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A National Soil Moisture Monitoring Capability

Volume II: Implementation Case

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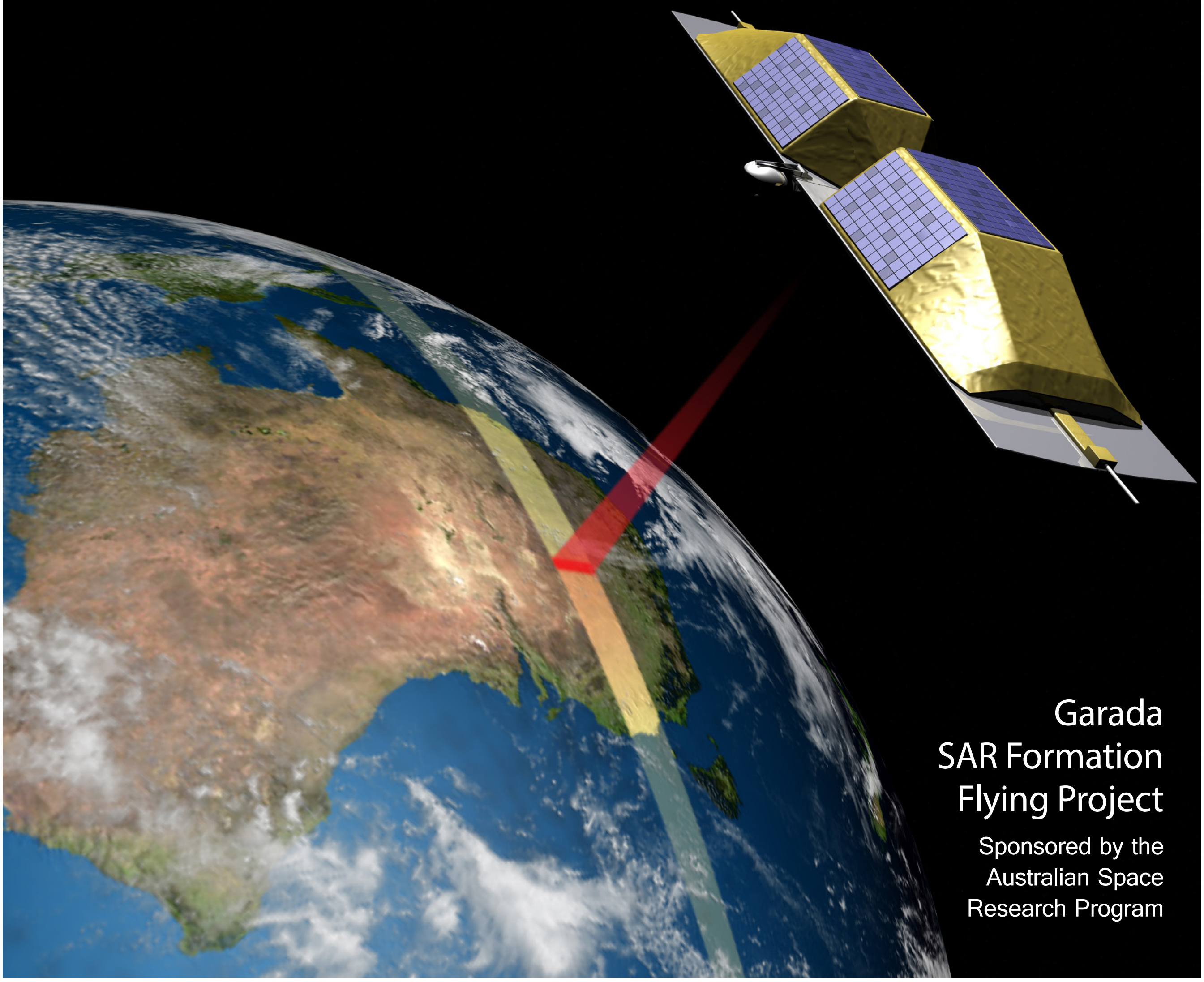

Garada
SAR Formation
Flying Project

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SAR Formation Flying

Final Report: A National Soil Moisture Monitoring Capability

Volume II: Implementation Case

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Disclaimer

Preface

This report "A National Soil Moisture Monitoring Capability – Volume II – Implementation Case" is the second report of two released on completion of the Garada "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

Australia is the driest populated continent with increasing water security issues arising from population growth and climate change. Other dry countries have responded by launching satellite soil monitoring assets. This report proposes Garada as an asset for Australia, to provide essential information for agriculture, weather prediction, land use planning, and environmental management.

The Garada system will cost in the order of $800 million, an investment that is easily recovered. Three arguments are presented here, any of which shows the satellite will pay for itself, if it can improve the efficiency of non-irrigated agriculture by 0.35%, *or* allow environmental goals to be achieved while reducing Murray-Darling Basin environmental flows by only 1%, *or* by allowing investment in irrigation infrastructure to decrease by 7%. There is a variety of ways the system can be funded, with an annual cost never exceeding $120 million.

Committing to the Garada system will create many high-productivity jobs, develop capability in the knowledge economy and give Australia sovereign control of this essential monitoring task. With Australia's traditional sources of data (other countries) drastically cutting back on satellite launches, and the changing rainfall patterns across the country, it is imperative that Australia act now to achieve on-going, cost-effective access to the space capabilities on which the nation relies now and in the future.

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1. The Problem: A Dry Continent

The Australian Government has identified that Australia has specific and serious problems relating to soil moisture:

- It is, and always has been, dry: "Australia is the driest inhabited continent on earth, with the least amount of water in rivers, the lowest run-off and the smallest area of permanent wetlands of all the continents. One third of the continent produces almost no run-off at all and Australia's rainfall and stream-flow are the most variable in the world." [1].
- Climate change makes this worse in some regions: "A long-term drying trend is affecting the southwest corner of Western Australia, which has experienced a 15% drop in rainfall since the mid-1970s"[1]. "The southeast of Australia, including many of our largest population centres, stands out as being at increased risk from many extreme weather events - heatwaves, bushfires, heavy rainfall and sea-level rise. Key food-growing regions across the southeast and the southwest are likely to experience more drought in the future."[2]
- Other regions have the opposite problem: "Heavy rainfall has increased globally. Over the last three years Australia's east coast has experienced several very heavy rainfall events, fuelled by record-high surface water temperatures in the adjacent seas."[3]
- Growing population is increasing the pressure on water resources: "There has been rapid development of groundwater resources over recent decades, driven by increasing population pressures in many coastal and rural communities and rising demand from many new and existing industries. Much of inland Australia is dependent on groundwater for water supply. Prior to the NWI [National Water Initiative], groundwater was often overlooked in the national water debate. The failure to adequately invest in groundwater data and knowledge, appropriate monitoring and tools and networks, has resulted in an inadequate understanding of the resource and overallocation in many aquifers."[4]
- Agriculture must continue to be more efficient: "To maintain the ability of Australia's agricultural sector to compete internationally and benefit from a profitable and sustainable export business, agricultural productivity must continue to improve while using land and water more sustainably"[5].
- The Great Artesian Basin is under increasing pressure. The Olympic Dam mine is extracting 15 million litres of water per day with projections of up to 75 million litres per day [4]
- The natural environment is also under pressure: "Australia currently has 65 Ramsar (an international convention that provides the framework for conservation of wetlands) listed

[1] [2], p4

[2] [2], p4

[3] [2], p4

[4] [3], p98

[5] [5], p7

wetlands covering 7.5 million hectares and more than 850 of national importance." [1] "In the past 200 years Australia has cleared so much land and drained so many wetlands, that we have the world's worst record for fauna extinction and over 100 species are now listed as threatened and endangered – 23% of mammals, 9% of birds, 5% of higher plants, 7% of reptiles, 16% of frogs and 9% of freshwater fish. The extensive loss of native habitat is having major impacts on ecosystem functioning in many parts of Australia, particularly wetlands. This in turn is threatening the survival of our wetland wildlife. The scientific evidence is suggesting that Australia is on the cusp of another wave of mammal, bird, freshwater fish and frog extinctions." [6]

Australia receives less rainfall than other major agricultural exporting nations, as exemplified by Table 1 containing data on wheat exporters. Note that the other two very dry countries, Canada and Argentina, have developed SAR missions similar to the one we are proposing here, that can monitor soil moisture.

