do that for all of Australia. This is a much higher update rate than for any current or developmental soil moisture satellite. A wide range of users would be able to access timely soil moisture data. The orbit selection was based upon the predicted performance of the radar sensor. An orbit perturbation analysis was also performed, to obtain estimates of the orbit deviations caused by various natural phenomena. These inform the amount of propellant the satellites would require to stay on the correct orbits for their entire mission lifetimes. Studies were also done on the requirements for determining and controlling the satellites' attitude. Standard techniques were determined to be adequate for the assigned mission.

Given the limited space industry in Australia, a study was performed to determine what parts of a SAR satellite procurement could be sourced here. Several databases were accessed to identify over 200 Australian companies with the potential to contribute to such a program in hardware, software, management or support roles. A plan was developed to leverage a satellite procurement program to enhance Australian skills and capabilities. The particular strength of Australian capabilities in space system ground segment development was noted.

The program produced a complete functional specification, system architecture, and implementation study for the system ground segment. Various locations on the Australian continent were determined to be suitable for downlinking the high data volume the satellites would generate; other global locations were also studied, including a proposed Antarctic station. The ground segment would provide robust control capabilities for the satellites, and distribute data rapidly to Australian users over the National Broadband Network.

In addition to demonstrating the feasibility and desirability of a SAR satellite for Australian data needs, the detailed analyses provided insights into anticipated program life cycle costs and technical risks.

The privilege of performing this project for the Australian Space Research Program resulted in a significant enhancement in space-related capabilities and growth in space activities at the University of New South Wales and the Australian Centre for Space Engineering Research. Numerous publications, presentations, conferences and press interactions resulted. Highly talented new staff were added to the Centre. Liaisons with international space organizations have resulted in numerous potential collaborations, and the Garada project has attracted the interest of major aerospace corporations around the world.

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1. INTRODUCTION

The Garada SAR Formation Flying project was proposed as a research effort to the Australian Space Research Program, and was performed between December 2010 and June 2013. The ASRP Guidelines explain the aim:

> *The objective of the Australian Space Research Program is to develop Australia's niche space capabilities by supporting space-related research, innovation and skills in areas of national significance or excellence.*
>
> *Under the Australian Space Research Program, space-related means:*
>
> *a. The designing, building, testing, installation, deployment and/or operation of hardware or systems developed:*
>   *(i) to be located in space;*
>   *(ii) for the purpose of getting into or returning from space; or*
>   *(iii) for the purpose of getting data or information to or from space;*
>
> *b. The design, development, testing, installation and/or use of applications that require the operation of hardware or systems listed at (a)*
>
> *c. Governance arrangements (such as legal, management and advisory structures) to support space hardware, systems or applications listed at (a) and (b); or*
>
> *d. Research into the environment in which space hardware or systems listed at (a) operate.*

The essence of the Garada project as stated in the research proposal was:

> *This project investigates synthetic aperture radar (SAR) satellites flying in small formations to significantly enhance real-time environmental monitoring. Developing the satellite-positioning accuracy essential for formation-flying, this project aims to realise major scientific innovation while addressing urgent national and global challenges.*

The proposed project outcomes were:

> *The Earth Environment Remote Monitoring Using Formation Flying SAR satellites (EERMUFFS) [the project name used in the proposal] consortium links Australia's leading satellite navigation researchers with key local and international industry partners to build a new national capability in state-of-the-art earth observation from space. This capability will have regional and global applications including enhanced environmental and disaster monitoring.*
>
> *By simulating various formations of SAR satellites, this project will identify optimum orbits for monitoring over Australia and the region. The project will also develop the precision Global Navigation Satellite Systems (GNSS) relative positioning required to operate satellites in formation. Together, these outcomes will enable meaningful advances in data quality and timeframes to be achieved. Through the use of formations of SAR satellites, which are unaffected by smoke, cloud, dust or volcanic ash (which hamper optical earth observation), the project will enable SAR to be used for a range of new applications such as time-critical*

disaster monitoring, detailed tomographic mapping and the remote measurement of biomass. Success in these areas will lead to further developments in SAR applicable to Defence and national security.

The key deliverables will be:

- *Selection of a baseline synthetic aperture radar (SAR) formation which can deliver "snapshot" digital elevation models and/ or tomographic biomass estimates. This baseline will include the band(s) of operation, method of radiation/ reception, and formation orbits.*
- *Development and testing of orbit models that indicate the feasibility of the baseline design.*
- *Models for control of satellites in formation, indicating the feasibility of the baseline design.*
- *Design and construction of a GNSS receiver appropriate for use in space. This receiver will also be able to perform bistatic radar experiments.*
- *Carrier-phase positioning algorithms that can run on this receiver and deliver the level of positioning accuracy required by the formation-flying SAR.*
- *An analysis of the capability of Australian industry to commission, or participate in, a small scale SAR satellite formation.*

The project director was Professor Andrew Dempster of the University of New South Wales, director of the Australian Centre for Space Engineering Research (ACSER). Other team members included BAE Systems Australia, EADS Astrium (UK), Curtin University, Delft University of Technology (Netherlands), and General Dynamics (New Zealand).

Figure 1: Garada SAR Formation Flying Project - Consortium Members Logos

The program was organized in 11 Work Packages. This volume of the Final Report begins with short summaries of the technical approach and accomplishment of each of the 10 technical work packages. Table 1 describes the technical roles of the team members and the work packages for which they were responsible.

Table 1: Breakdown of work packages assigned to each consortium member

Team member	Work Package Title	Work Package No.
UNSW ACSER	Space Systems Engineering and Radar Applications	1
	SAR Solution	2
	Bistatic Radar	4
	Prototype Receiver	5
	Orbit Models	7
	Project Management	11
BAE Systems Australia	Industrialisation Analysis	9
	Ground Segment Definition	10
EADS Astrium	SAR System Analysis	3
	Orbit Control Analysis	8
Curtin University and Delft University of Technology	Formation Flying Algorithms	6
General Dynamics NZ	Prototype Receiver	5

57 deliverables were produced in the 10 technical work areas, in addition to three working GNSS receivers and the associated technical documentation. Detailed reports on the technical work are provided in the annexes to this volume; the 57 deliverables are provided as a separate appendix. The deliverables are listed in Table 2. Because the mission concept was being developed in parallel with preparing deliverables, some deliverables were based on mission concepts that were not selected. Those deliverables are marked as SUPERSEDED in the table. In particular, the user requirements, risk analysis, mission baseline report and business case reported in TK 1.1, 1.2 and 2.1 have been replaced by Volume II of this report, “Implementation Case.”

Table 2: List of all work package deliverables completed throughout the Garada project.

Work Package 01 - Space Systems Engineering and Radar Applications
TK1.1 User requirements, risk analysis, mission baseline report - SUPERSEDED
TK1.2 Business case - SUPERSEDED

TK1.3 Mechanical configurations requirements and CAD model
TK1.4 Thermal requirements and baseline model, spacecraft communications system report, antenna trade-off report
TK1.5 Final report
Work Package 02 - SAR Solution
TK2.1 User requirements, risk analysis, mission baseline report - SUPERSEDED
TK2.2 SAR hardware and methods description, specification and performance requirements
TK2.3 SAR processor performance requirements (first and second reports)
TK2.4 SAR hardware description and actual specification
TK2.5 Sar signal processing description and actual specification
TK2.6 Final report
Work Package 03 - SAR system analysis
TK3.1 SAR System Trade-off report - SUPERSEDED
TK3.2 SAR System Specification Prelim. Issue
TK3.3 SAR System Specification Final Issue
TK3.4 Thermal Analysis, OBDH and Communications Subsystems Specification
Work Package 04 - Bistatic radar report
TK4.1 Design of airborne experiment
TK4.2 First airborne bistatic experiment
TK4.3 Design of bistatic receiver
TK4.4 Second airborne experiment
TK4.5 Final bistatic receiver design
TK4.6 Final report
Work Package 05 - Prototype receiver
TK5.1 Namuru testing for Bluesat
TK5.2 RF Front end
TK5.3 L1/ E1 baseband and software

TK5.4 L1/ E1/ L5 baseband and software
TK5.5 L1/ E1/ L5/ E5 baseband and software
TK5.6 Receiver functional testing
TK5.7 Receiver environmental testing
TK5.8 Final report
Work Package 06 - Formation flying algorithms
TK6.1 Analysis of error sources in space environment
TK6.2 Analysis noise characteristics for stochastic model
TK6.3 Algorithm development
TK6.4 Analysis impact of configuration design
TK6.5 Implementation aspects of algorithms
TK6.6 Experimental analysis
TK6.7 Final report
Work Package 07 - Orbit models
TK 7.1 Orbit requirements, lifetime analysis and disposal report
TK7.2 Preliminary orbit model design with STK
TK7.3 Detailed orbit design
TK7.4 Detailed force modelling
TK7.5 Launcher requirements and selection
TK7.6 Final report
Work Package 08 - Orbit control analysis
TK8.1 Constellation Attitude Orbit and Control System Trade-off Report
TK8.2 Derived AOCS requirements specification
Work Package 09 - Industrialisation analysis
TK9.1 Capability Requirements Matrix
TK9.2 Australian Industry Capability Report
TK9.3 Training Program in SAR Technologies

TK9.4 Preliminary Industrialization Plan
TK9.5 Project Industrialization Plan
Work Package 10 - Ground Segment Definition
TK10.1 Operational Concept Document (CONOPS)
TK10.2 Ground Segment Functional Performance Specification
TK10.3 Preliminary Ground Segment Architecture
TK10.4 Ground Segment ROM Cost Estimate
TK10.5 Ground Segment Definition Report
Work Package 11 - Project Management
TK11.1 through TK 11.10: Progress reports

In the last nine months of the project, a User Advisory Group was assembled, consisting of four of Australia's leading experts in soil moisture measurement, biomass measurement, and synthetic aperture radar. This valuable addition to the project was given the task of assessing the readiness of post-processing algorithms for space-based soil moisture measurement, and developing a recommended approach for the Garada processing algorithms. The User Advisory Group submitted a detailed report on their study of soil moisture algorithms; that report is Annex 12 attached to this volume.

Matching user requirements to a space system requirements set caused a deviation from the original concept. The most compelling mission was determined to be soil moisture measurement (see interviews with potential data users in Annex 14). To explain the importance of this mission to Australia, the team prepared a non-technical paper entitled "Finding Australia's Invisible Resource" (Annex 15), which received wide distribution.

Measuring soil moisture from space no longer required the tight formation described in the original proposal. However, the project continued the development of the formation flying algorithms, which was completed successfully. A multi-spacecraft program, which is the recommended configuration, could include a test of these algorithms on orbit. Such a test would most likely be conducted near the end of operational life of the two spacecraft, in deference to the primary mission of soil moisture measurement. The spacecraft would be repositioned from their operational configuration (widely separated) to within proximity of one another, and the formation flying algorithms tested.

The remainder of this Volume consists of:

- a description of the Garada team members and their capabilities;
- a short summary of each of the work package accomplishments;
- a summary of the other achievements of the Garada team during the program (including publications, presentations, etc., which are listed in full in Annex 13);

- a section of recommendations for moving the program forward to an acquisition of the soil moisture capability; this section also includes cost and schedule estimates for a complete acquisition and operational program; and
- Sixteen Annexes, containing the final reports of each of the Work Package teams, the requirements baseline, the User Advisory Group report, a listing of other program accomplishments and products, interviews with potential users of soil moisture data, the brochure "Finding Australia's Invisible Resource," and a list of acronyms used throughout the report.

During the program, the following success criteria were established. The government Space Policy Unit, which administered the ASRP, concurred that these were the appropriate criteria:

1. It delivers a detailed recommendation for a credible SAR mission. A credible mission is one that addresses the problems identified in the project proposal: "important national and transferable benefits for environmental monitoring and disaster mitigation, climate change science, national security and policy development". The recommendation will approach Phase 0 level and will include detailed concepts for a SAR payload, orbit models, ground segment, spacecraft subsystem design, and analysis of potential Australian industrial involvement.

2. It produces two GPS receivers specifically designed for satellite operation. The first, jointly developed with Garada and DSTO funding, is a single-frequency GPS receiver for operation on Bluesat and Biarri, a Defence cubesat mission, and will be integrated into spacecraft by the end of the Garada project. The second is an advanced dual-frequency dual-system receiver which will provide carrier phase measurements which can support high precision relative positioning.

3. It produces significant research outcomes related to SAR formation flying. These outcomes will include papers on precise relative positioning as well as research outcomes arising from formation flying missions that may not eventually be recommended, and trained postgraduate students.

4. It provides recommendations for a space-based GNSS reflectometry payload.

5. It results in increased engagement in space-related activity by both staff employed on the project, and a broader community. Capability will be raised in that community in space systems engineering and other more specialised disciplines that can be transferred to assist participation in research, innovation and skills development in areas of national significance or excellence.

6. It can be coordinated with outcomes from other Australian Space Research Program projects to produce strong potential future projects.

7. It contributes to key objectives expressed in the National Space Policy, and the two space-related infrastructure plans to be released in 2012.

Table 3 was prepared to summarise how the Garada program exceeded all of the above success criteria:

Table 3: Summary of how the Garada program exceeded all of the stated success criteria

1. Detailed recommendation for a credible SAR mission	· User requirements were collected for multiple potential applications · The application that was most compatible with the system concept, and that would have the greatest value to Australia overall, was the soil moisture measurement mission · A highly feasible system design, including both spacecraft and ground segment, was developed · The SAR sensor design, led by EADS Astrium, includes a detailed performance analysis, showing that the system meets or exceeds all known user requirements for soil moisture measurement from space · The system as analysed will support a complete soil moisture map of the Murray Darling Basin every three days, and approximately the same for all of Australia · The ground segment definition, performed by BAE Systems Australia, provides all required functionality including data processing, distribution of results to end users, and spacecraft command and control · Spacecraft subsystems, including power, attitude control, spacecraft structure, SAR antenna control, and thermal management, were analyzed and found to fully support the proposed SAR mission · A program plan for procuring the spacecraft, including the participation of multiple Australian suppliers, was outlined
2. Two GPS receivers specifically designed for satellite operation	· Three prototype GNSS space-capable receivers were developed and tested, and in one case, integrated into a space platform for project Biarri · Carrying one of these receivers on Garada would enable precision onboard orbit determination, which would enhance the geolocation and quality of the radar imagery · These receivers will have wide applicability to international space programs · These receivers represent a significant Australian space product
3. Significant research outcomes related to SAR formation flying	· New algorithms using GNSS to maintain tight spacecraft formations were developed · The algorithms were thoroughly tested in simulated space flight conditions · GPS receivers developed in the program were incorporated into the testing

4. Recommendations for a space-based GNSS reflectometry payload	· Conducted airborne experiments which were the world's first to demonstrate the ability of GNSS reflectometry to differentiate characteristics of Earth's surface · Conceptual design of space-based GNSS reflectometry payload completed · Reflectometry payload would use same GNSS circuitry designed for onboard orbit determination
5. Increased engagement in space-related activity	· ACSER has been contacted regarding the Garada mission by international spacecraft manufacturers · Officials at NASA have engaged with ACSER to identify opportunities for collaboration · Numerous graduate and undergraduate theses at UNSW being written on space-related topics · Space-related opinion pieces generated a combined readership of several thousand
6. Coordinated with outcomes from other Australian Space Research Program projects	· Garada ground segment definition included modeling of data flow to an Antarctic ground station (leveraging Antarctic Broadband ASRP project) · Garada maintained close interaction with Warrawal program for Master of Space Engineering at UNSW · Garada program provided input to (Carol Oliver's ASRP outreach project)
7. Contributes to key objectives expressed in the National Space Policy	Garada resulted in contributions of critical national importance to the following objectives of the National Satellite Utilisation Policy: · Space applications that have a significant security, economic and social impact, specifically Earth Observation, Satellite Communications and Position, Navigation and Timing—Garada is a uniquely capable Earth Observation system, and the program resulted in highly capable new hardware for Position, Navigation and Timing. · Strengthening those relationships and cooperative activities on which Australia relies, and will continue to rely to a substantial degree, for space system capabilities—the Garada soil moisture measurements would be of great interest to other nations, thereby strengthening relationships with those nations. · Continuing to support rules-based international access to the space environment; promoting peaceful, safe and responsible activities in space—the Garada system requirements were developed to be consistent with all existing treaties, conventions and regulations regarding the

	peaceful use of space, use of the radio frequency spectrum, and prevention of space debris. · Enhancing the coordination, understanding and strategic direction of Australia's uses and approach to space—by developing Garada to address a critical need for Australia's environment and economy, the program demonstrated convincingly how space can be used strategically to Australia's advantage. · Promoting collaboration between Australian public and private research and development organisations with industry in space-related activity, including space science, research and innovation in niche areas of excellence or national significance—Garada represented a major collaboration between research institutions (UNSW, Curtin, TU Delft) and aerospace corporations (BAE Systems Australia, EADS Astrium). · Ensuring Australia's space capabilities will be used to enhance, and guard against threats to, our national security and economic well-being—by providing timely, gapless soil moisture measurements, Australia will have needed data to make optimal decisions on use and improvement to water resources, which are critical to both national security and economic well-being.

2. THE GARADA TEAM

The Garada SAR Formation Flying Spacecraft project was a collaborative project led by the University of New South Wales with five other partners, all of whom are world-class in their particular fields. The project consortium linked Australia's leading satellite navigation researchers with key local and international industry partners to build new national capabilities in state-of-the-art earth observation from space.

