Australia and SAR: A Road Map

John Richards

A report prepared for the CRC for Spatial Information, based on the study entitled Robust Imaging from Space, August 2012. It draws on that study, which, inter alia, provides a comprehensive compendium of past, current and future free flying, spaceborne SAR systems, and provides cost estimates. The author is grateful for having had access to that material.

Acknowledgement

The author acknowledges the assistance of Dr Peter Woodgate, CEO of the CRC for Spatial Information, for his very helpful comments and suggestions on the draft of this report.
PRECIS

The all-weather, wide-area imaging capability of synthetic aperture radar (SAR) satellites and their strengths for hazard mapping, coastal surveillance and carbon accounting lie behind existing and planned investments in SAR systems by other nations. Australia needs to determine whether it can continue to rely with confidence on overseas-provided data for similar applications of national interest, or whether it needs to secure future access to data by becoming a contributor to space and ground segment hardware.

There are significant benefits to Australia by investing in the national skills base in interpreting SAR imagery. SAR analytical skills are an order of magnitude more complex than those needed for understanding other space imagery. Australia would benefit from a SAR workforce that can address current needs, and also tackle innovative applications that we cannot now foresee. These applications will provide powerful tools for the future management of our natural and commercial resources.

For these reasons Australia needs to make forward looking decisions as to the most cost-effective way to gain access to SAR imagery, by balancing short and long term costs against security of access.

An incremental strategy that creates feasible options for Australian access to SAR imagery is needed, structured so that investing in skills development early on will give Australia the capability to make informed decisions about future Australian investments in this evolving technology.
EXECUTIVE SUMMARY

1. **SAR is a form of satellite imagery that has particular benefits to Australia in the management of its natural and commercial resources, and its coastlines, and in its monitoring of hazards.** The all-weather, all-time-of-day, imaging capability of SAR and its relative strengths for hazard mapping, coastal surveillance and carbon accounting lie behind investments by other nations with comparable surveillance and resource management interests to Australia. They include Canada, Argentina, Italy, Germany, China, Japan and the European Space Agency. All have their own space and ground hardware and thus can control coverage and image acquisition strategies to meet their long term and episodic needs. The experience of each to date has prompted their investment in follow-on programs, often with improved capability, as does the opportunity to derive products from radar data that cannot be obtained by other means. These include maps of topographic change, three dimensional tomographic images and products that permit an analyst to discriminate between bodies with rapid fluctuations, such as the sea and flood waters (even under canopies), and those which don’t change, such as dry land and ships at sea.

2. **Australian access to SAR data may not be secure unless Australia contributes to acquisition costs.** Australia’s civilian applications of SAR have always depended on the data recorded and often provided at concessional rates by overseas agencies. While acceptable in an R&D setting, Australia must question whether it can continue with that strategy for applications of national interest, or whether it needs greater security of data access. Placing a mission into orbit is the most costly part of the SAR process, and operators of space and ground hardware may in future seek greater contributions from users like Australia who benefit from high-value, low-cost activities using their data.

3. **There is a range of investment options available to improve SAR capability**

It is difficult at this time to see a firm economic argument in favour of a dedicated Australian spacecraft or instrument. There is, though, the half way option of seeking investment as a partner in planned missions by operators with a proven track record. While not as expensive and high risk as developing our own system, it offers the benefits of lifting Australian experience with space hardware and instrumentation, allowing some influence over coverage and imaging characteristics, and showing Australian preparedness to contribute to the high cost end of acquisition while benefiting from the high value interpretation and product generation phase.

4. **Interpreting SAR imagery properly is challenging but essential.** Before any sensible decision can be taken about hardware, Australia needs to invest in raising the national skills base for the interpretation and use of SAR products so that our applications specialists are able to exploit fully all that SAR imaging has to offer, even with reliance on non-Australian data supply. Irrespective of the longer term, that would not be a wasted investment. Improved skills would encourage the generation of value added products by small business, and would open up marketing and aid possibilities in our region. A raised national skills level would also allow a detailed investigation of the importance of investing in Australian instruments or platforms, or of seeking partnering opportunities with nations which already have mature systems in orbit.
5. **An incremental Australian investment strategy is the best approach**

This report recommends a three phase incremental investment strategy in which an initial stimulus of the value adding sector, as shown in the table below, provides the opportunity to benefit from SAR capabilities at low cost, while investigating fully the benefits of space and ground sector partnering. If pursued, the partnering option also provides time to make informed decisions on a fully Australian SAR system. That is important because data gathering in the future may be more appropriately based on emerging developments in satellite clusters and the use of bistatic and multiple transmitter/multiple receiver radar systems, all of which need to be evaluated. Moving between the phases seen in the table would be contingent on successive cost-benefit analyses.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Cost and Period</th>
<th>Key Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Develop the value adding sector by improving the national skills base in SAR image interpretation.</td>
<td>$5m over 7 years</td>
</tr>
<tr>
<td>2</td>
<td>Partner with an existing SAR system provider and contribute to costs.</td>
<td>$340m over 8 years</td>
</tr>
<tr>
<td>3</td>
<td>Australian owned instruments and or satellites.</td>
<td>$740m over 13 years</td>
</tr>
</tbody>
</table>
1 Introduction

Imaging with synthetic aperture radar (SAR) is a valuable adjunct to the more common earth observation from space (EOS) systems, which use optical instruments. Not only does radar imaging have particular technical advantages over optical methods, but the earth surface properties sensed are often complementary to those that are detected with imaging in the visible and infrared, the so-called optical wavelengths. There can be significant benefits in using the two technologies cooperatively.

This report summarises the essential elements of SAR technology, and provides a road map with options for Australian future engagement with SAR imaging. The purpose of the map is to ensure that Australia’s spatial management needs in resource exploitation, environmental management, and safety and security, benefit cost-effectively from the unique advantages this technology brings. It makes the underlying assumption that a decision has already been taken to examine SAR in favour of, or together with, imaging in the visible and infrared as a technology for Australian investment. As a result this report does not include a comparative assessment of SAR and optical EOS techniques.

2 Structure of the Report

Investment as a nation in SAR remote sensing technology can be expensive if the aim is to design, or influence the design of, spacecraft and sensors matched to Australian needs. It is clearly less expensive to be a purchaser of products recorded by the missions owned by other nations, but then the results may be sub-optimal in terms of national requirements. There is also the question of continued access to data, and access at reasonable cost, especially if Australia is not seen as a serious player with other nations in the data acquisition phase of remote sensing, in which it makes meaningful contributions internationally to the development and operation of SAR systems.

In order to understand the trade-offs in pursuing one option against others, and whether hybrid strategies are possible, it is important to have a feel for the nature of SAR imaging and to appreciate, albeit qualitatively, the information about the landscape and its features revealed by radar that are not available in optical imagery. It is also necessary to know what radar data is currently available and what is planned for the timeframe relevant to this report\(^1\).

This document is structured in the following manner.

Section 3 presents a brief summary of SAR imaging. A fuller technical overview is given in Appendix B, which is non-mathematical but sufficient to allow important concepts to be appreciated. A series of case studies is presented in Appendix A in order to allow the unique advantages of SAR to be appreciated.

