Risks of Data Supply of Earth Observations from Space for Australia

Report prepared for the CRC for Spatial Information November 2015

Australian Government
Geoscience Australia

Australian Government
Bureau of Meteorology

CSIRO

Symbios Communications

crc•si

Funding for this project was provided by the Australian Bureau of Meteorology, CSIRO, and Geoscience Australia

LIST OF CONTENTS

EXECUTIVE SUMMARY

This supply risk assessment has considered a sample of requirements for Australian applications of Earth Observations from Space (EOS). These requirements were derived from case studies undertaken by ACIL Allen as part of a companion economic study which assesses the socioeconomic value of different EOS data applications. The case studies looked at agriculture, weather forecasting, ocean monitoring, water resource assessment, natural hazards and insurance, monitoring landscape change, and mining and petroleum.

Based on the case studies, the assessment canvassed experts to define priority data sets, helping to establish emphasis, from which four main instrument types were identified.

- **Low resolution optical data**: coarser than 80m spatial resolution (i.e. image pixel size).
- **Medium resolution optical data**: between 80m and 10m spatial resolution.
- **High resolution optical data**: finer than 10m spatial resolution.
- **Imaging radar (SAR) data**: C-, L-, and X-band radar spatial resolution 80m – 10m.

The assessment identified several other instrument types that are needed to fully address the requirements from the case studies: sounders and limb scanners; radar altimeters and scatterometers; passive microwave; hyperspectral imagers; LiDAR Altimeters; and, Digital Elevation Model (DEM) datasets which can be derived from a number of different instrument types.

Based on these requirements, current and future continuity of supply for the four main instrument types, and to a lesser extent the other types, was assessed. Based on this assessment, it appears that the EOS data requirements can be addressed to a significant extent – though adaptation will be required in order to make optimal use of supply options available.

Three broad conclusions can be drawn from the study:

- **The nature of the best available public good data streams for the four main instrument types will change.** Some of these changes will be positive, and some will be negative, but overall, supply for these types is expected to remain strong.
- **The additional data streams coming online in the 2015-2016 timeframe will greatly increase data volumes.** This is in part because of greater spatial and spectral resolution, in part because of more supply sources and more accessible archives, and in part because of greater revisit frequency. These factors mean that ground segment and data management solutions (e.g. the Australian Geoscience Data Cube, Google Earth Engine) will likely become more important in enabling users to be able to manage and make use of this new data. This also underscores the need for strong coordination with international partners, and potentially for new coordination frameworks (e.g. CEOS Virtual Constellations).
- **The cost of investing in a dedicated satellite space segment has reduced with advances in small satellite technology.** While public good data streams from overseas will continue to be the dominant supply, the business case for a dedicated Australian national Earth observing satellite or satellites, or contribution to an international partnership, looks increasingly attractive. Space segment investment would need to be supported by the ground segment, resulting in additional requirements to receive, standardise, and apply data in a common framework such as the Australian Geoscience Data Cube.

A number of points support these broader conclusions.

Evolution of Best Available Public Good Data Streams

- Australian EOS data requirements tend to reflect the best available public good data sources.
- Continuing close alignment with ongoing U.S. activities including missions from USGS (Landsat), NOAA (VIIRS), and NASA (MODIS, future technology) will help to ensure continuity of supply.
- Emergence of new operational data streams from Europe's Copernicus programme (e.g. Sentinel-1, Sentinel-2, Sentinel-3) will boost supply. Building the relationship with European agencies, and in particular the emerging EC and ESA programmes will build supply and bolster continuity prospects.
- The collaborative relationship with Japanese EOS data providers appears likely to continue to be complicated for non-geostationary data streams. Japan's geostationary Himawari-8 may enable new non-meteorological applications.
- China's EOS programme is actively working on an option for almost every instrument type included in the study, and has a broad and deep EOS programme under development (by a multitude of different agencies and institutes).
- India has chosen to invest in strong indigenous capacity to build and launch their own satellites with little outside support, but applications are largely focused on their particular national priorities.
- Sentinel-2A will improve upon Landsat-8's performance in terms of spatial and spectral resolution, and coverage area, and will greatly reduce medium resolution optical supply risk.

Increasing Data Volumes

- While new supply options could provide a major boost to a number of application areas, ground segment and data handling systems will need to be improved to take best advantage.
- Platforms like the Australian Geoscience Data Cube (AGDC), in combination with the National Computational Infrastructure (NCI), can offer scalable solutions to data handling and processing challenges.
- The development of national-scale solutions and supporting infrastructure will require significant investment, will carry a continuing operating cost, and may increasingly become an essential piece of the nation's spatial data infrastructure.

Space Segment Investment

- Overall, commercial data supply is strong, growing, and diversifying – which is producing increased competition. But acquisition costs will continue to throttle access for Australian users not accustomed to having budgets for data purchase.
- The emergence of lower cost platforms (e.g. CubeSats) based on development with commercial off the shelf (COTS) components will result in significant cost reductions in securing access to space infrastructure. If these platforms can reach a level of performance that makes them fit for purpose, they may potentially be disruptive.

INTRODUCTION

General

This document has been prepared by Symbios Communications Pty Ltd for the Cooperative Research Centre for Spatial Information (CRCSI). It is the final report on a Study on the Risks of Data Supply of Earth Observations from Space for Australia.

The CRCSI has overseen the coordination of different components of an overall study programme (Study on the Economic Value of Earth Observations from Space to Australia and Access to Enabling Data) and has brought together:

- economists (ACIL Allen) assessing the socioeconomic value of EOS applications;
- consultants (Symbios) studying the risks of space data supply; and,
- a Reference Group comprising key federal agencies that are stakeholders including Commonwealth Scientific and Industrial Research Organisation (CSIRO), Geoscience Australia (GA) and the Bureau of Meteorology (BOM).

The programme develops the necessary linkages for identifying applications to justify government support by virtue of their significant socioeconomic benefit to the nation and the circumstances around the supply outlook, including risk, possibility of commercial or public good availability, and the related costs. The Australian Government would like to establish line of sight between the applications of EOS data and their benefits, along with the relevant data supply mechanisms and their costs, to ensure clear business cases can be constructed for EOS data.

The scope of this document is to report on the assessment of the Earth Observations from Space (EOS) data supply for Australian operational activities (i.e. non-R&D), and to draw conclusions regarding the risks around different scenarios. In this case, EOS does not include airborne and *in situ* instruments.

Contents

Section 2 describes the seven application case studies chosen to match those selected for detailed economic analysis.

Section 3 describes the main EOS data requirements associated with each of the case studies. It also provides an overview and analysis of these requirements and identifies the most used and important data types for the nation.

Section 4 considers the EOS data supply heritage for each of the data types and summarises the current situation for each.

Section 5 provides an assessment of the future supply risk for the main data types, assessing the continuity outlook, the key missions and sponsoring agencies for Australia, the main risks and contingencies.

Section 6 presents benchmark costs for different scenarios, including continuation of the status quo with an emphasis on public good data; purchase of commercial datasets; or development and operation of dedicated space infrastructure such as a payload or small satellite.

Section 7 summarises the supply scenarios and presents conclusions.

APPLICATION CASE STUDIES

Overview

A companion economic study assessing the value of different EOS data applications was performed by ACIL Allen, and included seven case studies.

1. Agriculture
2. Weather forecasting
3. Ocean monitoring
4. Water resource assessment
5. Natural Hazards and insurance
6. Monitoring landscape change
7. Mining and petroleum

A wide range of applications and data requirements were identified in the case studies. These data requirements are analysed in Section 3, and form the basis for the supply analysis and risk assessment in Sections 4 and 5.

Applications and Targeted Areas

Agriculture considers the application of EOS data nationally, regionally, and at the enterprise level (i.e. on the farm). This includes more efficient management of government programmes such as drought relief and biosecurity (at the macro end of the scale), to the assessment of pastures, paddocks, and pest and crop data models.

The focus of the economic study is on both enterprise and paddock level applications in both broad acre agriculture and horticulture. Areas targeted include improved livestock and pastoral management, improved biomass monitoring, and reduced damage costs from better management of pests and diseases. The data security analysis also focuses on national crop monitoring.

Weather forecasting considers the role of EOS data in the accuracy and reliability of forecasts. EOS data has been instrumental in improving both short term and seasonal weather forecasting in recent years. This includes improved weather and extreme weather event warnings, efficiencies in agriculture, transport and offshore petroleum, and improved volcanic ash warnings for aviators.

The focus of the economic case study is on government weather services, the benefits of which are transmitted broadly across the community, including the public, industrial, and military domains. Benefit areas include efficiencies in industrial logistics and planning (e.g. aviation, shipping), reducing the cost of response to, and recovery from natural disasters, and agricultural efficiency.

Ocean monitoring looks at the role of EOS data in supporting monitoring and exploitation of Australia's vast ocean Exclusive Economic Zone (EEZ). This includes the ship tracking and monitoring of maritime borders, ocean conditions for fisheries, the monitoring of illegal fishing, and oil spill monitoring. In addition, ocean variables are a significant input to weather and climate modelling.

The focus of the economic case study is on marine water quality (in particular in the great barrier reef), conservation, and protection of the tourism industry. In addition, monitoring of oil spills, seeps, ocean colour, and plumes is covered. This data security study also looks at broad sea surface monitoring of temperature and topography.

Water resource assessment is a major concern to Australia, with water needed for irrigation (e.g. farmers, graziers), forestry, industrial users, environmental flows for the country's river systems, and for human consumption. Applications like land cover mapping, soil moisture mapping, surface and ground water modelling, catchment modelling, and supply and demand forecasting all make use of EOS data.

The focus of the economic study is on support to water resource assessments as part of overall catchment management and water resource planning, assessing water quality, helping to establish environmental baselines as well understanding changes over time.

Natural hazards and insurance benefits significantly from EOS data through improved national-scale estimation of potential damage and loss, damage reduction through more timely and better coordinated response, and through to improved claims management.

The economic study looks at several actors across the disaster cycle, including the insurance industry, emergency responders, government preparedness and recovery, and ultimately looks at the community benefits from improvements across these areas.

Monitoring landscape change focuses on vegetation mapping by the mining industry for licence compliance and by governments for land use monitoring. For industry, sovereign risk and the cost of compliance are reduced and the investment environment is made more stable, and for government, operating costs are reduced.

The economic study looks at increased efficiency in vegetation mapping, which translates into greater efficiency and lower costs. For the government sector, reduced costs for land use planning, regulation, and monitoring are explored.

Mining and petroleum uses EOS data in a number of areas, with the case study focusing on onshore mining, including vegetation mapping, exploration, open cut mining, and bathymetry.

The economic study looks at surface mineral maps produced from ASTER imagery, developed with the state Geological Surveys and Geoscience Australia, and delivered as pre-competitive geoscience data. In addition, it looks at monitoring open cut mining activities and stockpiles, and the monitoring Coal Seam Gas (CSG) well activities.

EOS DATA REQUIREMENTS

Approach

A wide range of data requirements were identified in the economic case studies. For the purposes of the supply risk assessment domain experts were engaged to identify the priority data sets (ideally no more than 2 or 3 in each case) considered the most critical for realisation of the application.

Table 1 lists the experts consulted, and the priority data sets and emphasis identified.

Application	Expert (Agency)	Priority Data Sets and Emphasis
Agriculture	Alex Held (CSIRO)	National Crop Land Use dataset
Weather forecasting	Agnes Lane (BOM)	BOM uses dozens of satellite inputs in its routine operations, but the following were identified as being a priority: Atmospheric sounder data Geostationary imagery Ocean vector winds and height
Ocean monitoring	Gary Brassington (BOM)	Given the many and varied possible specific topics under this heading, it was decided to focus on the requirements of the BlueLINK ocean monitoring and forecasting system for defence, shipping and offshore platform applications. The priority data sets in this case are: Global Sea Surface Temperature data set Global Sea Level data set
Water resource assessment	Luigi Renzullo and Juan Guerschman (CSIRO)	Water Resource Assessment data Soil moisture maps
Natural hazards and insurance	Norman Mueller (GA), Craig Arthur (GA), Martine Woolf (GA)	National fire monitoring data set National flood monitoring data set
Monitoring landscape change	Christian Witte (QLD Govt)	Land cover dataset Land use dataset
Mining & petroleum	Tom Cudahy and Cindy Ong (CSIRO)	Mineral maps for exploration Environmental monitoring of mines

Table 1 - Application experts and priority data sets

In each case, these experts have assisted with the specification of the EOS data type requirements associated with development of the relevant priority data sets and derived information. In an effort to provide comparable requirements, the experts followed a template with a standard description of the data including coverage, spatial and temporal resolutions, latency, and other important technical characteristics. The completed templates can be found in Appendix A, and a summary of required data types is presented in Table 4.

Data Type Definitions

The data types used in the requirements analysis are derived from the definitions in Section 1.3 of the *Australian Government Earth Observation Data Requirements to 2025*. Six types were defined in the report, including “Other EOS” which groups four others.

Data Type	Summary	Example Instruments
Low Resolution Optical	Optical imagery with a spatial resolution coarser than 80m	IMAGER (Himawari-7), AVHRR/3 (Metop-A and NOAA-19), VIIRS (Suomi-NPP) and MODIS (EOS-Aqua and EOS-Terra)
Medium Resolution Optical	Optical imagery with a spatial resolution between 10m and 80m	ETM+ and OLI (Landsat), SLIM 6 (UK-DMC-2), (Future: MSI Sentinel-2)
High Resolution Optical	Optical imagery with a spatial resolution less than 10m	WV110 (WorldView-2) (RBG), NAOMI (SPOT-7), REIS (RapidEye) and BGIS-2000 (Quickbird) (RGB)
Synthetic Aperture Radar (SAR)	Imaging microwave radars (active) generally using C-, L-, and X-band frequencies at spatial resolutions ranging from finer than 1m up to 10’s of m	C-Band: RADARSAT-2, Sentinel-1A L-Band: ALOS-2 X-Band: TerraSAR-X, TanDEM-X
Atmospheric LiDAR	Ultra violet, visible, near infrared and short wave infrared instruments with spatial resolution in the range of 100 m used to track aerosol and air molecules, measuring cloud top height and identifying atmospheric discontinuities	The only operational instrument in this category is CALIOP (CALIPSO)
Other EOS	– Radar altimetry – Microwave imaging radiometry – Cloud and precipitation radars – Microwave radiometers	Poseidon-3 (JASON-2), SIRAL (CryoSat-2), AMSR-E (EOS-Aqua), CPR (CloudSat) and Aquarius (SAC-D)

Table 2 – Data type definitions

During the course of the case studies and subsequent expert consultations, several additional data types were identified, and will be considered as "Other EOS". These are summarised in Table 3.

Data Type	Summary	Example Instruments
Very High Resolution Optical	Optical imagery with a spatial resolution finer than 1m	WV110 (WorldView-2) (panchromatic), BGIS-2000 (Quickbird) (panchromatic)
Atmospheric temperature and humidity profiles	Passive measurements of the distribution of infrared (IR) or microwave (MW) radiation emitted by the atmosphere – captured as either nadir soundings or via limb scanning	MW sounders: AMSU-A, ATMS, MWHS, IMWAS IR sounders: CrIS, IASI Limb scanners: GRAS, ROSA
Hyperspectral Imagers	Spectrally rich optical imagery simultaneously acquiring radiance measurements in many narrow, contiguous spectral bands, typically 100s of focused on adjacent regions less than 10nm, typically at spatial resolutions in "Medium Optical" range	Hyperion, (Future: HSI, HYC)
LiDAR altimetry	A satellite-based altimeter (as opposed to aircraft-based) that exploits LiDAR, generally with an accuracy of ~20cm for ice and land, and 75cm for clouds - other observations common to atmospheric LiDAR also possible, such as vegetation canopy height	Satellite: ICESat GLAS (past), (Future IceSat-2 ATLAS) *In Australia most frequently acquired by aircraft at present.*

Table 3 - Additional other data types

Case Study Requirements

An important feature of the design of the overall study programme is preserving the link between specific EOS data, how they are used for specific applications, and the measured benefits of those applications. This enables all of the elements of a business case to be derived.

Domain experts have identified what they consider to be the priority activities and data sets for each of the applications. The priority EOS data types supporting these applications are a subset of the numerous data types specified in the description of the case studies developed by ACIL Allen in the companion study.

To ensure that we have a consistent argument and retain the necessary *line of sight*, Table 4 compares the full list of data requirements identified in the case studies with the priority list developed with domain experts. The resulting requirements underpin the supply and risk analyses in Sections 4 and 5.

The data types included in the "Data Type" and "Priority Data Set Types" columns of Table 4 are expressed in the terms used by the case studies and expert consultations. In the "Priority Data Types for supply risk analysis", the types have been translated into the terminology defined in Tables 2 and 3.