UNSW has Australia's largest engineering faculty. It leads three ASRP projects and was a partner in two others. UNSW hosts Australia's largest group of satellite navigation researchers and is developing a strong team in satellite systems and remote sensing.

EADS Astrium has an established position as a global system/satellite prime contractor, with demonstrated record in SAR instrumentation and systems, bistatic radar, InSAR and formation flying. EADS Astrium provided specialist satellite systems engineering expertise to the consortium, exploiting their heritage and experience in SAR spacecraft.

BAE Systems, is a leading provider of communications, electronic warfare systems, mission support systems, navigation, sensor and spatial information systems. BAE Systems Australia provided a detailed ground segment study, Australian industry capability report and an established relationship with DSTO.

Curtin University and Delft University of Technology are highly capable research institutions. They brought some of the world's best expertise in high-precision positioning for satellites applied to formation flying algorithms.

General Dynamics (NZ) designed world first dual and triple-frequency FPGA-based multi-Global Navigation Satellite System receivers.

Involvement in the Garada project by the University of New South Wales was led by Professor Andrew Dempster with contributions from Professor Chris Rizos, Dr Steven Tsitas, Dr Robert Middleton, Dr Mauro Grassi, Dr Gordon Roesler, Dr Kegen Yu, Dr Li Qiao, Dr Nagaraj Channarayapatna Shivaramaiah, Dr Eamonn Glennon, Dr Jinghui Wu, Dr Joon Wayn Cheong, Dr Mohammad Choudhury, Peter Mumford, James Carrapetta, Joseph Gauthier, Vaidhya Mookiah, Vinh Tran, Scott O'Brien, Nam Khanh Pham, Yuanyuan Zhou, Rui Li, Yang Yang, Bo Yang, Tao Wang, Fariborz Sobhanmanesh and Nima Alam. UNSW also had contributions from undergraduate students including: Thomas Cooney, James Laughlin, George Constantinos, Foh Fan (Isaac) Yong, Scott Dorrington and Haifa Ben Aouicha.

UNSW's research and development in the FPGA multi GNSS receiver were largely tied to Mr Kevin Parkinson's work from General Dynamics. EADS Astrium's work on the project was led by Andrew Larkins with contributions from David Hall, Martin Cohen and Nunio Silva. BAE Systems contribution to the project was led by Dr Ian Tuohy with contributions from John Norrington and Michael Hopton.

Curtin and Delft Universities' work was led by Professor Peter Teunissen and Associate Professor Sandra Verhagen with contributions from Nandakumaran Nadarajah, Dr Peter Buist and Dr Gabriele Giorgi.

The Garada project also had various contributions from its advisory group. Dr Nick Stacy and Dr Tim Payne from DSTO, Martin Unwin from Surrey Satellite Technology Ltd (SSTL), Dr Markus Markgraf and Dr Simone D'Amico from the German Space Agency DLR.

Figure 2: Garada Team

3. PROJECT TECHNICAL OVERVIEWS

3.1. Mission concept and requirements

This work package was carried out by Dr Steven Tsitas of UNSW. The scope and goals of this work package were to define the space systems engineering and investigate the proposed radar applications of the Garada SAR Formation Flying project. Without well defined requirements, and applications dependent on very high temporal resolution (time between images), the scope expanded to include modifying the research direction of the Garada SAR Formation Flying project and leading the requirements analysis of the space system. This expanded scope included proposing a strategy for ACSER of designing low cost, light weight spacecraft using advanced technology to endow the spacecraft with the capabilities of larger spacecraft. Large numbers of these low cost spacecraft able to meet the high temporal resolution requirements could therefore be envisioned.

Multiple research and commercial initiatives were proposed as spin-offs from the research of this work package. These include: the proposal of an Australian Antarctic ground station for LEO spacecraft downlink, using a future Antarctic Broadband satellite relay to return the data to the mainland; using GPS to provide a common timing signal for local oscillators on bistatic SAR spacecraft; Fibre Optic distribution of RF signals across a microchip amplifier SAR antenna using silicon photonics; protected hard real time operating system use on spacecraft; and a small SAR satellite using Ka band, ultracapacitors for peak power generation and a deployable dish.

The first deliverable report *"TK1.1 User Requirements, Risk Analysis, Mission Baseline Report"* the work involved interviewing potential users of a Garada flood monitoring system, one of the originally proposed applications. The interviews revealed a consistent demand for approximately 1 hour temporal resolution, with a spatial resolution of a few metres. Since this temporal resolution requires a large number of spacecraft (the exact number was analysed by WP7) a low cost light weight designed was proposed and investigated in order to keep the overall system cost down. A proposal was made to build and sell these low cost SAR spacecraft to other countries to build up the constellation numbers to achieve the required temporal resolution. However feedback from the project end of year meetings in 2011 resulted in no consensus of support for these proposals. A suggestion was made that the system should be relevant to the problems of the Murray Darling Basin in order to maximise the chances of support from the government for implementation.

The second deliverable report *"TK1.2 Business Case"* the suggestion that the Garada SAR Formation Flying space system should be relevant to the problems of the Murray Darling Basin was investigated, specifically the requirements of measuring soil moisture in the Murray Darling Basin. A formation of two spacecraft half an orbit apart allows the temporal resolution requirements of three days for soil moisture monitoring in the Murray Darling Basin to be met while also satisfying the requirement that two spacecraft be used.

To further investigate the relevance of the soil moisture mission to Australia, interviews were conducted with five senior personnel involved with Australian agricultural and environmental issues. The results of these interviews are contained in Annex 14 to this volume. In addition to confirming the importance of the mission, new applications for soil moisture data were identified. Among these were: dust storm prediction; land use planning; carbon storage in root zones; and assessing the effects of climate change.

The third deliverable "*TK1.3 Mechanical Configurations Requirements and CAD Model*" provided the updated baseline for the Garada SAR Formation Flying mission was described which also demonstrated how design decisions flow from the requirements described in the GARADA requirements summary. George Constantinos described the structural design of the Garada spacecraft derived in the mission baseline, including CAD models and Finite Element Analysis of the structure.

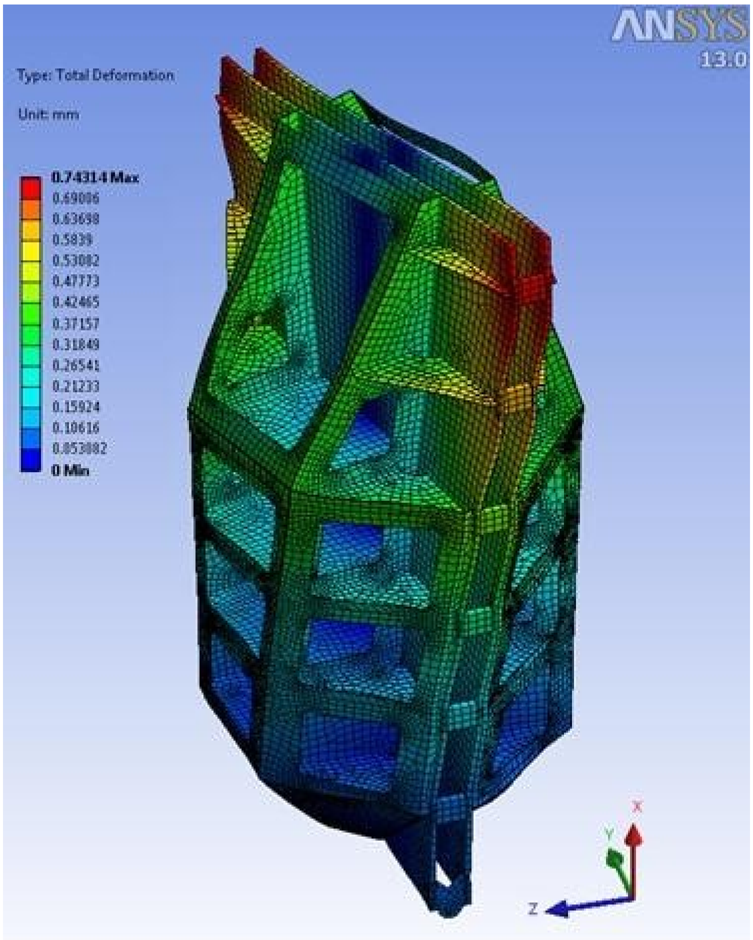


Figure 3: Finite Element Analysis of the Garada Satellite structure

In the final deliverable *"TK1.4 Thermal Requirements and Baseline Model, Spacecraft Communications System Report, Antenna Trade-off Report"* the maximum duty cycle – what percentage of the orbit the SAR operates – supported by the power system of the spacecraft was calculated. This was found to be 100% - continuous operation is possible, from a power point of view – which creates the requirement to determine the highest duty cycle that can be supported by the thermal system (validated to 21% duty cycle). The spacecraft communications system was described at a system level, defining requirements and describing a system consisting of dual X-Band transmitters and 1000 Mbps downlink.

While the proposed spacecraft is large, with an antenna size of 15.5 m x 3.9 m, the spacecraft subsystems that were investigated at a system level have a high level of technological maturity, except for the antenna subsystem and the platform structure. The antenna subsystem is envisioned to be based on circuit based microchip amplifiers, which is at a low level of technological maturity. For implementation this must be matured to a level for reliable space hardware through continued research and testing.

The other main area of technical risk is the scientific approach to measuring soil moisture from space using SAR, specifically within the Murray Darling Basin. This risk was addressed in the report by the User Advisory Group (Annex 12). It proposed that airborne tests using L-Band SAR continue to be conducted to ensure scientific consensus of the accuracy and utility of retrieved soil moisture measurements.

3.2. Radar concept

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, then a 4th year undergraduate at UNSW.

There were five deliverable documents for WP2 excluding the 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"* 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 was identified as the main application of interest and was the driver for all subsequent design decisions.

The next deliverable, titled: *"TK2.2: SAR Hardware and Methods Description and Specification"* 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 were 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.

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.

"TK2.4: SAR Hardware Description and Actual Specification" 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".* That thesis won the VSSEC-NASA Australian Space Prize 2012. The novel design using COTS (Commercial Off The Shelf) parts exclusively was 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 any polarisation and receiving in both H and V polarisations, as well as providing an internal calibration loop.

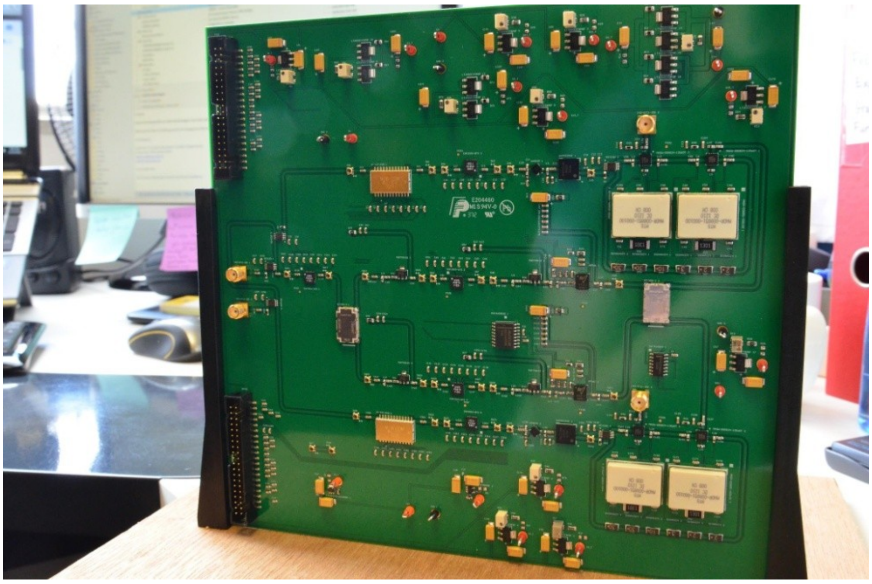


Figure 4: Prototype Electronic Circuit for an L-Band Phased Array Synthetic Aperture Radar

The final deliverable *"TK2.5: SAR Signal Processing Description and Actual Specification"* 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 a 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.

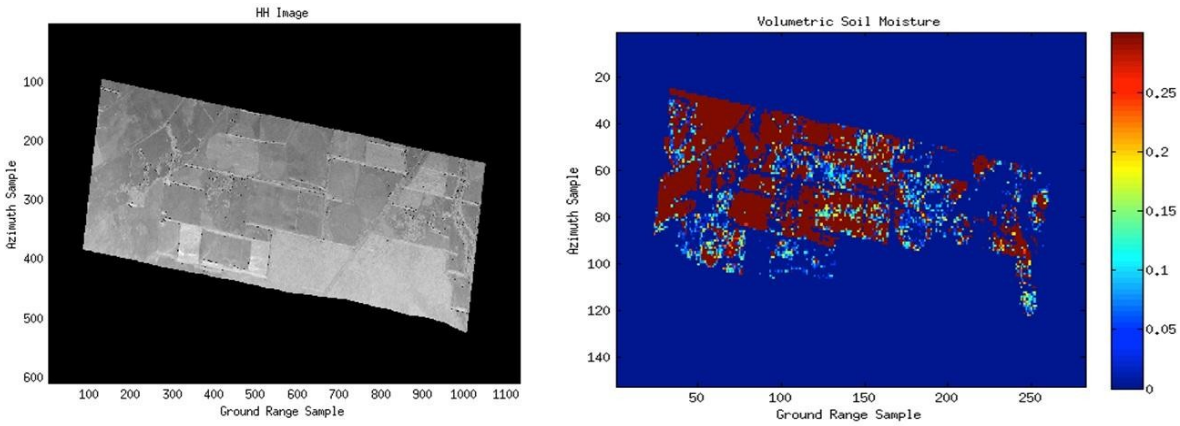


Figure 5: SAR image from the PLIS aircraft, left, processed for soil moisture content, right

Overall, WP2 details 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.

3.3. Radar system specification

The scope of this work package was to take the needs and requirements of the Garada system, as defined by the UNSW team, and then identify a range of design options that would fulfil these requirements.

These options would then be compared and contrasted from a number of perspectives, including relative cost, suitability for delivering the required capability, complexity, development maturity and risk, so that an informed down-selection of candidate solutions could be performed, resulting ultimately in a single preferred solution being selected that could then be further detailed and refined.

This single preferred solution would then be examined further and detailed in the SAR Payload Specification. This document would define the SAR system drivers and then go on to discuss the system architecture of the chosen configuration. The functions of key sub systems within the SAR payload would be discussed and their potential implementation outlined. It was envisaged that the SAR Payload Specification would be delivered first as a Preliminary issue, and then at a later date a final issue would be updated and delivered. This approach would aid in capturing late requirements.

This work package started with a set of requirements for a system that could provide rapid identification of flooding across Australia. This requirement demanded a solution comprising a constellation of many satellites. The SAR technique proposed by UNSW for flood identification would operate with groups of satellites operating in formation. The need for many satellites directly leads to the need for each satellite to be very low cost in order that a complete system be considered affordable. Furthermore, a solution was sought that offered the opportunity to involve a high proportion of indigenous capability within Australia.

The Garada team outlined a SAR-based technique for identifying floods based on using a bistatic pair of receivers to form a coherence map of the imaged scene from which flooded areas could be identified due to their poor coherence compared with the rest of the scene. This required a formation of either 2 or 3 spacecraft depending on whether or not one of the receivers can also transmit. X-band was selected as the preferred band due to the 3m resolution requirement and the need to be low cost. The low cost aspect also led to the need for the antenna to be as small as possible to remain compatible with a low cost launch.

At the end of 2011 user requirements surveys caused the system requirements to change and this would change the SAR system significantly. The key application for the Garada mission became the measurement of soil moisture over agricultural areas (predominantly the Murray Darling Basin) at high spatial resolution. Additional applications of forest change detection in support of Reducing Emissions from Deforestation and Forest Degradation (REDD) (detecting clear cutting of forests) and flood and disaster monitoring were also to be considered.

These new requirements drove the SAR system to generate coherent quad-polar L-Band imagery with a potential revisit interval of 2-3 days. This was achieved using a close formation of a pair of satellites to enable single pass interferometric observations. The satellite design was of a 'snapdragon' configuration with an innovative fully active phased array antenna.

The maturity of the described SAR System was mixed. The main structure was well defined, having its origins with Astrium's TerraSAR-L concept. Similarly, the Back End Electronics could be based on products already in development by Astrium and other Space companies. The main area of innovation would be in the active phased array antenna which would require a degree of development and prototyping ahead of a potential flight programme.