In Section 4 the pull factors that support the adoption of SAR in Australian EOS operational use and research are considered. That includes a summary of the lessons learnt from the case studies.

---

\(^1\) The report Robust Imaging from Space, August 2012 shows that there is a considerable archive of historical data available, and summarises the data that is currently being recorded. Those current programs may not be best suited to our national requirements.
Section 5 argues that the future potential of SAR is important to consider at this stage in our understanding of the technology and its current state of maturity.

Section 6 is a principal section of the report. Against pull factors and potential developments formerly identified it introduces investment options for Australia by differentiating national SAR engagement into the space segment, the ground segment and the value added segment, the last of which opens up opportunities for regional engagement both on an aid basis and as a fee-for-service activity. The importance of training in the interpretation and application of SAR imagery is emphasised as an essential element that underpins any future Australian SAR activity. The concept of agents – expert radar image interpreters – is introduced as a means to service both domestic and regional users.

Section 7 elaborates on specific investment possibilities and provides timelines for alternative pathways that align options to timeframes and indicative expenditures. It concludes with a tabular road map.

3 The Benefits of SAR Imaging

Optical imaging uses reflected sunlight in the visible and infrared range of wavelengths to form images of the earth’s surface. In contrast, SAR remote sensing is based on recording earth surface features with radio waves, similar to those used in mobile telephones and WiFi. Since the Second World War the radio waves of interest – the so-called microwaves – have been known by the letter designators shown in table 1, which are used in this treatment. Waves at a given wavelength are radiated onto the earth’s surface and the radiation that is scattered back to the SAR contains information about surface properties.

<table>
<thead>
<tr>
<th>Band</th>
<th>Typical SAR wavelengths (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>66.7</td>
</tr>
<tr>
<td>L</td>
<td>23.5</td>
</tr>
<tr>
<td>S</td>
<td>12.0</td>
</tr>
<tr>
<td>C</td>
<td>5.7</td>
</tr>
<tr>
<td>X</td>
<td>3.1</td>
</tr>
</tbody>
</table>

SAR radiation is technically pure, compared with sunlight; as a result it is possible to look for differences between two or more images that reveal information on the topographic properties of the landform; this technique is widely used and is referred to as interferometry. Interferometry cannot be performed with optical EOS data.

SARs can be described as single polarisation (SP), dual polarisation (DP) and quad or full polarisation (QP). It is not essential to understand the technicalities of those terms, but just to appreciate that

---

2 The full ranges of wavelengths associated with each letter are shown in Appendix B; those in Table 1 are the values commonly encountered in SAR remote sensing.
their value in remote sensing, and also their complexity and system cost, goes in the order SP→DP→QP. These allow a valuable tool called polarimetry to be used to help understand earth surface properties.

From Appendix B the following are seen to be the unique advantages of radar earth observation compared with optical imaging:

a. SAR is an all-weather, all time of day, imaging modality, and is only affected by exceptionally heavy rain at very short wavelengths.

b. Earth surface features respond differently at radar wavelengths than at optical wavelengths, making radar a different, and yet complementary, diagnostic tool.

c. The purity of the radiation employed in SAR imaging means that sophisticated products can be derived from recorded radar images, including maps of topography and topographic change with time. The availability of interferometric and polarimetric products makes SAR a very useful technology in many applications, and gives it an operational edge over optical imaging in many cases. Current research shows that three dimensional (tomographic) imaging is also possible.

4 Pull Factors

Investment in SAR can be substantial, especially with involvement in space and ground hardware, so it is clearly important to examine carefully those applications for which SAR has an edge and which would justify an investment of any magnitude. In broad terms, they fall in the following non-Defence categories:

a. Public good applications:
   i. Resource monitoring and management (crops, forests, waterways, mapping)
   ii. Environmental monitoring and management (carbon accounting, land clearing, water pollution)
   iii. Safety and security (vessel detection, coastal management)
   iv. Hazard mapping and monitoring, including emergency response (flooding, coastal inundation)

b. Private sector applications
   i. Domestic resource utilisation (agriculture, commercial forestry, mapping, exploration geology)
   ii. Providing regional value adding on a fee-for-service basis (which could also form the foundation of an aid program)

The set of case studies given in Appendix A demonstrate broadly the use of SAR in these sorts of areas. The lessons drawn from the case studies, which are summarised in Table 2, are:

a. Cropping and environmental applications generally favour the longer wavelengths of P and L band.
b. Forest monitoring applications are best handled by a combination of long wavelengths (P and L), for assessing woody biomass, and short wavelengths (typically X) for assessing canopy green biomass.

c. Flood mapping can be carried out at any wavelength, but longer wavelengths (P and L) are preferred when inundation under canopies is important.

d. Vessel detection and coastal applications are best served by shorter wavelengths, and typically X band.

e. The in-between wavelength of C band is a compromise and but offers benefits over L and X band respectively for some low level crop applications.

f. There is little experience with S band.

g. Success in the applications referred to in a-d above is enhanced if cross and either dual or full polarisation imagery is available, and if derived properties such as interferometric coherence can be employed.

**Table 2.** Significant SAR characteristics revealed in the case studies of Appendix A

<table>
<thead>
<tr>
<th>Application</th>
<th>SAR wavelength</th>
<th>Full polarisation helpful?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>L</td>
</tr>
<tr>
<td>Cropping</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Forestry</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Environment</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Flooding and hazards</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Coastal surveillance</td>
<td>?</td>
<td>x</td>
</tr>
</tbody>
</table>

? = not enough known at this time

At this stage in the application of SAR technology internationally, it is difficult to uncover case studies that show how earth observation with SAR can beneficially displace other methodologies long used in Australia in agriculture, forestry and resource applications generally. That is not to say that such benefits will not ultimately be realised – it is just that it is too early in the R&D cycle to be able state those outcomes with confidence.

What is clear from the case studies, however, is that there is a range of applications of importance to Australia for which SAR is ideally suited and for which solutions are not currently available or current methodologies are less effective generally. There are three areas that stand out in this regard:

a. Hazard mapping and monitoring
b. Coastal zone surveillance
c. Forest carbon accounting

While some still require underlying research, that research will supplement understanding in the other application areas identified from the case studies where work is still needed. Thus, while important in their own right, a focus on these three will form the basis of longer term and wider SAR applications in Australia. This is consistent with the philosophies adopted by overseas agencies engaged in SAR; not a “field of dreams” approach, but recognition of the incipient importance of the technology to many public-good and commercial applications, and the need to be situation-ready when the various R&D programs conclude, and when innovative applications present themselves. It can be a technology with long development and investment cycles.
5 Future Trends

While factors such as the future potential of technologies are generally antithetic to significant public investments, the state of development internationally of SAR applications, derived products and methods for SAR image understanding, means that the technology has not reached a sufficient level of technical maturity to ignore future potential altogether. If Australia waits until many of the emerging applications have matured then it may have to be a fast-follower if it wants to realise commercial benefits\(^3\), particularly in the value adding sector. It may also find itself in the position of having to license intellectual property developed by other nations for its own needs.

The alternative is to engage in, and even partly lead, new developments so that intellectual property rights are more likely to be available directly for use, rather than by way of license. That of course entails taking risks by funding new research, but 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.