Case study	Application	Data Requirement	Priority Data Set *[From Table 1]*	Priority Data Set Types	Priority Data Types for supply risk analysis
Agriculture	More efficient management of government programmes such as drought relief	Medium Resolution imagery	National Crop and Land Use Dataset	• Medium Resolution Imagery • Low Resolution Imagery • SAR	**High Resolution Optical** **Medium Resolution Optical** **Low Resolution Optical** **SAR**
	Pastures from space	High resolution imagery			
	Biosecurity				
	Pest and crop data models				
	Horticulture monitoring and management	High resolution imagery			
Weather forecasting	Weather warnings and impact on agriculture, transport and offshore petroleum	Infrared atmospheric sounding interferometer Geostationary imagery GPS-RO	Atmospheric sounder dataset Geostationary imagery dataset Ocean vector winds and height	• Atmospheric temperature and humidity sounders • Imagery derived from geostationary orbit (VIS and IR) • Radar altimeters	**Low Resolution Optical (GEO VIS and IR)** **Other EOS:** **Radar Altimetry** **Atmospheric temperature and humidity profiles (soundings and limb scanning)** **Microwave Imaging Radiometry (scatterometer)**
	Extreme weather event warnings	Geostationary imagery Advanced scatterometer	Geostationary imagery dataset Ocean vector winds and height	• Imagery derived from geostationary orbit (VIS and IR) • Radar altimeters	
	Volcanic ash warnings	Geostationary imagery	Geostationary imagery dataset	• Imagery derived from geostationary orbit (VIS and IR)	
Ocean monitoring	Ocean conditions to guide fishers	Sea surface temperature Altimetry Ocean colour Scatterometer	Global Sea Surface Temperature Global Sea Level	• Low resolution optical IR (i.e. radiometer) • Microwave (i.e. radiometer) • Precision Altimeter packages (i.e. altimeters)	**High Resolution Optical** **Low Resolution Optical (IR, i.e. radiometer)** **SAR** **Other EOS:** **Microwave Imaging radiometry (scatterometer)** **Radar Altimetry**
	Maritime borders and Illegal fishing monitoring	High resolution imagery SAR			
	Oil spill monitoring	SAR			

Case study	Application	Data Requirement	Priority Data Set *[From Table 1]*	Priority Data Set Types	Priority Data Types for supply risk analysis
Water resource assessment	Models: Surface and ground water, catchment, supply and demand	High resolution imagery Medium resolution imagery Low resolution imagery	Water Resources Assessment Soil moisture	• Very high resolution imagery • Medium resolution imagery • Low resolution imagery	**High Resolution Optical** **Medium Resolution Optical** **Low Resolution Optical** **SAR** **Other EOS:** **Microwave Radiometry (passive and active, soil moisture)** **Ocean Colour**
	Water Quality	High resolution imagery Medium resolution imagery Low resolution imagery Ocean colour	Water Resources Assessment	• High resolution imagery • Medium resolution imagery • Low resolution imagery	
	Soil moisture mapping	Microwave passive and active		• Microwave passive and active • SAR	
Natural hazards insurance	Preparing Responding Recovery Insurance	High Resolution Imagery (incl SWIR) Medium Resolution Imagery (incl SWIR) SAR	National fire monitoring National flood monitoring	• High Resolution Imagery • Medium Resolution Imagery • Low Resolution Imagery	**High Resolution Optical** **Medium Resolution Optical** **Low Resolution Optical** **SAR**
Monitoring landscape change	Vegetation mapping in the mining industry Generalised data for the tourism industry	Medium Resolution Imagery High Resolution Imagery	Queensland land cover dataset for natural resource management by government	• Medium Resolution Imagery	**High Resolution Optical** **Medium Resolution Optical**
	Land use data for government in regional and peri-urban areas Localised land use data for the property industry	High Resolution Imagery	Queensland land use dataset for natural resource management by government	• High Resolution Imagery	
Mining and petroleum	Exploration	Multispectral Hyperspectral Imagers VNIR-SWIR (at airborne resolutions)	Mineral exploration	• Multispectral VNIR (15 m pixel), SWIR (30 m pixel) and TIR (90 m pixel) • Hyperspectral Imagers VNIR-SWIR (at airborne resolutions) • Very High Resolution Optical	

Case study	Application	Data Requirement	Priority Data Set *[From Table 1]*	Priority Data Set Types	Priority Data Types for supply risk analysis
	Vegetation mapping Open cut mining	Very High Resolution Imagery DEM	Mineral mining and environmental monitoring	• Hyperspectral Imagers VNIR-SWIR (at airborne resolutions) • LiDAR altimetry • SAR/Interferrometry	**High Resolution Optical** **Medium Resolution Optical (multispectral VNIR, SWIR)** **Low Resolution Optical (TIR)** **SAR (Interferrometry)** **<u>Other EOS:</u>** **Hyperspectral Imagers VNIR-SWIR (at airborne resolutions)** **LiDAR Altimetry**
	Bathymetry				

Table 4 - Comparison of full list of data types with priorities

Requirements Analysis and Instrument Types

In order to enable the assessment of supply continuity, **the data type requirements gathered during the case studies, and the priority data sets identified by the domain experts, have been translated into the 13 instrument types** of interest listed in Table 5.

During the study, it was observed that often the minimum requirements indicated by respondents are essentially based on what Australia currently gets for free. For example, it was found that MODIS was often referenced as the minimum requirement for low resolution optical. And in this case, in practice the spatial and spectral characteristics of a comparable instrument like VIIRS might well be workable for most applications. The same applied for other class-defining instruments like Landsat.

The instrument type requirements across the case studies show that low, medium and high resolution optical, and SAR emerge as priorities, accounting for 20 of the 35 requirements. The next four types comprise the bulk of the remaining requirements, with very high resolution optical imagers, and three atmospheric/oceans-related data types are required in more than one case.

Case Study	Agri.		Weather		Ocean		Water		Hazard		Land Mon.		Mining		
Instrument Type	**C**	**E**	**C**	**E**	**C**	**E**	**C**	**E**	**C**	**E**	**C**	**E**	**C**	**E**	**Total Cases**
Low Resolution Optical		✓	✓	✓		✓	✓	✓		✓			✓	✓	6
High Resolution Optical	✓				✓		✓		✓	✓	✓	✓			5
SAR		✓			✓			✓	✓					✓	5
Medium Resolution Optical	✓	✓					✓	✓	✓	✓	✓	✓			4
Very High Resolution Optical							✓	✓			✓		✓	✓	3
Radar Altimetry				✓	✓	✓									2
Sounder			✓	✓	✓										2
Scatterometer			✓	✓	✓										2
Ocean Colour					✓		✓	✓							2
Hyperspectral													✓	✓	1
Passive microwave							✓	✓							1
LiDAR Altimetry and DEM													✓	✓	1
GRO			✓												1
Total Types	**4**		**5**		**7**		**7**		**4**		**3**		**6**		**35**

Table 5 - EOS data types by case study

C = case study reference, E = expert designation

Based on this breakdown, the supply outlook for the main four instrument types will be analysed more closely for risk and continuity of supply in Sections 4 and 5.

1. **Low resolution optical** (>80m) provides images over a wide swath (1000’s of kms) covering broad areas, but at coarser spatial resolution, and often with good spectral resolution – a.k.a. “MODIS class” instruments. In addition, this category is broad enough to cover both **ocean colour** (application-focused low resolution optical) as well as **sea surface temperature** from optical radiometers. The new generation of **geostationary imaging** instruments (e.g. Japan’s Himiwari-8) are also included in this category. These geostationary instruments have the potential to provide comparable data quality, but at a much higher observational frequency than current low Earth orbit (LEO) wide swath radiometers. These data streams are generally available on a public good (free and open) basis.
2. **High resolution optical** (<10m) provides images with much narrower swaths (10’s – 100’s of kms), over relatively limited areas, but at much finer spatial resolutions (though often with coarser spectral resolution). Generally, these data streams are available on a commercial basis. In some specific cases, high resolution images are provided via a direct arrangement with a government or national space agency, for example via Memorandum of Understanding. For the purposes of the supply analysis, **very high resolution optical** (<1m) images will also be grouped with this type as they are also generally only available on similar terms.
3. **SAR** provides radar images at medium swath widths (100’s of kms) with the spatial resolution depending on the radar band and mode used (<1m to 10’s m). While experimental SAR instruments are being built (e.g. P-band, S-band), the continuity of supply study will focus on the three most commonly identified in the case studies – C-band, L-band, and X-band. The continuity outlook, as well as the data policy, varies between each of these bands.
4. **Medium resolution optical** (10m to 80m) provides images at medium swath widths (100’s of kms) with finer spatial resolution than the low resolution optical instruments, but decreased spectral resolution – a.k.a. “Landsat class”. These data streams are generally available on a public good basis.

Performance Specification Characterisation

For the purposes of assessing whether current and future instruments address the requirements gathered during the study, the most demanding specifications in each of the five key performance areas have been gathered from across the cast studies. Case study data experts were asked to identify both the optimal and minimal performance specifications required to realise application outcomes, and so both the most demanding minimal and optimal requirements have been included. Minimal requirements enable the basic / existing level of services, while optimal requirements allow for additional functionality and/or future enhancement.

Instrument Type	Spatial Resolution	Spectral Bands	Coverage Area	Coverage Frequency	Latency
Low resolution optical	Minimal: 250m Optimal: 100m	Minimal: VIIRS *VIS - TIR: 22 bands 0.4 - 12.5 µm* Optimal: MODIS or better *VIS - TIR: 36 bands in range 0.4 - 14.4 µm*	Land minimal and Optimal: National wall-to-wall Ocean minimal and optimal: Global	Land minimal: Twice daily Land optimal: Multiple daily Ocean minimal: daily Ocean optimal: Continuous: hourly - 24h	Minimal: 30min Optimal: 10min
Medium resolution optical	Minimal: 20m Optimal: 10m	Minimal: ETM+ or better *VIS - TIR: 8 bands: 0.45 - 12.5 µm* Optimal: *VIS - TIR*: > 8 bands	Minimal: State wall-to-wall Optimal: National wall-to-wall	Minimal: weekly Optimal: daily	Minimal: 24 hours Optimal: 2-3 hours
High resolution optical	Minimal: 10m Optimal: Sub-10m	Minimal: Visible and NIR Optimal: VIS – NIR – SWIR – TIR	Minimal: Sub-State sites Optimal: Sub-State sites/regions	Minimal: Every five years Optimal: Daily	Minimal: Weeks Optimal: Weeks
Very high resolution optical	Minimal: 1m Optimal: 50cm	Minimal: Visible and NIR Optimal: Visible	Minimal: Site Optimal: More than one site	Minimal: Daily to monthly Optimal: Daily	Minimal: Weeks Optimal: Flood mapping down to hourly
SAR	Minimal: 30m Optimal: 30m	C-band, L-band, X-band	Minimal: Site Optimal: National wall-to-wall	Minimal: Weekly Optimal: Hours	Minimal: Weeks Optimal: Hours

Table 6 - Most demanding minimal and optimal instrument type performance specifications

While these specifications help to define the required performance envelope for each instrument type, a number of applications are still possible with lesser performance. For example, the minimum low resolution optical coverage frequency and latency for national fire monitoring is twice daily coverage within 30 minutes. However, national crop and land use can be accomplished with a minimum of 8-16 day MODIS composites delivered 2-3 days after acquisition of the last image in the composite. The detailed requirements can be found in Appendix A.

In addition to the main instrument types, the continuity of other instrument types will also be briefly assessed, including:

- **Sounders and limb scanners** for their role in providing atmospheric temperature and humidity profiles (as key inputs to weather forecast models);
- **Radar Altimeters and scatterometers** for their role in ocean observations;
- **Passive microwave sensors** for their role in making soil moisture measurements; and
- **Hyperspectral imagers** for their role in mining exploration and monitoring; and,
- **LiDAR Altimeters and DEM datasets** for their role in mining operations and the monitoring of open cut mines.

EOS DATA SUPPLY HERITAGE

Introduction

Supply for the **instrument types identified from the priority data types and priority data sets in the requirements analysis in Section 3 come from a variety of sources**. Supply arrangements are in place with key strategic partners like the U.S. and Japan. Some are underpinned by the World Meteorological Organisation's (WMO) resolution 40, which assures the public good flow of data for weather-related observations. Non-weather-related data supply is based on a mix of public good data streams, bi-lateral arrangements, and commercial purchases.

This section looks at the heritage of supply for each of the main instrument types, and identifies key country, agency, and programmatic relationships that support the data flows that address those requirements.

Low Resolution Optical (> 80m)

Low resolution optical instruments address requirements for six of the seven case studies considered: agriculture, weather forecasting and ocean monitoring, water resource assessment, hazard and risk monitoring, and mining exploration. These data streams are typically used for broad area monitoring of both land and oceans. The technology utilised for low, medium, high, and very high resolution optical instruments is similar, though there is a performance trade-off between spatial and spectral resolution, design complexity, and cost that differentiates these types.

Australian Context

Along with medium resolution optical (Section 4.5), Australia has long been a heavy user of low resolution optical data. Most recently, Australia has been a significant user of MODIS data in a number of cases, downlinking the data directly to service near real time (NRT) applications. Low resolution optical is well suited to Australia and Australian conditions, requiring coverage over broad areas, and with favourable cloud conditions (i.e. generally fewer clouds).

The NRT applications flagged during the case studies included national and regional scale fire monitoring, where MODIS and VIIRS were specified as key data streams. Notably, while VIIRS capability is more limited with fewer bands, it is capable of doing a similar job as MODIS, but the revisit is not as frequent with only one instrument currently operating. A second NRT application highlighted was national flood monitoring, which is heavily reliant on having both optical and SWIR bands. Both fire and flood monitoring are areas where new data streams like Sentinel-3 and Himawari-8 may be important.

Respondents also cited frequent use of the MODIS 8-16 day composite products for non-NRT applications like crop condition monitoring (NDVI) and water resource assessment.

Current Applications and Instruments

Typically, finer spatial resolution means coarser spectral content (i.e. fewer/broader bands), and vice versa, with cost going up if both spatial and spectral resolution are to be optimised. These trade-offs are becoming less pronounced as technology improves, but there are physical limits to performance.

Instruments with measurements across a number of regions of the electromagnetic spectrum are termed multi-spectral, while instruments that simultaneously acquire observations in many (hundreds) of narrow (typically less than 10nm) contiguous spectral bands across adjacent regions are referred to as hyperspectral. The supply heritage of hyperspectral data is discussed in Section 4.6.

For the purposes of this study, low, medium, and high resolutions are delineated along the lines defined in Section 3.2: low resolution meaning coarser than 80m, medium resolution meaning 80m to 10m, high resolution meaning 10m to 1m, and very high resolution meaning finer than 1m. Typically, low and to a large extent, medium resolution data streams area available on a public good basis. Whilst high and very high resolution data streams are usually available on commercial terms for operational users. (Commercial providers sometimes make high resolution imagery available for R&D, applications development, and humanitarian purposes.)

The low resolution optical instruments identified by Australian users are summarised in Table 7. Instruments shown in bold were identified as the main low resolution supply options.

Instrument	Orbit	Imagery	SST[1]	OC[2]	Agency	Country	Current / Future (year)
MODIS	LEO	✓	✓	✓	NASA	U.S.	Current - 2020
VIIRS	LEO	✓	✓	✓	NOAA	U.S.	Current - 2027
IMAGER (MTSAT-2)	GEO	✓	✓		JMA	Japan	Current - 2017
IVISSR (Y-2)	GEO	✓	✓		NSMC-CMA	China	Current - 2016
AVHRR	GEO	✓	✓	✓	NOAA/EUMETSAT	U.S./Europe	Current - 2021
U.S. Navy Composite[3]	-		✓		U.S. Navy	U.S.	Current
Vegetation (Proba-V)	LEO	✓			ESA / Belspo / VITO (commercial)	Europe / Belgium	Current - 2016
AHI (Himawari-8, -9)	GEO	✓	✓		JMA	Japan	Current - 2030
AMI (GEOKOMPSAT-2A)	GEO	✓	✓		KMA	Republic of Korea	Future (2017)
GOCI-2 (GEOKOMPSAT-2B)	GEO	✓		✓	KMA	Republic of Korea	Future (2018)
OLCI (Sentinel-3A)	LEO	✓		✓	EC/ESA	Europe	Future (2015)
AGRI (FY-4)	GEO	✓	✓		NSMC-CMA	China	Future (2016)
SGLI (GCOM-C)	LEO	✓	✓	✓	JAXA	Japan	Future (2016)

Table 7 – Low resolution optical instruments current and future
[1] used primarily/partially for sea surface temperature, [2] used primarily/partially for ocean colour
[3] composite of 2-3 satellites in GHRSST L2P format

Sea surface temperature (SST) and ocean colour instruments were identified as two important sub-types within low resolution optical – both providing important inputs to weather, ocean monitoring, and water resource- and quality-related activities. Ocean colour instruments are differentiated by providing sufficient performance in the green-blue region of the visible spectrum, while low resolution optical SST focuses on highly differentiated measurements in the infrared range. SST measurements are also collected by microwave radiometers not covered in this analysis, and the Bureau of Meteorology noted that they source their sea surface temperature data sets from a U.S. Navy composite product which combines a variety of satellite data streams.

Many of the instruments in Table 7 might be described as multiple-purpose, providing sea surface temperature or ocean colour measurements as well as widely applied land surface imagery.

Current Data Streams

While a number of data streams have been identified in the course of the study, there are several "class defining" instruments which have underpinned the continuity of supply for Australian low resolution optical users. The NOAA/EUMETSAT **AVHRR** instrument is currently providing twice daily global multi-spectral coverage at a spatial resolution of just over 1km. It has been operated by NOAA since 1979, more recently in parallel by EUMETSAT since 2007, and provides the longest available global low resolution optical data record.

In August 2013 NOAA and EUMETSAT reaffirmed their 30 year cooperation, signing a long-term agreement that EUMETSAT's MetOp satellites will fly in the mid-morning orbit, while NOAA's polar satellites and the Suomi NPP spacecraft fly in the afternoon orbit. Both agencies share all the data, which form the backbone of forecasts from all major weather centres globally, and ensures low resolution optical coverage is available to non-weather users in the morning and afternoon orbits.

At present there are five instances of AVHRR being flown, three by NOAA and two by EUMETSAT. Several case study responses noted AVHRR as a valuable data stream, but it does not meet the minimum requirement for spatial resolution outlined in Table 6, and so is only applicable to a subset of applications.

NASA's **MODIS** instrument was first launched in 1999, and currently flies on the Terra and Aqua missions. Both are well into their second decade of service, and well beyond their intended design lifespan. MODIS is operated as a research mission, though many operational applications have been enabled by its finer spatial and spectral resolution relative to AVHRR. The presence of a direct broadcast mode, which enables users to download the data directly from the satellite as it passes overhead, has also driven MODIS adoption, in particular for non-meteorological, NRT applications.

In 2011, NASA and NOAA launched the Suomi NPP mission, carrying the first of five anticipated instances (three funded) of the **VIIRS** instrument. Based on its spatial and spectral resolution, VIIRS is expected to provide a viable continuity option for many AVHRR and MODIS applications. While case study responses indicated that VIIRS is being evaluated, and in some cases employed, as a continuity option for a number of MODIS applications, some cited the reduced number and different wavelengths of the bands as a limit to its utility. In addition, the broader ocean colour community has expressed performance concerns about VIIRS early calibration and faster than expected system degradation, and these issues are still being evaluated.

VIIRS on Suomi NPP, MODIS, and AVHRR all support timely access to data through direct broadcast modes. While using this capability requires the user to setup their own ground segment and processing system, it greatly reduces latency - which is critical for several of the NRT monitoring activities covered in the case studies. Of the six applications requiring low resolution optical, four are NRT and their latency requirements are summarised in Table 8.

Application Area	Minimal Latency	Optimal Latency
Weather Forecasting	<10 minutes	
Sea Surface Temperature	12 hours	Will move to real time
Flood Monitoring	6 hours	1 hour
Fire Monitoring	30 minutes	10 minutes

Table 8 – Latency requirements for NRT low resolution optical applications

Latency from a global downlink for polar orbiting missions (e.g. Suomi NPP) is often more than two hours. This is because the data is stored on the satellite, downlinked during the next overfly of the ground station at Svalbard, Norway, and then processed and made available for download. While internet distribution is important for data sharing, local reception of direct broadcast is essential in reducing latency to less than 30 minutes, which is important for many applications.

In future, it is anticipated that new data streams (e.g. Sentinel-3 and Himawari-8, both discussed in Section 5) will employ internet-only data distribution system, which may introduce additional latency and impact on the timeliness of some NRT services.