Country	Wheat exported (million tons) [7]	Annual rainfall (mm) [8]
United States	35.4	715
France	19.2	867
Canada	17.5	537
Australia	13.5	534
Argentina	8.5	591
Ukraine	5.5	1,875

Table 1 Rainfall for the top six wheat exporting nations

Managing the interaction of water and soil clearly has grave national significance, and it is not difficult to argue it may in the near future be the issue of greatest national significance.

2. Addressing the Problem: More Moisture Data, Better Decisions

The first principle of "Australia's Satellite Utilisation Policy" is to "Focus on space applications of national significance"[6]. "Australian Government efforts will focus on space applications that have a significant security, economic and social impact, specifically Earth Observation…"[7].

"Australia is one of the world's least densely populated countries (after Mongolia and Namibia), with fewer than three people per square kilometre" [1], making remote sensing from space the logical solution to many nation-wide issues, such as soil moisture monitoring.

[6] [9], p2

[7] [9], p9

Garada is a satellite system designed for a soil moisture monitoring mission. In *Finding Australia's Invisible Resource* [10], we outlined many ways that such a mission could be useful in addressing some of the important issues noted above[8]:

- Weather: it aids predicting cloud formation
- Broad-acre farming: better knowledge of soil moisture allows more efficient movement of cattle; more timely and efficient planting can occur for non-irrigated crops
- Water erosion: it helps identify where planting can stabilise soils
- Wind erosion: it helps predict dust storms, and plan dust mitigation
- Land use planning: observing long term trends can allow orderly transitions; real-time data allows better responsiveness: current maps are static and outdated.
- Protecting ecologies: water diversion for environmental flows can be made more effective
- "Tipping points": identifying the tipping point more accurately allows a farmer to change land use, or get off the land sooner
- Carbon storage: if soil condition is maintained, carbon stored in root zones is "permanent"

Australian researchers have already shown that synthetic aperture radar (SAR) is an appropriate and capable instrument for measuring the moisture in soils. Figure 1 shows data collected by the Polarimetric L-band Imaging Synthetic Aperture Radar (PLIS) facility [47], which is an Australian aircraft-based L-band polarimetric SAR, designed for soil moisture research.

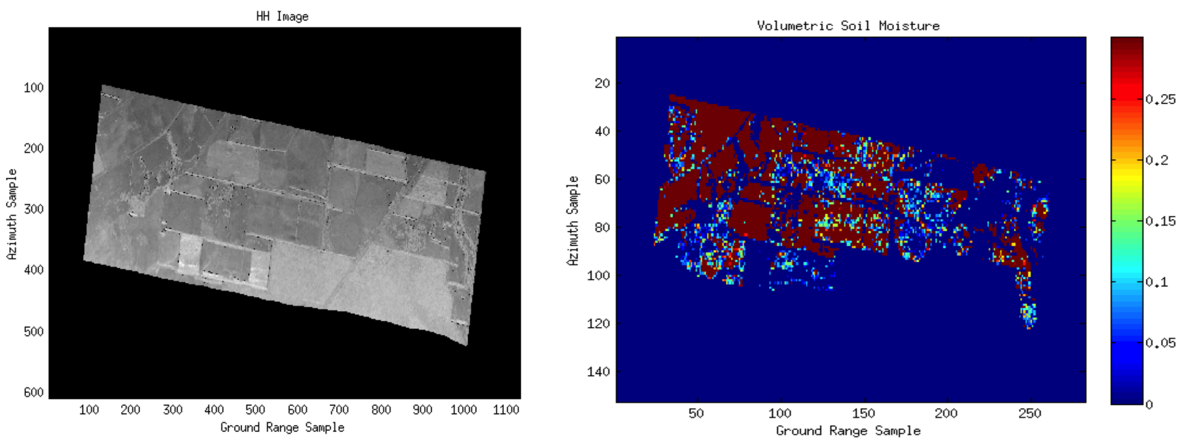

Figure 1 SAR image from the PLIS aircraft, left, processed for soil moisture content, right

<u>Key technical parameters required to achieve the capability.</u> Our expert User Advisory Group advised soil moisture monitoring from satellites can ideally be achieved with "a fully polarimetric S-, L-, 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" and that "An exact orbit repeat with 2-3 day revisit is needed to meet the requirements of most soil moisture applications and retrieval algorithms" and "a 50m spatial resolution of the derived soil moisture product would be required" [19].

[8] Extensive literature exists on all these topics. Indicative, rather than definite, examples are given for soil moisture and: cloud formation [11], timely planting [12], water erosion [13], dust storms [14], land use planning [15], environmental flows [16], tipping points [17], carbon storage [18]

Soil moisture monitoring is a very demanding application, so Garada has been designed to a very high set of specifications. That means that other applications of an L-band SAR satellite are also possible. These include forestry monitoring, flood monitoring, marine applications and many more. In other words, it is a high-utility satellite that can have myriad valuable functions across Australia and globally.

3. Garada: an Engineered Solution

To meet Australia's needs, we would highlight the design that our team, which included very experienced engineers from major aerospace companies, produced under the Garada project. Our work showed that this capability is readily implementable within ten years. Garada would include a pair of large synthetic aperture radar (SAR) satellites, like the one illustrated in Figure 2. The SAR sensor and basic spacecraft design was executed by the European aerospace firm EADS Astrium. BAE Systems Australia performed the ground segment design, which is vital to the effective use of the system because of the enormous data volumes. UNSW, with the assistance of both firms, conducted the systems engineering, ensuring consistency among the various aspects of system performance. UNSW also established the user requirements by engaging across a range of stakeholders.

Garada requires a large, highly capable spacecraft. Each weighs 2400 kg and when its antenna is deployed, it spans 15.5 m x 3.9 m. They are designed to fit into a Falcon 9 rocket from Space Exploration Corporation in the US—currently the least expensive launch vehicle for large, valuable satellites.

The satellites transmit pulses at L-Band (1.2575GHz carrier, 85MHz bandwidth, pulsing at 1400-2500Hz), and those transmissions are polarised both vertically and horizontally, both in transmit and receive. It is the combination of these polarisations that allows soil moisture to be extracted. The signals hit the ground at incidence angles between 8° and 50°, giving a swath of 380km and spatial resolution of about 10m (i.e. when images are reconstructed from the pulsed signals, they are 380km wide with 10m pixels). For an introduction to how SAR works, see the Appendix.