To position Australia well in this regard investment would be needed to enhance the skills of the Australian SAR work force, including in research. While analyst expertise is important for interpreting optical imagery, the degree of knowledge required for radar image interpretation is of a higher order, owing to the much greater complexity of the data. This point is taken up in the next section in relation to value adding.

6 Investment Segments and Training Complexity

There are various ways of compartmentalising the SAR image capture and utilisation chain to help understand where investments might be placed. One is shown in Fig. 1, and consists of three broad elements acting in sequence to convert radiation scattered from the landscape into products of value to a variety of end users. These are:

a. **The Space Segment**, consisting of the satellites themselves and the need to launch and place them into orbit. It also includes the SAR sensor. This segment converts backscattered radiation measurements to data ready to be downlinked to the ground segment.

b. **The Ground Segment**, consisting of the receiving hardware and antennas, and the software, needed to convert the data recorded by the satellites, and subsequently downlinked, into image products for provision to users. It also includes station keeping hardware and software to maintain satellites in the correct orbital position.

---

\(^3\) While a fast-follower strategy might make sense for high volume, low complexity products such as mobile telephones and motor vehicles, the uniqueness of derived products from radar imagery, and the intellectual investment behind their creation, makes it a risky approach if the products are expected to have high value in resource exploitation and national interest applications. As the perceived economic gain derived from a given product goes up then so does its value and price. That has to be balanced against being in at the beginning.
c. **The Value Adding Segment**, consisting of those organisations and individuals expert in applying radar data and in deriving innovative products, along with specialised software; these convert image data to value added and derived products (such as topographic and thematic maps, and maps of coherence).

This decomposition is used in the next section to focus attention on specific investment options. Here we take up the essential aspect of training. Investment in value adding requires a skilled workforce, particularly in operational use, as against research. Without a skilled workforce there is little sense in ground and space segment investments, so that we are led naturally to the value adding segment as Australia’s first priority for investment.

![Diagram of SAR system](image)

**Fig. 1.** The three segments of a SAR system; the blue (shaded) line shows the value enhancement chain and the conversion roles of each segment in the chain.

For SAR image analysis the interpreter has to understand, at minimum, how the scattering behaviour of earth surface features depends on wavelength, look angle and polarisation state. The latter two are not relevant to optical imagery. When interferometric products are of interest the analyst has to be aware of the performance limitations of the imaging geometries selected, along with the importance of derived properties such as coherence as diagnostic tools. The emergence of techniques such as tomography opens prospects for better information extraction for some applications, but again the complexity in understanding both the imaging process and what is being mapped is much greater than for optical image interpretation.

As a consequence the level of training required for radar image understanding is high. Australia was well positioned in the 1980s and 1990s in terms of radar image interpretation skills, with expertise available in DSTO, CSIRO and the universities, but, with a few exceptions, much of that expertise was either allowed to dissipate or has not kept pace with recent developments. If Australia is to make optimal use of existing SAR technologies and ensure it is well skilled to accommodate newer and emerging developments, then it needs agencies with radar expertise not widely available at present.

---

Because of the danger of losing key skills if significant experts leave in this highly complex technology, Australia ideally should have at minimum three agencies with the appropriate expertise. Because of technology developments they must be underpinned by research components.

There would also be value in having available skilled personnel who would operate on a commercial basis to undertake the interpretation task for both commercial and government users, either independently or collaboratively, so that optimal use of the technology can be realised. Those data interpreters would need to provide on-demand services in response to particular application needs, and could also provide their own speculative derived-products into the marketplace.

The interpretation scenario is even more complicated when coincident radar and optical data sets are to be analysed in combination. Because the two imaging modalities respond differently to earth surface properties, their use together will often allow better value added products to be derived. The complexity of knowing how to combine the data sets again, almost certainly, means that the average user will not have the expertise in both modalities and in how the information they provide on the landscape should be fused. The notion of image interpretation services noted above would seem to be needed for a successful operational remote sensing program.

That leads to an additional beneficial consideration, based on providing a radar remote sensing service into our region.

Providing a regional value-adding operation would open up a significant service sector to Australian agencies skilled in the use and interpretation of SAR imagery and its derived products. Because Australia’s major regional neighbours lie in the tropical zone, cloud cover presents a significant barrier to routine and successful resource assessment from space using optical technologies. Since cloud cover is not important to radar imaging, SAR is an ideal technology for the tropics and has been so recognised for many decades. Yet its successful application requires advanced skills, and certainly an expertise base an order of magnitude greater than that needed for optical image interpretation. With appropriate investment in training to re-equip Australian researchers and applications specialists Australia would be well placed, because of its alliances and trade ties, to provide such a service. It would represent a large and evolving market for Australian commercial operators and could form part of a regional aid program of significance. It is difficult to quantify the market, but econometric modelling, informed by EOS experts, would allow reasonable estimates to be derived in the short term.

Although the three-segment model of Fig. 1 has been proposed here as a means for understanding the cost of engaging with SAR remote sensing, it is a model that could also be applied to understand the economic value of entry at various points in any earth resources data acquisition system. By focusing separately on the space, ground and value adding segments it is possible to weigh the level of investment in the hardware segments against the economic value estimated to accrue from product generation. If increased funding of the space and ground hardware leads to image data of higher economic value, including the implicit value in being able to influence tasking of the space and ground segments, then the hardware investment would be justified. Otherwise national interests would be served by remaining a purchaser of data.
7 Investment Options and Timelines

When contemplating increasing Australia’s public investments in SAR as an earth observation technology, it is necessary, first, to decide to which of the segments in Fig. 1 major expenditures should be directed, if not all three. Clearly, Australia’s major interest is in end products and so, at minimum, the value adding segment should be its first priority, as noted above. Investment in that segment alone means 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.

In order to have a say in data specification, and to guarantee continuing access in the longer term, it would be necessary for Australia to be seen as investors in data acquisition\(^5\). That means it has decisions to make in terms of ground station provision, satellite provision, or both, and on the extent of its involvement. Ultimately, of course, it may determine that it is in its national interest to have a dedicated spacecraft and ground receiving facility. That is an expensive and high-risk pathway\(^6\), and it is difficult to see it as supportable in the foreseeable future for purely civilian applications. Nevertheless it is shown as one of the choices in Fig. 2, which lays out five alternative pathways that Australia may wish to consider, and from which we draw the following observations.

Although not as expensive as a dedicated Australian spacecraft, the option of an Australian instrument on the satellite of another nation is appealing, but involves several assumptions: that bus mass and space can be negotiated; that Australian expertise is available for design and maintenance; and that the risk of launch or equipment failure is acceptable. It would seem that this may be a better option once Australian expertise has improved and Australia’s position as a partner in data acquisition has been secured by other, less risky and lower cost approaches.

The option of seeking to be a partner in the program of another nation offers several benefits as a means for developing Australia’s reputation as part of the supply community and in terms of buying its seat at the international table of decision makers in SAR technology. It is lower in cost than the options of supplying Australian hardware, and yet should give it a say in the data types of importance to Australian mapping and monitoring needs. It is the option promoted here, and is developed further in the following analysis. It has the added advantage of sitting midway between a full dependence on overseas supply, as at present, and a totally Australian SAR system, and thus can form part of an evolutionary pathway – or road map – that we take up below.