Finally, the **Vegetation** instrument on Proba-V (ESA) is intended as a gap filler between the end of VEGETATION on SPOT-4 and -5, and the launch of Sentinel-3A. It provides global public good low resolution optical data coarser than 300m (via ESA), while data finer that 300m is sold commercially by Belgium's VITO.

Geostationary Data Streams

The current class of geostationary satellites carry coarser resolution optical instruments. However, the Japan Meteorological Agency 's (JMA) **IMAGER** on Himawari-8 provides up to 500m resolution in the visible band, and 2 km in the infrared, with 16 bands in total, bringing it closer to the capabilities of MODIS. This may broaden the scope for applications beyond weather forecasting.

High Resolution Optical (< 10m)

High resolution optical instruments address requirements for five of the seven case studies considered: agriculture, ocean monitoring, water resource assessment, hazard and risk monitoring, and mining exploration. These data streams are typically used for applications requiring detailed mapping, land use mapping, product verification and accuracy assessment, post incident assessments, mining environmental monitoring, modelling and assessment of catchment and flood areas, and applications in urban areas and coastal zones. As noted in Section 3.4, for the purposes looking at continuity of supply, **very high resolution optical** (<1m) instruments will also be grouped with high resolution as its supply is largely dictated by commercial providers.

Australian Context

Australian uses of high resolution optical data discussed in the case studies focused on its role in detailed monitoring and mapping activities, as well as on an *ad hoc* basis in response to events like floods and storms. In addition, high resolution data is used in mineral exploration and mine environmental monitoring, in the horticultural industry, and by a number of local governments and councils across Australia. The smaller coverage footprint of these instruments – typically 15-30km wide up to 100km – means they are employed mostly for site-specific applications.

Mapping activities covered include residential expansion, derivation of detailed crop types (e.g. seasonal and perennial classes), and land use classification (e.g. conservation and natural environments, dry land and irrigated plantations, intensive uses, and water).

Of particular interest for Australian mineral exploration is World View-3's new SWIR band, which provides a data stream that has been missing since the failure of ASTER's 30m SWIR band.

Current Applications and Instruments

Supply for high resolution optical is almost exclusively commercial, with two major commercial providers dominating the market – Digital Globe and Airbus Defence & Space (Airbus D&S). Commercial data is also contributed on a free but scene-limited basis by suppliers in support R&D, application development, and for humanitarian purposes, for example in support of business development or the International Charter on Space and Major Disasters.

Previous Symbios studies estimate that 80% of the commercial high resolution market is for spatial information (i.e. finer resolution), rather than spectral information (i.e. number of bands). While there has been some interest from the military in high resolution SWIR (resulting in a SWIR band being added to World View-3), generally speaking the applications being developed are focused on detailed observations of the boundaries of objects, rather than their colour.

In addition to high resolution spatial content, commercial providers also differentiate themselves through responsive, on demand, and customised acquisitions.

Instrument	Supplier	Best Resolution *panchromatic / visible*	Current / Future (year)
World View-1, -2, -3	Digital Globe	0.3m / 1.24m	Current
Ikonos	Digital Globe	0.82m / 3.2m	Current – 2015
QuickBird	Digital Globe	0.55m / 2.16m	Current
GeoEye-1	Digital Globe	0.41 m/ 1.65m	Current
Pléiades	Airbus DS	0.5m* / 2.0m	Current
RapidEye	Blackbridge	n/a / 5.0m	Current
SPOT-5	CNES	5.0m / 10m	Current – 2015 (currently being deorbited)
SPOT-6, -7	Airbus DS	1.5m / 6.0m	Current
ZY-3	CRESDA	2.1m / 6.0m	Current – 2017
Dove Constellation	Planet Labs	n/a / 3.0 – 5.0m	Current
SkySat	SkyBox	0.9m / 2.0m	Current

Table 9 – High resolution optical satellites current and future
*** Pléiades acquires 0.5m pan and colour images, and 2.0m multi-spectral.**

Because of the requirement for high spatial resolution, and in some cases on-demand acquisitions (i.e. during an emergency), aircraft acquisitions are frequently used to address user needs. In some cases, these acquisitions can be pooled between government departments which can be cost effective. But generally speaking, aircraft acquisitions are not systematic and not as repeatable as satellite acquisitions – though they can address very high end user requirements for spatial and spectral (i.e. multi-spectral, hyperspectral) data. The development of constellations with many satellites (10's into the 100's in the case of Planet Labs), is reducing revisit time with the potential to deliver multiple coverages per day at a sub-5m resolution, and these systems are discussed in Section 5.

In order to give an indication of the costs involved, Table 10 summarises estimates used in the *Australian Government Earth Observation Data Requirements to 2025* for new acquisitions and archive access over the Australian Exclusive Economic Zone. For comparison, the *Continuity of Earth Observation Data for Australia: Operational Requirements to 2015 for Lands, Coasts and Oceans* (CEODA-Ops, 2011) report estimates the current government expenditure on remote sensing data supply in Australia is approximately $100 million per annum.

Data	Resolution	New acquisition [per km²]	Exclusive Economic Zone (approx.)	Archive [per km²]	Exclusive Economic Zone (approx.)
SPOT6/7, 4 band pricing	1.5m	$7.00	$60 million	$5.50	$47 million
Pléiades, 4 band pricing	0.5m	$24.00	$208 million	$14.00	$121 million

Table 10 – Indicative high resolution optical data costs

While current supply for commercial high resolution optical data is strong, there are a wide variety of satellites and sources to choose from. Although there is some consolidation under the main market actors, this diversity of sources can pose coordination challenges for users – both in terms of coordinated acquisitions, as well as data handling and processing. The main suppliers offer value added post-processing services, such as radiometric correction, orthorectification, improved image location precision, and stereo imagery, but these services can double the cost.

Current Data Streams

The main market actors, **Digital Globe** and **Airbus DS**, are the principal suppliers of high resolution data for Australian (non-military) users. Their offerings mirror the market demand for spatial information over spectral content, with most of the instruments offering 4-5 bands in the visible range.

Case study users access these high resolution data streams on an *ad hoc* basis, rather than systematically or through long term supply contracts. This reflects the occasional nature of the requirements and the necessity for users to balance budgets – and means that coordination of supply is a challenge.

Geoscience Australia manages the Optical, Geospatial, Radar, and Elevation Supplies and Services Panel (OGRE), a cooperative procurement panel established to allow more efficient and effective acquisition and use of commercial imagery supplies and associated services, and to encourage greater coordination and cooperation within all levels of Australian Government.

Since its establishment in 2010, OGRE has facilitated the procurement of over $20 million of Earth observation data and services by Australian government users and resupplied over $11.7 million of data to government agencies. In 2011, GA purchased an Australia-wide 22m resolution mosaic from DMC International Imaging under a Creative Commons license and continues to encourage government users to adopt the widest possible licenses available when purchasing commercial data.

Synthetic Aperture Radar (SAR)

SAR instruments address requirements for five of the seven case studies considered: agriculture, ocean monitoring, water resource assessment, hazard and risk monitoring, and mining exploration. Potential applications of SAR are wide ranging, and provide unique capabilities relative to the more traditional optical data streams – owing in large part to their all weather (e.g. cloud, smoke), day/night imaging capability.

Australian Context

Several potential Australian SAR applications identified during the case studies:

– enhanced differentiation of crop types for agricultural monitoring;
– flood mapping and monitoring;
– monitoring of ocean oil seeps;

- monitoring of maritime traffic;
- monitoring of soil moisture using the public good Sentinel-1 time series; and,
- monitoring of deformation in support of a dynamic datum, and specifically subsidence around mining sites using interferometry (see more below).

However, while some development work has been considered or even started on these applications, they are all largely aspirational at present.

In general, Australia's use of SAR data is less developed when compared to its use of optical data streams, including in some application areas where overseas users are applying SAR. For example, SAR has been employed to monitor maritime traffic and oceans operationally in Europe and Canada for at least a decade – and this application provided one of the prime motivations for launching their SAR satellites.

Another application area where SAR is commonly deployed overseas is flood mapping. SAR data can be used to directly monitor the flood in progress – leveraging its ability to "see through clouds" during what are often relatively cloudy periods, as well as at night when optical data cannot be acquired. Several barriers to the adoption of SAR usage for flood monitoring in Australia were identified:

- in order to be responsive to an incident, acquisitions need to be tasked, and data must be downlinked which means delivery often takes place more than 24 hours after acquisition (as opposed to MODIS which is available in about 3 hours, and Landsat in about 8 hours);
- there is normally a cost associated with SAR acquisitions (as opposed to public good MODIS and Landsat data, and soon Sentinel-2 and -3). Public good Sentinel-1 data could help with cost, but mechanisms for on demand acquisitions and quick delivery are not currently clear;
- for longer term applications (e.g. dynamic datum), consistent time series are critical but haven't been widely available – in large part due to the need to order and pay for SAR data; and
- it is more work to process SAR data, with fewer skilled analysts available. The base product is less intuitive for the end user, and so processing is required (as opposed to optical data, where the unprocessed Level 1 product can be interpreted by most users).

SAR also can be used as a primary input to digital elevation models (DEMs) that are used in modelling processes (e.g. floods) – though DEMs are generally developed well in advance of an incident.

Australian researchers, and several state agencies, have had a long-standing and leading role in developing Australian and Global SAR applications for mapping vegetation height, biomass and other structural properties through participation in JAXA's Kyoto and Carbon program, through all of its stages.

Current Applications and Instruments

While a number of operational services have been implemented globally – in particular around maritime operations and ice monitoring – a general lack of public good SAR data streams has inhibited application growth. Historically, SAR instruments have either been operated on a research basis, without an operational service level ground segment, or the data is only available commercially which has made cost a barrier to adoption. Inconsistent availability of archive data has also proved problematic.

However, in 2014 Europe launched the Sentinel-1A mission, which is the first public good operational SAR data stream. This public good data has the potential to mirror what regular public good MODIS and Landsat data has done for low and medium resolution optical applications. Operational continuity is envisioned for the Sentinel-1 series, with 1B scheduled for launch later in 2015, and continuity with 1C and 1D units being planned, which should increase confidence in application developers.

One important differentiator of SAR data streams is the electromagnetic frequency used for acquisitions. SAR instruments are active instruments which transmit a radar pulse (analogous to a sonar ping), and then sense the reflected radar signal. While a number of different frequencies have been utilised on an experimental basis, the three most used wavelengths are known as C-band (4-8 GHz), L-band (1-2 GHz), and X-band (8-12.5 GHz). Important applications exist for instruments in each of these three bands, and continuity also varies along these lines. Future emerging applications leveraging additional bands (P-band, S-band) are discussed in Section 5.4.

In general, SAR instruments are sensitive to objects of the same size as the radar wavelength, and larger. Objects smaller than the wavelength gradually become transparent/invisible to the radar as they decrease in size.

L-band (23.5cm wavelength): This is currently the longest wavelength used in spaceborne SAR, and it penetrates leaves and foliage providing information about forest structural parameters such as branches and stems. Applications include distinguishing between forest and non-forest, direct detection of above-ground (dry) biomass up to 100-150 tons/ha, and forest cover change detection using time series. L-band is unique in its capacity to detect inundation in flooded forests even below a closed canopy, and is used for the mapping of ice in combination with other SAR wavelengths which are sensitive to different layers of ice. Other applications include rice paddy monitoring, mapping of paleo-geology in arid deserts, and to a lesser extent ocean applications. L-band SAR data from the ALOS series is expected to provide the basis for Australia's first *operational* whole of continent biomass mapping program in the near future.

C-band (5.6 cm wavelength): The main C-band applications are in ocean and ice monitoring, with the short C-band wavelength sensitive to small waves on the water surface which is useful for mapping of winds and waves and detection of oil spills. The C-band wavelength does not penetrate a closed forest canopy and therefore provides limited information about forest structure, however it provides more information in open forest environments such as woodlands where the signal can interact with ground, stems and branches. Rice paddy monitoring is also an established C-band application. Very short repeat C-band observations (~3 days) are useful for the monitoring of deformation caused by earthquakes and volcanoes, while longer time series (1-2 month baseline) have proven useful for detection of deforestation and logging roads.

X-band (3.1cm wavelength): The characteristics and usage of X-band are similar to C-band – however it provides higher spatial resolution due to its shorter wavelength. This has proven useful for the detection of selective logging and forest degradation. X-band SAR is also frequently used for military applications.

SAR instruments are designed to operate in different acquisition modes with varying beam profiles and different radar polarisations. These acquisition parameters are often tailored to certain applications, or designed to boost performance characteristics such as resolution or coverage area. However, this also means that for certain applications only acquisitions in certain modes are useful – and this requires coordination of acquisitions.

With the exception of Sentinel-1A, all current SAR missions are operated on a commercial basis. Often the commercial arrangements include a public-private partnership between a national government and national industry. And the mission and instrument have been developed in part as a national technical capacity building activity, with the government securing their supply of data for national applications and security purposes in exchange.

Instrument	Band	Supplier	Commercial	Country	Current / Future (year)
RADARSAT-2	C-band	CSA/MDA	Yes	Canada	Current – 2015+
Sentinel-1	C-band	EC/ESA	No	Europe	Current – 2023+
RADARSAT Constellation	C-band	CSA	No (projected)	Canada	Future (2018 – 2025)
COSMO-SkyMED	X-band	ASI	Yes	Italy	Current – 2017+
TerraSAR-X	X-band	Airbus DS	Yes	Europe	Current – 2015+
TanDEM-X	X-band	Airbus DS	Yes	Europe	Current – 2015+
RISAT-2	X-band	ISRO	No	India	Current – 2015
Meteor-M-N1 and N2	X-band	ROSHYDROMET	No	Russia	Current – 2020+
WSAR (HY-3A – 3C)	X-band	NSOAS	No	China	Current - 2027
PAZ	X-band	CDTI	No	Spain	Future (2015 – 2020)
LOTUSat 1 and 2	X-band	VAST	No	Vietnam	Future (2017 – 2023)
SCLP	X-band	NASA	No	U.S.	Future Concept (2030+)
ALOS-2	L-band	JAXA / RESTEC	Yes	Japan	Current - 2019
SAOCOM	L-band	CONAE	No (projected)	Argentina	Future (2016 – 2025)
NISAR	L-band / S-band	NASA / ISRO	No	U.S. / India	Future (2020 – 2025)
NovaSAR	S-band	SSTL/Airbus	Yes	U.K.	Future (2016+)
BIOMASS	P-band	ESA	No	Europe	Future (2020 – 2025)

Table 11 - SAR satellites current and future

A number of countries have a strong heritage of SAR development, aligned somewhat along the lines of bands. Japan has a strong heritage of L-band instruments, dating back to the late 1970's. Europe (ESA) and Canada have long operated C-band instruments, in particular focused on shipping and sea ice in the North Atlantic and the Arctic. And Germany and Italy have strong heritage in operating X-band instruments for both maritime surveillance (national security), as well as the generation of high resolution DEMs.

A number of other countries, including Russia and China also have a heritage of developing successful SAR missions. While the U.S. participated in the historical development of the technology, and have collaborated with some upcoming radar and SAR instruments, they do not have a contemporary national civil SAR programme. And a new entrant, Argentina, will launch the first of a series of four L-band SAR satellites (notably with an announced public good data policy outside Europe) starting in the 2016 timeframe.

The all-weather, day/night capability of SAR missions means that the systematic planning of global observations can be reliably implemented with repeated coverage during each cycle (typically 2-4 weeks). It also means that for some missions, available power, data storage, and downlink capacity limit the potential for acquisitions outside of these systematic plans. Therefore, if there are specific ongoing requirements it is important that they are reflected in the plans. For example, Sentinel-1A does not address special requests outside of its systematic planning unless they are related to calibration and validation or emergency response.

One of the unique capabilities offered by SAR instruments (in particular L-band and C-band) is **interferometry**. This technique takes advantage of radar's precise ranging capabilities, employed to measure the difference between successive observations. The repeated measurements enable detection of small scale (cm) changes in ground deformation, with uses including tectonic deformation, volcanic, subsidence, ice flows, and digital elevation modelling. In the Australian context, this technique is useful for subsidence detection applications around mining sites.

Current Data Streams

C-Band

The main heritage, and current missions, in the C-band SAR range come from Europe (ERS, Envisat, Sentinel-1), and Canada (RADARSAT series). Currently the two main operational data streams are **RADARSAT-2** and **Sentinel-1A**. RADARSAT-2 is operated commercially by McDonald, Dettwiler and Associates Ltd. (MDA), and prior to the launch of Sentinel-1A was the main C-band SAR instrument used globally. The advent of Sentinel-1A has provided a public good data stream, which holds the potential to open up a large number of new applications.

While the advent of the public good Sentinel-1 series is likely to impact RADARSAT-2's commercial business, the main trade-off for prospective users will be the availability of data. If the requirements for a given application are addressed by Sentinel-1's baseline acquisition strategy, then it will almost certainly be the data stream of choice. While commercial operators will still be able to service users that require certainty in the scheduling of acquisitions, or acquisitions in particular modes or at particular resolutions.

Based on prices determined in a 2009 Symbios study, the purchase of a single national wall-to-wall coverage of RADARSAT-2 (at 25m resolution) data for Australia would cost on the order of $2.5 million (before volume discounts). Given the high cost of commercial SAR, users should be expected to focus development efforts on Sentinel-1, except for cases where specific requirements exist. In addition, where the price tag for even a single national coverage may have been prohibitive in the past, the development of national-scale applications such as soil moisture monitoring using C-band SAR can now be contemplated. This, and other applications like interferometry, could be the first major push into the 'mainstream' for SAR in Australia.

X-Band

The main heritage, and current X-band SAR missions, come from Germany and Italy. Existing X-band SAR applications are largely focused on military and national security monitoring activities.

Italy's **COSMO-SkyMed** is a four satellite constellation, operated commercially in cooperation with the Italian Department of Defence. The four satellites mean that the constellation offers near-daily revisit opportunities.

Data from Germany's **TerraSAR-X** and **TanDEM-X** missions is sold commercially by Airbus DS, and includes both imagery products as well as the WorldDEM, which is being marketed as the new standard for DEM – advancing on the SRTM-30 dataset.