Each satellite flies in a near polar orbit at an altitude of 630 km with a 6 day repeat path. They oppose each other in the orbit plane, so one of them passes over the same spot every three days. The orbits are synchronised with the sun, so they pass through the equatorial plane at 6 am local time (rising latitude) and 6pm (falling latitude). The satellite downlinks its data at 1 Gbps at X-band, preferably to ground stations in Australia (to ensure the data is as timely as possible, and to utilize the National Broadband Network for data distribution to diverse users).

One of the innovative aspects of Garada's design was the transmit/ receive circuitry for each radar element, which is based on a novel distributed microchip design. The goal was to maximise the use of commercially available chips in the radar, which would lower its cost and reduce manufacturing time. It would also increase the number of Australian-manufactured components in the system. The student who developed and tested this design won the NASA-VSSEC 2012 Australian Space Prize.

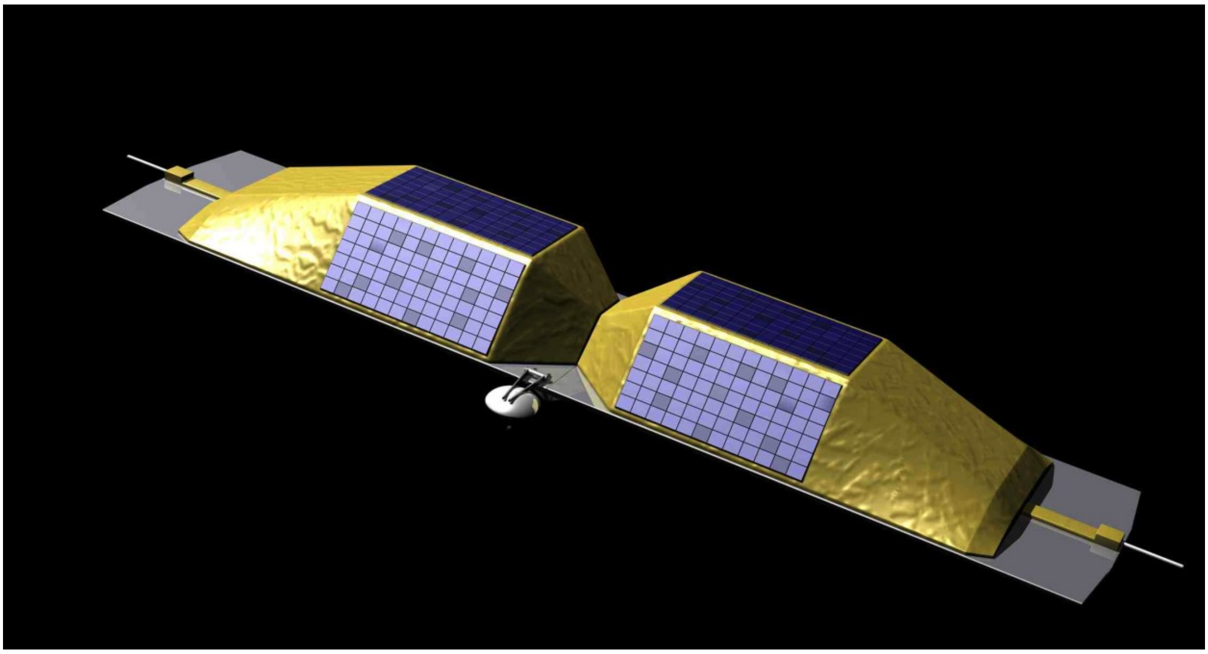

Figure 2 Garada satellite

4. Can Australia Afford (not) to Invest in this Capability?

4.1. It can easily pay for itself

Given the foregoing, there is little question that the data that could be produced by a Garada-like system would be of immense value to Australia. Any hesitation in progressing to acquire it might only be based on questions of affordability.

Commentary about the affordability of earth-observing satellites for Australia has in general been negative. One recent Australian SAR report, for instance, suggests that “It is difficult at this time to see a firm economic argument in favour of a dedicated Australian spacecraft or instrument.”[9] A second states that “The cost of building, launching and establishing all the ground operations of a single SAR satellite payload would be of the order of $500 million plus annual operating costs and, is prohibitive.”[10] Neither of these reports examines whether such a satellite could provide a return on investment. Although it was not in the scope of the project to produce an economic or financial argument for the support of the Garada project, we present here some relatively simple calculations which show that Garada may be expensive, but it could quite easily pay for itself.

Countries that own SAR satellites know that they get value for their money. “The experience of [Canada, Argentina, Italy, Germany, China, Japan and the European Space Agency] to date has

[9] [21], p3

[10] [22], p42

prompted their investment in follow-on programs, often with improved capability"[11]. In other words, not only was the original investment seen as worthwhile, it was valuable enough to repeat. It's also interesting to note that SAR satellites seem always to exceed their design lifetime, as shown in Figure 3.

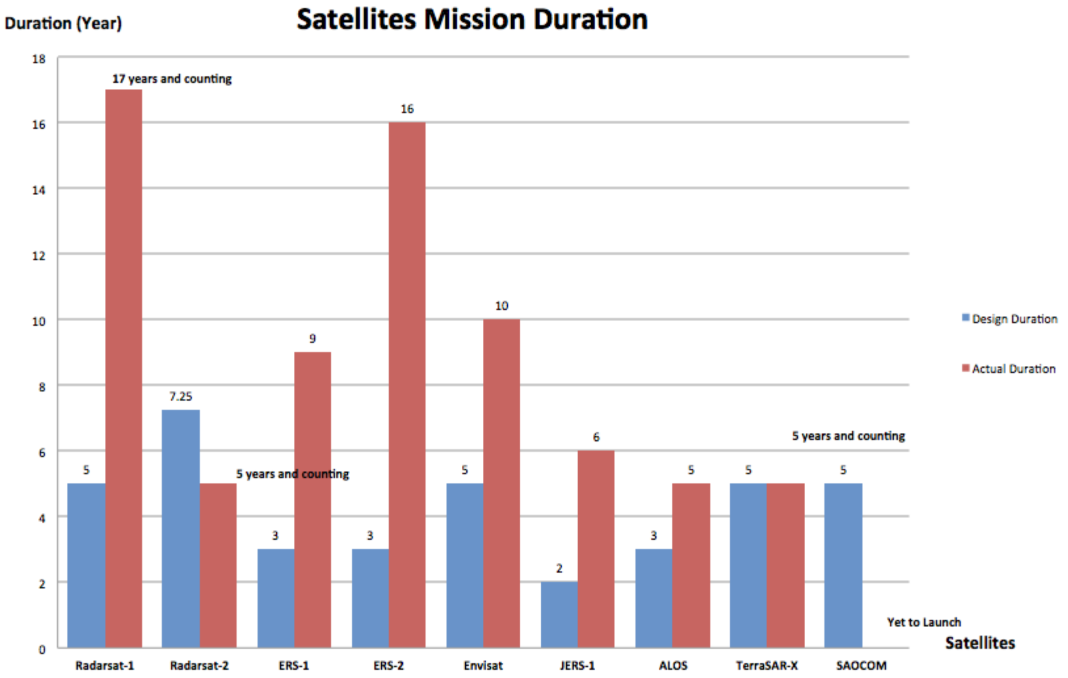

Figure 3 Historical Record of SAR Satellite Lifetimes

It is likely that the $500M cost suggested in [22] is an underestimate, as factors like operations and launch costs may not have been included. Our life cycle estimate for the Garada capability can be seen in Table 2. We estimate that the Garada mission is likely to cost much more than is estimated in [22], around $800M for two spacecraft operating for an 8 year lifetime. However, with design, manufacture, launch and operations, the total program length would be 14 years, with the maximum spend in any year of the program would be $120M in only two years - see Figure 4.