---

\(^5\) In the three transitions shown in Fig. 1, that from radiation to data, while essential, adds least value but requires the largest investment in terms of funding the space and ground segments. In contrast, the value adding segment of imagery to products is the least expensive, relatively, yet it adds most value to the information chain. It would not be unreasonable for the operators of space and ground hardware to anticipate increased contributions from those who benefit substantially from value added activities using their data.

\(^6\) Currently a build and launch would cost in the vicinity of $400M. While launch services are available from, for example, the US, Russia or India, the investment risk is high because of launch or instrument failure. While capital loss can be indemnified, opportunity costs incurred through single launch failures cannot.
Having selected a partnering option the decision that then needs to be taken is whether Australia seeks a role in current programs or in those that have been approved for the future. There seems little value in the former since there is no room to tailor programs to Australian needs and immediate Australian data access is not essential. The logical choice is to seek partnership in a program that has received approval to proceed but may still be open to partnering proposals. To minimise investment risk, future programs with a successful heritage are to be preferred. Figure 3 shows two possibilities in each of the common wavebands used in radar remote sensing, along with the single program proposed for S band. Table 3 shows the country or agency responsible for each mission. Which of those missions seems to meet Australia’s needs best?

From the findings in Section 4 it is seen that the Australia’s needs could be covered with a combination of L and X band imaging. If systems planned at those wavelengths also provided fully polarised imagery then best flexibility is offered in terms of future Australian applications, albeit after suitable research has been undertaken. It is therefore a viable option to seek partnership, for example, in SAOCOM (Argentina) and CSG (COSMO Sky Med Second Generation from Italy); this is
enhanced by the fact that Argentina and Italy are already collaborating in these missions. This would give near coincident X and L band imagery that is fully polarised. While it would be helpful to have P and C band data as well, it is difficult seeing the marginal cost-benefit of going to those additional wavebands for other than research purposes at this time. The X and L band combination should meet most operational needs for the foreseeable future and would also provide material for developing high levels of Australian skills in SAR research and image interpretation.

---

**Fig. 3.** Programs for consideration if the option is to seek partnership with future, approved missions

**Table 3.** Owners of the programs referred to in Fig. 3.

<table>
<thead>
<tr>
<th>Program</th>
<th>Responsible country or agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAOCOM</td>
<td>Comisión Nacional de Actividades Espaciales (CONAE)</td>
</tr>
<tr>
<td>PALSAR</td>
<td>Japan Aerospace Exploration Agency (JAXA)</td>
</tr>
<tr>
<td>HJ-1C</td>
<td>National Committee for Disaster Reduction, State Environmental Protection (NDRCC/SEPA)</td>
</tr>
<tr>
<td>Radarsat</td>
<td>Canadian Space Agency (CSA)</td>
</tr>
<tr>
<td>Sentinel</td>
<td>Global Monitoring for Environment and Security (GMES) program, ESA</td>
</tr>
<tr>
<td>TSX-NG</td>
<td>German Aerospace Center (DLR)</td>
</tr>
<tr>
<td>CSG</td>
<td>Italian Space Agency (ASI)</td>
</tr>
</tbody>
</table>

Other options are possible, including the TSX-SG program and PALSAR-2, but the timeframe and existing linkages of the SAOCOM/CSG combination means that that would be a high value alliance.

---

SIASGE consortium: Italian-Argentine Satellite System for Emergency Management, a joint programme of the Italian Space Agency and the Argentine Space Agency CONAE (Comision Nacional de Actividades Espaciales)
partner. The C band Radarsat and Sentinel programs would be acceptable, but would represent a wavelength compromise for the applications of importance to us.

Having chosen, in principle, the route of partnering in the space/ground segment, how can Australia’s investment be best utilised? Figure 4 shows a pathway for pursuing the option of seeking partnership in the X and L band programs of other nations\(^8\). It is structured so that the value added segment is enhanced first, in preparation for entering the partnership. Should a decision be taken not to proceed to invest in hardware segments then the funding of value adding is not wasted. Essentially, it means a reversion to the last configuration of Fig. 2, albeit with a much better informed and active value adding sector than is currently the case.

---

\(^8\) The costings for the options in Fig. 4 have been drawn from *Robust Imaging from Space*, August 2012.
If the decision is taken to proceed with a space/ground hardware partnership then, along with the investment in value adding, expertise will be developed in order to consider ultimately whether a fully Australian program is warranted, or whether Australian needs remain served by working in collaboration with other nations. That decision point is also shown in Fig. 4. A benefit in delaying that decision is that the world of platforms is changing from total reliance on large, single and expensive busses to clusters of smaller satellites. Clusters have the advantages of sharing the risk of launch and bus failure over several platforms, and improving temporal coverage. The small COSMO Sky Med cluster is a good early example of this principle. But there is still some way to go in terms of proving the value of microsatellites for SAR applications, particularly at the longer wavelengths.

This can now be encapsulated in a recommended strategy, as outlined in Table 4. It is based on the nesting of options shown in Fig. 4 and the principle that a decision not to proceed to a subsequent phase does not waste investments to date. The timetable shown in Fig. 4 is set by the projected launch dates and lifetimes of the Argentine and Italian programs that could form the centrepiece of Australian investment in space and ground hardware. Should different international partners be contemplated there would need to be a commensurate adjustment to Fig. 4 and Table 4.
**Table 4.** Decision roadmap for enhancing Australian SAR engagement for earth observation

<table>
<thead>
<tr>
<th>Phase</th>
<th>Sequential decisions</th>
<th>Typical reasons behind decisions</th>
<th>Likely subsequent activity</th>
</tr>
</thead>
</table>
| 1     | Fund enhanced value adding segment | 1. Agreed SAR benefit in coastal monitoring, hazard mapping, carbon accounting and topographic applications.  
2. Acceptance of the potential for SAR in agriculture, forestry and urban environments.  
3. Need to create a better Australian skills base in SAR earth observation.  
4. Can use the outcome of 3 to explore future benefits of SAR and derived products.  
5. Attractiveness of potential regional markets and aid programs. | 1. Fund up to three R&D centres to build a critical mass of expertise.  
2. Provide assistance funding for small business to establish value adding agencies for SAR, and SAR in combination with other data types (optical, thermal, lidar).  
3. Initiate a detailed study of the benefits of investment in the space and expanded ground segments made possible by partnering in overseas L and X band programs.  
4. Alternatively, conclude that Australia’s earth observation future does not rest heavily on SAR, apart from the use of data from other operators, and proceed no further. |
| 2     | Fund partnering in the space segment and any necessary additional ground facilities. | 1. The results of the detailed study in Phase 1 have demonstrated the cost-effectiveness and public benefits of this solution.  
2. Delivers some control over when and where SAR data is acquired, suited to Australian needs.  
3. The need to develop greater Australian experience with SAR instrumentation and space platforms is now a driver. | 1. Determine the most appropriate programs in which to seek equity and initiate discussions with relevant agencies.  
2. Determine the optimum time to enter the space segment.  
3. Determine the funding model.  
4. Determine the lead Australian agency for this Phase.  
5. Based on the early experience with this Phase, and a detailed study of cost-effectiveness, explore the advantages of a dedicated Australian space segment based on either a single platform or a cluster. This could involve the provision of Australian instruments, or the design of a complete platform(s). |
| 3     | Fund a dedicated Australian space segment. | 1. The Phase 2 studies have identified significant benefits (spatial and temporal coverage, wavebands and polarisations) in having an Australian platform or platforms. | 1. Determine the funding model.  
2. Determine the lead Australian agency for Australia’s long term SAR program.  
3. Initiate a study of a follow-on program, possibly with both public and private equity. |
APPENDIX A