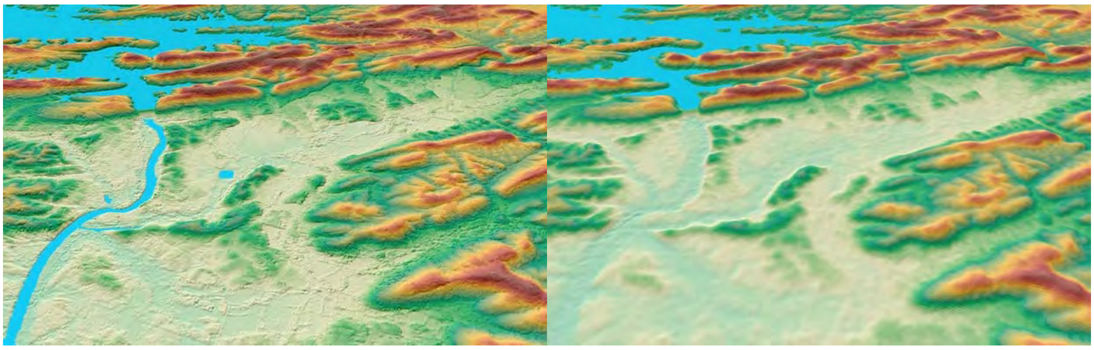


Figure 1 – WorldDEM (left) vs. SRTM-30 (right) (Credit: Airbus DS)

L-Band

The main heritage, and only current L-band SAR mission comes from Japan. Geoscience Australia holds an ALOS time series (including PALSAR) resulting from its hosting of a ground segment node. **ALOS-2** was launched in 2014, and is operated on a commercial basis. The Baseline Observation Scenario (BOS) of ALOS-2 is carefully planned to address a number of application areas, including: baseline mapping, forest and wetlands monitoring, crustal deformation, rapid deforestation, polar ice, glacier movement, emergency observations, and calibration and validation.

Medium Resolution Optical (10m to 80m)

Medium resolution optical instruments address requirements for four of the seven case studies considered: agriculture, water resource assessment, hazard and risk monitoring, and land monitoring. Applications of this type are amongst the most common in the Australian context, and include broad area land cover and land cover change analyses, forest and crop monitoring, environmental impact assessment (leveraging archives dating back to the late 1970's in some cases), hazard risk assessment and monitoring, and water management.

Australian Context

Australia has long been a leading user of medium resolution optical data, and has a strong legacy of Landsat usage. Australia operates important ground station and processing infrastructure as a part of the Landsat network, and this infrastructure has helped to ensure strong access and build an extensive archive maintained by Geoscience Australia.

Medium resolution optical is particularly well suited to application in Australia because of its broad areas (at more than 7.5 million square kms, the Australian landmass is 5% of the global total), and frequently clear and sunny skies in most areas of the country.

During the case studies, the respondents referenced medium resolution (i.e. Landsat) as providing the basis for products which synthesize or leverage other data types. In particular, the use of medium resolution in conjunction with low resolution optical (for even broader, more frequent coverage), or high resolution optical (for finer coverage over more closely settled areas) was cited. The the combination of visible, near infrared (IR) and mid-IR bands enables this data set to be applied widely - its use would not be as widespread without the mid-IR bands.

Synergies with SAR data appear less prevalent, but this may be an area that opens up with the flow of Sentinel-1 data, and with developments in data handling and processing techniques.

Current Applications and Instruments

The opening of the Landsat archive in 2008 for public good access changed the landscape for medium resolution optical data supply. For the past few years with the end of Landsat-5 and the degraded operation of **Landsat-7**, there was a significant risk of a data gap in the Landsat series. However, this was mitigated with the launch of **Landsat-8** in 2013.

It is worth noting that prior to the opening of the Landsat archive, data in this class were available mostly on a commercial basis, costing into the $1000's for an individual scene (185x180km). Since the end of the commercial data policy, the cumulative number of global downloads of Landsat scenes is approaching 25 million, and the rate of downloads is still increasing.

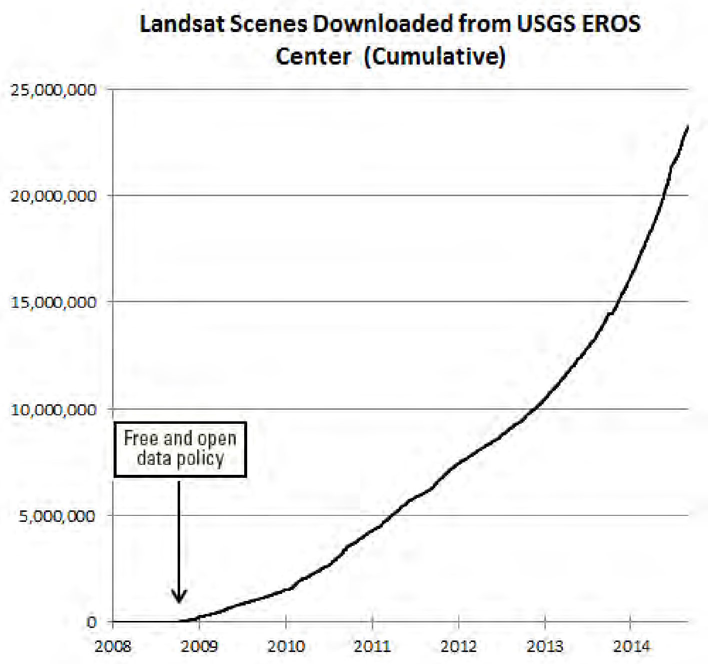


Figure 2 – Landsat scenes downloaded since the advent of the public good data policy (Credit: USGS)

A recent study by the Landsat Advisory Group of the National Geospatial Advisory Committee concluded that the economic benefit of Landsat data for the year 2011 alone was estimated to be $US 1.70 billion for users in the United States, and $US 400 million for international users resulting in a total annual value of $US 2.19 billion. Landsat data is also often used to produce additional broader societal benefits, such as scientific research or the mitigation of natural hazards, and these benefits are difficult to measure in dollar terms.

The medium resolution optical data type is a workhorse globally, and the full potential of the public good data policies being implemented by agencies providing these data streams is only just beginning to be realised. Less than 10 years ago broad coverages and long time series of data in this class would have cost thousands of dollars. As technology and processing tools improve, and new entrants start to build applications, these public good data streams will be further leveraged. And as new data streams come online (e.g. Sentinel-2), economic and societal benefits should only be expected to expand based on increased new acquisitions as well as accessible archive data.

Over time, there have been many instruments of this type launched by many countries, however the main current instruments in the Australian context are the **ETM+** (Landsat-7), and **OLI** (Landsat-8). There are viable continuity options should Landsat become unavailable, and future anticipated missions fail to become operational, including the **SLIM-6-22** imager on UK-DMC-2, **LISS-III** on India's RESOURCESAT. In addition, the **PAN and MUX** instruments on CBERS-4 provide a potential public good medium resolution optical data coverage.

Instrument	Agency	Country	Current / Future (year)
ETM+ (Landsat-7)	USGS	U.S.	Current – 2017
OLI (Landsat-8 / -9)	USGS	U.S.	Current – 2023+
SLIM-6-22 (UK-DMC-2)	DMCii	U.K.	Current - 2016
LISS-III (RESOURCESAT)	ISRO / Commercial	India	Current - 2021
PAN and MUX (CBERS-4)	CRESDA / INPE	China / Brazil	Current - 2017
MSI (Sentinel-2A / -2B)	EC / ESA	Europe	2015 – 2027+

Table 12 – High resolution optical instruments current and future

In addition to the continuity of the Landsat series, **MSI** is expected to be launched in Sentinel-2 in 2015, and is on the verge of providing a second true global workhorse in this class – also available on a public good basis. Overall continuity, and the potential of Sentinel-2 are discussed in Section 5.5.

Current Data Streams

ETM+ and **OLI (USGS)** on Landsat represent the only current global workhorses for medium resolution optical - in particular, OLI on Landsat-8. While Landsat-7 continues to operate, the ETM+ instrument suffered a failure in 2003 (scanline corrector), meaning that approximately 22% of the data in scene is missing. Landsat-7 is expected to be operated until it is no longer viable, or runs out of fuel which is projected to happen in 2020. The Landsat-7 orbit will be allowed to drift in order to conserve fuel, which will in turn cause the local overpass time to drift - impacting the utility for some applications.

Landsat-8 was launched in 2013, and the OLI instrument is expected to operate until 2023, with resources to potentially operate beyond that. There is a commitment to a sustained land surface imaging programme with Landsat-9 being developed as a copy of Landsat-8, and options for Landsat-10 being considered.

While it is not a strictly a medium resolution instrument (at 100m), TIRS (thermal bands) was added to Landsat-8 when users (i.e. U.S. state water resource managers looking at surface energy balance models, or SEBAL) argued their heavy reliance on the highly accurate thermal measurements obtained by Landsat-8's predecessors, Landsat 5 and Landsat 7, to track how land and water are being used.

Australian case study experts did not report the same dependence for Australian water resource monitoring citing other methods of calculating water usage (i.e. evapotranspiration modelling). TIRS was launched as a research instrument which means there is less redundancy and higher risk of failure. It is an actively cooled instrument containing life-limited parts (i.e. coolant, moving parts), has a three-year design life, and so is expected to fail before the overall end of Landsat-8 operations. NASA and USGS are considering strategies for continuity of thermal observations which are discussed further in Section 5.5.

PAN and MUX were launched on the joint Chinese-Brazilian CBERS-4 in late 2014, and provide a potentially viable continuity option for medium resolution optical. However, the mission ground segment is not currently setup to service a global user base, and systematic observations are currently only scheduled over Chinese and Brazilian territory, and Chinese areas of interest in Asia. There is currently no global acquisition strategy, and so in the event that CBERS-4 was to be used as a continuity option, acquisitions over Australia would need to be negotiated.

LISS-III on India's RESOURCESAT is a viable operational source of medium resolution data. The data is available, but only on commercial terms, and systematic observations of Australia have not otherwise been coordinated outside of commercial supply contracts. Should both Landsat missions fail, and Sentinel-2 not eventuate, LISS-III could provide gap filling capability for focused coverage areas with a commensurate budget for data purchase.

A number of countries have flown medium resolution optical instruments of varying quality, data accessibility, and overall utility. While these have doubtlessly been used by users across Australia, likely in research projects, none have yet risen to the level of providing operational supply. Examples would include Russia's **Resurs** series, Thailand's **THEOS**, the Ukraine's **Sich**, Turkey's **RASAT**, and affiliated Surrey Satellite Technology Limited (SSTL) backed DMC missions (in addition to SLIM-22-6) such as **NigeriaSat**.

Presuming the existing and planned medium resolution optical missions realise their potential, the community may be about to enter a "golden age" of data availability. As discussed in Section 5.5, the launch of the future Sentinel-2A and -2B missions, and Landsat-9, may pave the way to having three, and at times even four, medium resolution optical global coverage missions operating simultaneously. This raises the possibly of weekly or better revisit times, which coupled with improved data handling and processing tools and platforms being developed holds great potential for application developers.

Other Data Types

As outlined in Section 3.4, several 'other' data types were identified during the case studies. These were identified as applicable to only one or two of the case studies, but none the less are important to consider in the supply analysis. They serve important activities that feed into the development and delivery of national programs.

Sounders and GPS radio occultation (GPS-RO) instruments provide important inputs into national weather forecasting services, providing timely (i.e. via direct broadcast) measurements of atmospheric temperature and humidity profiles – both key inputs into weather forecast models. Soundings are currently routinely provided in both microwave and infrared wavebands, but there is increasing interesting in hyperspectral sounding applications.

There are three main instrument classes making operational atmospheric temperature and humidity observations.

Class	Observation	Example Current Instruments
LEO Sounders	Passive measurements of the distribution of infrared (IR) or microwave radiation emitted by the atmosphere, from which vertical profiles of temperature and humidity through the atmosphere may be obtained. Measured from primarily LEO orbits.	**Microwave:** AMSU-A / -B (NOAA, Metop, Aqua), ATMS (Suomi NPP), (I)MWAS (FY-3) **Infrared:** CrIS (Suomi NPP), HIRIS (NOAA, Metop), IASI (Metop), IRAS (FY-3)
Geostationary Sounders		**Infrared:** Sounder (GOES – Americas coverage only), Sounder (INSAT – India coverage only)
GPS-RO	Measurement of GPS signals that pass tangential to the Earth's surface through the atmosphere, improving the accuracy of vertical profile measurements of temperature and humidity.	GOX (COSMIC-1), GPRSO (Ørsted, Terra-SAR), GRAS (Metop), ROSA (OCEANSAT-2, MEGHA-TROPIQUES, SAC-D)

Table 13 – Atmospheric temperature and humidity observations

Table 13 notes a number of current operational LEO sounders, with data provided operationally and freely via the WMO Information System (WIS), as well as via direct downlink, including several high heritage instruments from NOAA and EUMETSAT. The potential of soundings from geostationary platforms was mentioned in the weather case study, with the benefit being increased frequency of observations. However, there are currently no geostationary soundings covering Australia.

A number of GPS-RO instruments are currently operating, including the GOX instrument on the **COSMIC-1 constellation**. This ageing constellation is nearing its end of life both programmatically and in terms of performance, and currently has five satellites (was six). Other GPS-RO instruments are operational, including GRAS on MetOp, and ROSA – however continuity of the high heritage COSMIC series is of greatest interest.

Radar altimeters and scatterometers provide important ocean observations, which serve as key inputs for weather forecasts, and both types were flagged by both the weather and oceans case studies. Radar altimeters provide measurements of sea surface topography, while scatterometers measure the ocean surface roughness – an important proxy for wind speed and direction.

These ocean observations are particularly important for Australian weather forecasting as almost all of the Earth's surface south of Australia to Antarctica is ocean, and this severely limits the number of direct systematic weather observations possible. These observations are important boundary inputs to Australian weather forecast models – and data from satellites is the only viable source of these inputs at the temporal frequency and timeliness required.

Figure 3 shows the relative improvement in Southern Hemisphere weather forecast skill compared to the Northern Hemisphere since 1981. The closing gap between the quality of the 3-, 5-, 7-, and 10-day forecasts between the two Hemispheres is largely attributed to the incorporation of satellite observations (soundings) over the Southern Ocean, where previously no observations existed. Where in the Northern Hemisphere, there is a much higher percentage of land cover, which means there are proportionally many more ground observations available.

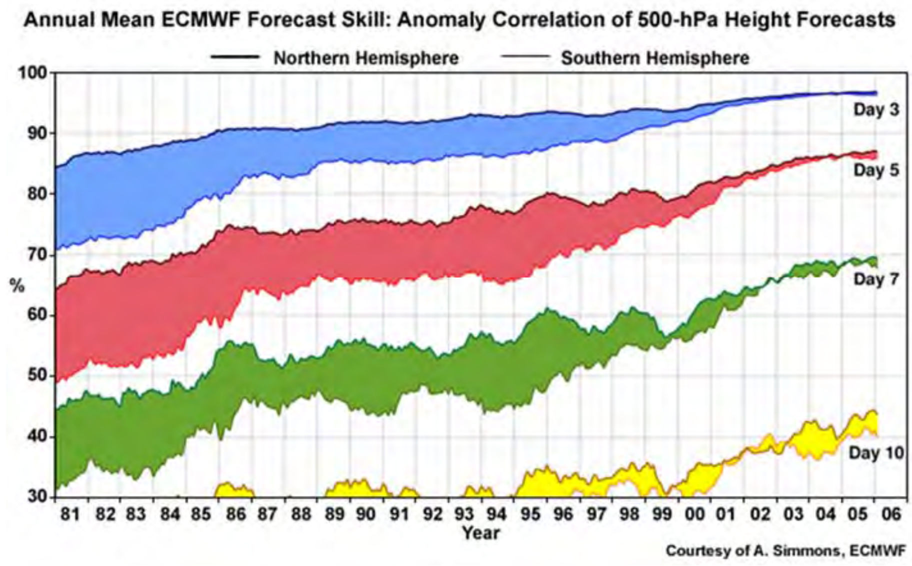


Figure 3 - Increased Southern Hemisphere forecast quality resulting from the addition of satellite observations (Credit: ECMWF, NOAA)

The principal current series radar altimeters are flown the ongoing **Jason missions**, which provide a continuous data record (via its POSEIDON instrument) back to 1992. These missions are developed and operated jointly by NASA, CNES, NOAA, and EUMETSAT. Jason-2 is currently operational, and is expected to be joined by Jason-3 in late 2015 or 2016. The **SIRAL** (ESA on CryoSat-2) and **AltiKa** (CNES/ISRO on SARAL) instruments are also currently providing valuable radar altimetry data streams. The Chinese **ALT** instrument is also currently operating, but timely data access is not available, which has limited its utility.

The Bureau of Meteorology reported that their radar altimeter data (from the likes of Jason, SIRAL, and AltiKa) is sourced from the Radar Altimeter Database System (RADS). RADS is an effort to establishing a harmonised, validated and cross-calibrated sea level data base from satellite altimeter data. It operates within the framework of the Netherlands Earth Observation NETwork (NEONET), an internet facility, funded by the Dutch government, for exploitation of remote-sensing expertise and data.

The main current scatterometer data streams are **ASCAT** (two operational by EUMETSAT/ESA on MetOp-A and -B), and **Aquarius** (one operational by NASA/CONAE). NASA's **SeaWinds** scatterometer experienced a partial failure in 2009 which has limited its role to providing complementary calibration and validation measurements – and it is near its end of life both pragmatically and technically. The Chinese **SCAT** instrument flies on HY-2, but as with ALT, data access has limited its applicability. India launched Oceansat-2 in 2009 but the scatterometer has since failed, though India plans to replace it with SCATSAT-1 in 2016. The RapidScat instrument has also been recently deployed on the International Space Station and is being used operationally in some centres.

Passive microwave instruments have recently started to emerge as an important source of soil moisture measurements. The depth of microwave soil moisture measurements depends on the wavelength used, with penetration into the soil being about half the wavelength.

Until recently, the main source of microwave observations for soil moisture was the scatterometer **ASCAT** (C-band, 5.6cm wavelength) which provided observations for the top two centimetres of the soil on a national scale. While ASCAT's primary mission is ocean observation, two dedicated L-band microwave (23.5cm wavelength) soil moisture missions have been launched and are currently operating – **SMOS** (ESA, 2009), and **SMAP** (NASA, 2015).

Microwave imagers, such as **AMSR-**2 on the **GCOM-W1** satellite, are an important source of SST information, providing coverage in persistently cloudy areas.

Hyperspectral imagers simultaneously acquire radiance measurements in many narrow, contiguous spectral bands, and the field is often referred to as 'imaging spectroscopy'. Hyperspectral imagery is a relatively new type of Earth observation data and its utility is still being assessed in many application areas – one promising area of interest for Australia is mineral exploration, and in the mining case study, the frequent use of aircraft based hyperspectral imager was referenced.