[11] [21], p3

Description		Estimated Cost
Satellite 1 (inc $80M design)		$240M[12]
Satellite 2		$160M
Launch @ $54M[13]	2 launches	$108M
Ground segment[14]		$87M
Operations @ $25M/ year[15]	8 year life	$200M
Total		**$795M**

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

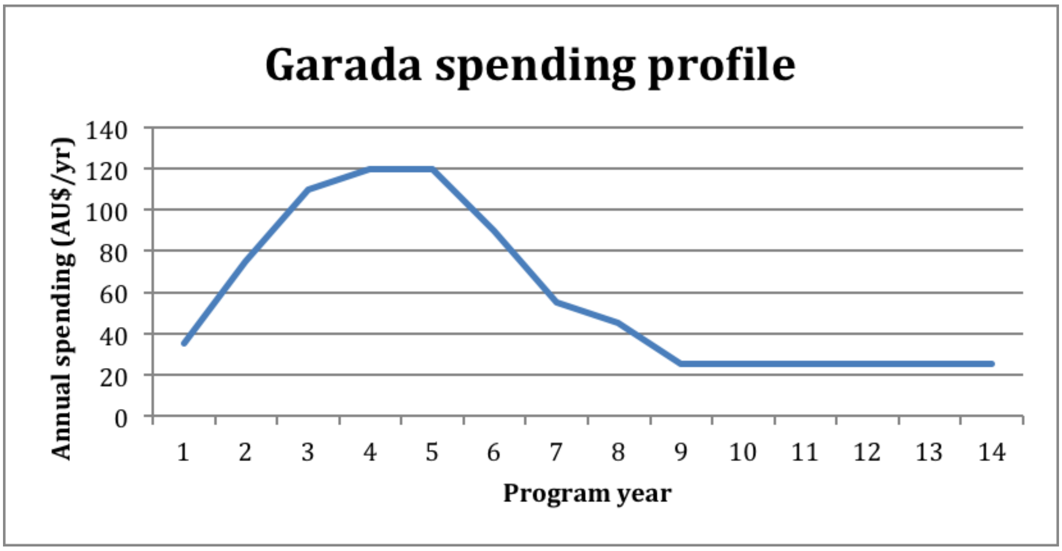

Figure 4 Garada spending profile (launching years 7 and 8)

As noted in section 2, 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 [25] states Australia's Gross Value for Agricultural

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[12] 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

[13] Assumes launch using Space-X Falcon 9, currently priced at $54M (2012) http://www.spacex.com/falcon9.php

[14] 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.

[15] Consistent with operations costs in [23]

Production for 2009/10 was $39.7B [16], 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 non-irrigated 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.

Payoff by improvements to irrigated agriculture infrastructure. 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[17]. 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[18]. At that rate of spend, irrigation infrastructure would have a value of around $12B by the time Garada is launched. So, if the provision of Garada data could reduce irrigation infrastructure cost by 7%, or reduce annual spending on infrastructure by 30%, 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 instead relying on satellite data.

Payoff by improved targeting of environmental flows. It is similarly possible to examine how environmental water could be more efficiently used. Agriculture generates $4M per GL of water consumed [29]. In *The Basin Plan* [30], 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 over the entire MDB every three days 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.

4.2. It will create many high-productivity jobs

Investing in satellites reinvigorates economies, and is a driver for creating high-technology jobs and skills development. These jobs are created in two ways: jobs in the space industry creating jobs in the wider community, and jobs in the “upstream” space industry (satellites, launchers) creating jobs in the “downstream space industry (data processing, ground support etc). In the first category, each space job creates 3-5 wider community jobs: “for every 10 jobs directly supported by the UK space industry, another 26 in total are supported indirectly in the supply chain and from the induced

[16] The National Farmers Federation claims Australia’s agricultural output for 2009/10 was $48.7B [27], so our number is more conservative. Similarly, the ABS gives the figure of $46.0B for 2010/11 [28] but they didn’t have irrigated data for that year.

[17] [26], Tables 4.5 and 4.7

[18] [26], p35

spending of those directly or indirectly employed by the UK space industry."[19] In the US, "In 2009, for every dollar spent commercial space transportation industry, USD 4.9 resulted in indirect and induced economic impact", "creating 213,230 jobs" [20]. At the French satellite launch facility, "one direct job being responsible for 4.4 induced jobs"[21]. In the case of "upstream" jobs creating "downstream" jobs, the multiplier is more like 6 [34]. There are many case studies in [34] of how satellite investment generates downstream wealth. The recent Australian study [21] also gives the example: "… the Canadian experience with SAR is a good example of the importance of farsighted investments in emerging technologies. Not only has that allowed the development of the high profile and successful Radarsat program, but early Canadian research positioned that country and its sponsored, commercial operators such as Macdonald Dettwiler and Associates (MDA), a start-up out of the University of British Columbia, to capture a significant part of the ground station market, including the market built around the correlation software required to form image products from the data recorded by SAR satellites."

Productivity is of prime importance to the Australian government. In its Asian Century White paper, it asserted that "By 2025, Australia's GDP per person will be in the world's top 10, up from 13th in 2011, requiring a lift in our productivity."[22] This makes investment in satellites very wise. Not only does such investment generate many jobs as identified above, but the jobs it creates are high-productivity jobs. A UK study found "the space industry helps to facilitate improved supply-side performance of the UK economy, creating capabilities and enhancing productivity across the wider economy"[23] and that after extraction and production/distribution of electricity, space employees have the highest productivity, contributing the most per person to GDP[24].

Australian studies also support these findings: "The key findings and recommendations of this report are: 1. Those nations that have a relatively high supply rate of SAR imagery have more rapidly developed high value applications, particularly in the northern hemisphere." [25]

4.3. It will enhance Australia's role as a good global citizen

In addition to the undeniable benefits to Australia, a satellite system like Garada is likely to be of great benefit to Australia's neighbours, and it offers the opportunity to offer genuine aid to developing countries. "Of the world's … freshwater roughly 99 percent is either trapped in glaciers and ice caps, held as soil moisture or located in water tables too deep to access… in Asia, water shortages… are emerging as a major social and economic threat, especially in China and India." [37] "One of the greatest threats to water security is simply scarcity, where demand outstrips supply. This can result from geography, overexploitation or inadequate infrastructure, and climate change will put further pressure on the availability of freshwater in many parts of the world… in Sub-

[19] [31], px

[20] [32], p82

[21] [33], p138

[22] [35], p9

[23] [36], p3

[24] [36], p16

[25] [22], p56

Saharan Africa … where almost all agriculture is rain-fed, soil moisture provides the single largest source of freshwater for food production" [38]. "Satellite imaging is being used to locate potential mosquito breeding sites in southern Zambia, in a bid to reduce malaria transmission in the area. Researchers use the data, containing information such as soil moisture and water drainage patterns, to identify areas where the mosquitoes live and breed." [39] There is a global push "to elevate the importance of water issues within the UN General Assembly negotiations on the Sustainable Development Goals — a set of globally-agreed future objectives to succeed the UN Millennium Development Goals in 2015" [40] In this context, the world desperately needs instruments like Garada.