Case Studies

Case Study 1: Hazard Mapping – Floods
Observing flooding over large areas even in cloud cover and at night

Case Study 2: Soil and Plant Moisture Determination
Measuring agricultural field soil moisture and biomass even through clouds

Case Study 3: Ship Localisation and Surveillance
Observing ships reliably under all weather conditions

Case Study 4: Improved Vessel Detection by Reducing Sea Clutter
Detecting vessels at sea even in moderately rough sea states

Case Study 5: Forest Biomass Assessment
Estimating forest biomass over large areas

Case Study 6: Terrain Deformation Mapping
Accurately assessing deformation resulting from earthquakes, subsidence and ground water changes over large areas

Case Study 7: Oil Slick and Sea Pollutant Monitoring
Detecting and monitoring oil spills over large areas

Case Study 8: Aquaculture
Identify and manage fish and shrimp farms over large areas
**Case Study 1: Hazard Mapping – Floods**

*Observing flooding over large areas even in cloud cover and at night*

**Objective and data used**
To assess the ability to estimate the extent of flood inundation from satellite imagery. X band COSMO SkyMed data and L band JERS-1 data.

**Findings**
The studies cited below under Source Documents identify the benefits of the property called SAR coherence as a more effective tool for flood inundation than the simple, recorded image product. Using near-coincident Landsat imagery to delineate flood boundaries in Wanaaring and Goodoga in 2010, Xiaojing and Ge found that SAR coherence based maps were between 88% and 98% accurate. It needs to be kept in mind that the Landsat data could only be used as a baseline because there was no cloud cover at the time the experiment was carried out. In contrast, data for generating coherence maps can be obtained under virtually any weather conditions, and certainly when cloudy.

**Lessons for Australia**
This application of SAR is well suited to mapping and monitoring large scale coastal and inland flooding, such as happens all too regularly in this country. It is a reliable technique, both theoretically and because it is time of day, and weather independent.

**Methodology**
In case study 3 below, interferometric coherence, effectively the degree of pixel-level correlation between two scenes, is used to mask out water and to allow ships and other hard targets to be discriminated more easily. Because the water surface is constantly changing its coherence is low compared with cover types that don’t change between acquisitions. When SAR is to be used for flood mapping the opposite strategy is used. We look for regions of low coherence because they are associated with flood waters. That is the simple basis behind these two studies. While flood extent in open regions can also be gauged from optical imagery, a major benefit of radar is that long wavelengths penetrate canopies allowing the flood outline to be delineated in forests, such as in the Amazon and in riverine regions in Australia, again using interferometric coherence.

Northern NSW flood as seen by colour IR aerial photography, mapped by GPS from helicopter and as mapped using X band SAR coherence (blue). From Linlin Ge, E., Simmons, D. Abernathy, X. Li, 2010. Integrated remote sensing for monitoring major inland flood events in New South Wales, Australia. *The 15th Australasian Remote Sensing & Photogrammetry Conf.*, Alice Springs, Australia, 13-17 September, p. 293-312. Used with permission of SSSI.

**Limitations**
Time of acquisition is the major limitation in this application. With current missions the technique cannot be used reliably on-demand, but it can certainly be applied to map longer term (days to weeks) inundation once imagery has been recorded. At best, turnaround times would take several hours from satellite overpass to provision of imagery to emergency responders.

**Source documents**
### Case Study 2: Soil and plant moisture determination

**Measuring agricultural field soil moisture and biomass even through clouds**

<table>
<thead>
<tr>
<th>Objective and data used</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reasonable agreements were found with predicted soil moisture content from radar data and commensurate rainfall records. An important demonstration in this study was the strong empirical relationships between L and X band radar responses, and soil moisture and plant water content. The study draws attention to previous research that has demonstrated a strong relationship between like (HH) and cross (HV) polarised L and radar response and the moisture content of moderately rough, bare soils. The dependence of plant water content on radar wavelength was different for narrow and broad leaf crops, and highlighted the benefit of having two widely separated wavelengths; horizontally polarised L band was seen to be well correlated with the water content of broad leaf crops such as sunflower, corn and sorghum, while vertically polarised X band was seen to have a strong negative correlation with the water content of narrow leaf crops such as wheat and alfalfa.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lessons for Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notwithstanding the technical difficulties encountered in this study, and a slightly questionable approach, it produced enough evidence to demonstrate the viability of assessing crop and soil moisture contents in the microwave wavelength range. Although it is not clear whether this is a more successful methodology than other remote sensing techniques for biomass and soil moisture determination, the all-weather capability of radar makes it attractive. Even though Australia’s cropping regions are generally not heavily cloud covered there is anecdotal evidence that the repeat cycles of most optical missions that might be used for crop assessment still encounter clouds, causing problems when time series information is important for modelling.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-agricultural cover types were masked out so they would not interfere with the study. Empirical relationships between radar backscatter in the two wavebands, and plant water content and soil moisture content, were supplemented by scattering models that allowed soil surface roughness to be accounted for. A neural network classifier was used to generate maps of soil moisture content and plant water content (biomass) for a region in Lombardy, Italy.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>As with many similar studies the availability of data was a major limitation. Temporally coincident L and X band imagery was a significant concern, and points to operational difficulties if the radar data required in studies such as these is not recorded by the same platform or by platforms that are scheduled to provide near simultaneous coverage. Such scheduling could only be expected if different platforms are part of a partnership consortium, such as SIASGE that underpins this work.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source document</th>
</tr>
</thead>
</table>
# Case Study 3: Ship Localisation and Surveillance

**Observing large ships reliably under all weather conditions**

## Objective and data used
Detection and recognition of ships as an adjunct to the automated identification system (AIS). TerraSAR-X, X band imagery in ScanSAR, strip and spotlight modes.

## Findings
Vessels over 60m in length were detected 93% of the time in this study by developing a linear regression between the actual length and that assessed from radar imagery. Sea state often created problems for the detection of smaller vessels. Otherwise there was a remarkable correlation (95%) between the radar estimated ship length and the actual (AIS) value. AIS is a European Automated Identification System used with commercial and other cooperative shipping.

## Lessons for Australia
Because of the length of our coastline and the size of the extended economic zone, this approach is appealing as a potentially cost-effective means for shipping surveillance and identification. Clearly, the technique needs to be refined to give better results on smaller vessels and those with non-metallic super structures. In Case Study 4 we see an innovative means for reducing sea clutter and thus improving the chance of positive detection and reduced false alarm rate, possibly for smaller vessels as well.