Imaging spectroscopy has the potential to allow greater understanding of vegetation dynamics and physiology and also helps to determine the most discriminating spectral bands for particular target materials and/or conditions. There is only one currently satellite-based hyperspectral imager – NASA's **Hyperion** (launched in 2000). It provides hyperspectral images at 30m over a swath of 185km, though revisit rates will limit utility for some applications.

LiDAR Altimeters and DEM datasets were flagged for their role in mining operations and the monitoring of open cut mines. LiDAR instruments provide precise and accurate measurements of elevation, and can help in the monitoring of changes over time with sustained observations. There are no current satellite-based LiDAR altimetry data streams, with most acquisitions being made from aircraft. It should be noted that airborne LiDAR acquisitions are one of the largest single investments in spatial data by local and state governments across Australia. In addition, Australian-based companies making LiDAR acquisitions operate globally.

DEM datasets are not an instrument type, but rather an application of a number of different possible data types (including LiDAR, but more typically SAR and optical imagery) to create a detailed model of the ground elevation. These models are used as an input to modelling processes (e.g. floods), and in a broad range of mapping applications.

A number of satellites and space-based observations have played an important role in creating DEMs, including NASA's **Shuttle Radar Topography Mission** (SRTM, 2000), the joint U.S.-Japanese **ASTER** global DEM (GDEM, 2009), Japan's PRISM-derived DEM, and Germany's **TanDEM-X** (2010-2014). Once constructed, DEM data sets don't require frequent observations to maintain, but over time improved observations have resulted in greatly increased accuracy and produced finer resolution DEMs.

For some time, the SRTM 30m (SRTM-30) DEM was considered the standard, though access to the data was restricted due to U.S. Government national security concerns. However, SRTM-30 is in the process of being released globally by the U.S.'s National Geospatial-Intelligence Agency (NGA) – and is being improved on with complementary gap filling data releases from NASA. Japan has also recently released a global 30m DEM known as ALOS World 3D, available for free download. In addition, the TanDEM-X derived World DEM provides resolution finer than 12m commercially.

Analysis

The supply agencies for the main current **low resolution optical** data streams are from the **U.S.** (NASA, NOAA) and **Europe** (EUMETSAT) from LEO, and **Japan** (JMA) from geostationary. Current supply is strong, and expected to be further bolstered in the near future by the addition of Sentinel-3 and Himawari-8, as well as Korean geostationary imagers in 2018, and Chinese geostationary imagers in the future.

The main current supply agency for **medium resolution optical** data is from the **U.S.** (USGS), though this will start to shift later in 2015 with the introduction of Europe's Sentinel-2A. In addition, a number of viable commercial substitutes exist – the main two arguably being RESOURCESAT from India, and SSTL from the U.K.

The main current supply of **high resolution optical** data is from commercial providers based in the **U.S.** and **Europe**. These providers operate a number of missions offering spatial resolutions down to 0.5m – though recent decisions by the U.S. Government to relax these restrictions is likely to make finer resolution optical imagery more generally available.

Generally speaking, Australia's use of **SAR** data is considerably less developed than the use of optical data, including in some application areas where overseas users are routinely and preferentially applying SAR. When required, the main current supply options for **C-band SAR** are the commercial RADARSAT-2 (MDA, **Canada**), as well as the public good Sentinel-1A from **Europe**. The expectation is that with public good SAR data available from Sentinel-1A, users will adapt their relevant applications, and that new applications will emerge.

The main current supply option for **L-band** SAR is **Japan's** commercial ALOS-2 mission, with no further L-band SAR missions operating – increasing supply risk for this data type. The main supply options for **X-band** SAR are currently **European** (TerraSAR-X) and **Italian** (COSMO-SkyMed) commercial missions, and with multiple missions flying and continuity planned supply risk is low.

Data Type	Americas	Europe	Asia	Commercial
Low Resolution Optical	NASA, NOAA	EUMETSAT	JMA	
Medium Resolution Optical	USGS			India (RESOURCESAT), SSTL
High Resolution Optical				Airbus DS, Digital Globe
SAR		EC, ESA		Airbus DS, MDA, COSMO-SkyMed, RESTEC/ALOS-2

Table 14 – Current main data suppliers (as of June 2015)

Overall, current data supply for Australia for the main data types studied is adequate with some need for users to be adaptable based on non-optimal (but acceptable) performance specifications, and with some areas for concern around continuity. The full continuity of supply picture is discussed in Section 5.

SUPPLY RISK ASSESSMENT

Introduction

Requirements for Australian EOS data usage were derived from the seven case studies conducted by ACIL Allen, in consultation with case study experts, and are summarised in Section 3. Section 3.4 identifies the most demanding minimal and optimal performance specifications for the four main instrument types required to support the applications studied.

Section 4 looks at the current state of supply for each of the four main instrument types, and identifies key current supply agencies.

This section provides an assessment of the future supply risk for the main instrument types, assessing the continuity outlook, the key instruments and sponsoring agencies, and the main risks and contingencies.

Low Resolution Optical (> 80m)

Continuity Outlook Summary

Low resolution optical has been identified as a priority by a number of the most prominent Earth observation programmes globally, with significant investments being made by governments in the U.S. (AVHRR, MODIS, VIIRS), Europe (AVHRR, Sentinel-3), and Japan (Himawari-8 and -9, GCOM-C) to ensure continuity of these observations.

For several years now, there has been an acknowledged continuity risk with the aging and gradual degradation of the MODIS instruments – both operating substantially beyond their expected operational lifespan. This risk was mitigated by the launch of VIIRS in 2011, however its suitability for some applications has yet to be confirmed.

The prospects for continuity are bolstered significantly by European investment in Sentinel-3. And there is potential that Japan's Himawari-8 and -9 geostationary low resolution optical instruments, a great improvement on the current performance of MTSAT-2's IMAGER, may provide further continuity. Himawari-8 has been successfully launched, and as of early 2015 is undergoing checkout. Once operational, data distribution for Australian users will be coordinated by the BOM. In addition, Japan is planning to fly GCOM-C1 within the next year which will provide MODIS-like performance from LEO.

There is some short term risk to continuity in the next year as several key data streams ramp up to operations, and reliance on the aging MODIS instruments continues. But the longer term risk for this data type would be considered low.

Key Instruments and Agencies

Table 15 summarises the characteristics of the main current and future low resolution optical instruments. The colour coding in the table indicates whether the performance meets or exceeds the most demanding minimal and optimal requirements from the case studies as summarised in Table 6 (Section 3.4).

- **Green:** meets or exceeds the most demanding optimal requirement.
- **Yellow:** meets or exceeds the most demanding minimal requirement.
- **Red:** does not meet the most demanding minimal requirement.

This assessment is predicated against the most demanding applications in each of the five instrument characteristics. This does not mean that the instruments don't meet the requirements of any applications – in fact, all listed are or will be workhorses in the class.

Instrument *Years*	Spatial Resolution	Spectral Bands	Coverage Area	Coverage Frequency	Latency
AVHRR *1979-2021*	1.1km	VIS-TIR: 6 bands	Global	Twice daily with constellation	Direct broadcast
MODIS *1999-2017+*	250m	VIS-TIR: 36 bands	Global	1-2 day revisit	Direct broadcast
VIIRS *2011-2027*	400m	VIS-TIR: 22 bands	Global	1-2 day revisit	Direct broadcast
OLCI (Sentinel-3) *2015-2024+*	300m	VIS-SWIR: 21 bands	Global	1-2 day revisit	Internet download 30 minutes up to 3 hours
AHI (Himawari) *2015-2013*	500m	VIS-TIR: 16 bands	Hemisphere	10-15 minutes (after end of scan)	Internet download
SGLI (GCOM-C) *2016-2021+*	250m	VIS-TIR: 19 bands	Global	2-3 days	Internet download

Table 15 – Main current and future low resolution optical instrument characteristics
+ indicates that continuity beyond current end year is being considered

While no single instrument meets all of the optimal performance requirements, each one of the main instruments meets at least one optimal and two minimal requirements.

MODIS (NASA) addresses three of the optimal requirements, and two of the minimal requirements for low resolution optical, and will remain an important data stream until its end of life. Currently, the programmatic end of life is 2017, but it is expected that funding for operations will be extended until the satellites are no longer technically viable.

According to an analysis (http://www.istl.org/11-fall/article1.html) by NASA Goddard Space Flight Center Library referencing the website *Web of Science*, MODIS was cited by academic papers more 40,000 times between 2000 and 2009. Based on these research efforts, it has become the basis of a number of operational services. In addition to continuity of the data stream, it is important that MODIS operations overlap with as many of the future data streams as possible, allowing for direct comparison, and the adaptation of current applications to future data flows.

The role of NASA as a provider agency for low resolution optical is likely to wane with the eventual demise of MODIS. This is in keeping with NASA's role as a research and development focused agency, rather than a provider of operational services.

VIIRS (NOAA) addresses two of the optimal requirements, and two of the minimal requirements for low resolution optical, and is expected to remain an important data stream. It appears to be the U.S. Government's proposed continuity option for both AVHRR and MODIS. As cited in several of the case studies, the technical capability of VIIRS to address the user requirements to the full breadth of the MODIS user community is still being investigated. While in many ways, VIIRS builds and improves on previous sensors, the loss of 14 bands relative to MODIS is likely to inhibit some applications.

Figure 4 shows the current and future plans of NOAA and EUMETSAT to fly AVHRR and VIIRS. AVHRR is currently flying on NOAA-15, -18, and -19, as well as on MetOp-A and –B, and will fly on MetOp-C in 2018. While VIIRS is currently flying on Suomi NPP, and is planned to fly on JPSS-1 through JPSS-4.

Based on nominal mission lifetime, the plan is to have only one VIIRS instrument flying at a time, with the exception of 1-2 year overlap periods between missions. Similarly narrow overlap periods are planned for EUMETSAT's AVHRR instruments. This means that MODIS users looking for continuity with VIIRS will have to adjust their expectations for revisit times with only one instrument planned to be in operation most of the time.

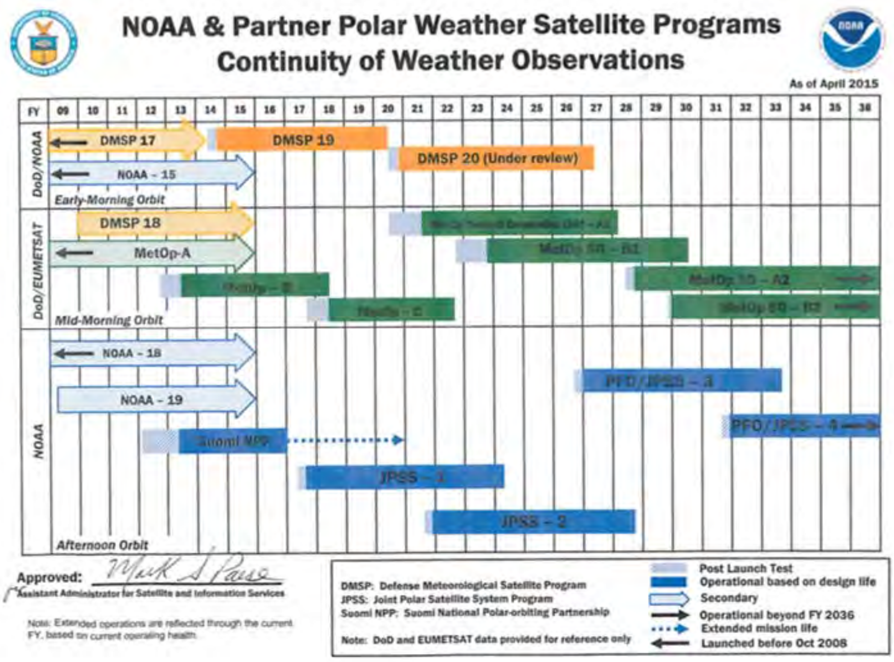


Figure 4 – NOAA and Partner mission plans as of April 2015

Securing funding support for the JPSS programme has been a difficult process for NOAA, with the original plan being to fly most of the JPSS instrument suite jointly with NASA and the U.S. military on the now cancelled National Polar-orbiting Operational Environmental Satellite System (NPOESS) missions. These plans were abandoned, and the JPSS programme has struggled to gain firm funding commitments. While Table 16 shows there is still some uncertainty around budget requests, the JPSS-1 and -2 missions were allocated significant funding for U.S. FY2015, while funding for JPSS-3 and -4 remains to be confirmed but is being discussed.

NOAA Budget

Figures are rounded and in millions of U.S. dollars.

Program	2015 Enacted	2016 White House Request	Difference
Joint Polar Satellite System	$916.3	$809.0	▼ -$107.3
Polar Follow-On (JPSS-3, JPSS-4, Gap-filler)	-	$380.0	-
Geostationary Operational Environmental Satellite System	$980.8	$871.8	▼ -$109.0
COSMIC 2	$6.8	$20.0	▲ $13.2
Jason-3	$23.2	$7.5	▼ -$15.7
DSCOVR	$21.1	$3.2	▼ -$17.9

Source: National Oceanic and Atmospheric Administration — SPACENEWS GRAPHIC

Table 16 – NOAA FY2015 and FY2016 budget requests (Credit: Spacenews, NOAA)

EUMETSAT's plans to fly AVHRR appear to end after MetOp-C (with nominal end of life in the 2022 timeframe), though they are considering a comparable instrument on the MetOp-B1 and –B2 missions to pick up from the end of MetOp-C.

The role of NOAA as a provider agency for meteorological data, and in particular in this case for VIIRS imagery over oceans, will remain quite important. Because of NOAA's institutional focus on ocean observations, it remains to be seen whether the VIIRS programme will give weight to the requirements of the land monitoring community in future evolutions of the instrument.

OLCI (EC/ESA) addresses one optimal requirement, and two minimal requirements, and is expected to provide a high quality continuity option operationally from late-2015, with the instrument specifications aligning well with land surface and ocean colour observation requirements. Plans for a re-fly of OLCI on Sentinel-3B in 2017 are well advanced, and continuous operational data flows are anticipated. Based on these launch plans, and a nominal seven year mission lifespan, two OLCI instruments can be expected to be operational for significant periods of time.

As is the case with the other future data streams, application service providers will need to invest in the adaptation of existing applications to new data streams. However, operational continuity for Sentinel-3 under Europe's Copernicus programme increases confidence in future data supply. Existing MODIS users will have to adapt to the reduced resolutions available from OLCI (300m vs 250m of MODIS) and VIIRS (400m).

SGLI (JAXA) will address two of the optimal requirements, and three of the minimal requirements when it flies on GCOM-C1 in late 2015. While follow-up flights are being considered, programmatic continuity is in question with JAXA's future plans indicating almost all environmental satellites will cease after the current generation under construction. Users are unlikely to invest significantly in GCOM-C given the multiple uncertainties around the programme.

AHI (JMA), currently flying on Himawari-8 and scheduled to fly on its successor Himawari-9 (2016), holds the potential to support a new class of land cover applications – in addition to the valuable ocean and cloud imagery applications they are intended to service.

Himawari is operated by JMA, who are expected to remain invested in the WMO Information System (WIS). While direct broadcast of the data has been dropped from Himawari in favour of internet download, as a matter of data policy it is expected that all Himawari data will be made available freely and openly via the WIS, as well as likely via direct download from mirror FTP sites, and via direct links to Australia's National Computational Infrastructure.

AHI provides a spatial resolution of 500m for some visible bands, features six visible bands (i.e. first full colour images from geostationary since the 1960's), and includes a total of 16 bands across the VIS, NIR and IR wavelengths. While some research and development will be required to translate this increased performance into operational products, and some combination with other LEO data streams may be needed, there is great potential for this new class of geostationary imagers to provide a significant boost to data supply and continuity. An application development pathway for those new geostationary data streams is currently being discussed between Japan and Australia.

Advanced MI (KARI, KMA) will be launched by Korea in 2018, and will provide a comparable and compatible data stream to Himawari-8 and -9, which will further increase the availability of coarse resolution optical from geostationary. Coordination of acquisition schedules has been discussed, which could make new imagery available every five minutes. Chinese geostationary imagers are also expected to provide similar data streams in the future.

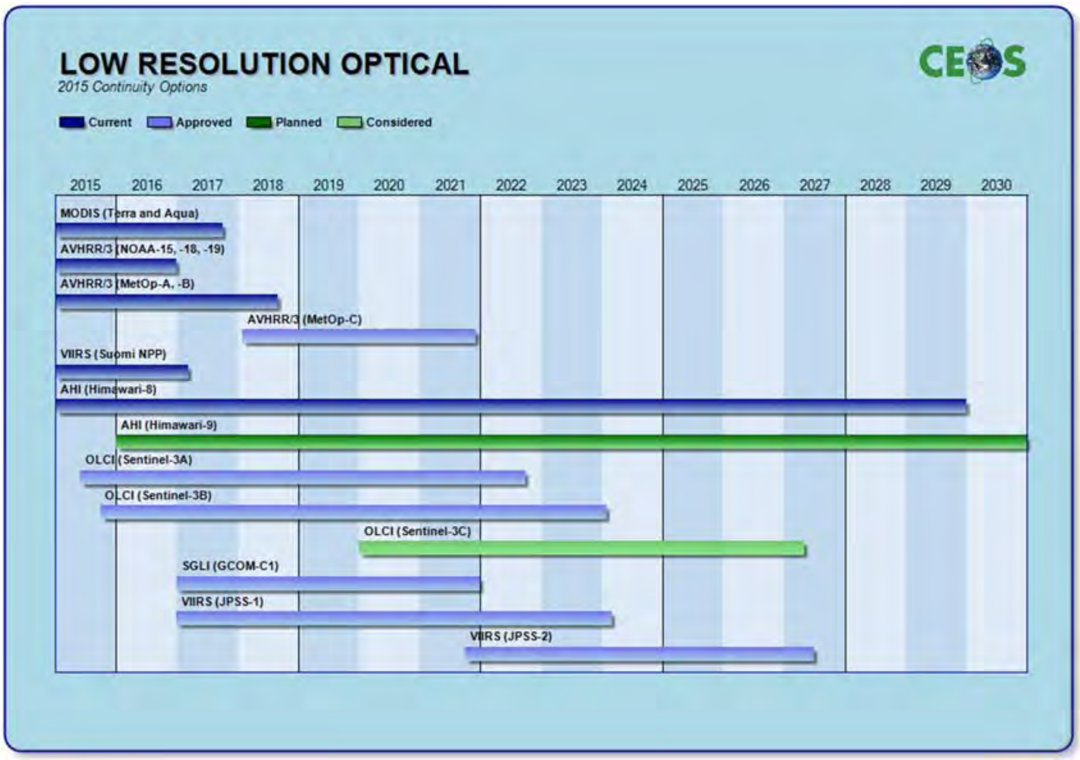


Figure 5 – Low resolution optical continuity options

Ocean Colour and Sea Surface Temperature

As discussed in Section 4.2, ocean colour and sea surface temperature (SST) represent specialised applications within the low resolution optical instrument type.