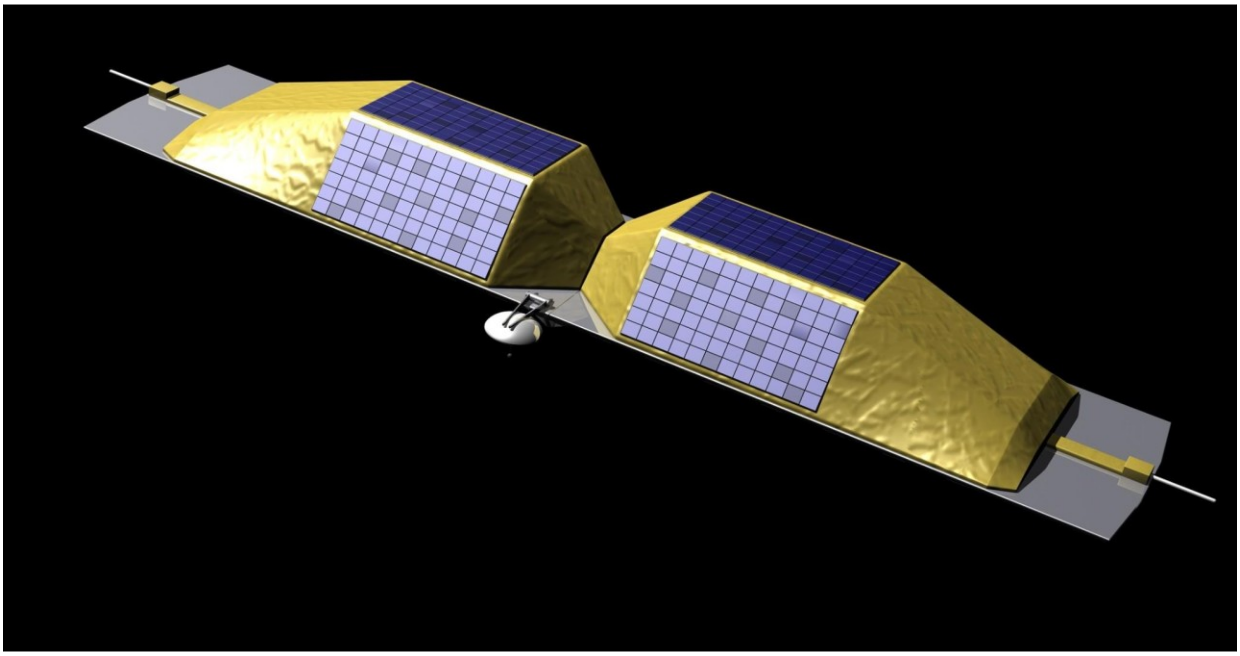


Figure 6: Proposed design of the Garada Satellite

Astrium was also originally tasked with investigating the feasibility of an airborne demonstration of the chosen SAR concept and to detail an implementation plan for such a demo. After an initial assessment of the cost of such a demo Astrium was asked to stop work on this work package and was redirected to perform a thermal analysis of the Garada spacecraft.

This document analysed the Garada satellite and SAR system for the effects of potential operating modes on general payload temperatures, confirming the viability of the spacecraft and its thermal design. The viability was subsequently confirmed for all operating modes considered.

As this was a preliminary analysis, further work was suggested. This would involve applying dissipations specific to the Garada mission hardware and heater sizing for the operational and non-operational cases. There may be opportunity for some thermal trimming of both external and internal properties (adjusting exposed areas and their thermo-optical properties) which would reduce power demands. Launch and Early Operation Phases (LEOP) would also be examined once these phases of the mission had been defined in more detail.

3.4. Bistatic radar and GNSS reflectometry

The original concept of multiple spacecraft for bistatic SAR measurements was eventually determined to have limited utility for the most important potential Garada missions. However, a related approach is the use of Global Navigation Satellite System (GNSS) signals reflected off the Earth to characterise the surface properties.

This work package investigated how to use (GNSS) reflectometry (GNSS-R) to retrieve a range of geophysical parameters including: near sea surface wind speed, sea surface height, abnormal forest condition, and soil moisture. GNSS-R is a cost-effective remote sensing technology which exploits the free GNSS signals that are available virtually any time and anywhere on the globe. GNSS-R was originally proposed for remote sensing about two decades ago; however, it is still not yet a mature technology and there are still many challenging problems to be resolved. This work package aimed to explore this technology by focusing on the design and conduct of four low-altitude airborne experiments using a UNSW-owned light aircraft and software GNSS receiver, and on the bistatic receiver design. In addition to verifying a number of GNSS-R applications using the experimental data, it was intended to obtain new findings and develop new techniques and methods. The final goal was to develop a spaceborne GNSS reflectometer to operate with a spaceborne SAR in the same satellite. The GNSS-R measurements will be processed using reliable and robust algorithms and the results will be combined with the SAR observations to achieve a performance gain.

Five deliverables have been generated. The first deliverable *"TK4.1 Design Airborne Experiment"* reports on the first airborne GNSS bistatic sensor experiment (as a free host payload) which was conducted on 14 June 2011. In addition to addressing a number of issues including the sea wave spectrum, the sea surface scattering and the correlation power, preliminary data processing results including correlation delay waveforms were presented. The second deliverable *"TK4.2 First Airborne Bistatic Experiment"* reports on the second airborne experiment conducted on 4 November 2011, with a focus on the data processing, delay waveform and delay-Doppler waveform generation, and near sea surface wind speed estimation using the model fitting approach. The results demonstrate that accurate sea surface wind speed estimation can be achieved using GNSS signals.

The third deliverable *"TK4.3 Design of a Bistatic Receiver"* reports on the initial design of the bistatic receiver dedicated to the computation, in real time, of complex-valued (in-phase and quadrature) cross-correlations between the received GNSS signal and the local signal replica stored in the receiver. Some detailed information about the initial design of the signal processing back-end is presented and a number of parameters including those associated with generating the delay-Doppler waveform are initially specified. The fourth deliverable *"TK4.4 Second Airborne Experiment"* reports on the third airborne bistatic sensor experiment conducted on 19 September 2012, by flying the aircraft over some land areas in the basin of Sydney and over forests in the southwest of Sydney and northwest of Wollongong. A small fraction of the collected data has been processed. Some preliminary results, shown in Figure 7, demonstrate that the reflected signal peak power can be exploited to identify the abnormality in the forests such as the areas where trees are absent or the forest density becomes much smaller.

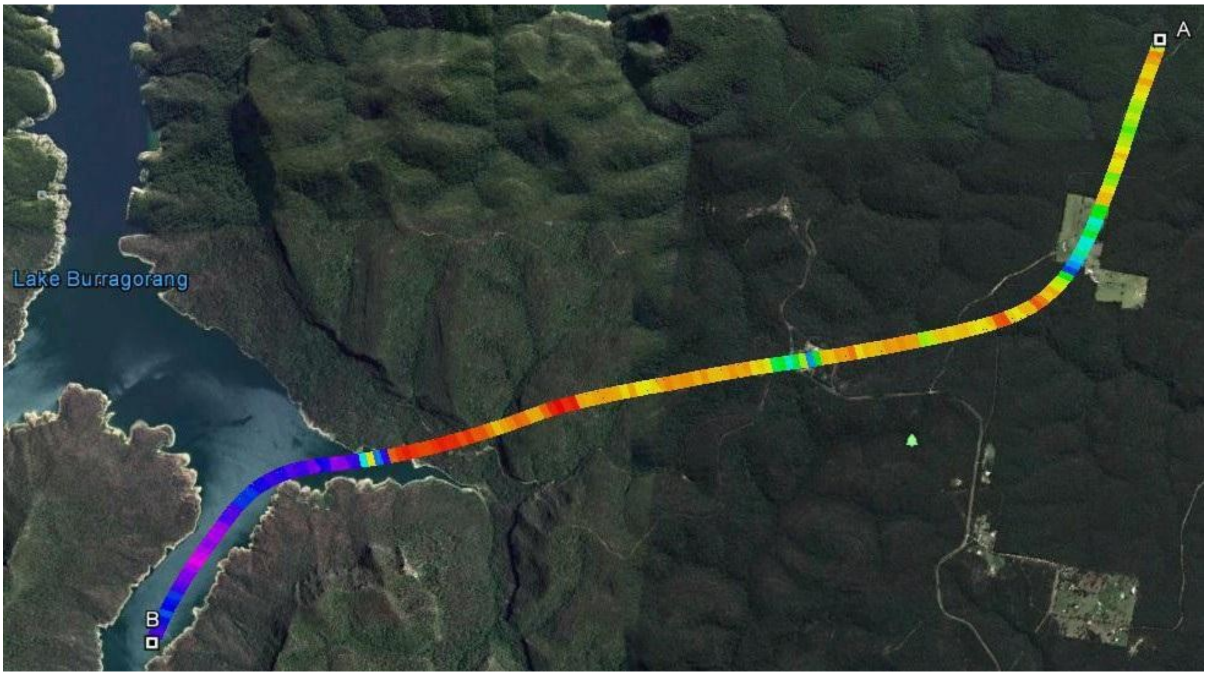


Figure 7: Variations in received GNSS peak power due to changes to the ground surface

The fifth deliverable *"TK4.5 Final Bistatic Receiver Design"* reports on the bistatic receiver design, providing detailed discussions on the number of front-ends and the utilisation of multi-frequency and multi-GNSS constellations. The focus was also on the design of the fourth airborne experiment to collect data for research in retrieving GNSS-based soil moisture.

There are a number of significant findings resulting from the research activities associated with this work package.

1. It was demonstrated that power ratio measurements can be used to estimate the delay of the reflected GNSS signal relative to the direct one. Two cost functions can be defined to estimate the desired power ratio and the sea surface height (SSH) through minimising the cost functions. Applying the experimental data to this new method demonstrate that the error of mean SSH estimation can be of the order of decimetre in the presence of significant wave height of about 4 metres. This method does not require any *a priori* knowledge of sea state information or any theoretical model. Thus, its performance is not affected by the modelling errors and uncertainties.
2. Airborne experimental data of direct and reflected GNSS signals can be used to detect abnormal conditions in forests. Multiple specular reflection tracks associated with multiple GNSS satellites whose elevation angles are greater than such as 30^{o}

can be employed to identify forest abnormal conditions in areas of relative small dimensions such as 30m wide.

3. When using the model fitting method, accurate near sea surface wind speed estimation can be achieved by using signals of GNSS satellites whose elevation angle is relatively small such as 20^o. Thus, a performance gain can be realised by utilising measurement data associated with multiple satellites. Finally some findings related to soil moisture estimation will be available from processing the data to be collected in the next airborne experiment.

To implement the GNSS-R technology in a spaceborne platform, two aspects with regard to the maturity of the technology need to be addressed. The first one is the system aspect, while the second one is associated with post data processing and data fusion. The GNSS-R system does not only need to directly generate two-dimensional delay correlation waveforms and/or three-dimensional delay-Doppler waveforms in real time so that the end users can readily apply these waveform data for research or applications, but it should also have the option to generate the intermediate frequency (IF) data so that the end users may use the IF data for research to develop new and advanced techniques. In a decade, signals from four different GNSS constellations (GPS, GLONASS, Galileo, and Beidou) can be utilised. Thus, the GNSS-R system should be able to accommodate some or all of these signals which have different frequencies and are from different constellations. When observations from multi-frequency and multi-GNSS constellations are available, techniques or algorithms are needed to effectively combine these observations. When the GNSS reflectometer is used with other sensors such as SAR, the observations from different sensors need to be combined to achieve another diversity gain.

Based on the above discussions future work should focus on the systematic design and manufacturing of a GNSS bistatic receiver that can accommodate multi-frequency signals transmitted from multiple constellations and is suited for land, airborne and spaceborne applications. The UNSW-built Namuru receivers will be used as the basis to simplify the design. Also, it should focus on the development of innovative techniques and algorithms to achieve optimal fusion of observations from multiple constellations and from multiple sensors.

Personnel participating in the research activities were:

- Dr. Kegen Yu, University of New South Wales
- Mr. Scott O’brien, University of New South Wales
- Dr. Nima Alam, formerly with University of New South Wales; now with Trimble
- Prof. Chris Rizos, University of New South Wales
- Prof. Andrew Dempster, University of New South Wales

Personnel participating in the conduct of one or more of the four airborne experiments were:

- Prof. Jason Middleton, University of New South Wales
- Mr. Greg Nippard, formerly with University of New South Wales
- Mr. Peter Mumford, formerly with University of New South Wales
- Dr. Eamonn Glasson, University of New South Wales
- Dr. Bo Yang, former visitor of University of New South Wales

Personnel participating in the collaboration were:

- Prof. Jeff Walker, Monash University
- Dr. Alessandra Monerris, Monash University

3.5. Developing a satellite navigation receiver for the space mission

Work package 5 in the Garada project chiefly involved the task of developing a satellite navigation receiver for the space mission. The on-board satellite navigation receiver is intended to provide high accuracy positioning and navigation capability using the Global Navigation Satellite System (GNSS) signals. The Garada prototype multi-GNSS receiver achieves this space grade positioning and navigation capability by receiving, processing and utilising four major open service GNSS signals: GPS L1 C/A, Galileo E1, GPS L5 and Galileo E5a.

The Garada multi-GNSS prototype receiver in this large work package involved the development of hardware and software and was split into several phases. In addition to the multi-GNSS receiver, an "upgraded" version of a single frequency Garada GPS receiver was part of the original proposal, for use on Bluesat. When the Defence Science and Technology Organisation offered funds for the development of a receiver for Biarri (a Cubesat formation flying mission), a new receiver was developed instead. That receiver processes only the GPS L1 C/A signal. The first, second and the third phases in work package 5 added the capability of E1, L5 and E5 signals respectively to the L1 functionality derived from the Biarri receiver. The functional testing towards achieving the space qualification was one of the focus elements of the last phase.

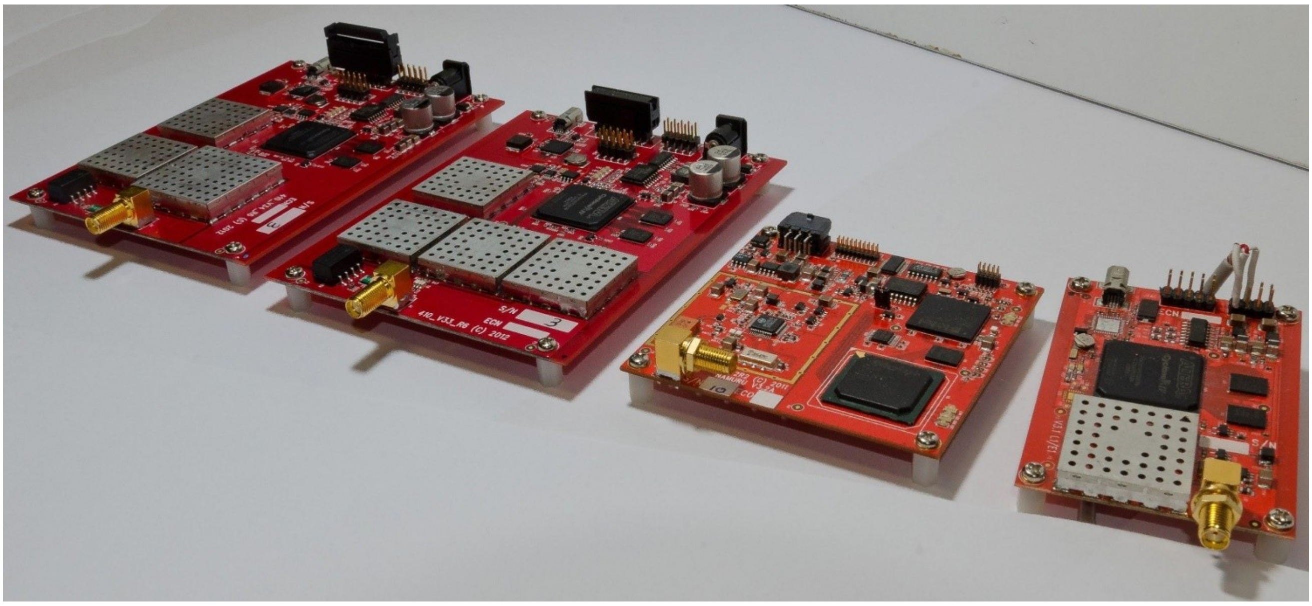


Figure 8: Namuru Receivers produced throughout the Garada Project.
From Left to Right: Namuru V3.4, Namuru V3.3 (the "Garada receiver"), Namuru V3.2 (the "Biarri" receiver), Namuru V3.1

The tasks in this receiver development work package belonged to five components: the hardware, the digital baseband signal processor, the firmware, the post processing software and the testing.

The receiver hardware encompasses the Radio Frequency (RF) down converter which receives the signal from an antenna and transforms it into a digital stream to feed the signal processing section. The baseband module performs the tasks of search acceleration, acquisition and tracking of the satellite signal the results of which are then fed to a microprocessor. The microprocessor analyses and decodes the signal to generate the platform's position, velocity and time solution.

Garada Receiver Hardware:

The design, fabrication and testing of the hardware (PCB, Printed Circuit Board) was the responsibility of General Dynamics, NZ. In order to allow stage-by-stage development of the respective receiver components, GD produced three boards (including the Biarri receiver) to add to UNSW's Namuru family of GNSS receivers. Namuru V2.4 was the platform receiver that existed before the Garada project and was used extensively to test some of the algorithms during the course of the Garada project until the Garada-specific boards Namuru V3.1 and Namuru V3.3 were delivered to UNSW. Namuru V3.2 is the Biarri GNSS receiver.

Garada Receiver Digital Baseband Signal Processing:

The digital baseband section handles the computationally intensive task of acquiring and tracking the satellite signal. The Namuru family of GNSS receivers use Field Programmable Gate Arrays (FPGAs) to do the baseband signal processing. The signal from the RF down converter is simultaneously processed by different channels where each channel is assigned to track the signals from any one GNSS satellite. Namuru V3.1 and Namuru V3.3 use Altera Cyclone IV FPGAs for this operation. Cyclone IV series of FPGAs produce less digital noise and at the same time offer the logic density required to implement four-signal correlator blocks. The Garada baseband has been implemented in Verilog Hardware Description Language in a highly modular fashion keeping in mind the scalability and ease of data interaction with the firmware.