## Methodology
Using shoreline data land was masked out of the imagery; range and azimuth ambiguities from strong shore or sea based features were modelled and removed, as were antenna side lobe effects. A constant false alarm rate (CFAR) detector was then applied to allow ships to be identified successfully against sea scatter. The hijacked MV Sirius was used as a target for part of this work. Broad coverage ScanSAR imagery was used to locate the vessel, while strip and spotlight images were used for precision location and vessel length assessment. Vessel velocity determination was also carried out by producing two degraded resolution products from each original image, and then looking at the displacement between them. Automated Information System (AIS) data was used both to assist in identification and to corroborate the results obtained on vessels so equipped.

## Limitations
For non-cooperative (non-AIS) vessels, the several-day time lapse between SAR acquisitions means that vessels, once found, could be lost before the next satellite overpass. Although X band maximises the ship radar signature it also generates significant sea clutter and thus lowers the signal to noise ratio for the CFAR detector.

## Source document
Case Study 4: Improved Vessel Detection by Reducing Sea Clutter

Detecting vessels at sea in moderately rough sea states

Objective and data used
Reliable ship detection against sea state noise
COSMO SkyMed quad polarised X band imagery

Findings
SAR coherence has been seen to be an excellent mechanism for improving the chance of vessel detection against sea state clutter. That is particularly important at X band, because it allows the high target signal strength to be exploited.

Lessons for Australia
Multiple time imagery makes coherence analysis possible and, as demonstrated, that has the potential to improve the chance of vessel detection in our region. The COSMO SkyMed program is dual use (civilian and military) largely because of its high resolution, high chance of detection, X band capability. Such dual use arrangements should not be overlooked in Australian SAR planning. In principle, the approach here could be used with the spotlight mode of Case Study 3 to help in ascertaining vessel characteristics, including shape and length.

Methodology
Although similar in intent to the previous case study this one demonstrates an innovative approach that makes special use of the coherent and polarised nature of SAR data to enhance the prospect of detection of ships and other structures such as oil platforms. Effectively, it minimises the confounding effect (clutter) of sea surface scatter. Because of the time offsets of the different polarised signals in COSMO SkyMed, sea surface returns are uncorrelated over the short period between the transmission of different polarisations, whereas the correlation is maintained across polarisations for hard, constant targets such as ships.

Limitations
The major limitation is the availability of SAR acquisitions at the time required. In this exercise the target zone was fixed to the region around the Deepwater Horizon accident.

Source document
**Case Study 5: Forest Biomass Assessment**

*Estimating forest biomass over large areas*

<table>
<thead>
<tr>
<th>Objective and data used</th>
</tr>
</thead>
<tbody>
<tr>
<td>To assess the ability to estimate forest stand biomass from L and P band radar imagery. Aircraft P and L band SAR data, along with laser scanning to assist in biomass ground truth estimates.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation between both like and cross polarised backscatter at the longer wavelength P band and L band imagery was demonstrated, although it was seen to be stronger at P band. The L band data showed saturation at biomass levels of about 150t/ha, whereas the relationship at P band was fairly linear up to 290t/ha. Biomass estimates had errors in the range on 38-46% for the L band data and 18-25% for the P band data.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lessons for Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>This is one of those applications that is classically matched to Australian conditions and needs. The area to be assessed for forest carbon accounting is vast and there are no other viable techniques for tackling the problem. Provided biomasses do not exceed about 150t/ha, we learn from this study that L band data will be acceptable in our context, but the research has still to be completed. Also, this work, being based on aircraft data, could not control the effect of incidence angle. Early Australian radar research on forest monitoring with radar (Z. Ahmed and J.A. Richards, Multiple incidence angle SIR-B forest Observations, <em>IEEE Transactions on Geoscience and Remote Sensing</em>, vol. 27, no. 5, September 1989, pp. 586-591) showed the importance of incidence angle on biomass (age) saturation and the value of building structural forest models rather than relying totally on regression relationships.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem biomass ground truth was generated by using laser scanning to estimate stem volume; from this above ground dry biomass was derived via previously determined relationships for different tree species. Regression equations were then used to relate like and cross polarised backscatter in the two radar wavelengths to laser scan estimates of stem biomass. The regression parameters had to be estimated and several simplifying assumptions were needed to keep the problem tractable.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>This is an immensely complex problem, especially because of the difficulty in getting reliable ground truth estimates of dry above ground biomass. Nevertheless, the technique remains one of the only feasible prospects for forest biomass assessment on a wide scale, and is being pursued by many investigators.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source document</th>
</tr>
</thead>
</table>
Case Study 6: Terrain Deformation Mapping

**Accurately assessing deformation resulting from earthquakes, subsidence and ground water changes over large areas**

**Objective and data used**
To measure the degree of land subsidence resulting from mining and ground water extraction, and to note landform changes associated with seismic events and changing swamp water levels. Along track (different time) interferometric SAR (InSAR) data, L, C band and X band.

**Findings**
Land subsidence, and change generally, is readily detected using DInSAR techniques.

**Lessons for Australia**
This procedure is easily implemented, skills are available, and there are generally no timing concerns.

**Methodology**
By interfering two or more images recorded from the same orbital position at different times it is possible to measure changes that have occurred to the landform between acquisitions. This is a very sensitive technique, allowing changes of the order of a centimetre easily to be measured. The technique of differential InSAR (DInSAR) is used to allow the effect of the underlying static topography to be removed as a potential error source. The method can map changes associated with volcanism, landslides, earthquakes, mine subsidence, urban subsidence as a result of ground water removal, and variations in water level in a swamp.

**Limitations**
While the technique is highly sensitive to small changes, verification that the levels indicated by the radar are accurate remains a concern for some investigators. Nevertheless, as a detection technique it is unmatched for simplicity. If there is overlying vegetation the sensitivity can suffer if the imaging wavelength is short.

**Source documents**


### Case Study 7: Oil Slick and Sea Pollutant Monitoring

**Detecting and monitoring oil spills over large areas**

| **Objective and data used** | To detect oil spills.  
Simple L band radar imagery. |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Findings</strong></td>
<td>Oils slicks and other sea surface pollutants are readily detected in SAR imagery because they damp the sea surface capillary waves that couple to radar energy.</td>
</tr>
<tr>
<td><strong>Lessons for Australia</strong></td>
<td>With our large coastline and economic zone radar imaging is a convenient method for detecting and long-term monitoring of sea surface pollutants.</td>
</tr>
<tr>
<td><strong>Methodology</strong></td>
<td>Detection and monitoring oil slicks and other sea surface contamination with imaging radar was demonstrated with the first of the space borne systems available, some 35 years ago. A classic image is shown below which clearly delineates an oil spill or other pollutant as a set of darks streaks. Radar energy couples to the small capillary waves on the ocean’s surface caused largely by wind ruffling. If those capillary waves are damped, as a result for example of an oil slick, then the radar response is commensurately damped. Two ships are visible sailing upwards and downwards in the image. The radar illumination was from the bottom. The ships are evident by their bright returns and by their wakes; the latter are visible because they disturb the surface capillary waves. The wakes are, however, displaced from the ships because of the Doppler-based signal processing that is used to create an image from the raw radar data in SAR. If the ships were sailing across the image then the wakes would be in line, but displaced forward or aft of the respective vessel.</td>
</tr>
</tbody>
</table>

| **Limitations** | The only significant limitation for fast developing slicks is the revisit cycle of the radar platform(s) |
**Case Study 8: Aquaculture**

*Identify and manage fish and shrimp farms over large areas*

**Objective and data used**
To map and monitor fish and shrimp farms
C band Radarsat and ERS imagery.

**Findings**
Shrimp and fish farm inventories are readily carried out using SAR data, and updating is straightforward. From field testing, the accuracy of identification of fish ponds was in the high 90% range in the study by Travaglia et al. For shrimp farming in Sri Lanka the cost was estimated to be 2.35 USD per square km to do the initial inventory with 0.80 USD per square km for regular monitoring.