4.4. It gives Australia autonomy

Garada-like projects give Australia sovereign control of its destiny. The government states "Australia has recognised its space dependencies in recent years"[26], and by "depending on … the goodwill of other nations"[27], Australia is exposed to the danger of "relying solely on the countries who have supplied capabilities"[28]. "Future access is uncertain because the satellites on which Australia relies are reaching the end of their life-spans, and new satellites are not always replacing them."[29] Our analysis shows this problem is bad and in fact getting worse [20].

The problem with perpetually using data from foreign satellites is that Australia has no control over the specification of the data. The instrument is designed by an agency over which Australia has no control, to meet the requirements of another country. Australia must take the data in the form provided. Not only that, the data is only available when the satellite is not doing the tasks assigned by the owners. Tasking a satellite is obviously the priority of the owner. "Australia is invariably regarded as a data-taker and not a data-specifier, in that the imagery it has to work with may not have characteristics well-matched to Australian needs. The right types of imagery may simply not be available; and, of course, with time Australian users may have to pay commercial rates."[30] "The failure of Australia to have consistent policies in place in relation to EOS data access and acquisition has had a major impact on EOS research and development in Australia by pushing programs, both research and operational, towards the use of 'free data' sources which may not be optimal for the particular applications sought."[31]

5. Are There Other (Cheaper) Alternatives to an Australian Satellite?

Australia has never owned its own earth observation satellite. It is the "Blanche Dubois of satellite earth observation" relying on the "kindness of strangers" [20]. "Australia is totally reliant on foreign

[26] [9], p3

[27] [9], p3

[28] [9], p3

[29] [9], p5

[30] [21], p12

[31] [22], p13

satellites for EOS data" [49]. Some call this freeloading. So, is freeloading still an option for Australia, rather than committing to Garada? Can we get soil moisture data from our usual overseas sources?

No, and yes. Garada aims to produce a soil moisture map for the whole of the Murray Darling Basin and most of the Australian continent every three days at a resolution of 10m. No other proposed mission can do that. There are, however, four planned missions whose purpose overlaps with Garada's: SAOCOM, ALOS, SMOS and SMAP.

The closest in type is Argentina's SAOCOM [41]. This is also a pair of L-band satellites designed for soil moisture. The mission life is five years, and it has ground resolution of 10-100m. However, the revisit is 8 days. Similarly, Japan's ALOS-2 [42] will be an L-band satellite with 10-100m resolution. Its revisit time is 16 days. Neither of these meet the 2-3 day repeat required by soil moisture monitoring applications [19]. ESA's Soil Moisture and Ocean Salinity (SMOS) satellite is currently operational and looks at the L-band emissions from earth and can give a global map every three days, with a resolution of 30-50km [43]. NASA's Soil Moisture Active Passive (SMAP) has a resolution of 1-3km [44]. Neither of these meets the 50m resolution requirement [19]. So alternatives exist, but they are either too infrequent or have insufficient resolution. Because they are all foreign missions, Australia will not have priority when tasking the missions, so acquisition of complete and regular maps of Australia, or even just the Murray-Darling Basin, are highly unlikely. Getting any of that data for free is also becoming less and less likely.

Manual and instrumented surveys need not be considered. To achieve 25m-separated measurements across the Murray-Darling basin, an *annual* survey would require over 10,000 staff by our estimates if done manually or a massive infrastructure if fully instrumented. The legal issues regarding land access and practical issues regarding protecting the sensors from normal farm activity also rule this option out.

To estimate the cost of SAR surveying the Murray-Darling Basin using aircraft, a cost calculator was used [45]. Small and medium aircraft were examined. Crew were assumed at $50/hr, the SAR swath was assumed to be half the cruising height, and the cost of the SAR instrument was not included. The small aircraft was a Cessna 172 ($175/ hr, 2 crew, cruise at 194km/h at 3km altitude, giving a 291 sq. km/hr rate of survey, a marginal cost of $0.94/sq.km, and 3,436 hr = 172 20-hr weeks to cover the MDB). The medium sized aircraft was an Embraer 120 ($1,887/hr, 3 crew, cruise at 556 km/h at 8km altitude, giving a 2,224 sq. km/hr rate of survey, a marginal cost of $1.09/sq.km, and 449 hr = 15 30-hr weeks to cover the MDB). It is clear from the cost comparison in Table 3 that although aircraft are competitive on a whole survey basis, it is not possible for aircraft to deliver timely data across the basin.

	Light aircraft	Med. aircraft	GARADA One spacecraft	GARADA Two spacecraft
Acquisition cost	$300K + SAR	$11M + SAR	$381M	$595M
Ops cost per day	$1,100	$12,222	$68,500	$68,500
Time to survey MDB	3 years	4 months	6 days	3 days
Cost of each survey of MDB	$944,900 + SAR/2 **	$914,600 + SAR/24 **	$1,193,000	$816,000

Table 3 Cost comparisons for aircraft and spacecraft SAR surveys of the Murray Darling Basin

The conclusion is that there are other methods of acquiring soil moisture data, but they do not meet the end user requirements. Non-space-based solutions are wholly inadequate for timely data. They will also be limited by the weather, whereas the Garada spacecraft can obtain undisturbed data in any weather, through total cloud cover.

6. Is it Ready to Go Now?

There are several risks that need to be mitigated before Garada as designed in this project is ready to fly. These are not insignificant risks. The science behind the proposed soil moisture methodology is still being developed [19]. The "snapdragon" configuration of the satellite (its fold-in-the-middle shape – see Figure 2) does not have tested space heritage. And the distributed antenna transmission/ reception circuitry has also not been tested in space before. These are the main engineering risks that need to be dealt with, and we discuss them at length in our technical reports.

There are two solid methods for dealing with the science risk. SAOCOM may not be able to meet Australia's needs for timely, gapless soil moisture monitoring, but it will be able to provide very similar imagery. Thus, all the necessary algorithms can be designed and tested on real satellite SAR imagery, along with ground truth, in Australia, to prove those algorithms. Currently due to launch in 2014/2015 [46], SAOCOM will be producing output well in advance of a Garada launch. ALOS-2 will launch later in 2013 [46]. In parallel with testing that leverages those missions, testing can be conducted with data from the Polarimetric L-band Imaging Synthetic Aperture Radar (PLIS) facility [47], which is an Australian aircraft-based L-band polarimetric SAR, designed for soil moisture research. The type of imagery produced by PLIS is shown in Figure 1.

The structure and antenna risks are not extreme for the introduction of a new technology. Risk is mitigated by performing extensive design and test programs beyond that which is required for a proven technology.

7. Can Australia Do It?

Given that Australia's high-tech industry segments have not been extensively involved in space programs, what is the degree to which Australia could lead and deliver such a project? In the course of the Garada project, we have identified significant contributions that Australian companies and other organisations could make. These contributions are in the area of components and subsystems, as shown in Figure 5 [48].

The ways Australia could be involved in the development of a project like Garada also vary according to how the project is funded, and this would affect how much benefit there is to Australian industry.

Parts of the Garada system that could be provided by Australian industry include global navigation systems, communications, antennas, structures, mechanisms, actuators, electronic boards, harnesses, electronic modules and boxes, power supplies, RF components, and systems engineering.