Garada Receiver Firmware:

The microprocessor within the FPGA chip that is on the board is the GNSS receiver sub-system master. The firmware (i.e. the embedded software) written for the processor is responsible for controlling receiver operations and also to interacting with other payloads of the satellite. The development started with the Biarri baseline firmware "Aquarius". Written in C and C++ languages, the Garada firmware configures the receiver RF and baseband sections, receives the measurements and data from the baseband and decodes the navigation messages. The decoded navigation messages and the satellite range measurements go through filtering and position solution algorithms to produce the PVT (Position, Velocity and Time) output. The firmware is responsible for generating the receiver messages as per the National Marine Electronics Association (NMEA) protocol that contains different parameters and the status of the receiver operation. The host communication module interacts with the system master (in the final system this would be the mission computer) to accept operating instructions and act accordingly.

Garada Receiver Post-processing software:

A GNSS receiver generates two kinds of measurements, the code-phase measurement and the carrier-phase measurements. The former is accurate but not precise; the latter is precise but may not be accurate. Combining the two types of measurements provides an accurate and precise solution. However the combination algorithms require enormous processing power and can't be done on board (with current-day technical limitations). This has led UNSW to the development of post processing software as part of this project. UNSW started off with the open-source RTKLib and has developed an advanced version of the software "RTKLib Pro" that is tailored for the Garada receiver measurement processing. RTKLib Pro accepts data in the RINEX format and produces the pseudo-range and carrier-phase baseline solutions with the associated statistics, for all the four-signals in context: GPA L1 C/A, GPS L5, Galileo E1 and Galileo E5a.

Test Platform and Data Collection Setup:

UNSW rented the multi-GNSS signal simulator from Spirent Communications for the duration of the project. This is a two-box solution with the first box GSS8000 generating GPS L1 C/A, Galileo E1 and Galileo E5 signals and the second box GSS7700 generating the GPS L5 signal. A combiner GSS8368 combines the signals from the two boxes which then feeds the receiver antenna input. The simulator was being used for testing the position and timing solution of the receiver with the proposed Garada satellite orbit models and also to collect raw signal samples to aid the receiver development. Proposed satellite orbit parameters were taken from the analysis and recommendations of the Orbit modelling work package. Several test scenarios were created in the Spirent simulator and the scenarios were run repeatedly to test the solution quality as well as to aid the hardware and firmware debugging process.

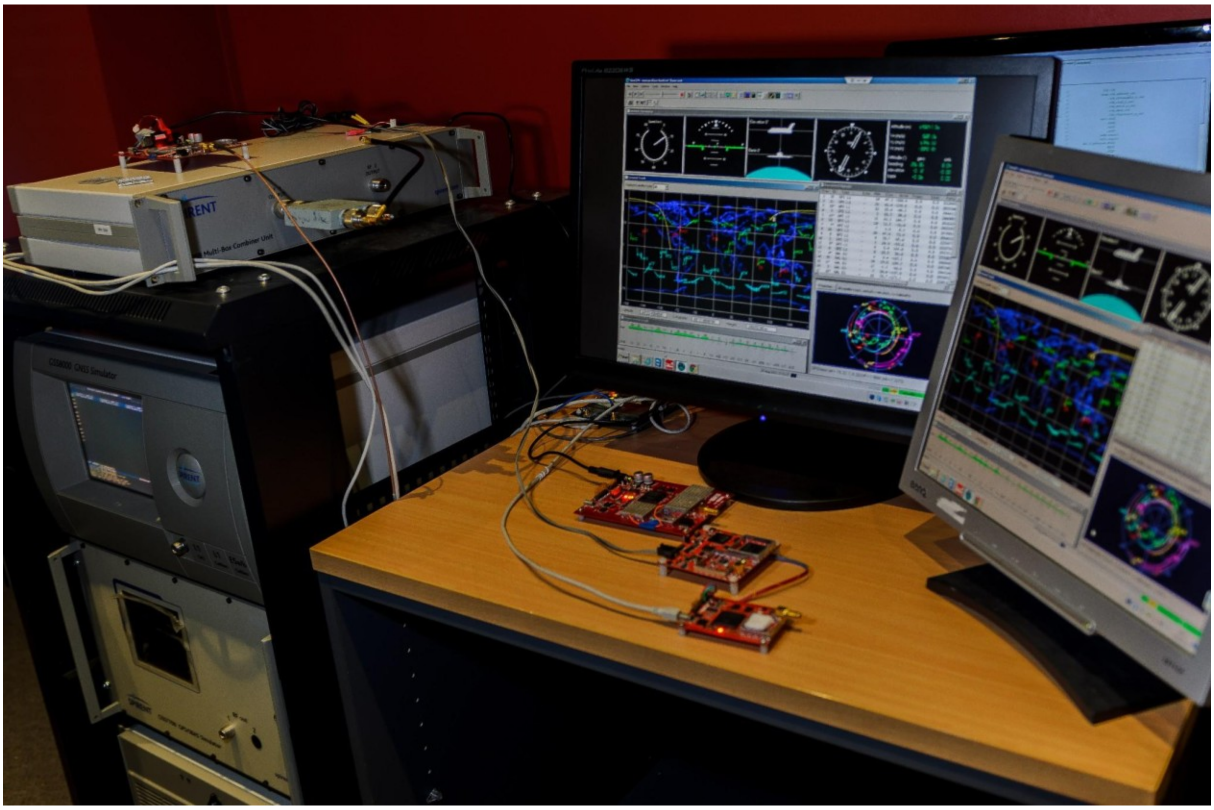


Figure 9: Spirent Simulator and Namuru Receivers at UNSW

Tests Results Overview:

The Garada receiver's initial tests were conducted for the L1+E1 signal combination. Position quality tests were performed for both absolute position and relative position. Rigorous testing has being conducted to focus on detection, identification and correction of firmware bugs which may cause GPS + Galileo position solution quality and availability.

Static tests with the GPS L1 C/A signal produced an accuracy of ±5m in (RMS 1-sigma in 3D). In-orbit kinematic tests exhibited ±5m (in 3D) and the base-line solution produced ±5cm (in 3D). Further tests were conducted with two signals one each from GPS and Galileo constellations. The GPS L1 C/A + Galileo E1 constellation scenario was configured in the Spirent as per the Spirent offered ICD version of the Galileo. Since the real Galileo satellites are also available (but only 4 of them have been launched, so not all are visible over Sydney at the same time), real signal GPS L1 C/A + Galileo E1 tests were conducted. As ephemeris data is not accurate at Sydney, absolute positioning with Galileo satellites cannot be conducted at the moment. However, the baseline solution has been processed which shows an accuracy of ±5m (in 3D). Further tests will be conducted for pseudorange and carrier-phase outliers.

Future Activity:

Integration of the L5 and E5a band signals and the hardware and firmware testing for L5 signals is underway.

3.6. Formation flying algorithms for multi-satellite missions

Delft University of Technology, team members: Dr. Sandra Verhagen, Peter Buist, Gabriele Giorgi
Curtin University, team members: Prof. Peter Teunissen, Nandakumaran Nadarajah

The aim of this work package was to develop models, methods and algorithms for precise formation-flying positioning and demonstrate the formation flying capabilities using the GNSS carrier phase based positioning and attitude determination concepts. This implies adequately accounting for a wide range of error sources in the dynamic environment, as well as capturing the noise characteristics in a stochastic model. Our novel GNSS solution methods for integrated positioning and attitude determination allow further improvements over traditionally obtained solutions. The realization of real-time kinematic satellite-formation geometry, independent of gravitational and non-conservative forces, offers a significant increase in spacecraft autonomy and simplification of spacecraft operations.

The first step was the development of the functional and stochastic model for GNSS-based relative positioning and attitude determination. Special attention was given to linearization errors, the influence of large receiver clock offsets on relative positioning, velocity estimation, the use of Doppler observations and application of the ionosphere-weighted model to account for ionosphere errors in case of longer distances between the elements of a formation. Furthermore, a receiver test procedure was designed and used to assess the receiver noise characteristics of the GNSS receivers.

In order to demonstrate the achievable accuracy for both relative positioning and attitude determination, experimental data have been used as summarised in Table 4. Both hardware-in-the-loop simulations with the Namuru receiver, as well as other datasets were used to allow a performance assessment. This includes multi-frequency, multi-GNSS data from GPS, Galileo and Compass. An important aspect has been an analysis of mission and receiver design aspects on the performance, since the configuration design (e.g., 3D geometry, data capture scenarios, functional and stochastic model) impacts on the formation positioning quality.

The scenario considered here is the problem of GNSS-based precise relative positioning of two (or more) satellites in a formation, as well as GNSS-based attitude determination of the satellites. The orientation of a body with respect to a given reference frame can mainly be estimated by employing a number of GNSS antennas onboard a satellite. The accuracy of the angular estimation depends mainly on two factors: the quality of the GNSS observations and the distance between the GNSS antenna, i.e., baseline lengths. Often one has no control over the latter, since the size and geometry of the platform limit the maximum distance at which the antennas can be placed. Thus, the challenge of obtaining precise angular estimates relies on obtaining accurate results from the available observations.

Fast and reliable carrier-phase ambiguity resolution is the key to precise positioning and attitude determination. The carrier-phase observations are mainly 'biased' by an unknown integer number of cycles, called the integer ambiguity, preceding the observed fractional phase. Once this integer ambiguity is correctly resolved, the very high precision of the carrier-phase observations – a factor 100 better than the pseudorange observations – can be fully exploited.

A major contribution of this work has been the development and implementation of a modified version of the standard LAMBDA method for integer ambiguity resolution, which exploits the fact that the geometry of the multi-antenna configuration on-board the satellites are known. The experimental results in this report confirm that with this new method the ambiguity resolution performance is improved dramatically, which results in more precise and reliable attitude estimates. The attitude angular accuracies have been further improved by employing recursive filtering to at least 0.03 degrees with single-frequency GPS and GPS+Galileo simulated Namuru data for the LEO scenario considered here; see Figure 10.

In addition, a relative positioning algorithm was developed – called attitude bootstrapping, which benefits from the improved ambiguity resolution capability for the attitude determination. It has been demonstrated that this results in very high precision results with a much higher availability. The example in Figure 11 shows that for very short inter-platform distances and in the absence of multipath and atmospheric errors a relative positioning precision of several millimetres is feasible.

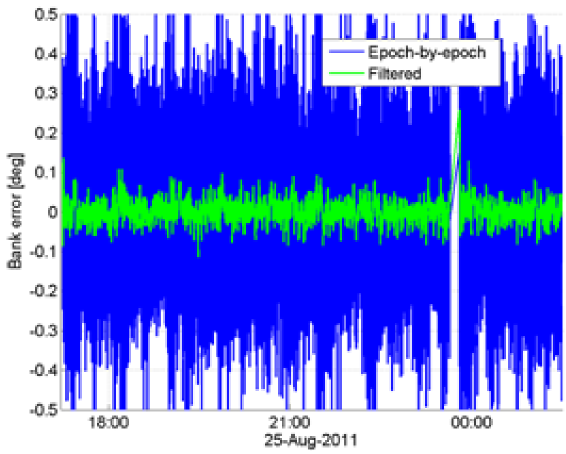
A last asset is the incorporation of the so-called Detection-Identification-Adaptation (DIA) procedure, which tests for outliers and carrier-phase cycle slips. These may result in large errors in the estimated positions and attitude angles, and should therefore be removed if possible. It has been shown that the implemented DIA procedure is indeed very suitable for detecting and identifying anomalies that may be present in the data and adapting the results to remove the impact of the anomalies.

All in all, the potential of stand-alone, unaided, single-frequency attitude determination and relative positioning of LEO satellites has been demonstrated both for GPS-only and dual system (GPS +Galileo) formation flying.

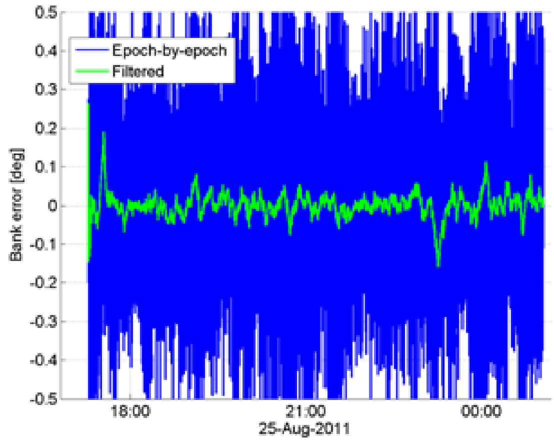
Table 4 : Experiments and data used for Work Package 6, Formation flying algorithms (all GPS-only unless stated otherwise)

Receivers	Experiment	Goal
NamuruV2	Zero- and short baseline	Noise assessment
NamuruV2Rx	CubeSat simulations	Attitude determination
Trimble R7 / 4000	Multi-baseline experiment (real data), 2 platforms each with 5 antennas	MC-LAMBDA, attitude determination and relative positioning
NamuruV2Rx	LEO mission simulations, 2 platforms each with 3 antennas, inter-platform distance 100 m	data quality analyses, MC-LAMBDA, attitude determination, absolute and relative positioning
-	Software simulations	Impact of system, frequencies, noise, baseline length, mask angle and orbit
NamuruV3.2Rx	LEO mission simulations, 2	Data quality analyses, MC-

	platforms each with 3 antennas, inter-platform distance 100 m	LAMBDA, attitude determination, absolute and relative positioning, DIA
Septentrio PolaRxS	Static GPS+Galileo simulations, 1 platform with 3 antennas	MC-LAMBDA, attitude determination
Trimble NetR9	Static GPS+Galileo+Compass real data, baseline (8m)	MC-LAMBDA, attitude determination
NamuruV2.4Rx	LEO mission GPS+Galileo simulations, 2 platforms each with 3 antennas, inter-platform distance 100 m	MC-LAMBDA, attitude determination



(a) NamuruV3.2Rx (GPS-only)



(b) NamuruV2.4Rx (12 channel: 8 GPS+ 4 Galileo)

Figure 10: Bank error with the simulated data of a LEO mission. Comparable results are obtained for elevation and pitch. Root mean square error of recursively filtered bank estimate is 0.03 deg. Gaps in the data are due to receiver resetting.

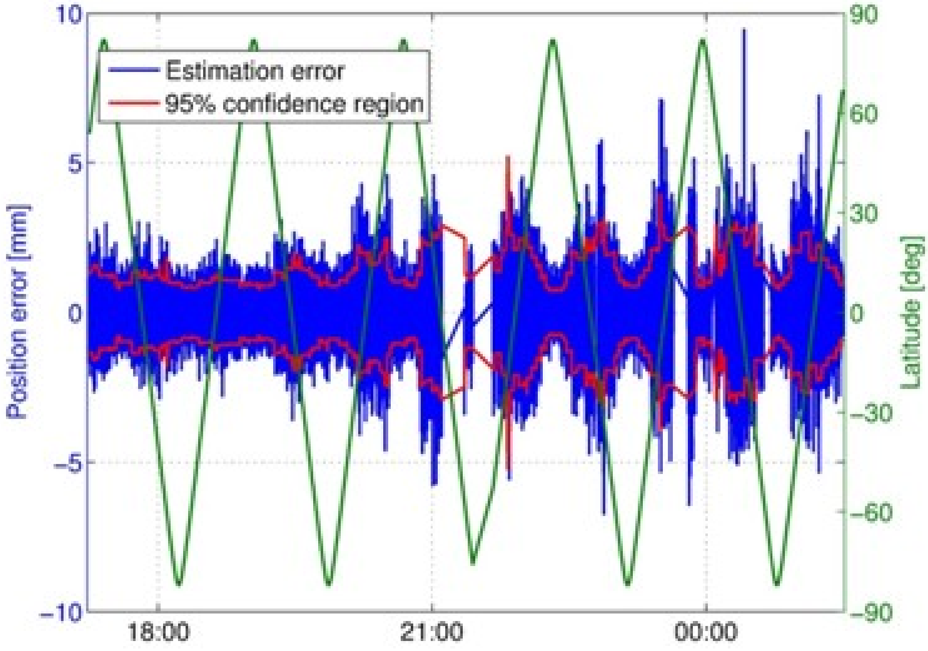


Figure 11: Relative positioning error with attitude bootstrapping (fixed solution) with the simulated data of a LEO mission with the NamuruV3.2Rx data. Inter-platform distance is 100 m. Only results for X-component, comparable results for Y- and Z-components. Root mean square error of baseline estimate is 2 mm. Gaps in the data are due to receiver resetting.

3.7. Orbit modelling and analysis, mission planning

Work Package 7 "Satellite Orbit Models" was focused on determining the optimum orbit for the mission and selecting the candidate launcher vehicle. This WP was led by Professor Chris Rizos and the tasks were performed by Research Associate Dr Li Qiao. This WP was key to understanding the coverage of the system, and informed many of the other studies.

Orbit modelling is a complex task as it involves trade-offs between different mission and user requirement parameters. During the mission analysis conducted in WP1, it was concluded that the key application that could be provided to deliver significant benefit to Australia is soil moisture monitoring (using as a guideline the Murray Darling Basin – MDB). The coverage requirements therefore relate primarily to soil moisture mapping. MDB is highlighted as a key area of interest as the area produces one third of Australia's agricultural output. **A coverage revisit interval of 2-3 days would be required to satisfy the mission goal**. The payload will revisit the target area at the same time of day on subsequent passes in order to monitor the soil moisture content. Since the required SAR antenna is large in size, the mission has a big power budget requirement. This implies that maximum access to sunlight is a crucial orbit requirement. The Garada satellite will therefore be inserted into a dawn-dusk orbit where the satellite stays in sunlight on a continuous basis.