The International Ocean Colour Coordinating Group (IOCCG) has identified a number of current and future instruments and characterised their suitability for ocean colour measurements (http://www.ioccg.org/sensors_ioccg.html). Current "best in class" instruments include MODIS and VIIRS. Chinese (COCTS, CZI, MERIS) and Indian (OCM-2) instruments provide additional measurements, but the calibration, quality, and availability of this data has been variable in the past.

The main future instruments identified for ocean colour observations are OLCI (Sentinel-3), as well as ongoing supply from VIIRS. In addition, Korea's GOCI is currently providing ocean colour data in the vicinity of the Korean peninsula from geostationary orbit, and future geostationary instruments may expand this coverage. For example, ocean colour products from Himawari-8 and -9's geostationary instruments are being considered – but some work remains to establish whether they will be viable. In addition to direct measurements of ocean colour, important contextual rainfall information generated by the BOM is provided by satellite observations and supports the assessment of water quality.

There have been questions around the suitability of VIIRS for ocean colour observations both in terms of band selection (vis-à-vis MODIS), and also faster than expected instrument degradation. It is expected that these issues will be better characterised as more data is gathered, and will be addressed in the design of future re-flies of VIIRS on JPSS-1 and -2 – however there is still some uncertainty for the ocean colour observations.

OLCI includes strong support for ocean colour products, and the design and specifications appear to support that. The actual suitability and instrument performance remain to be confirmed after launch (currently late 2015). If the promise is realised, OLCI will provide a strong continuity option for ocean colour observations.

The Group for High Resolution Sea Surface Temperature (GHRSST) provides stewardship of global observations, including around continuity of satellite data supply. Key current SST missions include several current low resolution optical instruments (microwave measurements are also used) – namely AVHRR and MODIS. As noted, VIIRS is the primary U.S. continuity option for AVHRR and MODIS, and this includes support for SST observations – and so continuity will depend in part on the success of future VIIRS re-flies on JPSS.

In addition, the SLSTR instrument on Sentinel-3 is focused on land and sea surface temperature observations using low resolution optical, which presents another strong option for continuity.

Main Risks and Contingencies

While prospects for continuity in the supply of low resolution optical imagery are strong, several risks do exist.

1. **Short term failure of one or both MODIS** instruments would likely cause a supply shock for dependant applications, mostly due to the fact that many applications have built their data flows out to MODIS will little consideration for continuity, focusing mostly on its broad coverage, spectral bands, and direct broadcast. In the event of such a failure, a number of contingency options exist – with the two most likely being the adoption of VIIRS and/or Sentinel-3A data streams by current applications. Given that there are two MODIS units, a simultaneous failure is unlikely, and so if one unit were to fail, application developers would be able to take that as a firm cue to start looking at contingency data streams.

2. **The end of MODIS direct broadcast** has been foreshadowed for a number of years. However, this change will have a significant impact on the user community, and introduces additional uncertainty around network (i.e. internet) performance and data access. AVHRR and VIIRS are expected to continue to be available via direct broadcast, but for applications that will rely on OLCI (Sentinel-3) and SGLI (GCOM-C) for continuity, there is some risk. In the case of missions dependent on Svalbard downlink (like Sentinel-3), the increase in latency can be up to two hours. The OLCI on Sentinel-3 mission requirement for product availability is within three hours of acquisition (though actual performance will have to be assessed).

   Australia is heavily invested in NRT applications of MODIS. It is likely that in the transition, a number of application providers will have to adapt their data flows, relying increasingly on internet connectivity, and also potentially accept longer delays before products are available. Plans underway to try and host Sentinel-3 and Himawari data on Australia's National Computational Infrastructure (NCI) should help to mitigate this risk.

3. **Uncertainty has characterised the Japanese EOS programme** since the sudden change to the ALOS data policy. It would seem that the prospective GCOM-C data stream is exposed to this risk, given that the Himawari data streams are provided via the WIS.

4. **Development of the Copernicus ground segment and data policy implementation** remains a work in progress. The announced public good data policy is close to ideal – however as the implementation of the supporting ground segment proceeds, fundamental technical issues remain to be addressed, and funding arrangements for a ground segment to support operational users outside of Europe need to be confirmed. For low resolution imagery, it is unlikely that a data policy change will take place, and the risk around ground segment development is being mitigated by pursuing direct discussions with the European Commission (EC) on an Australian ground segment component. These discussions appear to be positive, but the outcome and its implications are not yet known. The adequacy of the ground segment to meet fundamental user requirements remains to be seen – and this is true of all Sentinel series missions of ESA/EC.

Risk Assessment

There are currently two operating MODIS instruments, with VIIRS providing an operational backup for most applications. These low resolution optical sources are set to be joined by Sentinel-3A by the end of 2015 – which will offer a directly comparable supply, and a 3B unit planned for launch within a year of the first. VIIRS continuity is planned with the launch of an additional unit on JPSS-1 in 2017. With this, it is likely that there will be 2-3 operational instruments at any one time in LEO.

Himawari-8 will offer coverage of Australia's hemisphere from geostationary orbit from mid-2015. This data stream provides a comparable, though coarser, spatial resolution relative to LEO instruments, but at a greatly increased frequency of observation (10 minutes for Australia). While some application development is required in order to leverage this data stream, it holds the promise of providing continuity for a number of applications. Himawari-9 is planned for launch in 2016.

	Technical Continuity Risk	Programmatic Risk	Political/policy Risk
Risk Level	Low	Medium	Low
Rationale	A number of high quality low resolution optical instruments are being developed that meet or exceed requirements. Latency loss may be the biggest risk – with users accustomed to twice-daily MODIS direct broadcast. The advent of geostationary data streams has the strong potential to bolster continuity further – given application development investment	Securing funding for JPSS missions (VIIRS) has been challenging European ground segment (OLCI) planning is late and adequacy uncertain GCOM-C programme continuity is very uncertain	Unlikely that low resolution data will see any shift in data policy of any of the main providers

Table 17 – Low resolution optical risk assessment

There is a slightly elevated programmatic risk with funding for VIIRS on JPSS uncertain in the recent past, with the global ground segment for Sentinel-3A remaining to be defined, and with uncertainty around Japan's GCOM-C beyond the first mission. However, it appears as though JPSS funding is now assured for the first two missions, and the dialogue with the EC on establishing an Australian hub is promising. Continuity of Japanese EOS programs is likely to remain uncertain for the foreseeable future.

High Resolution Optical (< 10m)

Continuity Outlook Summary

Continuity of high resolution optical data streams is almost exclusively the domain of commercial data providers, with traditional space agencies supporting their national industry, but not typically engaging in data supply beyond support for R&D and humanitarian purposes. Commercial data providers are often underpinned financially by large national security related supply contracts, for example with the likes of the National Geospatial-Intelligence Agency (NGA) in the U.S. As noted in Section 3.4, for the purposes of the continuity of supply analysis, **very high resolution optical** (<1m) instruments will also be grouped with high resolution as they are also generally only available on commercial terms.

According to Euroconsult (2014), the expected compound annual growth rate for the EOS imagery market for the period 2013-2022 is expected to be 15-25% - with the overall market growing to $US 6 billion annually. These growth prospects mean that supply will likely be strong as commercial actors invest to address a growing need.

The proliferation of public good medium resolution optical data (see Section 5.5) is going to continue to squeeze the commercial market towards high and very high resolution or specialized products like hyperspectral imagery. For example, while considered to be medium resolution, Europe's Sentinel-2 (scheduled for launch in 2015) will incorporate four visible to near-infrared bands at 10m. Once this data is available freely and frequently to users, many applications may be adapted to take advantage, trading off zero supply cost for slightly coarser resolution, and with the confidence that this high quality data will be available on an operational basis.

Evidence that the commercial providers recognize this shift can be seen in the push by Digital Globe on the U.S. Department of Commerce to remove the historical 50cm national security limitation on public sales of imagery. This change was granted in 2014, enabling the sale of 41cm data from GeoEye-1, and paves the way for the sale of the 25cm data from World View-3 and GeoEye-2 (scheduled for launch in 2016). It is estimated by Reuters that Digital Globe could realize an additional $US 400 million in revenue through the relaxing of this restriction.

Increased resolution is not expected to account for all the growth in the commercial market in the coming years. The emergence of newer actors leveraging advances in small satellite technology (under 500kg, and principally under 100kg) to create dense constellations of 10's or 100's of low cost satellites is expected to create a significant market for high frequency (multiple daily) optical coverage at high and very high resolution.

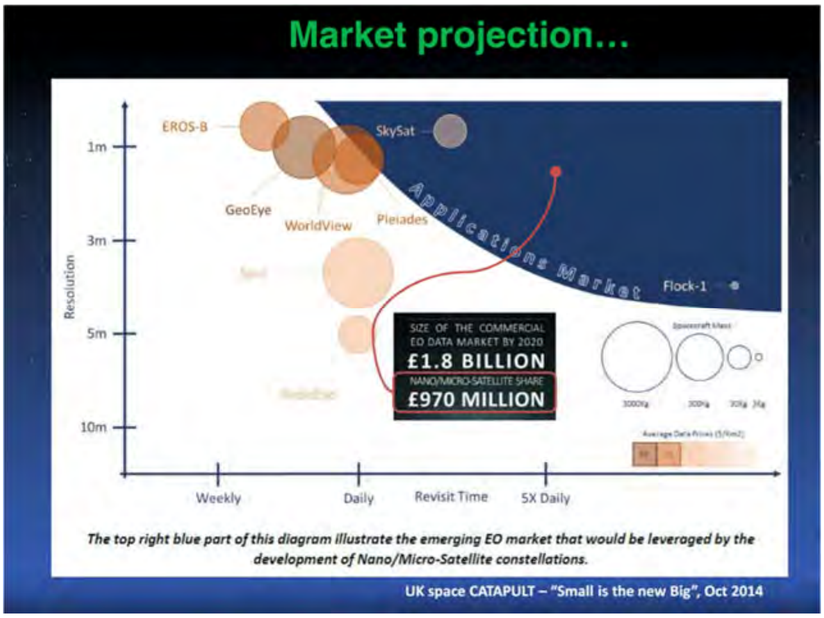


Figure 6 – High Resolution vs. Frequency of Observations (Credit: SSTL)

SSTL estimates that this new market could account for approximately 50% of total commercial high resolution data sales by 2020. The growth is projected to be driven by the applications enabled by rapid revisit, and the notion that data quality is not as important as data availability and efficient distribution in some cases. Rapid revisit may become as prolific a driver for the development of new EOS data applications as public good data streams like MODIS, Landsat, and Sentinel.

During this study, only one of the case studies (disasters – flood monitoring) identified the potential for rapid revisit. Notably at high and very high resolution, most of the requirements identified were in support of land cover mapping and change mapping by the likes of SPOT – with continuity there provided commercially by SPOT-6 and SPOT-7.

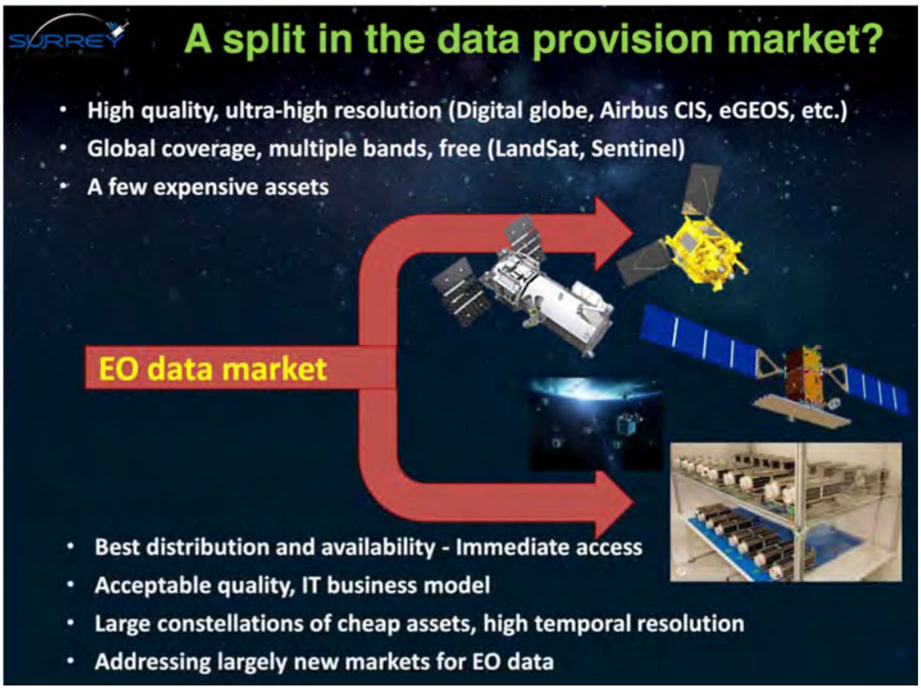


Figure 7 – High Resolution Optical EOS Market Split (Credit: SSTL)

The advent of rapid revisit services (like Planet Labs) may also be accompanied by a shift to more frequent and systematic acquisitions by commercial providers hoping to build dense time series, support mosaicking, and underpin reliable data availability. This should also support new business models – for example, users could pay a fixed subscription fee for access to a service that provides a steady flow of pixels (acquisitions) over defined areas of interest. These kinds of services will potentially remove the need to order data up front, and in turn may remove a barrier to entry for new users.

While the emergence of these new actors and business models holds the potential to open up new application areas, it is not likely that they would displace the existing commercial providers, whose programs are based on the technical heritage and experience of the likes of SPOT and are backed by significant existing markets and government supply contracts. Essentially, the trade-off may become between the image quality and consistency of the existing suppliers, versus the immediate low cost access that large constellations of cheaper satellites enable.

Key Instruments and Agencies

Very high resolution <1m: Data flows from the **World View** and **GeoEye** series of instruments, as well as from **Pléiades** will continue to dominate the very high resolution (<1m) data supply into the future. Additional investment and new missions being planned and launched after the removal of the historical 50cm national security limitation on public sales of imagery in the U.S. have opened up this market. (See *Main Risks and Contingencies*, Point 2.)

High resolution ~5m: Data supply at the 5m resolution has been dominated by **SPOT-4** and **SPOT-5**, as well as **RapidEye** in recent times. With the end of the SPOT-4 and SPOT-5 missions, **SPOT-6** and **SPOT-7** are expected to provide a measure of continuity. RapidEye, after becoming the first commercial high resolution constellation in 2008, suffered significant business challenges which culminated in bankruptcy and a sale to Blackbridge. After addressing these challenges, the business is now profitable, and planning for the next generation of satellites and investment is underway. These plans are not yet public, and the future direction for the constellation remains to be seen, with potential outcomes including a move towards finer resolution, more frequent revisit, or better spectral performance.

High resolution ~10m: Ten years ago, 10m data represented the core of the commercial high resolution market. As technology has improved, spatial resolutions have become almost an order of magnitude finer, while maintaining and improving data quality. However, a number of important applications are still enabled by 10m data – including state and national scale monitoring and mapping activities. With the entrance of Sentinel-2A in 2015, providing public good operational 10m data, significant application development should be expected. This may create a dependency on public good 10m data, which could present a future continuity risk with just one public good 10m data stream planned at present – thereby leaving application developers to scramble for commercial data continuity in the event of a supply interruption.

Main Risks and Contingencies

1. **Commercial users dictate future priorities** and so there is some risk that those priorities are not in alignment with Australian user needs. This consideration applies to consumers of high resolution data globally, and commercial providers by their nature need to be responsive to user needs in order to stay viable. But ultimately their priorities are subject to profitability and the marketplace, and the supply profile will be governed by shareholder return and the influence of the major customers (e.g. NGA in the U.S.).

2. **Re-tightening of sub-50cm data restrictions by the U.S. Government:** the relaxation of restrictions on the **very high resolution** market by the U.S. has opened up current and future data streams. While it seems unlikely, if these restrictions were re-tightened, then very high resolution data supply would be considerably reduced, though Pléiades (France) would likely continue to provide an option in the 50cm range.
3. **Source switching** between the range of high resolution supply options can lead to sometimes significant data handling and processing chain changes for users. These adjustments require resources and expertise on the part of application developers, which may make continuity of data supplier more important. The development of more flexible and extensible data handling systems and platforms, employing similar approaches to the Australian Geoscience Data Cube (AGCD), can help to mitigate these costs.
4. As noted in Section 5.2, **development of the Copernicus ground segment and data policy implementation** remains a work in progress. This also impacts on the supply of Sentinel-2 data. While this is at the coarser end of the high resolution range, it is likely to be an important data stream and is attracting significant interest in the case study responses even before launch.

Risk Assessment

Supply of high resolution optical is commercially based, and with a strong market (underpinned by national defence), supply prospects are strong. Recent announcements of the relaxing of the restriction of the sale of sub-50cm images by the U.S. Government should open up finer resolution supply.

The adoption of constellations with 10's and 100's of satellites also appears likely to bolster supply. And also open up a new axis for growth in applications built around low latency and high frequency revisit. The likes of SSTL, Planet Labs, and Skybox are likely to be the leading supply options, with potentially a completely new cadre of application developers engaging, and the outcome remaining to be seen.

	Technical Continuity Risk	Programmatic Risk	Political/policy Risk
Risk Level	Low	Low	Low
Rationale	Key providers have strong continuity plans with equivalent or better quality. Sentinel-2 may bend behaviour and requirements to coarser resolution and some adaptation may be needed which may require investment.	Multiple sources available. U.S. sources tied to the national intelligence procurement plans.	Increased commercial competition good for net EOS data consumers.

Table 18 – High resolution optical supply risk summary

Supply of high resolution optical data appears strong, with risk low, and competition increasing. As a net consumer of commercial satellite data, these are good trends for Australia. However, the market will largely dictate the future supply profile, and being a relatively small consumer, Australia is not likely to have a strong influence making it potentially vulnerable to any retraction of data supply.

Synthetic Aperture Radar (SAR)

Continuity Outlook Summary

Current supply of SAR data streams is largely from the commercial sector, often backed by national space agencies representing both industrial development and national security interests. While there are a number of SAR data streams current and future, the continuity prospects for these data streams varies significantly between frequency bands.

Continuity of **C-band** SAR is best placed, with two 'workhorse' missions currently operational (RADARSAT-2 and Sentinel-1A), and continuity envisioned for both these high-legacy systems. By this time next year, presuming launch plans hold, Sentinel-1B should be in operation, with continuity planned beyond that. Sentinel-1 has a public good data policy, which should be expected to greatly increase adoption.