The Garada Australian Industry Capability Report and Industrialisation Plan specifically focused on this soil moisture SAR measurement capability. Our key findings from the Capability Report were:

- Spacecraft integration (the assembly of subsystems onto the structure, and the integrated testing following assembly) is not a capability that resides in Australia.
- Australia has strong capability in ground systems and is capable of priming the ground segment and undertaking the design and development.
- Australia's space systems capabilities are presently in the area of component suppliers.
- The extra specialised production processes and testing required for space systems, over and above that needed for commercial and military applications, are not commercially viable. However, this capability gap is being filled by the Advanced Instrumentation and Technology Centre (AITC) at ANU in Canberra. When completed in 2013, the AITC will provide science and industry with the capability to provide parts, components and small subsystems to the Garada spacecraft.

In our Industrialisation Plan (an appendix to Volume I of this report) we cite approaches to maximising the Australian content of the project.

The ways Australian industry could be involved in the development of a project like Garada also vary according to what project policies are pursued. We believe that small, targeted investments in key sectors would be highly leveraged and open significant new high-tech markets for Australia. Various approaches to procuring Garada would also affect how much benefit there was to Australian industry. We discuss this in the following section.

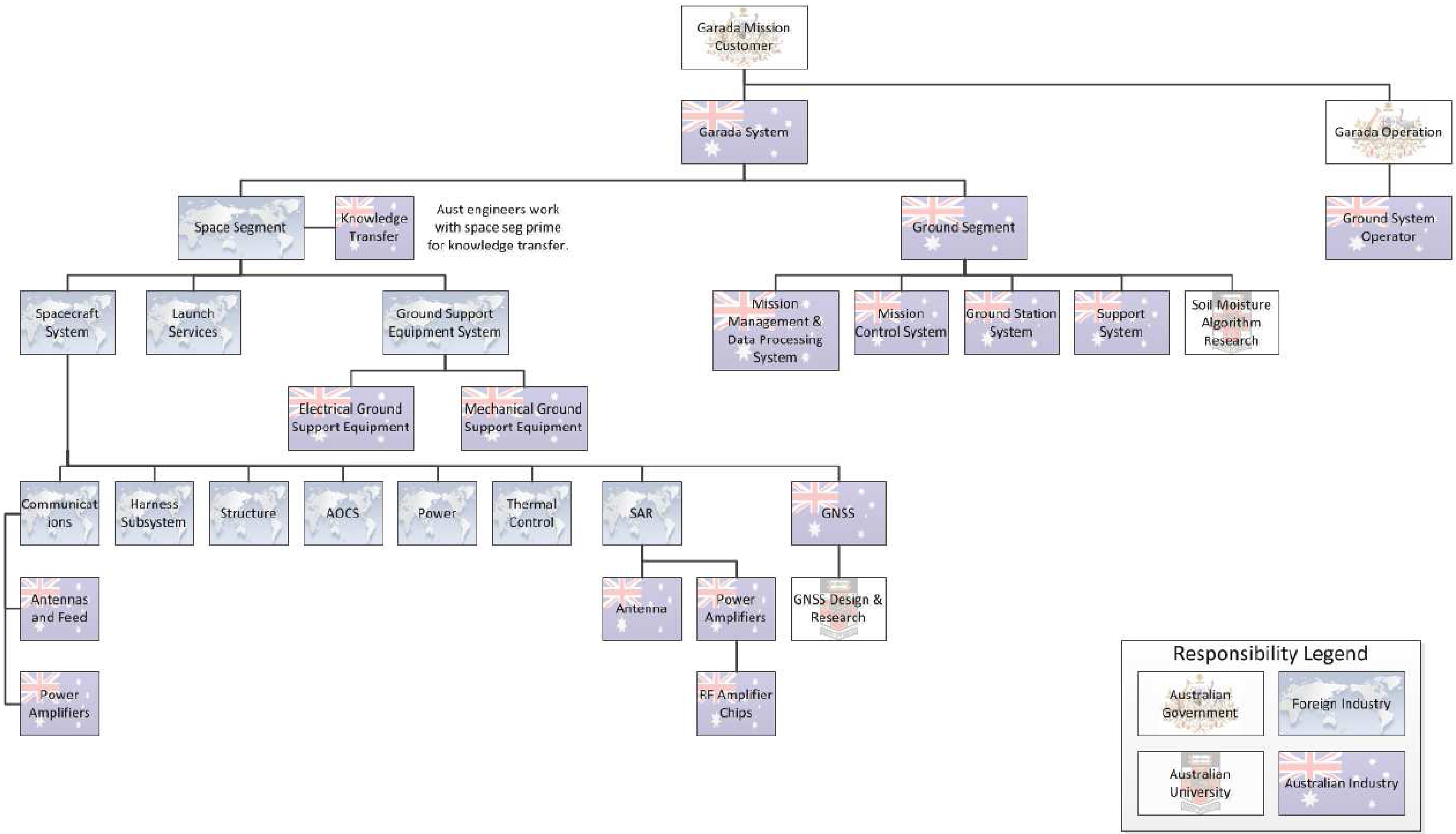

Figure 5 Garada Australian Industrial Involvement [27]

8. What are the Options for Acquiring such a System?

The Satellite Utilisation policy states that "Australia will, over time, continue to invest, as appropriate, in systems, sensors or satellites" and "the Australian Government will develop and retain domestic expertise across the government, research and industry communities, to ensure that Australia can cost-effectively access and use space capabilities." [32]. To meet all program requirements, many acquisition approaches could be implemented, each with its advantages. Here we describe three different acquisition models, any of which would result in the desired soil moisture measurement capability. The approaches span the range of options between "having the capability" and "directly managing the building of the satellites." The first of the three models provides the former without requiring the latter. All three models would provide the near-real-time, continent-wide, gapless coverage promised by the Garada concept.

To be clear, all three acquisition models would require spacecraft integration by an international aerospace company. This is the key capability lacking in Australian industry. However, integration is only one part of the overall program, and this should not discourage pursuit of this vital capability.

Model 1. "Hands-off" program to obtain data from commercial satellite program. This approach would not necessarily use the design work already performed in our project. It begins with the release of a Request For Information (RFI) asking for parties interested in meeting the top-level Garada requirements. Space system manufacturers would describe their approach to building a system meeting those requirements, for compensation as set forth in the RFI. Responders would also be asked to describe a funding profile that would incentivize them to bid for the project. Under this model, Australia neither owns nor operates the system, but provides a revenue stream to the satellite operator. Advance payments to the builder/operator would undoubtedly be required in order to reduce their risk. This approach provides the least benefit to the Australian economy and industry, as RFI responders are likely to be international, and are under no compulsion to use Australian suppliers (although involving Australian industry could be required via the Australian Industry Participation – AIP – initiative).

Model 2. Outsourced acquisition management with Australian ownership and operation. This approach could also be initiated with an RFI, the premise being that the satellites would be turned over to Australia once on-orbit checkout was completed. The responsibility for system development and launch would be outsourced to an experienced aerospace corporation. A variant of this approach would be to acquire the ground system separately. Given Australia's world-leading capabilities in satellite ground systems, this could both streamline the acquisition and ensure that at least the ground segment costs fed back into the Australian economy, with little involvement in the manufacture of the space segment.