To best satisfy the mission requirements, **a frozen, repeating, circular sun-synchronous orbit (SSO) is the best candidate orbit**. The SSO is generally favoured for Earth observation satellites that need to be operated at a relatively constant altitude suitable for imaging/sensing instruments. The proposed Garada orbit is at an altitude of 612.98km with inclination 97.84 degrees. The orbit will repeat after 89 revolutions in 6 days, completing 15 orbits per day. Since the soil moisture revisit requirement is 2-3 days, a two-satellite constellation is needed. It is desirable to place the Garada 1 and Garada 2 satellites at the same altitude (see Figure 12) to double the revisit frequency, and to maximise consistent near-simultaneous coverage. **Two 6-day repeat SSO satellites can meet the MDB 3-day revisit requirement** (see Figure 13).

In reality the orbit will change from its nominal geometry due to a variety of orbital forces. Therefore an orbit perturbation analysis was performed to estimate variations in the satellite trajectory relative to the reference orbit after a certain period of time. Sensitivity study results reveal that the Earth's irregular gravity field has the largest impact on satellite orbital motion. The atmospheric drag is the second largest perturbing effect, affected by space weather and the solar cycle. The above two orbital forces cause perturbations of a magnitude of tens of kilometres. The third body effect is relatively small, with a magnitude of some hundreds of metres. The solar radiation pressure effect produces a variation of less than one hundred metres.

Another WP7 task was the selection of the launch system to place the Garada satellite(s) into the desired orbit. Since Australia does not have any launch systems it was necessary to survey the international launch market and consider various candidate launcher options. The most important factors to be considered are reliability, performance, suitability, and price. Other considerations include availability and schedule, technology transfer safeguards, customer-provider relationship and partnership, as well as terms and conditions. The large antenna of Garada drives the mission towards a launch vehicle of the size of a Falcon-9. Falcon-9 is a rocket-powered launch system designed and manufactured by Space Exploration Technologies (SpaceX), headquartered in

Hawthorne, California. The launch cost is estimated to be of the order of US$49-54 million. The U.S. Delta IV-M and the European Ariane 5 could also be used to launch Garada, however with much higher launch cost (greater than US$100 million). Therefore the Falcon-9 is the favoured candidate for the launch system.

Figure 12: Geometry of Garada 1 and Garada 2

Figure 13: Two 6-day SSO constellation coverage over the MDB

Using the orbit propagator in the Satellite Tool Kit (STK), coupled to a STK/Matlab interface, a software tool was developed to analyse the performance of the proposed orbit design. STK is a leading commercial off-the-shelf analysis tool used by the aerospace industry. Specifically, a scripting environment where Matlab and STK are used in combination was developed. In this mode the STK software development kits are used as an “engine”. Matlab uses the COM interface capability of the STK/Integration module to send Connect commands directly to STK. All orbital calculations in the analysis section of WP7 have been performed using Matlab software and verified using STK v9.0. A product of WP7 is a set of software tools which could be utilised in orbit modelling, coverage analysis, and launch vehicle selection, etc. for future Earth satellite projects.

3.8. Orbit control

The scope of this work package was to understand the Garada SAR system, spacecraft, and concept of operations as defined by the UNSW team, and then derive the requirements that needed to be placed on the altitude orbit control system (AOCS). Maximum reuse of current AOCS elements was preferred to save cost. The design report would then present the design drivers, trade-offs, analysis and finally the baseline solution for the Garada AOCS. Due to the limited information available on the Garada mission concept and operation, the requirements as used for Astrium's TerraSAR-L concept were heavily relied upon.

The key drivers in the design of the AOCS were found to be: the large, variable and asymmetric inertias, which in turn drive the acquisition and safe mode strategies due to the potentially large gravity gradient disturbance torques which can be generated; the provision of a manoeuvre (slew) capability to enable sideways pointing; and normal mode performance which in turn drives the architecture.

In addition, due to the difference between the launch and operational configurations, the deployment strategy, which has to cope with widely varying inertias was considered another key area.

A view to exploiting heritage (hardware, architecture and concept) was to be maintained in order to keep costs low.

A baseline solution was defined and presented that met the derived requirements whilst maintaining proven heritage. Due to the use of a standard high accuracy multi-head star tracker, the nominal mission was found to be robust and accurate. It was determined that simple and robust equipment could be used for acquisition and safe modes which in turn reduces cost and risk – moreover a strategy can be utilised with heritage from previous activities.

Due to the similarities of the AOCS architecture to previous missions plus the reuse of existing hardware, further work is limited to increased detail of the overall design. No further development or prototyping is considered necessary.

3.9. Industrialization analysis

Garada Work Package 9 (WP9) was the responsibility of BAE Systems Australia. The task was undertaken by John Norrington, Garada Systems Engineer with support from Michael Hopton, Engineering Manager and Ian Tuohy, Space Systems Manager (acting as Garada Project Manager).

The purpose of WP9 as contracted under the Garada Consortium Agreement was:

> *To establish a viable programmatic basis from which a full implementation project can be planned. To review and determine the extent to which existing Australian industrial capability could contribute to such a program, identifying areas of niche capability, and potential gaps in requisite skills/expertise. To facilitate a knowledge/skills transfer in SAR technologies through a program of specialist training.*

Specific task (TK) deliverables were as follows:

- TK9.1 Capability Requirements Matrix
- TK9.2 Australian Industry Capability Report
- TK9.3 Training Program in SAR Technologies
- TK9.4 Preliminary Industrialization Plan
- TK9.5 Project Industrialization Plan

TK9.1 constituted a starting point to WP9 and entailed an assessment of the high level tasks required to develop, launch and operate the Garada system. The assessment culminated in a comprehensive Capability Requirements Matrix spanning the space segment, launch services segment and ground segment. The matrix maps each task in the Work Breakdown Structure to the skills and resources required to undertake the task.

TK9.2 entailed a focussed survey of the capability of Australian Industry to contribute to the Garada space and ground segments and also operational elements of the mission. The survey was based on a combination of published and unpublished information for approximately 190 organizations, and culminated in an Australian Industry Capability Report. As well as industry capability the report also covers the capabilities resident in academia and government. The report concludes that Australia has few indigenous capabilities relating directly to the space segment, but has strong capabilities in the ground segment area and is very strong on the downstream services of processing and applying information from Earth Observation satellites. Australian industry is very capable of priming and undertaking all of the work associated with the Garada ground segment. By utilising the new space integration and test facilities at the ANU's Advanced Instrumentation Technology Centre (AITC), Australian industry could participate in the space segment as a Tier 3 supplier of space qualified components to the spacecraft prime. Australia could also make a substantial contribution to the legal and insurance services required for the project.

TK9.3 addressed training in SAR technologies and took the form of a one-day SAR Workshop held at UNSW on 7Dec11. The program entailed tutorial and application themes and attracted ~75 participants from the government, research and industry sectors including SAR specialists (notably from Astrium and DSTO) and end-users.

TK9.4 built upon TK9.1 and TK9.2 and considered realistic opportunities for Australian industry to participate in the Garada system and mission, linking specific tasks to industry capability including niche expertise. Skills development and potential future applicability were also considered in the resulting Preliminary Industrialization Plan.

TK9.5 consolidated previous tasks and developed TK9.4 into a comprehensive Project Industrialization Plan that addresses project phasing, project reviews, project organization and contractual relationships, an indicative schedule and a roadmap. The plan also considers the role of Industry and Government, and how Garada will address objectives enunciated in Australia's Satellite Utilisation Policy and in the Australian Industry Participation Framework.

Key outcomes of WP9 include:

- A comprehensive and structured summary of the space-related capabilities of Australian Industry and the research sector.
- Mapping of capabilities to prospective Australian roles in implementing the Garada system including priming the provision and operation of the ground segment.
- Assessment of the skills that will be developed through the Garada project and the application of those skills to future national and commercial space-related needs.
- An indicative implementation plan that identifies a pathway for achieving significant participation in the Garada mission by Australian Industry and the research sector.
- Consideration of the role that Garada could play in meeting key objectives of Australia's Satellite Utilisation Policy especially enhancing Earth Observation infrastructure.
- Hosting of a national forum that brought principal SAR stakeholders together encompassing SAR system specialists and SAR end users in the Civil and Defence sectors.

In summary WP9 provided an important complement to other Garada work packages by identifying tangible and strategic roles for Australian industry and the research sector in building and operating the Garada system or a comparable Earth Observation mission. This constitutes an especially valuable contribution in the ground segment area noting the emphasis given in Australia's Satellite Utilisation Policy to progress a National Earth Observations from Space Infrastructure Plan (NEOS-IP).

3.10. Ground segment Definition

Garada Work Package 10 (WP10) was the responsibility of BAE Systems Australia. The task was undertaken by John Norrington, Garada Systems Engineer with support from Michael Hopton, Engineering Manager and Ian Tuohy, Space Systems Manager (acting as Garada Project Manager). Supplementary support was provided by other senior BAE Systems staff in connection with engineering and ROM cost elements.

The purpose of WP10 as contracted under the Garada Consortium Agreement was:

To define the SAR constellation ground segment based on the space segment concept and end user requirements. To encompass Telemetry, Tracking and Control (TT&C) functionality and data transmission, processing, archiving and product distribution.

Specific task (TK) deliverables were as follows:

- TK10.1 Operational Concept Document (CONOPS)
- TK10.2 Functional Performance Specification
- TK10.3 Preliminary Ground Segment Architecture
- TK10.4 Ground Segment ROM Cost Estimate
- TK10.5 Ground Segment Definition Report

TK10.1 underpinned WP10 by collating user requirements for the Garada system and distilling an Operational Concept Document (CONOPS) that considers operational scenarios and user needs, the policy/regulatory environment and system interfaces. This guided the definition of a set of system requirements and the derivation of a system architecture for the Garada ground segment.

TK10.2 entailed the generation of a detailed Functional Performance Specification (FPS) for the Garada ground segment based on the operational concept described in TK10.1, and incorporating BAE Systems' extensive expertise in the ground Satellite Communications sector. The FPS adheres to a recognized standard applicable to complex systems and specifies the functional and performance requirements of the five systems comprising the Garada ground segment. System external interfaces and safety and environmental requirements are also addressed.

TK10.3 built upon preceding tasks to derive a Preliminary Ground Segment Architecture capable of meeting Garada data processing and TT&C requirements, particularly the high SAR data rate needed for soil moisture measurements in the Murray-Darling Basin. It was determined that a combination of a new ground station at Mawson in Australian Antarctic Territory and the existing station at Hobart offers good coverage for the Garada mission. Functional models for the ground segment were produced together with an allocation of the functional to physical items. Detailed link budget calculations for the SAR data downlink were performed, together with consideration of mission operations' requirements. Extensive trade-offs of ground station locations, codecs, X, K and Ka band performance, bitrates, availability and EIRP (Effective Isotropic Radiated Power) were performed with recommendations made for the space to ground link.

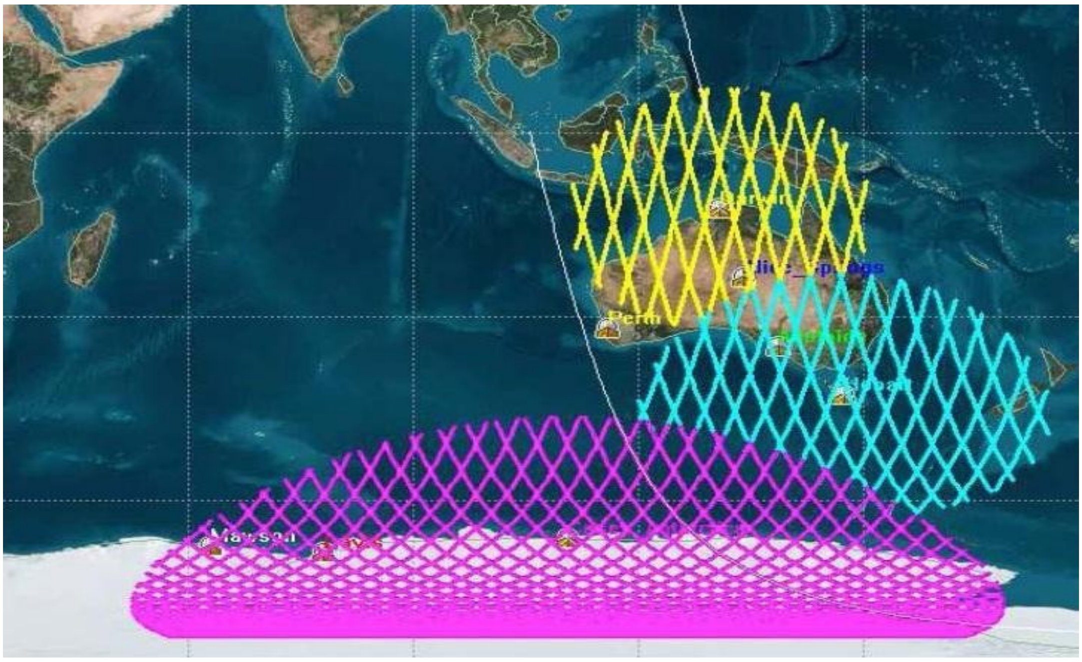


Figure 14: Proposed ground station communication coverage maps for Garada mission

TK10.4 utilized the outcome of TK10.3, supplemented by a detailed Work Breakdown Structure, to determine a Rough Order of Magnitude (ROM) cost for the Garada ground segment. The net ROM cost, based primarily on a validated parametric estimation model used by BAE Systems, is $87 million. This amount is necessarily based on a number of assumptions and caveats that are articulated in TK10.4.

TK10.5 consolidated and updated previous tasks to reflect the final Garada system baseline released by UNSW, resulting in a Ground Segment Definition Report. In addition to describing the Garada ground segment concept, operation, requirements, location, architecture and implementation, the report addresses elements that align with the National Earth Observations from Space Infrastructure Plan (NEOS-IP).

Key outcomes of WP10 include:

- Comprehensive assessment and definition of the Garada ground segment linked to end user needs and aligned with space segment capabilities and requirements.
- Determination of a ROM cost for the ground segment that complements an estimate for the space segment, providing an all-up ROM cost for implementing the Garada system.
- Illustration of the value of establishing an Earth Observation (EO) data reception capability at Mawson or other base in Australian Antarctic Territory.
- Lastly, participation in WP10 has broadened BAE Systems' understanding of the EO sector and has helped to position the company for bidding on future infrastructure opportunities.

In summary WP10, addressed an essential component of the Garada study and provides a foundation for progressing more detailed definition of the ground segment in prospective later phases of the project. It is noted that while focussed on Garada requirements, significant elements of WP10 have broader applicability to other Australian EO ground segment needs.

3.11. Data processing for soil moisture measurements

The User Advisory Group (UAG), which joined the Garada team in September 2012, was responsible for this analysis. The UAG consisted of Professor Jeff Walker of Monash University; Dr Rocco Panciera of Melbourne University; Professor Tony Milne of UNSW and the Cooperative Research Centre for Spatial Information; and Dr Mark Williams of HCG Corporation.

The UAG's task was to investigate the state of the art of radar measurements for soil moisture determination, including (but not limited to) space-based radars. The goal was to establish a theoretical baseline for an algorithm (or algorithms) that would be used to process Garada data.

The use of radar for soil moisture measurement has been under investigation since the 1970s. The first attempts to make these measurements from space occurred in the 1990s, when fully polarized space-based radars were placed in operation. Despite this heritage, the collection of accurate soil moisture measurements from radar data remains challenging. There are three principal reasons for this:

1. The radar signal is influenced by soil roughness in addition to soil moisture.
2. The radar signal is also influenced by scattering from vegetation on or near the ground.
3. For space-based measurements, polarization can be rotated as the signal passes through the (conducting) ionosphere, which can distort the apparent result.

Having multiple polarizations transmitted and received by the SAR sensor can be used to separate out and control for these effects. Therefore, the preferred radar mission design for soil moisture mapping would be a fully polarimetric S-, L-, or P-band system so as to cover the full range of conditions ranging from bare to forested, while the minimum mission would be a dual polarized (HH and VV) or compact polarimetric (providing the current knowledge gaps on compact polarimetry techniques can be filled) L-band system.

Full polarization will also assist with RFI mitigation and Faraday rotation/ionospheric correction. Orbit design can also help. A 6AM overpass time would be expected to minimize the Faraday and ionospheric effects.

An exact orbit repeat with 2-3 day revisit is needed to meet the requirements of most soil moisture applications and retrieval algorithms. A constellation of satellites will be required to achieve this, and thus inter-sensor calibration will be critical for the time-series based retrieval algorithms that are proposed. Use of Gallium Nitride (GaN) technology and SCan On REceive (SCORE) operation with digital beam forming will help limit the number of satellites required to achieve this temporal repeat requirement.

Presuming the minimum mission with a 2-3day exact orbit repeat is adopted, a 50m spatial resolution of the derived soil moisture product would be required to set an Australian radar soil moisture mission apart from the capabilities of other existing and/or near-term missions, such as Sentinel, SAOCOM and TanDEM-L. Moreover, the 50m resolution would be required to address issues in relation to irrigation scheduling and other soil moisture applications, such as environmental watering. If this resolution and/or temporal repeat are not achievable, then the possibility of partnering with one of the proposed missions should be explored.