Planning is also underway for a three satellite RADARSAT constellation (RCM, 2018). The current intention is that RCM will match Sentinel-1's public good data policy, however the details remain to be confirmed as launch approaches.

It is possible – based on current plans – that there could be five public good C-band SAR instruments operating by 2020.

Continuity for **X-band** SAR will remain partially dependant on Italy's four satellite Cosmo-SkyMed constellation (CSK), and its commercial and defence linkages. CSK continuity is being planned via a second generation constellation. Prospects for continuity of supply of the German TerraSAR-X / TanDEM-X are also strong, with DLR planning for TerraSAR-X next generation in 2018, as well as the High Resolution Wide Swath (HWRS) mission in 2022.

The Russian meteorological (ROSHYDROMET) and space agencies (ROSKOSMOS) are currently flying two polar orbiting X-band SAR instruments, and have plans to fly several more in the future. However, significant uncertainty around funding and politics, and constrained data access mean that these missions should not be considered as strong supply continuity options. Similarly, South Korea's space agency, KARI, is currently flying an X-band SAR instrument on KOMPSAT-5 – however very constrained data access and defence interests means it does not represent a strong supply option.

Several other X-band missions may represent future supply options, including Spain's PAZ (2015 – 2020), Vietnam's LOTUSat 1 and 2 (2017 – 2023), and China's HY-3A, -3B, and -3C missions (current – 2027). However, funding stability and a lack of technical heritage and ground segment experience raise doubts about availability and suitability. The emerging interest in X-band SAR for countries in Asia, and in particular South East Asia is of interest - with the main application area for these data streams thought to be the monitoring of maritime activity in the South China Sea. In addition, Thailand is thought to be seeking X-band capability via a partnership with Japan.

Continuity of **L-band** SAR is the least clear of the three main types. Currently, the only available data stream is Japan's ALOS-2 commercial mission. While indications are that Japan supports L-band continuity, there is significant uncertainty around its national Earth observation programme, and planning for a continuity mission hasn't formally started.

Argentina is planning a four satellite series of L-band satellites called SAOCOM, the first of which is planned for launch in late 2016. The intention signalled is that it will have a public good data policy for coverage outside of Europe, while Argentina's Italian partners have reserved European coverage. And while a systematic global acquisition strategy is being planned for SAOCOM, it remains to be seen whether the ground segment implementation can support these ambitions on an operational basis.

The U.S. (NASA) and India (ISRO) are cooperating on an L- / S-band SAR mission (NISAR) for launch in the 2020 timeframe – though based on past, stop-start NASA plans to develop an L-band SAR, these plans remain uncertain. Should this emerge as a strongly backed NASA mission, it could be expected to benefit from NASA's public good data policy.

In addition to the usual C-, L-, and X-band instruments, research and development of S-band and P-band sensors is also underway. ESA has recently approved a P-band Earth Explorer mission called BIOMASS, which aims to measure aboveground biomass directly. And SSTL has initiated the development of an S-band mission called NovaSAR, with a number of land and ocean monitoring activities considered. It is expected that data from BIOMASS will be public good, while NovaSAR is likely to be commercial.

Key Instruments and Agencies

C-Band

Sentinel-1 follows the lineage of ERS and Envisat, but is wrapped in the services approach to continuity established by Europe's Copernicus programme – and benefits from its public good data policy. Sentinel-1A was launched in April 2014, and is currently operational, with Sentinel-1B expected to launch in early 2016. Continuity planning for future 1C and 1D units is also underway.

The **RADARSAT** series represents the longest continuous C-band data series, with continuity currently provided by RADATSAT-2. The three satellite RADARSAT constellation mission (RCM) is currently planned for launch in the 2018-2019 timeframe, and present indications are that it will have a public good data policy. Even if RCM does adopt a commercial or partially commercial data policy, it appears as though there is a firm intention to maintain continuity in the series.

X-band

COSMO-SkyMed's four satellites were launched between 2007 and 2010, and it is currently in its ninth year of operation. At present, the expected end of life of the youngest of the four satellites is 2017 – though all remain operational, and it should be expected that they will continue to provide data until they are no longer viable. Continuity for COSMO-SkyMed is planned, with two second generation satellites (known as CSG) planned for launch – one in 2016 and one in 2017. It is expected that the commercial data policy will continue.

TerraSAR-X, and its companion mission, **TanDEM-X** were launched in 2007 and 2010 respectively. The initial primary mission of the TanDEM-X mission was to fly in formation with TerraSAR-X, collecting stereo imagery for the generation of a highly accurate DEM. However, now that mission has been completed, and both satellites provide global commercial X-band coverage. Continuity is planned with the launch of TerraSAR Next Generation (TSX-NG) expected in 2018. In addition, DLR is planning to continue the development of X-band technology with the launch of the High Resolution Wide Swath (HRWS) mission in 2022. This X-band SAR mission will aim to provide broad area coverage at high resolution through the use of specialised digital beam forming techniques.

Meteor-MP, Metero-M and **Obzor** are all 3-4 satellite Russian X-band constellations – with constrained data access and restrictive data policies. There are currently two instances of the BRLK instrument flying on Meteor-M N1 and N2, with six more planned – two on the remaining Meteor-M satellites, as well as on the four planned Obzor satellites. Given the precarious funding of the Russian space programme, and political uncertainty, these are not likely to represent strong continuity options.

Spain's **PAZ** satellite is projected for launch in 2015, and will carry a high resolution X-band instrument. This mission has been developed by Spain's nascent space agency, CDTI, in part as a national capacity development exercise. Access to data from PAZ is constrained, and as a one-off mission is not likely to be setup to provide broad coverage. It may represent a continuity option in the absence of other sources, but some significant work may be required to secure acquisitions, and to access and handle the data.

Korea's **KOMPSAT-5** carries a high resolution X-band SAR instrument, again with a defence oriented constrained data access policy. Continuity plans are underway, with **KOMPSAT-6** expected to carry a SAR instrument (band not confirmed), with launch projected for 2019. However, without access to the data streams this mission does not represent a strong continuity option.

Vietnam's **LOTUSat-1 and -2** satellites are projected for launch in 2017 and 2020 respectively, and will both carry X-band SAR instruments. Vietnam is very new to the build and launch of satellites, and significant delays and a high level of uncertainty would need to be assessed before they could be considered continuity options.

The first of China's **HY-3A, -3B, and -3C** satellites is planned for launch in 2015, with a second in 2017, and a third in 2022, and all three will carry high resolution X-band instruments. The missions are being launched by China's National Satellite Ocean Application Service (NSOAS), and expectations around acquisition strategy and data supply policy are unclear. However, while relatively short, the history of Chinese data supply is variable – in terms of access, reliability, and data quality – and this should temper expectations as a continuity option.

Thailand is also thought to be pursuing a national X-band capability, and the emerging interest in Asia in these data streams – in particular for ocean monitoring – is a trend that should be monitored.

L-band

ALOS-2 was launched in 2014 and follows from Japan's heritage of L-band SAR, with its predecessor, **ALOS,** operating from 2006 – 2011**.** Continuity planning for Japan's L-band missions is uncertain, with no formal plans for a post-ALOS-2 mission approved. Broader uncertainty around Japan's overall Earth observation programme introduces further risk. If continuity for ALOS L-band is implemented, it seems likely that the data policy will be commercial.

Argentina's four satellite **SAOCOM** series offers the promise of a public good L-band data stream, with SAOCOM-1A scheduled to launch in late 2016. A global acquisition strategy is being planned for the missions, but data availability, and especially ground segment capabilities remain to be seen. If this public good data stream begins to flow, it could have significant supply implications. Figure 8 shows the planned Australian coverage by SAOCOM which is anticipated to cover much of the northern, south western and south eastern parts of the country twice annually.

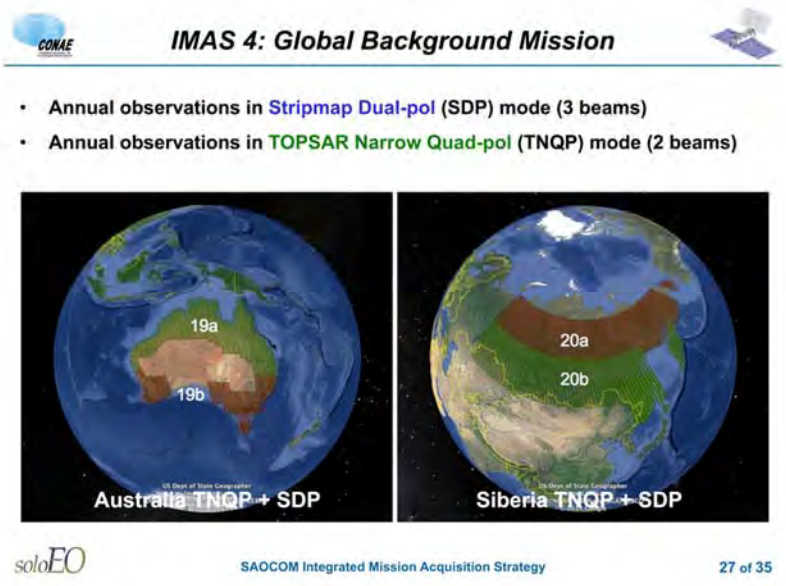


Figure 8 – Planned Australian coverage for SAOCOM's Global Background Mission (Credit: CONAE, soloEO)

NISAR is a joint ISRO (India) / NASA L-band / S-band SAR mission currently planned for launch in 2020. While NASA has a strong heritage of developing successful research missions - and a public good data policy – India's heritage is not as reliable. ISRO is a very capable and accomplished agency, with many successful locally developed and launched satellites. However, plans change frequently within ISRO, as does data policy and availability. Even if successful, at this stage NISAR is only expected to be a one-off research mission – though it does warrant following.

P-band and S-band

BIOMASS (P-band) In 2014, ESA selected the BIOMASS (P-band, 2020) satellite under its Earth Explorer programme. This programme is a science and technology development programme that has successfully launched a number of satellites in the past – and so there is a strong chance that BIOMASS will eventuate. It will be the first P-band SAR satellite, which is significant as the design, build, and deployment of a P-band antenna for space is particularly challenging. The satellite will be designed to directly measure above ground biomass (i.e. plants, trees), though as with many other science missions, new and unexpected applications for the data are likely to be found. At this point, BIOMASS is the only P-band SAR satellite announced, and so it should be treated as a one-off, with no current prospects for continuity.

NovaSAR (S-band) SSTL is developing the NovaSAR system, with significant investment from the U.K. Government. Based on development plans, the mission will be ready for launch in 2016 – however there is currently no customer or funding for launch.

Main Risks and Contingencies

1. **Relatively low Australian civil national heritage and capacity to handle and process SAR data**, in particular in application areas where SAR is employed on a routine basis overseas such as flood monitoring and ocean monitoring. Application developers may begin to incorporate SAR data on a more regular basis with increased regular free and open supply from the likes of Sentinel-1.

2. As noted in Sections 5.2 and 5.3, **development of the Copernicus ground segment and data policy implementation** remains a work in progress. This also impacts on the supply of Sentinel-1 data, though it is currently available via a rolling Science Archive. In this archive, the data is nominally removed after two months (though for the first year all data is being retained and made available).
3. **Ensuring Australian inclusions in systematic acquisitions**, in particular for Sentinel-1A. Without appropriate acquisitions over Australian land, coastal, and ocean regions – including required acquisition modes and beam polarisations – the value of Sentinel-1 data may not be optimised. While there aren't likely to be any competing acquisition priorities over Australian areas of interest, it is possible that operational limitations (e.g. instrument duty cycle, storage and downlink capacity limits) may need to be traded off against acquisitions. This risk should be mitigated by ensuring engagement and representation of Australian requirements within the mission planning process. This could be mitigated by developing a specific set of Australian SAR data requirements, including for Sentinel-1, which could be discussed with the acquisitions team.
4. **Loss of L-band continuity** is a considerable risk with ALOS-2 the only current supply option. While ALOS-2 was only recently launched, at present a single failure would disrupt supply, with the prospects for continuity some years off. The launch of SAOCOM-1A may help to mitigate this risk.
5. **SAOCOM data policy**, if maintained as public good, holds the promise of opening L-band data in the same way that Sentinel-1 is doing for C-band. However, Italian interests in the mission could risk a reversal of the decision. In addition, it is not clear that the ground segment implementation will be able to support the ambitions of SAOCOM's global acquisitions plans. This could be mitigated by closer coordination with CONAE when the satellite is launched.

Risk Assessment

The risk of supply for SAR data streams varies significantly between the various bands.

The continuity of **C-band** SAR supply looks strong through the Sentinel-1 (public good) and RADARSAT (commercial) programs. These are high-legacy, stable programs with clear user bases and strong backing from the relevant national governments. There is some question around whether data from the RADARSAT constellation mission (RCM, 2018+) will be public good, but the prospects for the development and launch of the missions look strong.

The highest risk to supply is for **L-band** SAR, which currently only has one operational data supply (ALOS-2). Planning for L-band ALOS continuity is being discussed, but nothing is currently confirmed, and this planning will be subject to the general uncertainty around the Japanese EOS programme. Argentina's SAOCOM programme may present a viable alternative, however they do not yet have a high heritage of delivering on operational, global coverage missions, and so there is some significant risk around when and how those data will flow.

There is some risk around **X-band** SAR supply, in particular with respect to data policy. There is a good supply of X-band missions given the importance of this data to military and national defence users. However, data access remains on commercial terms, and there is always the chance that the data access may be restricted on national defence grounds. Though for the foreseeable future, commercial supply appears to be assured.

	Technical Continuity Risk	Programmatic Risk	Political/policy Risk
Risk C-band	Low	Low	Low
Rationale	Two healthy operational missions, with a third to be launched within a year	Continuity planning well advanced for both main continuity options	Sentinel-1 open data policy is likely to set the course for C-band data streams
Risk L-band	Medium	High	High
Rationale	One operational mission, with several years until next is anticipated	Continuity planning for ALOS unclear Implementation of global acquisitions for SAOCOM remains to be proven	High uncertainty currently surrounds the Japanese EOS programme with ALOS the key continuity pathway Commercial data policy unlikely to change
Risk X-band	Low	Low	Low
Rationale	Six healthy operational missions, with planning for Cosmo-SkyMed and TerraSAR-X second generation	Continuity planning well advanced for Italian and German X-band missions.	Linkage to national security introduces uncertainty around future access Commercial data policy unlikely to change

Table 19 – SAR supply risk summary

Overall, supply of SAR data is set to improve in the short term, with the long term prospects for supply good. In particular, the opening up of public good data from Sentinel-1 holds the promise of greatly increasing the adoption of (C-band) SAR across a wide number of application areas. Coverage plans for Sentinel-1 over Australia are good, and as the community begins to adopt this data, there are significant opportunities for greatly expanded use, and a move into new application areas.

Medium Resolution Optical (10m to 80m)

Continuity Outlook Summary

After a period of relatively high risk immediately prior to the launch of Landsat-8 in 2013, medium resolution supply risk is currently low, and will be further reduced with the launch of Sentinel-2A in 2015. This is expected to be followed by Sentinel-2B in 2016, and Landsat-9 in 2023. If nominal 10-year mission lifetimes are realised, this means that there could be extended periods in the next 10 years where three global coverage missions are in operation.

CBERS-4 has the potential to provide global coverage, and while it currently only covers Chinese and Brazilian interests, it could represent a tactical continuity option if the requirement arose. And operational commercial supply options are also in place with instruments on the DMC missions, and through India's LISS-III programme – for which continuity is also being planned.

The colour coding in Table 20 indicates whether the performance meets or exceeds the most demanding minimal and optimal requirements from the case studies as summarised in Table 6 (Section 3.4).

- **Green:** meets or exceeds the most demanding optimal requirement.
- **Yellow:** meets or exceeds the most demanding minimal requirement.
- **Red:** does not meet the most demanding minimal requirement.

This assessment is predicated against the most demanding applications in each of the five instrument characteristics, and this does not mean that the instruments don't meet the requirements of any applications.

Instrument *Years*	Spatial Resolution	Spectral Bands	Coverage Area	Coverage Frequency	Latency
ETM+ (Landsat-7) *TBA-TBA*	PAN: 15m VIS-SWIR: 30m	VIS-TIR: 8 bands	Global	Single Instrument: Every 16 days (22% data loss due to sensor malfunction)	Via internet within 12-48 hours TBC
OLI (Landsat-8) *2013-2023+*	PAN: 15m VIS-SWIR: 30m	VIS-SWIR: 9 bands	Global	Single Instrument: Every 16 days	Via internet within 12-48 hours TBC
TIRS (Landsat-8) *2013-2023+*	100m*	TIR: 2 bands*	Global	Single Instrument: Every 16 days	Via internet within 12-48 hours TBC
LISS-III (RESOURCESAT-2) *2011-2021+*	23.5m	VIS-SWIR: 5 bands	Global	26 days	Based on commercial terms
ALISS-III (RESOURCESAT-3) 2021-2025	PAN: 10m VIS: 23.5m	VIS-SWIR: 4 bands	Global	26 days	Based on commercial terms
PAN (CBERS-4) *2014-2017*	PAN: 5m VIS-NIR: 10m	VIS-NIR: 4 bands	Currently China and Brazil, Australia or global may be possible with discussion	52 days	Internet download
MUX (CBERS-4) *2014-2017*	20m	VIS-NIR: 4 bands	Currently China and Brazil, Australia or global may be possible with discussion	26 days	Internet download
WFI-2 (CBERS-4) 2014-2020	60m	VIS-NIR: 4 bands	Focused on Brazil and the Amazon	26 days	Internet download
MSI (Sentinel-2) 2015-2025+	VIS-NIR: 10m Others: 20m Atm corr: 60m	VIS-SWIR: 13 bands	Global	10 days with one unit 5 days with two units	Internet download

Table 20 - Main current and future medium resolution optical instrument characteristics
+ indicates that continuity beyond current end year is being considered
*** requirements for thermal instrument**

In addition to providing operational medium resolution optical supply, Sentinel-2A will also provide three visible, and one near infrared band at 10m, which holds the promise of extending the benefits of medium resolution public good optical data further towards the high resolution range.

In the past, storage limitations on the satellite, coupled with limited downlink opportunities, have required medium resolution optical satellites to implement global acquisition strategies, prioritising certain areas for coverage which has meant that other areas receive less or no coverage. For example in the case of Landsat, this means that all potential imaging opportunities over the U.S. have been taken, and opportunities over other areas have been skipped or deferred if mission capacity did not allow.

However, the performance of Landsat-8 has meant that mission operators have been able to have the instrument ‘always on’ over day lit land areas globally. And in the case of Sentinel-2, ‘always on’ capability has been designed into the operations plan from the outset, and is expected to be realised as soon as the mission has completed its ramp-up phase. It is expected that in future ‘always on’ over land will become the norm for medium resolution optical instruments – especially those designed to provide global coverage.