Model 3. Australia-managed acquisition program with Australian ownership and operation. In this approach, program management responsibility would remain with an Australian government entity. The necessary technical expertise would be assembled through a rigorous hiring and vetting process. International assistance would be sought to establish the appropriate processes for program success. A competitive procurement process would initiate the program once the management team

[32] [9], p11

is in full operation. Final integration of the spacecraft would still be performed by an international aerospace company, but with aggressive sourcing of components from Australian industry.

In the absence of an Australian Space Agency, any of these three approaches would require the establishment of a technically competent Radar Satellite Program Office. This office would manage the acquisition process, and remain fully staffed during the operational phase. Staffing would require selection of top engineering graduates and high performers from industry. The office would have numerous technical responsibilities, including systems engineering, government inter-agency coordination, program advocacy, user advisory functions, financial accountability, education and outreach, public affairs, contracts and legal, and response to international interest. In models 2 and 3, the program office would have the additional responsibility of directing contractor operations. In model 3, the office would procure launches.

One obstacle to reaching a consensus on a significant national investment in a new technology area is the fear of failure. Space projects occasionally fail. However, it is important to note the vast amounts of international expertise that exist in the space radar area. These companies are already expressing excitement at the potential to participate in this program. With a well-structured training program for the Australian management team, support from relevant government agencies, and an uninterrupted funding stream, the chances of success are very high.

9. The Broader Picture: SAR Earth Observation from Space

Australia needs earth observation from space (EOS) more than most countries. "EOS data is used widely and to great advantage in Australia… and have particular value in a large, sparsely populated country that needs to monitor a long coastline and a wide range of natural disasters." "In contrast with the projected rapidly decreasing access to EOS data, Australia's EOS requirements are expected to increase significantly over the next decade" [49]. In the *Australian Strategic Plan for Earth Observations from Space* [50], six of the eight national priority areas are able to exploit SAR data.

The Garada Phase 0 design is delivered at a time when EOS, and synthetic aperture radar (SAR) in particular, are being discussed as potential solutions to many of Australia's problems. In *Australia's Satellite Utilisation Policy* [9], the opening sentence reads "Australia aims to achieve on-going, cost-effective access to the space capabilities on which the nation relies now and in the future."[33] As part of its efforts to achieve this, "the Australian Government will … prioritise research focused on Earth Observations from Space [and other things]…"[34].

Two reports on SAR were released recently. One was commissioned by the Cooperative Research Centre for Spatial Information (CRC-SI), *Australia and SAR: A Road Map* [21] and one was commissioned by the Space Policy Unit and compiled by the CRC-SI, *Robust Imaging from Space: Satellite SAR* [22]. Both reports cover the possible applications of SAR, and some arguments about how to develop an Australian SAR capability. Both recognise the pending shortfall in Australia's access to space assets: "the nation's complete dependence on the international space community to supply these data on a fee-for-service basis or as a matter of goodwill has heightened the need for

[33] [9], p1

[34] [9], p8

government to examine options for future supply" [22], and "Australian access to SAR data may not be secure unless Australia contributes to acquisition costs" [21].

Garada would not cover all of Australia's SAR needs, but would provide the L-band requirements, i.e. possibly half: "No single type of SAR imagery will meet Australia's needs in terms of capability. Early indications are that a combination of high frequency (X-band and C-band) and low frequency (L-band) sensors are most promising." [22] "Australia's needs could be covered with a combination of L and X band imaging" [21]. "There is currently no source of satellite SAR L-band data anywhere in the world. With the failure of ALOS PALSAR in April 2011 and the failure of ENVISAT in March 2012, there exists a need to secure ongoing access to SAR L-band data beyond 2012, otherwise there is a risk that data gaps will hamper the development and operation of promising programs and research." [22].

Both reports highlight the importance of soil moisture as an application. In [21], "soil and plant moisture determination" was one of eight SAR case studies examined, and in [22]: "Recommendation 1. Australia should develop a strategic plan to inform the development of high value satellite SAR applications [such as] soil moisture monitoring in the Murray Darling Basin."

Both reports also give alternative funding plans to those presented here.

In other words, the Garada instrument has been examined at a time when L-band SAR has been identified as important for Australia.

10. Conclusion

The main findings of this short report are:

i) Garada addresses a critical and growing need for moisture data for Australia.

ii) The satellite system has been designed to Phase 0 and a highly feasible approach has emerged.

iii) The satellite can easily pay for itself, despite a price tag of $800M.

iv) Australia can manage the acquisition of the capability in a variety of ways, engaging an international aerospace company to execute some key steps.

v) Australian industry will benefit from supplying parts of the spacecraft, as well as leading the ground segment development, and operating the system.

The ability to monitor soil moisture content from space, with very little delay and very frequent, gapless coverage will benefit Australia in many ways, and should be acquired as soon as possible. The variability and destructive nature of Australian weather, the noticeable variations in the climate, the increased demands on agriculture, the increasing scarcity of water for all uses, and the tenuous security of Australian environments and ecologies, all demand it.

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12. Appendix 1: A Beginner's Guide to SAR

This is an overview of SAR (Synthetic Aperture Radar) imaging without any overly technical detail. The principal concepts of SAR are best understood from the viewing geometry. The simplest case is the so-called *monostatic* one, where the same antenna is used for reception and transmission, which are time-multiplexed (i.e. they don't happen at the same time). Here we will discuss only the monostatic case, and this is currently the only type of spaceborne SAR in orbit (although TerraSAR-X will do bistatic, where a satellite receives from itself plus another satellite). Many of the terms used can be found in Figure 6.

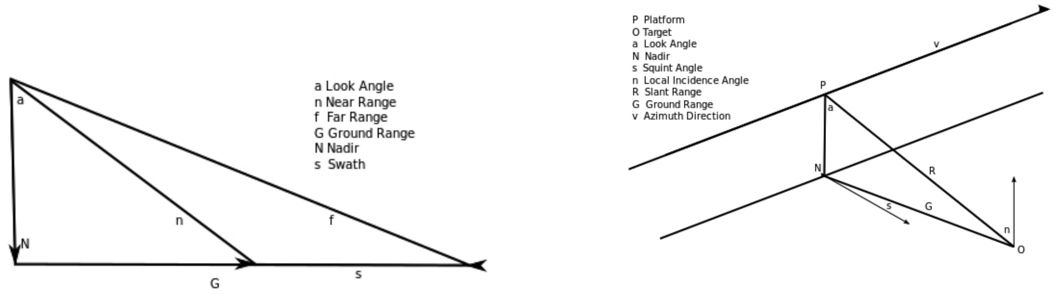

Figure 6 Simple illustrations of SAR terms. Left: satellite at the top of the triangle, moving into the page. Right: satellite moving along the vector v.

SAR is first of all a *side looking* radar. This means that, during transmission, the radiation extends from the antenna to the target area (normally the earth below) in a shape much like a cone and subtending an angle with the *nadir* or straight down direction. This is different to many optical sensors, for example, which tend to look straight down, and gives this type of radar its left and right looking 'handedness'.

Since the radar is primarily a ranging device, it cannot resolve the ambiguity of a target on the left or right *at the same range*. Therefore, SARs are typically operated in either a right or left looking mode at any one time. Most spaceborne SARs operate nominally right looking but can also be configured, through a roll manoeuvre, to image in the left looking direction.

The antenna used is typically a rectangular *phased array* antenna, although others are possible. Such an antenna is made up of an array of *phase centres* (small antennas), each of which can be carefully controlled to emit in a particular polarisation at a particular amplitude and with a particular phase offset compared to the other phase centres. This ability gives the antenna array the ability to perform *beamforming* and *beamsteering* as well as enabling it to operate *polarimetrically*.