Absolute accuracy in soil moisture is difficult to achieve, but detection of changes over time is highly feasible. Accordingly, a time-series soil moisture retrieval algorithm is recommended, making use of frequent radar observations to distinguish backscatter changes due to soil moisture dynamics from those due to changes in surface roughness and vegetation, together with decomposition of fully-polarimetric observations to determine dominant scattering mechanisms within each cell.

Attention to the retrieval algorithms, related ancillary information and calibration methodologies will be required before committing to a final system design, particularly if a compact polarimetric mode is to be adopted. This would require dedicated pre-launch airborne field campaigns that closely mimic the specifications of the proposed mission design. Such campaigns are currently being conducted by Professor Walker in support of the upcoming SMAP mission. Careful attention to post-launch algorithm validation and final algorithm selection should also be included as a fundamental component of any radar soil moisture mission for Australia.

3.12. Systems engineering

The discipline of systems engineering is an integral part of the best practices of the aerospace industry. It is critical to ensuring that the design, manufacturing and testing of a spacecraft will be compliant with the customer's requirements for its performance, and that it will perform satisfactorily in the space environment.

Although no systems engineering activities were proposed initially, it was felt that adding a requirements baselining process would be highly valuable for the Garada effort, as it would unify the efforts of the ten technical work packages. The requirements process was managed by Dr. Gordon Roesler of ACSER, assisted by undergraduate UNSW student Foh Fan (Isaac) Yong. Major assistance with requirements definition was received from BAE Systems and EADS Astrium team members. The requirements development process was similar to that used in the US by NASA's Jet Propulsion Laboratory.

In this process, requirements are hierarchical. The top level requirements, Level 1, are the expectations of the eventual user of the spacecraft, or the "customer." Since the customer for Garada is hypothetical at this point, several steps were taken to baseline a reasonable set of Level 1 requirements:

- Interviews of potential end users;
- Maintaining consistency with the ASRP guidelines and the proposed research;
- Establishing the User Advisory Group, whose knowledge of space SAR systems produced additional customer-like input;
- Incorporation of Level 1 requirements that are typical for other space systems.

The Level 1 requirements include the Requirements Summary as prepared under Work Package 1, but have been expanded to include requirements on the entire system rather than the sensor performance alone.

Figure 15 shows the requirements hierarchy established for Garada.

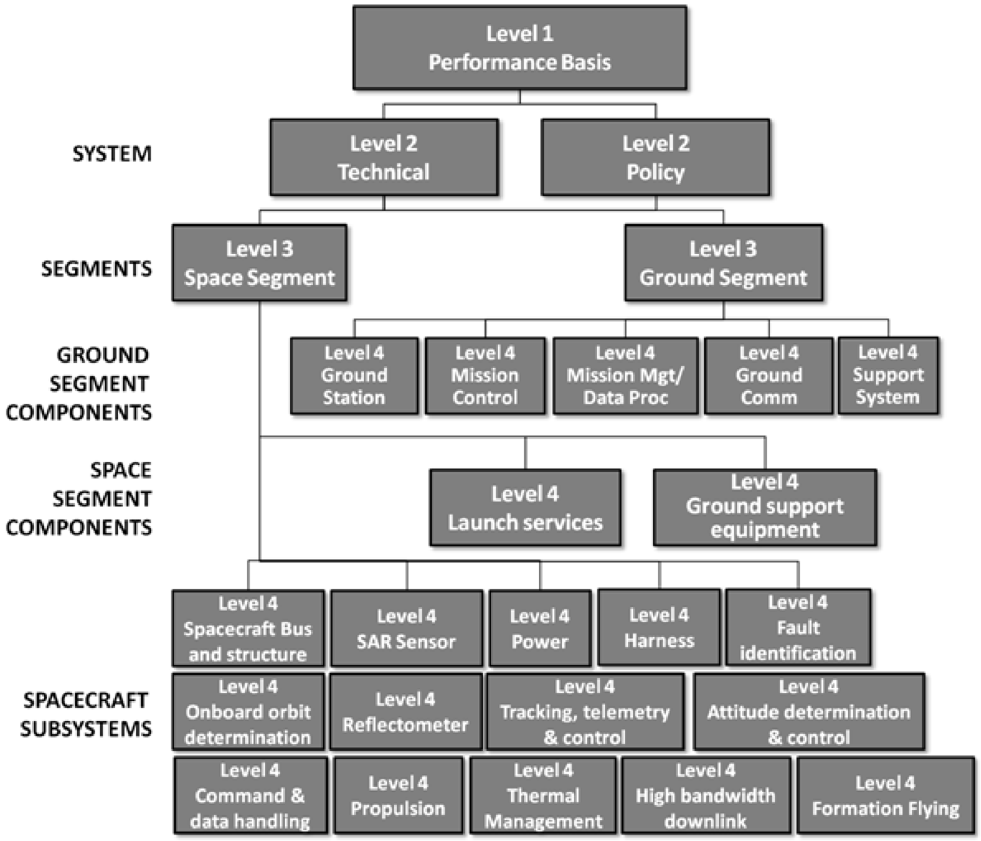


Figure 15: The requirements hierarchy established for Garada

Below the Level 1 performance expectations, the requirements translate the customer performance requirements into top-level technical functions. To generate these Level 2 requirements requires a knowledge of the engineering alternatives that are available to meet performance, as well as a knowledge of the performance of past systems and their limitations. Derivation of Level 2 Technical from Level 1 requirements requires engineering interpretations of the Level 1 performance expectations. Engineering experience and knowledge are used to assign technical approaches for achieving that performance, i.e., the Level 2 Technical requirements.

Co-equal with the Level 2 technical requirements are the numerous legal, regulatory, and policy requirements that any engineered system, such as a spacecraft, must meet. Spacecraft operations are governed by a number of international treaties and conventions. In addition, spacecraft must comply with some aspects of Australian law. There are also policies of the Australian Government that must be incorporated into the requirements. All of these, and some others, are at Level 2 because they affect the entire system, but are not at the level of customer performance requirements. Because they originate from laws, treaties, etc. rather than from customer performance expectations, Level 2 Policy requirements do not necessarily flow down from Level 1.

Lest there be any doubt, Level 2 Policy requirements can have significant impacts on the technical design of the system. One example is the requirement for a deorbit capability if the orbit lifetime exceeds 25 years, embodied in a United Nations convention. This impacts at least the propulsion system of the spacecraft. Another example is the frequency allocation for radar measurements provided by the International Telecommunications Union. The SAR System Final Specification prepared by EADS Astrium (deliverable TK3.3) contains an analysis of how this allocation affects radar resolution.

Below Level 2, the system is broken into major subsystems. For Garada, there are two major subsystems, the space segment and the ground segment. The space segment includes:

- The spacecraft delivered to orbit, with sensors and all internal subsystems;
- Mechanical and electrical ground support equipment; and
- Launch activities, which include the launch vehicle, spacecraft/launch vehicle integration, launch procedures, and range activities.
- The ground segment includes:
    - A Ground Station System (GSS) that undertakes the reception of payload and telemetry data and the transmission of command data to the Garada Spacecraft;
    - A Mission Control System (MCS) that undertakes the monitoring and control of the spacecraft and payloads, operations planning and scheduling, and GSS monitoring and control;
    - A Mission Management and Data Processing System (MMDPS) that undertakes the calibration and processing of the SAR and GNSS payloads, interpretation of imagery, receiving of customer requests and distribution of processed products to customers. This also includes any requirements on the processing algorithms and systems associated with determination of soil moisture levels from radar data;
    - A Communications System (CS) that handles all voice and data communications between the systems and with the outside world; and
    - A Support System (SS) that provides hardware and software maintenance and upgrades to the Ground Segment.

Because all data processing in Garada is intended to be performed on the ground after receipt of data, the ground segment requirements include the data processing requirements established by the User Advisory Group.

Annex 11 contains the detailed requirements established for Garada through level 3 (for the Ground Segment) and level 4 (for the Space Segment). Over 1,000 requirements have been established. These requirements should be regarded as preliminary, for the following reasons:

1. No requirements validation process has been undertaken. Requirements validation requires interaction between the systems engineer, the design team, and the customer. The current Garada design team consists of experts in some subsystems but not in all, and no actual customer exists. Therefore the requirements could not be validated.

2. Level 1 requirements are likely to change in a follow-on program. Because no actual customer exists, the Garada requirements effort acted in the customer's stead. Were a follow-on program to begin, an actual customer would exist. A rigorous process of interaction with the customer to validate or modify the Level 1 requirements must be undertaken at that time.

Were a SAR spacecraft program to commence in the out-years, requirements definition would be one of the first activities to undertake. In a typical spacecraft program, higher level requirements are developed in the first 1-3 months, and reviewed with the customer at the System Requirements Review. But in no sense are the requirements "complete" or "fixed" at that point. Requirements for subsystem and component performance begin to be specified then. Trade studies, risk reduction activities, and other analyses proceed throughout the preliminary design phase, and may have significant impacts on the requirements baseline. Requirements evolve iteratively, as improved understanding of performance limitations ramifies to the various parts of the system. Approval of the system requirements baseline is typically an exit criterion of the Preliminary Design Review. Changes to the requirements baseline during the detailed design phase are uncommon but can be accepted with the approval of design leads, the program manager, and the system engineer.

4. OPERATIONAL SCENARIO: A DAY IN THE LIFE OF GARADA

The Garada team, through their design studies, analyses and technology development projects, has established a highly credible system concept. Because there are so many aspects of Garada that affect its performance, it is perhaps challenging to see how they work together. This section uses a narrative approach to illustrate how the entire Garada system—which includes both the space segment and ground segment—collects, transmits, analyses and distributes the valuable soil moisture data, and how users might employ the data products.

When they were launched, the two Garada spacecraft were placed into a special orbit, which passes nearly over the Earth's north and south poles.

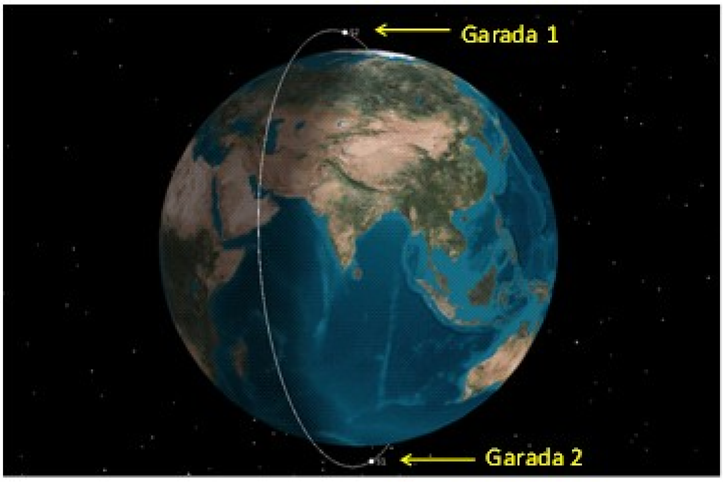


Figure 16: Geometry of Garada 1 and Garada 2

This orbit has three important properties [as explained in TK 7.3]:

1. It is directly over the "terminator," the line between daylight and night time. Thus when the spacecraft is rising, it will be dawn on the Earth below. This is the best time of day to make soil moisture measurements.

2. It retains its orientation with respect to the sun, so it remains over the terminator even as the seasons change. Thus, none of the spacecraft's propellant needs to be burned to ensure that measurements are always made at dawn.

3. It is a ground-track repeating orbit. Specifically, each spacecraft will pass over a given point on the Earth's surface exactly every six days. With two spacecraft, each point on the Earth is overflown by one or the other spacecraft every three days. The SAR radar swath from the Garada sensor is wide enough that this will produce gapless coverage.

Figure 17: Garada complete coverage over the MDB after 6 days

Every day, the Garada spacecraft will circle the Earth almost 15 times. Only two to three of those passes go over Australia. This means that these are the only opportunities for Garada to pass data to the ground station, which would probably be located at one of the three commonly used sites in Australia: Hobart, Alice Springs, or Darwin. This graphic shows the portions of the tracks in contact with Darwin and Hobart over 6 days. A station in Antarctica is also illustrated, but such a station does not currently exist, and there is no current means for returning the data to Australia.

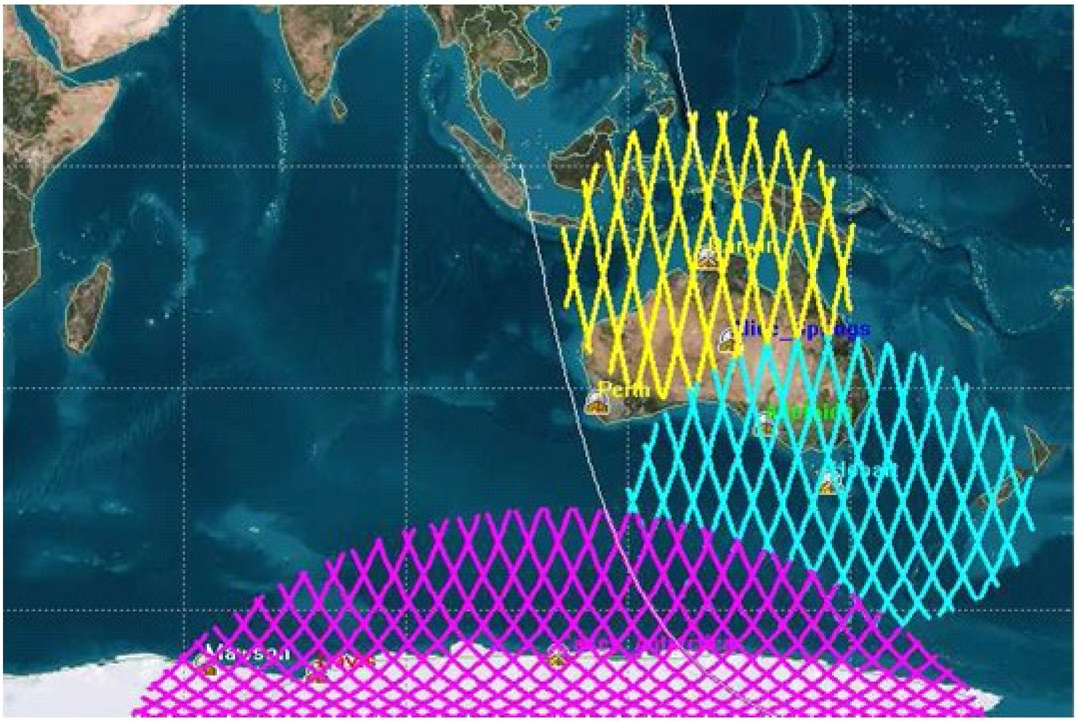


Figure 18: Potential ground stations for communication to the satellites for the Garada mission

During these ground station overpasses, Garada will be operating both of its communications systems: the Tracking, Telemetry and Control (TT&C) subsystem, and the High Bandwidth Downlink (HBDL) subsystem. The TT&C system helps ground operators refine the position of the satellites; it passes data down on the health and status of satellite systems; and it passes commands from the operators up to the satellite. One of the most important commands will be which areas of the Earth to collect soil moisture data on during the coming 24 hours before the next pass.

Let us begin the "Garada day" a couple of orbits before an Australian overpass. During this time, Garada's batteries are being charged by the solar panels. The spacecraft may need to "roll" around its longest axis (which is aligned with the direction of travel) depending on whether the imaging pass will be left-looking or right-looking.

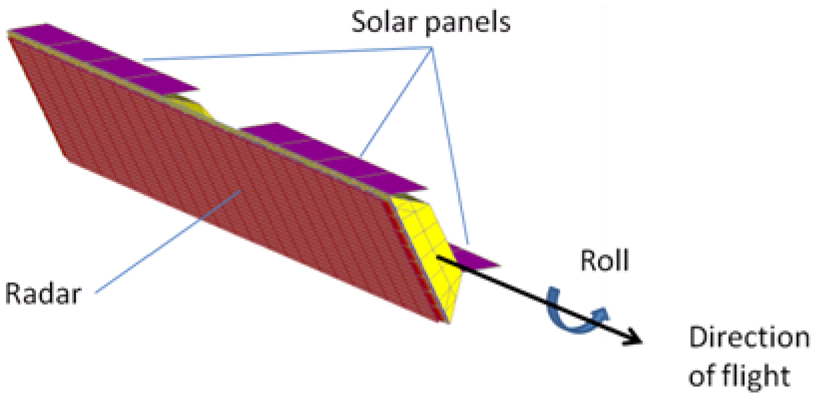


Figure 19: Demonstration of the Garada Satellite rolling on its axis to image both left looking and right looking

It will probably be necessary to operate heaters within the radar prior to imaging, to ensure that the electronics are warm enough to operate properly.