**Lessons for Australia**
Any tropical Australian aquaculture can benefit in the same manner as in this study but, more significantly, this is an application of particular importance to our regional neighbours. A skilled Australian value adding sector could assist in this work.

**Methodology**
Because much of the world’s fish and shrimp farming occurs in tropical and sub-tropical zones cloud cover is a particular problem for regular monitoring, making radar an ideal imaging modality for aquaculture management. Radar imaging offers an additional advantage because of its sensitivity to geometry and, in particular, to the walls of dykes that are used for the farms; those dykes are easily discriminated from open water and other water-covered surfaces, making shape detection as a method for pond identification a valuable analysis tool in the context of a GIS for the region of interest.

**Limitations**
Largely the processing skills required.

**Source documents**
APPENDIX B

The Technology of Synthetic Aperture Radar

A. Basic Terminology

Although the term synthetic aperture radar (SAR) is commonly used, and is adopted in this report, it is actually a means to an end. As we will see shortly, we are really interested in forming images of the earth’s surface with radio waves – more particularly microwaves – to complement the optical images recorded by missions such as Landsat and weather satellites. Employment of radar as a specific technique is only significant in so far as it helps in resolving the landscape into discrete picture elements in one spatial dimension. Resolution in the other spatial dimension is provided by a signal processing technique called aperture synthesis. Together, using the concepts of synthetic aperture and radar allows the landscape to be resolved into rectangular, discrete picture elements, or pixels.

The term optical is used to imply imagery recorded in the range of wavelengths of human vision and just beyond, out into what we call the reflective infrared region.

There are also thermal imagers which, when carried on remote sensing platforms, create images of the heat distribution emitted from the earth’s surface, largely as a result of its own temperature and surface thermal properties. We will have less to say about thermal earth observation in this report than optical and microwave imaging.

B. Fundamental Concepts

Optical instruments form images of the earth’s surface using reflected sunlight, much as a person sees features when looking out the window of an aircraft. The technical characteristics of the instruments allow the images to be recorded in a range of separate wavebands, some in the region visible to us and some outside the range of human vision, into the infrared. It is this collection of wavebands, sometimes as few as three and sometimes as many as 200 or more, that allows different features on the surface to be identified. Images are formed in each waveband so that the spatial distribution of features can be mapped; those images are characterised by their spatial resolution in metres, which defines the pixel size and which describes the smallest detail that can be detected, and the image or frame size, usually expressed in kilometres.

The main difference between optical and SAR imaging is that, with radar, we assume there is negligible solar energy reflected from the earth in the wavelength range of interest. We come to the relevant wavelengths below but, given there is no energy emanating from the surface, we have to provide our own source of illumination (or irradiation). As a result, a transmitter is carried on the platform and used to irradiate the portion of the earth’s surface to be mapped. Energy is scattered from the landscape and received back at the platform. The degree of scattering depends on the surface properties, and is thus diagnostic of what causes the scattering. That is our principal interest when using radar (microwave).

---

10 There is a small amount which forms the basis of passive microwave imaging, but we will assume it is insignificant here.
Providing our own source of microwave energy is the same principle as using a torch to see at night in the absence of sunlight. The reason radar technology is used, as we noted above, is that by sending out the irradiating energy in form of short bursts we can resolve the landscape into pixels broadside to the motion of the platform – the so-called across track direction. Spatial resolution in the direction parallel to the path of the platform – the along-track direction – is provided by the design of the antenna used to transmit and receive the radiation, and by the application of sophisticated signal processing techniques to the received backscattered signal, as noted earlier. For reasons that are not important in this short overview, the signals are radiated to the side of the platform, so the earth is viewed at an angle, rather than near vertically downwards as in the case of optical imaging platforms.

C. Wavelengths Used in Radar Imaging

Optical imaging wavelengths are those of visible and infrared light, typically in the range of 0.45-2.5μm. One μm is one millionth of a metre. The sun maximally radiates at about 0.5μm, and our eyes have high sensitivity in the vicinity of that wavelength.

Radar remote sensing technology uses short radio wavelengths called microwaves, typical of those used in television, mobile telephones, GPS and WiFi. To avoid interference with those and similar services the International Telecommunications Union prescribes specific wavebands for use in radar remote sensing.

Table B1 shows the terms used for the microwave portion of the radio spectrum, including the letter designators first used with radar wavelengths during the Second World War as a code\textsuperscript{11}. The designators shown are those adopted most commonly, but slight variants also exist. The wavebands of most interest to SAR remote sensing are L, C and X and, to a lesser extent, P and S. Although the K bands are shown for completeness they can be strongly affected by rainfall and the atmosphere and have not contemplated for use in remote sensing of the earth’s surface, except for specialised applications.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency range (GHz)</th>
<th>Wavelength range (cm)</th>
<th>Typical SAR wavelengths (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.3-1</td>
<td>100-30</td>
<td>66.7</td>
</tr>
<tr>
<td>L</td>
<td>1-2</td>
<td>30-15</td>
<td>23.5</td>
</tr>
<tr>
<td>S</td>
<td>2-4</td>
<td>15-7.5</td>
<td>12.0</td>
</tr>
<tr>
<td>C</td>
<td>4-8</td>
<td>7.5-3.75</td>
<td>5.7</td>
</tr>
<tr>
<td>X</td>
<td>8-12.5</td>
<td>3.75-2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Ku</td>
<td>12.5-18</td>
<td>24-16.7mm</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>18-26.5</td>
<td>16.7-11mm</td>
<td></td>
</tr>
<tr>
<td>Ka</td>
<td>26.5-40</td>
<td>11.7-5.5mm</td>
<td></td>
</tr>
</tbody>
</table>

It is critically important to note that microwave wavelengths are typically four to five orders of magnitude larger than optical wavelengths. As a result, we would expect earth surface features to

\textsuperscript{11} The following simple formula makes it easy to convert between frequency $f$ and wavelength $\lambda$:

\[ f(GHz) = \frac{30}{\lambda(cm)} \]
appear quite differently in the two imaging modalities, which indeed they do. That is because, first, the biophysical and biochemical properties of the materials making up the landscape are quite different at those wavelength extremes and, secondly, geometric detail looks different.