The *polarisation* of the electromagnetic wave refers to the direction of the electric field vector. By looking at the way the target changes the polarisation of the wave, additional information other than that detected from intensity and phase changes can be gleaned. The forming of a beam is accomplished by the destructive and constructive interference of the radiated waves from each phase centre. Beamsteering is a form of beamforming where the direction of the beam can also be varied electronically.

Here we will only consider the *stripmap* mode of imaging, in which beamsteering is not used. Other SAR modes, such as Spotlight and ScanSAR use beamsteering to achieve either greater or lesser spatial resolution at the expense of lesser or greater swath coverage, respectively.

The *beam footprint* is the intersection of a conical volume with the earth and moves at a comparable, but not equal, speed to the platform. In fact, for typical spaceborne SARs the footprint moves substantially slower than the platform itself, due to the satellite's high altitude. For airborne SARs, the speeds are typically almost equal. The beam footprint can usually be described by its *elevation* and *azimuth* angles. The former is in the across track direction while the latter is in the along track direction.

The angle the antenna makes with nadir is called the *look angle* and it is different to the *local incidence angle*, often shortened to *incidence angle*, which is the angle that the radiation makes, at each point, with the normal to the surface.

The local incidence angle is important in determining the amount of backscatter received from a resolution cell. The *radar equation* tells us that the backscatter received is inversely proportional to the sine of the local incidence angle.

This partly explains why the so-called *nadir return* can be a problem when imaging at low incidence angles and can obscure nearby areas by saturating the intensity of the image around that point. The other factor is *specular reflection*, which is much greater at nadir.

A *resolution cell* is the minimum area for which the radar can discern a reflectivity coefficient and each cell can be regarded as a parallelepiped, with a definite extent in two directions. In fact, the resolution of the SAR is one of its most important parameters, as explained below.

For a side looking radar, there is also the important distinction between *slant range* and *ground range*. Slant range is the natural coordinate of any radar to the extent that it is a ranging device, while ground range coordinates are the natural coordinates for maps or images of the earth, which users will ultimately use.

For SARs, the slant or ground range coordinates are *across track* directions. On the other hand, the along track direction is called the *azimuth* direction, by analogy with conventional, rotating, ground based radars. The *swath* is the extent of the radar beam in the *ground range* direction and can cover tens to hundreds of kilometres, depending on the mode.

The local incidence angle is thus an important parameter in the radar equation varying across the swath and with local topography. Note that surface roughness, when substantial compared to the wavelength, can have important effects on the backscattering received as the local incidence angles will vary rapidly from one resolution cell to the next. This dependence diminishes with increasing wavelength, or equivalently, decreasing carrier frequency. This is one reason that L-band SARs are preferred for applications such as extracting soil moisture, especially for agricultural lots at different phenological stages. At L-band, it may be possible to consider fledgling wheat crop as bare soil, for the purposes of the measurement of soil moisture.

The footprint, when projected onto *ground range* has a minimum and a maximum extent, known as the *near range* and *far range*. The selection of the *PRF* (*Pulse Repetition Frequency*) is related to these, as explained below. Note that the swath is simply the difference along the ground range direction between near and far range.

A SAR works as follows. As the platform moves in the along track direction, pulses of radiation are emitted in the across track direction towards the target area sideways at an angle. Each pulse is very short, and its frequency varies around the carrier frequency in a linearly increasing or decreasing fashion. This pulse is called a *chirp*.

Once the chirp is transmitted, the electronics are switched into a receive only mode, listening for echoes from the earth from previous pulses. The pulses are repeated at the PRF for the duration of the exposure, as the platform moves. What is characteristic of SARs is that a large synthetic aperture (where "aperture" is used to describe antenna extent) is formed by the movement of the platform so that the azimuth resolution is effectively *independent of the slant range*.

The simplest case for SAR imaging is when there is no *squint*, i.e. when the squint angle is zero. The *squint angle* is the angle between a line perpendicular to the platform's direction and the antenna boresight (i.e. the antenna beam's central direction). When it is zero or low, the SAR processing is simpler. However, the movement of the earth is equivalent to an antenna yaw and therefore squint must be taken into account especially in spaceborne cases. For airborne SARs, the movement of the platform rather than the earth is problematic and for these, sophisticated *motion compensation* must be implemented.

For a monostatic SAR, as the radar platform moves across a scene, the instantaneous slant range to a target is a hyperbolic function of time. Due to the *Doppler effect*, the frequency received from a target will change not only according to the linear FM modulation imposed by the transmitter on the chirp, but also due to the relative motion of platform and target. This Doppler shift is crucial for SAR processing and in making the ultimate azimuth resolution independent of slant range. In order to be able to compare the phase between one range line and the next, it is vital that the SAR be *coherent*. In practice, this means that the phase of the transmitted pulse will be constant from one pulse to the next.

The PRF has to be selected in a way so that ambiguities are suppressed. The PRF cannot be too high, as then not enough time is given in the receive window for the echoes from far range to return. On the other hand, as the PRF is the sampling frequency in azimuth, it cannot be too low, as the Doppler bandwidth is essentially sampled by the PRF and to avoid aliasing there is a minimum Nyquist frequency. Note that the Doppler bandwidth is related to the platform's velocity and that the far range echo return time is essentially given by the altitude and look angle of the platform.

In order to achieve good range resolution, the probing pulse must be very short. This is because two targets positioned within the scope of the probing pulse will contribute to the echo, resulting in the system being unable to differentiate the two. However, if too short, it cannot carry enough energy to discriminate between the signal and noise, ie. the *Signal to Noise Ratio* (*SNR*) will suffer. Thus the shorter the pulse, the higher the peak power of transmission needs to be, but there are serious practical limits to transmitting high peak power.

We mentioned that a very short pulse of radiation is emitted with a linearly increasing or decreasing frequency. The reason for varying the frequency of the pulse is to impose a structure on it that allows *pulse compression* to be used. Pulse compression is used on the ground during the processing of the raw data collected by the SAR to form an intelligible image.

The aim of pulse compression is to minimise peak power, maximise SNR and all the while maintain good range resolution. *Matched filtering* is another term for pulse compression. The echo signal is convolved with a time reversed complex conjugate of the transmitted signal, thus maximising the SNR and allowing a *lower* peak power to be used during a *longer* pulse. It turns out that the range resolution of a SAR is inversely proportional to the bandwidth of the transmitted pulse.

The hyperbolic form of the range equation, derived solely from the viewing geometry, means that the backscattering received from a single target will trace out a hyperbola in the system's memory array. The memory array will typically consist of one row for each range echo and one column for each sample. Now this spreading out of the target energy across the memory array needs to be taken into account when processing the raw data into an image. This phenomenon is called *Range Walk* or *Range Cell Migration*. Correcting this is an important step of the *Image Formation Processor* (*IFP*).

The way that an image formation algorithm works to transform a raw SAR data image into a Single Look Complex (SLC) image can be understood by considering a single point target with a sharp backscattering response. The correct algorithm is one that takes the raw data from such a point target and localises it to its geometric location in the scene. By the principle of superposition, any scene can be considered a linear combination of such point targets and can be processed in the same way.

‘A National Soil Moisture Monitoring Capability Volume II: Implementation Case’

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