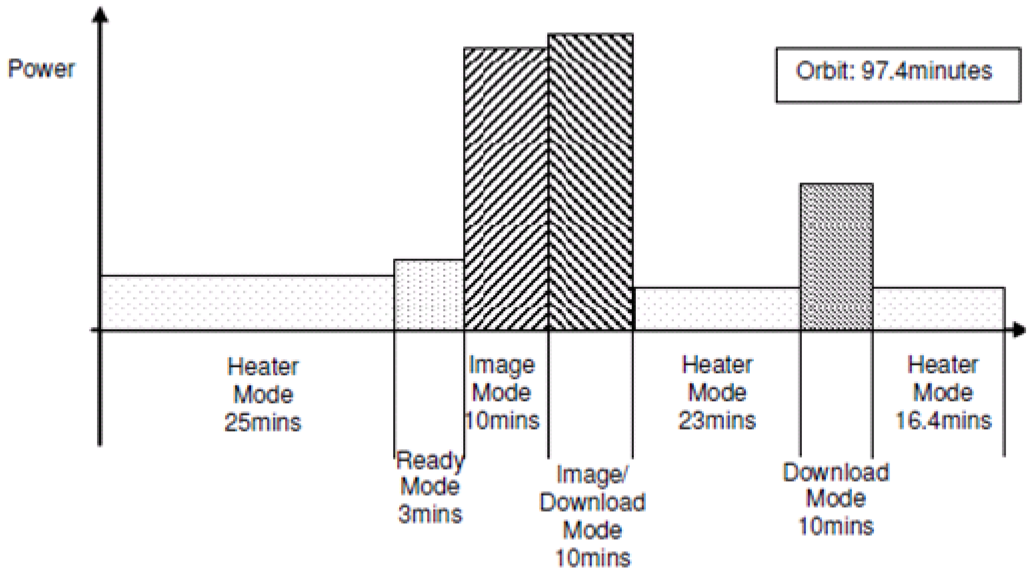


Figure 20: Diagrammatic Representation of Imaging/Wave Timeline for Right-Sided Looking

The Command and Data Handling (C&DH) subsystem has already received the imaging requirements via TT&C the previous day. When the satellite has arrived over the collection area, radar operation will begin and polarized radar returns will be collected—the essential data from which soil moisture data will be derived on the ground.

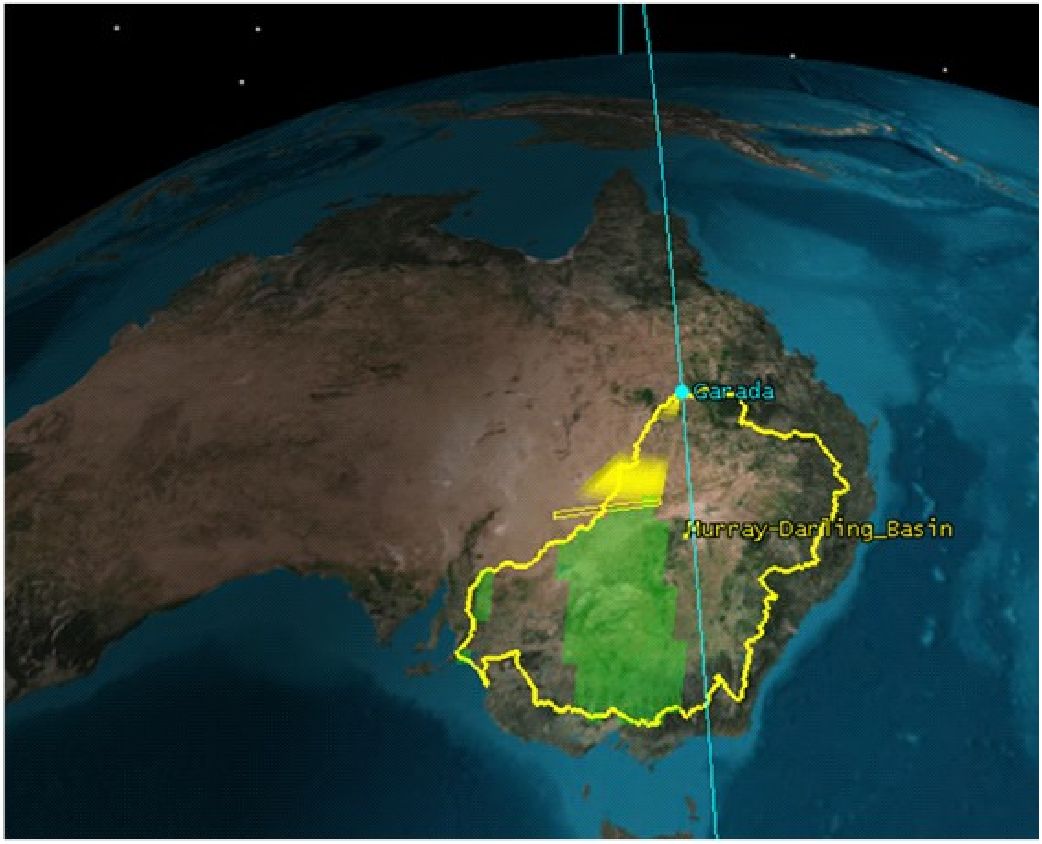


Figure 21: Murray Darling Basin Region imaged every 3 days by Garada satellites

A complete south-to-north swath across Australia can be as much as 3000 km long. In high resolution mode, about 50 GBytes of data (8-bit bytes) would be stored in the memory onboard the satellite [see TK 10.3, Annex D—Link Budget]. Possibly on the same pass, or on the next orbit, the HBDL subsystem would be used to downlink this data. A downlink rate of 700 Mbps or more for the HBDL is envisioned, so the stored data would be downlinked in about 9 minutes or less. Lower resolution is probably sufficient for many parts of the swath, and can be programmed in order to ensure that all data can be downlinked in a single pass.

The National Broadband Network would pass the received data from the Ground Station to the Mission Management and Data Processing Subsystem (MMDPS) of the Garada ground segment [see TK 10.3]. The MMDPS contains the software to generate soil moisture maps and other data products that have been formatted in accordance with user requirements.

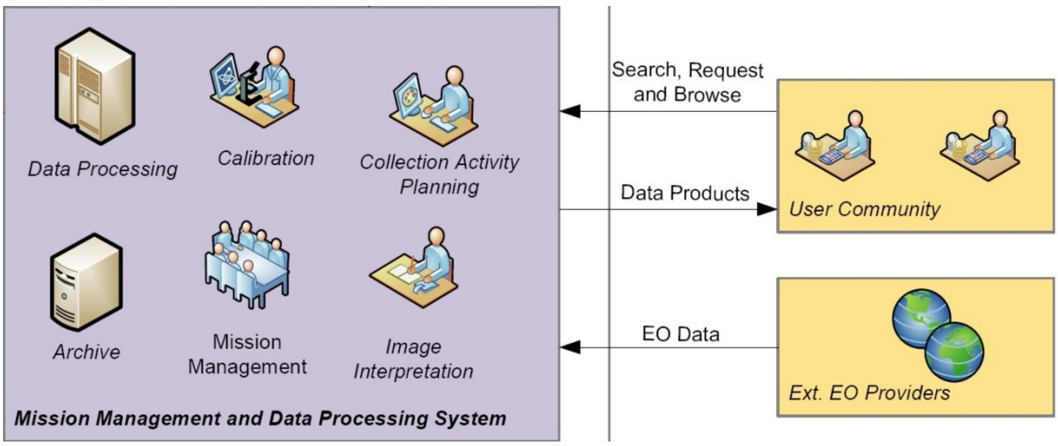


Figure 22: Mission Management and Data Processing Subsystem (MMDPS) of the Garada ground segment

Some of the soil moisture algorithms developed by the scientific community would be used by the MMDPS to produce standard products. Other algorithms could be run outside the system by other members of the user community.

While the satellite is in communication with the Ground Station, controllers will pass commands up to it. The Mission Control Subsystem (MCS) is the portion of the ground segment involved in satellite control.

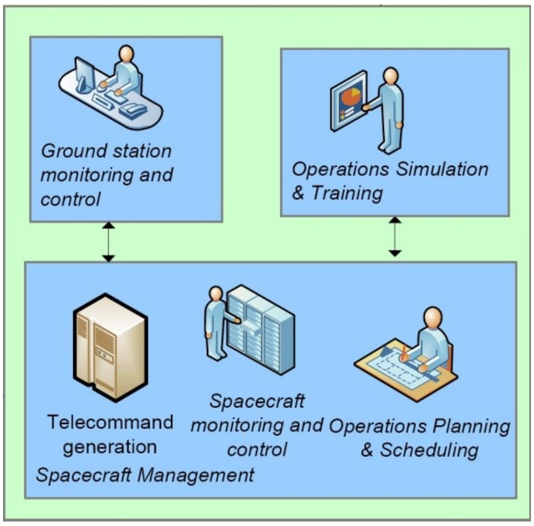


Figure 23: Mission Control Subsystem for the Garada System

Garada has enough power, memory, and downlink capacity to collect soil moisture measurements on other orbits during its day. Other nations will request such collections, and the areas to be mapped will be uploaded to the satellite during the same ground station overpass. This additional data volume for could potentially require arrangements for use of an additional ground site, probably outside of Australia. One potential site is Svalbard, north of Scandinavia, which Garada will overfly on almost every orbit. This data would be passed to the MMDPS via the Internet.

The MMDPS also handles requests for unique Garada services. Primarily, these would come from outside Australia, as the Australian continent is already being surveyed at the maximum rate. The MCS will plan and schedule the non-standard international operations. For example, a request could come from the Famine Early Warning System Network (http://www.fews.net/Pages/default.aspx) : "We are concerned about the moisture levels in the Sahel region of Africa." MMDPS would schedule data collection, coordinating data downlink with Australian or other ground stations, and ensuring that no interruption would occur to the Australian soil moisture product.

The product to be delivered to users would be tailored to their specific needs. A soil moisture map produced by the MMDPS today provided this image from the Murrumbidgee region:

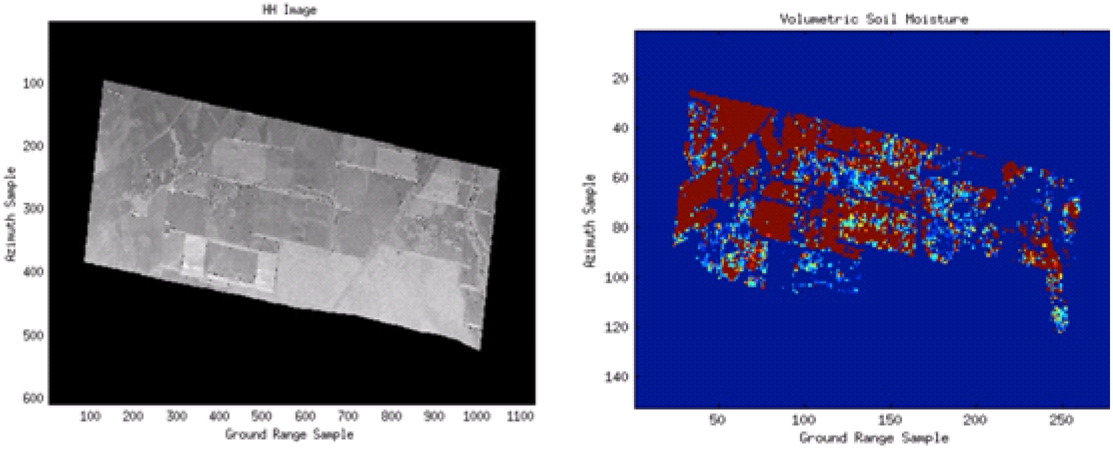


Figure 24: SAR image from the PLIS aircraft, left, processed for soil moisture content, right - (actual imagery source: airborne measurements by Monash University; soil moisture data processing by UNSW)

A farmer, grazier and natural resource manager look at their specific plots of interest and notice changes to the moisture since the last map 6 days ago. The farmer notices that soil moisture levels are adequate, and scheduled irrigation can be deferred. The grazier observes that soil moisture in one paddock has become critically low, and cattle are moved to an adjacent paddock to prevent overgrazing. The natural resource manager sees that a scheduled environmental watering is unnecessary, and in fact would cause over watering; the environmental watering is postponed.

The entire feed of Australian soil moisture measurements is also sent directly to the Australian Water Availability Project (AWAP) database, maintained by the CSIRO.

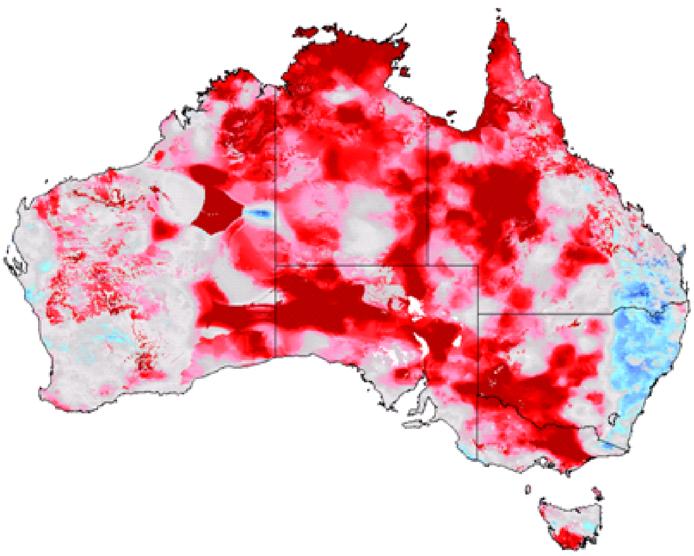


Figure 25 : Australian wide soil moiture map. Image - Australian Water Availability Project, CSIRO

Formerly based primarily on models and infrequent observations, the AWAP products are now generated using the timely, gapless soil moisture measurements from Garada.

5. OTHER ACHIEVEMENTS OF THE GARADA PROGRAM

The investment by the Space Policy Unit in the "Garada SAR Formation Flying" project was an incredibly significant catalyst for activity at UNSW. The benefits are as follows.

1) Garada attracted researchers

The Garada project directly led to the recruitment of five UNSW PhD students. Joseph Gauthier is studying how to synchronise satellites using GPS receivers (usually GPS synchronisation is restricted to stationary receivers). Vaidhya Mookiah is investigating quadrature bandpass sampling as a way of implementing cognitive receiver design for multi-GNSS (like the Garada receiver) Vinh Tran is investigating different GNSS receiver architectures that can be implemented on the Garada FPGA-based GNSS receiver. Scott O'Brien's PhD will analyse the data from the Garada reflectometry work package to see how best it can be used for soil moisture analysis. Nam Khanh Pham (Computer Science) is investigating the effects of single-event upsets on the FPGAs used in Garada GNSS receivers.

Three China Scholarship Council (CSC) PhD students joined the Garada team to study formation flying: Yuanyuan Zhou (single frequency relative positioning), Rui Li (orbit simulation/ ionosphere effects), and Yang Yang CSC PhD (orbit modelling/ relative positioning).

Two CSC postdocs also participated in the project: Bo Yang CSC (antenna array design), and Tao Wang (location technologies and SAR signals).

Three UNSW postdocs did projects inspired by Garada under the Faculty of Engineering Faculty Research Grant scheme: Fariborz Sobhanmanesh (SAR data compression/ Correlator), Nima Alam (GPS reflectometry), Joon Wayn Cheong FRG (snap-shot GPS).

Undergraduate students were also attracted to the project and made significant contributions. Thomas Cooney's (Electrical) thesis on chip design not only impressed the industrial partner Astrium, but also won the VSSEC/ NASA Australian Space Prize 2012. James Laughlin (Computing) designed a processor specifically to process SAR data. Haifa Ben Aouicha from École Nationale de l'Aviation Civile (ENAC) in France spent several months as an intern studying non-GPS synchronisation of satellites in formation. Three UNSW students spent summer internships with Garada and two continued to work on the project after that: Scott Dorrington (Electrical- satellite/ground communications), George Constantinos (Mechanical - deployable antennas, and then the satellite structural analysis), and Foh Fan (Isaac) Yong (Aerospace - Garada requirements documentation).

2) Garada was the catalyst for significant networking

Significant networking resulted from the way the Garada project was designed from the beginning, and from the way it was implemented. Three times over its two and a half year life, the project brought together the team partners (UNSW, Delft University of Technology, Curtin University, Astrium, BAE Systems, General Dynamics) with the advisory panel (from DSTO, ANU, US Air Force Laboratory, DLR – the German space agency, and Surrey Satellite Technology Ltd) to discuss the specifics of the project.

In the course of the project, a specialist User Advisory Group from Monash University, University of Melbourne, and CTG Consulting were consulted on specifics regarding the use of the Garada satellite. There were also consultations regarding user requirements with the Federal Department of Climate Change, the Bureau of Meteorology, CRC for Spatial Information, NSW State Emergency Service, Queensland Fire and Rescue Service, Emergency Management Queensland, Australian Maritime Safety Authority, NSW Office of Environment and Heritage, Victoria Department of Sustainability and Environment, MWH Australia and Murray Darling Basin Authority.

Similarly, in order to address technical questions arising from the project, the team consulted BAE Systems (the antenna group, in Sydney), Sillana, Electro-optic Systems, Aerospace Concepts, Loral, Boeing and MacDonald Dettwiler.

3) Garada created "line of sight" business

The GPS receiver proposed in the original grant application attracted the interest of DSTO, who invested $270,000 and with the funding of the combined projects, the "Biarri" version (i.e. version 3.2) of the UNSW "Namuru" GPS receiver was produced. This was a far more professional piece of work than was ever envisaged in the original proposal and has attracted interest from NASA, AFRL and others. UNSW will fly this receiver on its QB50 satellite to be launched in 2015. That receiver seems to have created a life and market of its own. The main, more sophisticated receiver developed under Garada, the version 3.3 Namuru, will be the only receiver of its type (dual system, L1/L5) designed for space. It should also attract a market well after the end of the project.

4) Garada was the catalyst for the establishment of the Australian Centre for Space Engineering Research (ACSER)

This is probably the project's most significant legacy. In addition to the matching funding delivered by UNSW to the Garada project, and all of the in-kind effort in the previous point, UNSW also invested in ACSER to the tune of $600,000 over three years. That investment followed directly from the award of the Garada grant. For some years, UNSW had been aware that it had a large group of disparate researchers (over 100, with over 60 in engineering) who were in some way active in research that involved "space". Garada triggered the formation of a centre to mobilise those researchers into a group. This has been remarkably successful.