D. What Radar Sees

When we view the landscape at optical wavelengths we see colours determined by the pigmentation of plants, and the mineralisation of soils and rocks. We also see the effect of moisture content: for example parched clay appears bright, but immediately turns dark if splashed with water; likewise moisture stressed plants tend to be brighter and less colourful. With few exceptions we do not see through substances; the sun’s radiation is scattered from the surface layers of plants and soil. Blue and green optical wavelengths do penetrate clear water and can travel into leaves, but generally we regard what we see in optical imagery as coming from surface layers. Also, compared with the wavelength scale of 1μm, most surfaces appear rough. The exception is mirrors (including optical corner reflectors) and the mirror-like behaviour of smooth water, which gives what we call sun glint when seeing reflected sunlight.

At the much longer microwave wavelengths many surfaces can appear smooth, depending on the comparison of the scale of roughness and the actual wavelength. Pigmentation and mineralogy are not nearly as important as determinants of appearance in radar imagery as they are at optical wavelengths. Moisture, however, is a critical determinant of the strength of radar scattering from earth surface features. Although a little simplistic, we can say that geometry and moisture content are the two most important landscape determinants of radar scattering. Such a view helps us to appreciate why radar imaging is important in the following. Moisture content affects directly the electrical behaviour of earth surface materials, which is summarised in a property called dielectric constant or permittivity, frequently encountered when talking about the radar scattering properties of materials. More precisely we should talk about complex dielectric constant or complex permittivity, but that complication is mentioned here only for completeness, and does not affect what is to follow.

The effect of moisture content and geometry varies with wavelength, and introduces us to the importance of the different wavebands identified in Table B1. Fig. B1 shows the dependence on gross geometry diagrammatically while Fig. B2 shows both the effect of moisture and surface roughness quantitatively.

E. The Technical Advantages of Radar

Because a radar platform carries its own source of illuminating energy, one immediate advantage of radar over optical imaging is that it can operate at any time of day or night and is not subject to diurnal or seasonal variations in irradiation level. More importantly, radar imaging is unaffected by cloud cover\textsuperscript{12}, smoke and smog because those media are transparent at the wavelengths used for

\textsuperscript{12} While it may seem unusual that clouds are not a problem, while moisture content is a major factor influencing the radar response of earth surface materials, the water particles in clouds are usually so small that the radar energy passes straight through by means of forward scattering. The same is true of ice particles in clouds, but the effect is further reduced by the low dielectric constant of ice compared with free water molecules.
radar imaging. Rainfall is also generally not a problem except at the shorter wavelengths under heavy rain states.

Because SAR forms images to the side of the platform we can also control the look angle, which is the angle with which the landscape is viewed. That adds a degree of complexity because the landscape responds differently at different angles of illumination, and can appear distorted if the angle is too small (measured out from the vertical under the platform).

Fig. B1. The scattering of incident radar signals from fundamental earth surface geometries, and its dependence on wavelength. Taken from J.A. Richards, Remote Sensing Digital Image Analysis, Springer, Berlin, 2013.

F. Further Sophistication

Because we can control the energy that is used to irradiate the landscape an enormous level of sophistication is possible in the way images are formed and used in radar, well beyond what can be done with optical imaging.
First, we can control the *polarisation* of the radiation, which is a property that describes the plane in which radio waves oscillate, normal to the direction of propagation. Although it is not necessary here fully to appreciate its meaning, it is important to know that the antennas used in SAR usually launch the waves with the plane of the polarisation parallel to the earth’s surface – called horizontal (H) polarisation – or vertical to the earth’s surface – called vertical (V) polarisation.

Vertical polarisation is strictly a misnomer, but we can ignore that here. When the radar energy strikes a feature on the landscape its plane of polarisation can be altered. Typically, if the scene is irradiated with horizontally polarised radiation the scattered radiation can have both horizontal and vertical components. The same is true if the incident radiation were vertically polarised. If the radar is capable of radiating and receiving with both polarisations then four scattered signals will be received and four images can be formed: these are referred to as the HH, VH, HV and VV
components. Strictly, the first letter refers to the polarisation of the backscattered radiation, while the second refers to the transmitted polarisation, although some people use the opposite convention. The cross-polarised images VH and HV often contain information on complex media, such as tree canopies, that is not easily revealed on the HH and VV like polarised images.

There is a second property of the transmitted radiation that is not present in incident sunlight. It is called coherence, which relates to the purity of the signal and, in particular, what is called its phase purity. Again, it is not important fully to appreciate what that means, but its implication is profound because it allows us to take two SAR images of the same region on the earth’s surface, say from two slightly different directions or angles, or at different times, and form a difference-like image by means of what is referred to as interference. The new image can be used to map topography or to detect regions of the earth’s surface that have changed between the two acquisitions, as a result of earthquakes, land subsidence and similar.

Because SAR operates with coherent radiation we can use the principle of tomography, the same as used in CT scans, to form three-dimensional images of the interiors of volumes, such as forest stands. This is a newly developing area in SAR that is still in the research laboratory.

Taking all this into account we now have a variety of SAR types available, as summarised in Table B2. There are a number of variations on these configurations, and how they are used.

**Table B2.** SAR variants

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Polarisations</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAR or single polarisation SAR</td>
<td>HH or VV</td>
<td>The simplest configuration, and the one most often encountered in practice.</td>
</tr>
<tr>
<td>PolSAR</td>
<td>HH VH HV VV</td>
<td>The most general polarisation configuration.</td>
</tr>
<tr>
<td>InSAR (interferometric SAR)</td>
<td>HH or VV</td>
<td>Involves at least two SAR acquisitions of the same geographical region from which topography can be mapped.</td>
</tr>
<tr>
<td>DInSAR (differential interferometric SAR)</td>
<td>HH or VV</td>
<td>Involves at least three SAR acquisitions of the same geographical region, allowing changes in topography to be mapped.</td>
</tr>
<tr>
<td>PolInSAR (polarimetric interferometric SAR)</td>
<td>HH VH HV VV</td>
<td>Involves at least two SAR acquisitions of the same geographical region from which topography can be mapped. The multiple polarisations also make it possible to build descriptive models of the landscape.</td>
</tr>
</tbody>
</table>

Another generalisation of SAR technology involves having the source of irradiation and the radar receiver on separate platforms. That is known as bistatic SAR (as against monostatic when the same platform carries the transmitter and receiver). There are tactical defence benefits in such an arrangement, but it also gives a different view of landscape properties. Sometimes bistatic SAR uses the energy scattered from GPS signals that reach the ground. Work is now being undertaken on SAR configurations involving many transmitters and many receivers (called MIMO SAR), but that is well beyond the scope of this analysis.

**G. Summary of the Important Concepts**
The important details from the foregoing discussion are summarised graphically in Fig. B3. There is one further point of importance, relating to the width of the swath of data recorded. As shown, it is commonly referred to as *strip mode*, because of the strip of data being imaged. If spatial resolution can be sacrificed, then it is possible to image over a much wider swath, using the principle of *ScanSAR*. That allows much greater and thus generally more frequent geographical coverage.

There is another modality called *spotlight imaging*, in which the resolution, usually of point targets, can be increased significantly by steering the antenna beam as the platform passes so the target is kept in view, at different perspectives, for a longer time than would be the case with strip mode imaging.

---

**Fig. B3.** Summary of the space segment and ground processing used in SAR imaging.