ACSER has funded several small "demonstrator" projects at UNSW. In 2011, the projects were prioritised for their ability to form collaborations between the Canberra and Kensington campuses: "Feasibility Study of an Air Drop Microgravity Capability", "3D Ranging and Mapping for Satellite Remote Sensing", "Fire Detection and Monitoring" "Spacecraft Experimental Bus". In 2012, they were prioritised for their ability to be implemented on cubesats: "Parameters for an experimental payload for tropospheric CO2 measurement using a space-born lidar platform", "Formation flying technology using UAV platforms", "Simulation of a high performance Attitude Control System for a 6U CubeSat". In 2013, that funding went to the QB50 project.

ACSER has been able to leverage money at School, Faculty and University level to produce a cubesat to be launched as part of the QB50 constellation. The satellite will use unique fast prototyping (3D printing) development and carry three UNSW payloads: the Garada V3.2 GPS receiver, a processor board running NICTA's Sel4 kernel, and an FPGA radiation experiment.

ACSER's main area of success has been outreach. Workshops that engage the academic, government, and industry communities have been: GNSS Vulnerability (March 2011), Synthetic Aperture Radar (Dec 2011), Disaster Management (Dec 2011), 6U Cubesats (May 2012), GNSS Remote Sensing (Dec 2012), Off-earth mining (Feb 2013). By running workshops internal to UNSW, ACSER aims to break down "silos" and get Schools and Faculties to work together. The topics have been: Demonstrator payloads (June 2011, March 2012), Swarm Satellites (July 2011), System Engineering, (August 2011) and UAVs (June 2012).

The last public workshop mentioned above, the Off-Earth Mining Forum, deserves special mention. This event attracted international attention with two live interviews on the BBC, interviews syndicated across US radio, coverage on four local television networks, mentions in the main newspapers in India and New Zealand, articles by two international press bureaus, as well as great coverage in the local press and radio. The keynote speaker, Rene Fradet, Deputy Director of NASA JPL, gave a public lecture on the Mars "Curiosity" laboratory to almost 1000 people in UNSW's Clancy Auditorium, for which tickets had to be allocated, as demand could have filled the venue twice. The event has led to a proposal to the Australian Research Council for a Centre of Excellence in Interplanetary Engineering, an invitation from the AIAA for Professor Dempster to join its Space Resources Technical Committee, and an initiative for all 1400 first year UNSW engineering undergraduates to do a design project in off-earth mining.

ACSER has attracted significant student interest, independent of the Garada project. For the QB50 project: two NICTA PhDs and a Computer Science undergraduate are working on the NICTA payload; one CSC visitor and a Masters student are working on attitude control; one undergraduate is working on bus integration; one undergraduate is modelling orbits; two PhD students are project managing. On off-earth mining, three undergraduates are working on mine methods (rock breaking etc), one is working on on-orbit robotic assembly, and one on refuelling orbits.

In addition to the events mentioned above, ACSER has raised the profile of UNSW with regards to space. Professor Dempster was invited to join the technical committee of the Spacecraft Formation Flying Missions and Technologies and Australian Space Science conferences, twice invited to brief the Trusted Information Sharing Network, invited to address the Australian Space Development Conference, the Australian Youth Aerospace Association, the local chapter of the American Institute of Aeronautics and Astronautics, the Progress in Radar Research conference, and to give an invited lecture on ACSER by the IEEE London chapter.

In summary, the Garada project has delivered a mighty boost to space activity at UNSW, and its new network of space stakeholders. The hope is that all this good work is not undone by the failure to follow-up the ASRP funding with any new initiative.

6. MOVING FORWARD: TECHNOLOGY MATURITY, OPPORTUNITIES AND RISK REDUCTION

The Garada project was a conceptual design effort (Phase 0). At that level, it demonstrated convincingly the feasibility of using a synthetic aperture radar spacecraft to provide timely, gapless, high resolution soil moisture data across the Australian continent. For maximum credibility, the design was based primarily on approaches that have proven successful in past space systems. However, in order to achieve the higher level of performance promised by the Garada approach, some novel components and approaches were of necessity incorporated in the design.

Three top-level actors jointly perform the acquisition of any complex system. These actors go by various names, but we will label them the requirements agency, the procurement agency and the delivery agency. (None of these actors are identified for Garada.) Here are simplified descriptions of the functions of these actors:

- The requirements agency specifies what mission(s) is/are to be accomplished, at what level of performance, by what operational date.
- The procurement agency establishes the program budget and top-level schedule in order to meet the needs of the requirements agency.
- The delivery agency is at the receiving end of both the requirements and procurement agencies. That is, the delivery agency must design, manufacture, test and operate the system to the specifications of the requirements agency (technical scope) while meeting the budget and schedule of the procurement agency.

To deliver an acceptable system when some subsystems and components are not fully ready for integration, that is, are technically immature, the delivery agency will conduct a risk reduction program in parallel with the design/manufacture/test program. Some risk reduction activities must take place before design even begins—these develop key subsystems and components without which the program could not achieve its technical goals. Other risk reduction activities will be conducted in parallel with design and manufacture. These activities enhance the technical maturity of preferred subsystems and components, but leave the delivery agency with alternatives should the required improvements not succeed.

Notice that the risk reduction activities must be accomplished on schedule and within budget. Any attempt by the delivery manager to request relief for technology failures, either from the requirements agency (relaxed mission goals) or the procurement agency (increased budget or extended timeline), is not guaranteed to succeed. Therefore, including immature technologies in a design imposes a risk to the delivery program. The delivery manager must balance the need for each such item to achieve the required performance with the range of possible outcomes (failure, success, partial success) of its risk reduction activities.

The Garada conceptual design phase (Phase 0) represented an opportunity to identify the technology risks that a subsequent acquisition program might accept. Therefore, we made an assessment of technology risk areas of the program, including identifying subsystems and components that are not fully qualified, and preparing a risk reduction plan for follow-on activities as described above.

Some immature but potentially high-payoff components were identified during the Garada studies. This could provide significant performance improvement. Table 5 gives the most important examples and the programmatic risk they entail.

Table 5: Key Identified subsystems requiring risk reduction activities

Subsystem	Novel component	Opportunity	Risk description
SAR Sensor	Antenna element	Full quad polarization can be measured	New design, RF performance not measured, untested in space environment
Spacecraft bus	Bus structural design	Support for large antenna in launch configuration, rigidity in deployed configuration	Heritage from previous design but not flown, mechanical performance modelled but not measured
TT&C	1,500 Mbps downlink	Ability to extend dwell time, support new applications and multiple users	No current provider of a system with this capability, development budget unknown
TT&C	Antarctic ground station	More opportunities for downlink during 89-orbit cycle	Cost uncertainty, severe limitations on data retrieval
TT&C	GPS receiver	Autonomous orbit determination, GPS reflectometry	Heritage from previous design but not flown, flight qualification required
Various	Secondary payloads	Provide the benefit of the platform and its subsystems to other payloads	Unpredictable influences on mass, power, and electromagnetic compatibility

The following is our assessment of the impact of each of these technologies on a program to procure the SAR soil moisture capability:

1. Antenna elements: low risk, high payoff. Design, test and qualify antenna elements in parallel with spacecraft development.

2. Spacecraft bus: medium to high risk, medium payoff. The bus design pursued in Garada is ideal for the SAR sensor (launch tolerance, planarity in operation) but other approaches have successfully been taken to fly SAR sensors. The Garada bus design does not have flight

heritage, and would require a rigorous testing program prior to committing to this approach. A follow-on program should seek multiple inputs on the bus design.

3. 1,500 Mbps downlink: high risk, low payoff. This high speed downlink would double the dwell time (data collection time) of the sensor. Studies have indicated that the sensor is neither power-limited nor thermal-limited, and therefore the higher dwell time would be achievable if the data could be downlinked. However, no modem to support such a high bandwidth downlink currently exists. It is unknown whether a manufacturer would support its development. A risk-free alternative exists to achieve the same dwell time, namely, to use an existing 800-Mbps system and downlink the data multiple times per orbit, e.g. downlink some of the data to an Australian ground site and some to Svalbard.

4. Antarctic ground station: high risk, low payoff. While such a site is attractive from the high frequency of overflight, there is no established means of retrieving the data from Antarctica in a responsive and affordable manner. As noted above, the use of multiple ground stations at other locations would provide a risk-free alternative.

5. GPS receiver: low risk, medium payoff. Having a reprogrammable onboard orbit determination system would increase the system utility. The receiver could be fully qualified in parallel with a spacecraft procurement program. Other receivers could be substituted at any time, the only performance degradation being the loss of the programmable feature.

6. Secondary payloads: high risk, unknown payoff. Because access to space is so rare and expensive, spacecraft procurement programs are constantly bombarded with requests to host secondary payloads. The risks posed by these include infringing on mass margins, electromagnetic interference, and missed delivery. One secondary payload that would pose minimum risk would be the GNSS reflectometry payload, which requires no more than a GNSS receiver, multiple antennas, and connections to the onboard processor.

Key to a decision on building a Garada system (or one having the equivalent soil moisture measurement capability) is the projected system cost. The program estimated the costs of various phases of an acquisition program. Our life cycle estimate for the Garada capability can be seen in Table 6. We estimate that the Garada mission is likely to cost around $800M for two spacecraft operating for an 8 year lifetime.

Table 6 : Projected Garada Mission Costs (not including: risk reduction activity, learning curve improvements for satellite 2, launch insurance)

Description		Estimated Cost
Satellite 1 (inc $80M design)		$240M[1]
Satellite 2		$160M
Launch @ $54M[2]	2 launches	$108M
Ground segment[3]		$87M
Operations @ $25M/ year[4]	8 year life	$200M
Total		**$795M**

While an $800M price tag seems very large, it is incurred over many years. With design, manufacture, launch and operations, the total program length would be 14 years. Typical aerospace program spending curves were used to predict a spending profile over the life of the program. The maximum spend in any year of the program would be $120M, and that occurs in only two years, as shown in Figure 26.

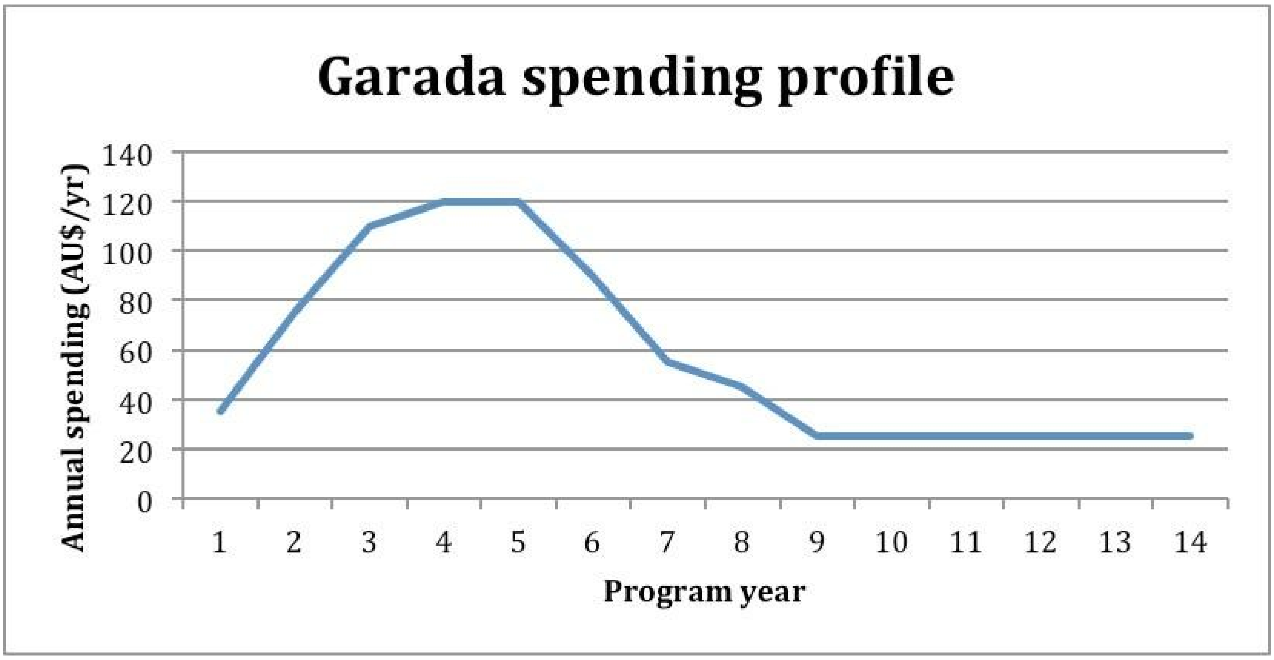


Figure 26: Garada spending profile (launch occurs in years 7 and 8)

[1] Because Garada is based on Astrium's TerraSAR-L, which was developed to phase B, the relatively good TerraSAR-L estimate was scaled for the larger Garada platform
[2] Assumes launch using Space-X Falcon 9, currently priced at $54M (2012) http://www.spacex.com/falcon9.php

[3] Assumes ground segment is 1/3 of satellite price. No extra ground segment required for second satellite as they will never both be visible at once.
[4] Consistent with operations costs in [1]

The soil moisture data obtained by Garada can be used for many valuable applications. We examine just a few to show how readily this investment could pay off. What follows are three easily measured and quantified arguments, *any of which* can be used to show return on investment.

<u>Payoff by improvements to non-irrigated agriculture.</u> Soil moisture is usually monitored using terrestrial methods in irrigated areas. So, for agriculture, Garada is likely to be most useful in non-irrigated areas. The Australian Bureau of Statistics [9] states Australia's Gross Value for Agricultural Production for 2009/10 was $39.7B[5], with $11.5B of that being from irrigated agriculture. In the Murray-Darling Basin (MDB), production was $14.4B with $4.4B from irrigation. In other words, Australia as a whole has $28.3B worth of agricultural production from non-irrigated areas, with the MDB making up $10.0B of that. So, the Garada mission could pay for itself *using this criterion alo*ne, if it was able to improve the efficiency of Australian agriculture by 0.35%, or if only the MDB is considered, 1.0%. Examples of how this could be done include the techniques listed above, using the data to adjust timing of crop planting and livestock movements.

<u>Payoff by improvements to irrigated agriculture infrastructure.</u> Turning to irrigated agriculture, the infrastructure used to support irrigation included up to 2000 soil moisture sensors being installed in 2008/9 (unfortunately the ABS statistics are not supplied for soil moisture sensors in more recent years) and a further 3000 intended for the following year[6]. In 2008/9, $300M was spent on irrigation equipment, giving a total equipment and infrastructure value of $8.5B, with $5.0B in the MDB[7]. So, if the provision of Garada data could reduce irrigation infrastructure cost by 7%, Garada would pay for itself *using this criterion alone*. An example of how this could be done is simply if some irrigators are able not to instrument their farms by relying on satellite data.

<u>Payoff by improved targeting of environmental flows.</u> It is similarly possible to examine how environmental water could be more efficiently used. Agriculture generates $4M per GL of water consumed [10]. In *The Basin Plan* [11], there is a requirement to reduce water used for irrigation in the MDB by 2750GL per year, which corresponds to a sacrifice of $11B in agricultural production. If that plan was more nuanced, it could respond to real data measurements on the ground made by Garada. If those measurements allowed the environmental flows to maintain the required environmental quality measures, yet use just 1% less water, Garada would pay for itself *using this criterion alone*.

All of these potential payoff methods are reasonable, and similar arguments can be made for soil moisture producing more efficient gathering of water, better response to disaster, health benefits from mitigating dust storms and so on. As we also mentioned, there are many other applications to which an L-band SAR can be put, many of which are also economically valuable.

[5] The National Farmers Federation claims Australia's agricultural output for 2009/10 was $48.7B [4], so our number is more conservative. Similarly, the ABS gives the figure of $46.0B for 2010/11 [5] but they didn't have irrigated data for that year.
[6] [3], Tables 4.5 and 4.7
[7] [3], p35

7. CONCLUSIONS

The Garada program resulted in the following major accomplishments, which can flow directly to a system procurement program within Australia:

1. User requirements were collected for multiple potential applications for the SAR satellite. The application that was most compatible with the system concept, and that would have the greatest value to Australia overall, was the soil moisture measurement mission. Multiple industries, environmental management agencies, and government offices expressed their support of this application. Detailed user needs were established. We believe that this capability is so important to Australia, and indeed the global water picture, that we have prepared Volume II of this report to provide details of this analysis.

2. Based on these user requirements, a highly feasible system design, including both spacecraft and ground segment, was developed for the soil moisture application. The performance of this space system would exceed any current or planned radar satellite in the same frequency band, and would provide soil moisture maps of unprecedented data quality and timeliness.

3. An industrialisation plan for procuring the spacecraft, including the participation of multiple Australian suppliers, was developed.

4. Three prototype GNSS space-capable receivers were developed and tested, and in one case, integrated into a space platform. These receivers will have wide applicability to international space programs, and represent a significant Australian space product.

5. The novel technique of GNSS reflectometry showed its value in differentiating properties of the Earth's surface beneath an airborne receiver. Further research using this technique is appropriate to identify further remote sensing applications.

6. New algorithms using GNSS to maintain tight spacecraft formations were developed and tested in simulated conditions, using receivers developed in the program. These algorithms are at a level of maturity to be incorporated in a flight program.

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9. ANNEXES: DETAILED TECHNICAL WORK PACKAGE REPORTS