In addition to finer spatial resolution, a new class of **hyperspectral** imaging instruments with greatly increased spectral resolution in the 30m range may also open up new possibilities. Future supply of hyperspectral instruments is discussed in Section 5.6.

Key Instruments and Agencies

ETM+ and **OLI (USGS)** on Landsat are the current global workhorses in this class. Continuity planning has been started with the announcement of the initiation of development of Landsat-9. The budget anticipates future continuity by calling for the exploration of technology and systems innovations to provide more cost effective and advanced capabilities in future land-imaging missions beyond Landsat-9, such as finding ways to miniaturize instruments to be launched on smaller, less expensive satellites.

MSI (EC/ESA) on Sentinel-2A (2015) and Sentinel-2B (2016) are expected to provide ‘best in class’ medium resolution optical coverage that, together with Landsat, promises to provide new levels of data availability and enhanced capabilities. While the implementation of the ground segment may take some time to be completed, access will be on a public good basis. Spatially, MSI improves on Landsat for most bands (20m vs. 30m), and for four visible and near infrared bands, will provide finer resolution data down to 10m. Spectrally, the band configuration of MSI was developed to be compatible with, and improve upon, Landsat and SPOT.

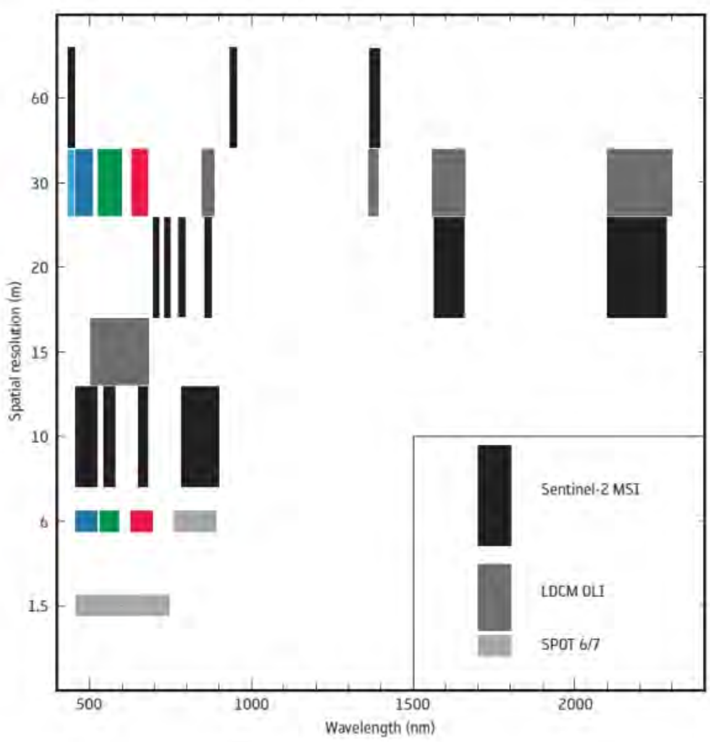


Figure 9 - Comparison of Spatial Resolution and Wavelength Characteristics of SENTINEL-2 Multispectral Instrument (MSI), the Operational Land Imager (OLI) On-Board LANDSAT-8, and SPOT 6/7 Instruments (Credit: ESA)

The *National Crop and Land Use* dataset (Table 29), the *National fire monitoring* dataset (Table 37), and the *Queensland land cover* dataset (Table 31) all flagged the possibility of a blended Landsat/Sentinel-2 product – which is supported by compatibility between the bands - as an excellent opportunity to expand the temporal coverage of medium resolution optical, providing better than weekly revisit times (as opposed to 10-16 days from an individual Landsat or Sentinel satellite). The development of this blended product will take some investment, but with strong data continuity prospects for both missions, the investment would bolster continuity of data supply (potentially enabling Landsat and Sentinel-2 to be applied on a sensor-agnostic basis), and also provide greatly improved revisit.

While MSI and ETM+ / OLI provide a very strong continuity option in the VIS-SWIR bands – with MSI providing 4 more bands than OLI – MSI does not provide a continuity option for the thermal bands covered by Landsat-8's **TIRS** instrument. While these bands are used by a specialised user community and were not flagged at TIRS resolution (100m) in the case studies, they are applicable to an application area of interest to Australia (water), which underscores the importance of TIRS continuity. (Several low resolution optical instruments like SLSTR on Sentinel-3 do include thermal bands, but at a resolution 1km as compared to 100m for TIRS.)

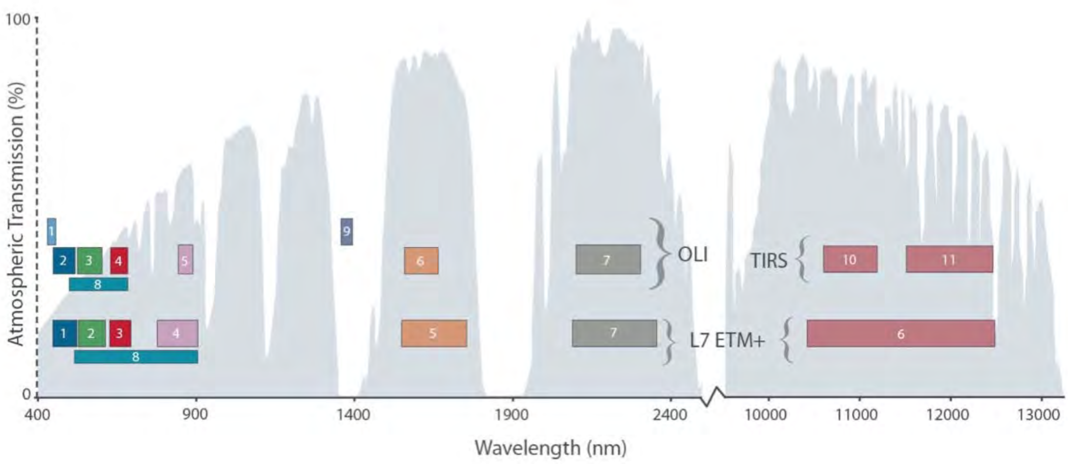


Figure 10 – ETM+, OLI, and TIRS bands including thermal infrared

PAN and MUX on CBERS-4 may provide a viable continuity option with acceptable, if reduced, performance relative to ETM+, OLI, and MSI. The data policy is public good, but Australian acquisitions are not currently taken on a systematic basis, and so this would need to be negotiated with China and Brazil. Continuity is expected, with plans for CBERS-4A launch in 2018 underway.

CBERS-4 also carries the **WFI-2** instrument, which is approved for re-fly on the Amazonia-1 mission in 2017. While WFI-2 offers significantly reduced spatial resolution (60m), and limited spectral resolution (4 bands), should continuity become stretched it may provide a limited option on a public good basis.

LISS-III on India's RESOURCESAT missions provides another current, potentially viable continuity option, again with sub-optimal but likely acceptable performance, and on commercial terms. Continuity is planned with the flight of **ALISS-III (Advanced LISS-III)** considered in 2021 to follow-on from the expected end of LISS-III.

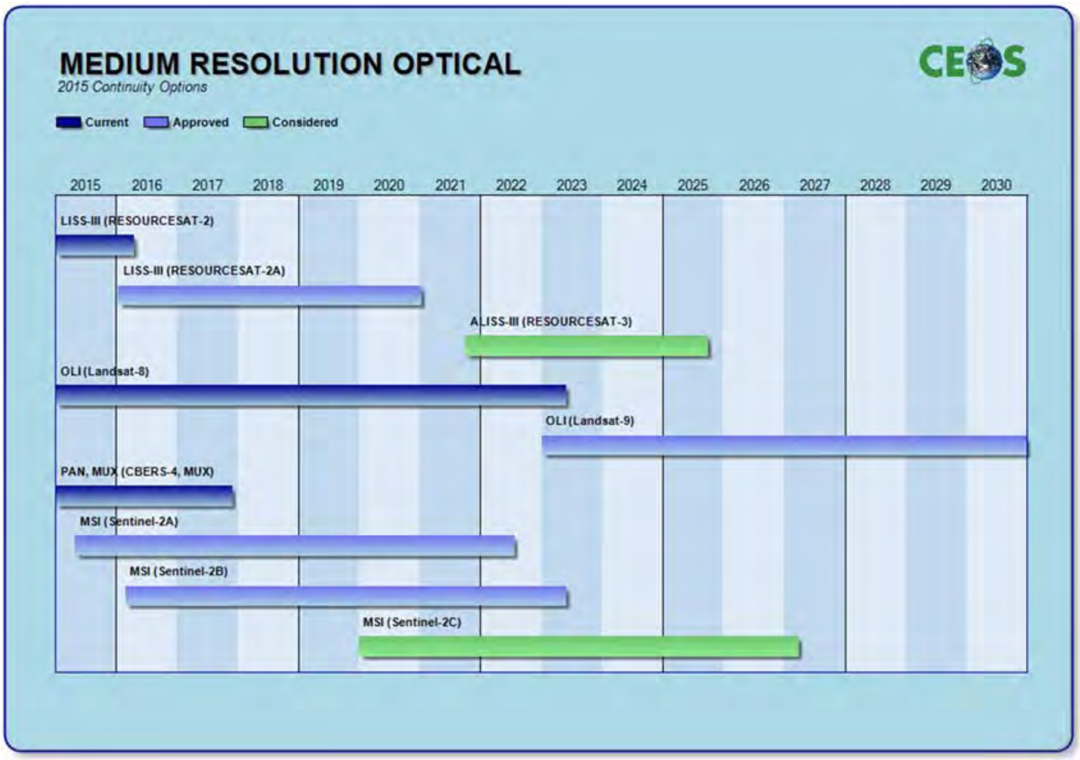


Figure 11 - Medium resolution optical continuity options

Main Risks and Contingencies

1. **Ensuring Australian representation in Landsat and Sentinel-2 systematic acquisition plans** is important to realise the full potential of these data streams. Without regular and reliable data access, applications development may be unnecessarily constrained. This is mitigated by the fact that Landsat-8, and Sentinel-2 will be "always on", and by GA's proactive approach to both USGS and the EC.
2. **Failure of TIRS and loss of thermal data from Landsat-8** is a potential continuity issue as there are no other current or planned thermal data sensors at this spatial resolution. This is mitigated by plans to upgrade the TIRS instrument and re-fly on Landsat-9.

Risk Assessment

Supply of medium resolution is on the cusp of moving from a period of relative uncertainty and reduced options, into a period of relative abundance. Starting with the opening of the CBERS and Landsat archives, data access has greatly increased. With the addition of Landsat-8, the limitations of Landsat-7's scanline corrector malfunction have been mitigated, which has greatly increased the quality of data supply. Public good access to this data, as well as significant improvements in IT infrastructure, networks, and reductions in the incremental cost of storage and processing, have led to applications based on leveraging long time series of data. The cost of acquiring the data, and limitations on affordable infrastructure, mean that these applications would have been impossible 10 years ago.

Supply of medium resolution optical is set to greatly improve in terms of quality and quantity following the launch of Sentinel-2A in June 2015. Sentinel-2A improves on Landsat's spatial and spectral resolution, and its revisit time (down to 10 days from 16 days). Its public good data policy means the data will be free to flow to users, and its continuity of supply (with Sentinel-2B planned for launch within a year of 2A) means that users will have a rich new data stream into the future.

Interoperability between Landsat and Sentinel-2 means that users could expect sub-weekly coverage with 3-4 satellites in operation. And if the development of a blended Landsat/Sentinel-2 product can be achieved, then there is an opportunity for applications of medium resolution optical data to become truly "sensor agnostic" – which greatly increases robustness of supply.

	Technical Continuity Risk	Programmatic Risk	Political/policy Risk
Risk Level	Low	Low	Low
Rationale	Current missions offer sufficient supply and operating well, and in 2015 Sentinel-2A is expected to greatly bolster long-term supply	Funding for the space segment of the main public good continuity options is in place Additional continuity options are also funded Australia is being proactive on supporting and engaging in the implementation of Copernicus ground segment. ESA/EC still appear to have no credible solution to effective access to the entire Sentinel-2 data archive on terms equivalent to the USGS archive.	Public good data policies are established for the two main global coverage missions, as well as from the Chinese-Brazilian CBERS mission

Table 21 – Medium resolution optical supply risk summary

In addition to supply from Landsat and Sentinel-2, there are a wide range of other providers which further underscore continuity of supply. Some of these missions are tailored to particular needs of other countries, and some are commercial – but a number could provide continuity should data supply from the "big two" become limited.

Other Data Types

Sounders and GPS-RO instruments

The current and future supply of **LEO microwave and infrared sounders is strong**, with operational continuity assured by the meteorological agencies – in particular **NOAA** and **EUMETSAT**, but also increasingly the NSMC-CMA (China) and other agencies. In addition, **infrared hyperspectral soundings** from LEO are critical to weather forecasting operations, and are supplied from the same operational satellites as the microwave sounders, so continuity risk is low.

Interest in **soundings from geostationary orbits** is increasing, though **supply of this data remains uneven**. Coverage is provided over the Americas by the NOAA's GOES instruments, though the upcoming GOES-R mission will not carry a sounder – and these observations do not cover the Australian region. India's geostationary INSAT carries a sounder, but this also does not provide coverage of the Australian region.

The Bureau of Meteorology expressed aspirations to secure a supply of soundings from geostationary orbit, but it is not currently clear how this requirement will be met. China's FY-4 series, which will provide soundings from geostationary orbit from 2016, Australia is at the edge of the expected coverage region, and data looks likely to be available via WMO channels.

The main source of GPS-RO data has been the six satellite **COSMIC-1 constellation**. However, at one stage only four satellites were operational, and currently there are five (one was recovered from a technical fault). Planning is underway for **COSMIC-2**, with NOAA working to secure funding for six equatorial and six polar orbiting satellites, and with the first six to be launched in 2016. The six equatorial satellites are funded, but the six polar satellites are not. At this point, the overlap between COSMIC-1 and COSMIC-2 is expected to be as few as two satellites, however this depends on technical performance of COSMIC-1 and the launch schedule for COSMIC-2. While other GPS-RO instruments are currently available and planned, there will be some uncertainty around supply until full funding for COSMIC-2 is confirmed.

Radar altimeters and scatterometers

There are two key applications for **radar altimeters** to be considered for the purposes of continuity assessment – maintenance of the long term climate data record of global sea level (continuous since 1992), and support to operational ocean monitoring services. The climate data record is maintained by the **Jason series**, and while funding for continuity has been uncertain in the past, it appears to be strong at present. **Jason-2** is currently operational, and **Jason-3** is scheduled for launch in mid-2015, with the two missions expected to overlap. In addition, **Sentinel-6** will provide continuity for Jason (known as Jason-CS) with the first of two units planned for launch in 2020 and a second five years later.

Operational monitoring activities such as the Bureau's ocean model require at least three, and ideally four or more operational altimeters in order to address latency requirements for their products. At present, there are two operational altimeters in addition to Jason – **AltiKa on SARAL**, and **Cryosat-2**, and so the minimum requirement is met. **Sentinel-3A** will carry a radar altimeter, and is scheduled for launch in late 2015 or early 2016. This will further bolster operational supply, and it is expected that **Sentinel-3B** will be launched one year after 3A, which should further bolster supply.

The joint NASA/CNES/CSA/UKSA **SWOT** mission is planned for launch in 2020, and will be the first in what may be a new class of swath mapping radar altimeters, providing in effect altimetry 'images' rather than point measurements. SWOT is planned as a one-off science mission, but if the concept is proven follow-on instruments may result.

Continuity for scatterometer measurements is underpinned by **ASCAT** with two instruments operational by EUMETSAT/ESA on MetOp-A and –B, and a third to be launched on MetOp-C in 2018. The first of four copies of China's **SCAT** instrument is currently operating, with further launches planned on HY-2B through 2D between 2015 and 2019 – though data access is limited. EUMETSAT is currently planning to launch the **SCA** instrument on EUMETSAT Polar System, Second Generation-b (EPS-SG-b) in 2022, which should provide continuity for ASCAT. In addition, Russia's meteorological agency, ROSHYDROMET, is planning to launch three instances of their **Advanced Scatterometer** instrument on Meteor-MP N1 – N3 between 2017 and 2019.

Passive microwave

Soil moisture is the main current land cover application of passive microwave instruments, and current supply has been underpinned by **ASCAT**. ASCAT is relatively coarse resolution, and for soil moisture is being employed outside of its usual application area. Additional supply is provided by the research missions **SMOS**, and more recently **SMAP**. Continuity for scatterometers (i.e. ASCAT) is discussed above, while both SMOS and SMAP appear to be one-off research missions whose prospects for continuity will be linked to operational uptake based on strong application outcomes.

An additional potential source of soil moisture observations using ('active') microwave will be the application of **Sentinel-1** data (C-band SAR, 5.6cm wavelength – same as ASCAT). In the past, securing and funding repeated SAR acquisitions over the broad areas involved in soil moisture monitoring would have been prohibitively expensive. However, with the advent of public good SAR from Sentinel-1, systematic derivation of soil moisture products may be feasible – though research and application development is required before the utility can be fully assessed. **SAOCOM** (L-band, same as SMOS and SMAP) may also provide valuable soil moisture observations, and includes a dedicated beam mode for soil moisture – though tasking would need to be coordinated in order to provide coverage.

Hyperspectral

Hyperspectral imaging from satellites is still relatively new, though it holds great promise and could be thought of as being at the same stage in its development as SAR was 10-15 years ago. In addition to improvements in technical capacity and instrument quality, terrestrial data storage and processing capabilities have improved to the point where the handling of the large data files generated by hyperspectral imagers is much more feasible.

Currently, there is only one satellite-based hyperspectral imaging instrument (**Hyperion**, NASA), and it is nearing the end of its operational life. However, there are good prospects for new missions with improved sensors that may help to demonstrate the full potential of space-based hyperspectral. Italy is planning the launch of **PRISMA** in 2017 which will carry the HYC instrument with constrained data access, and Germany is planning the launch of **EnMAP** in 2018 which will carry the HSI instrument and feature a public good data policy for science use. Both these instruments will provide hyperspectral data in the visible to SWIR range at a spatial resolution of 30m, though the swath width is comparatively narrow at just 30km. The narrower swath will mean that revisit times will be long (in the order of 20-30 days), and coverage areas are constrained.

In addition to space agencies, there has been significant recent commercial interest in the development and launch of hyperspectral imaging instruments. In late 2014, Boeing won its first commercial order for the 502 Phoenix small satellite platform from start-up **HySpecIQ** of Washington D.C. The first of two commercial, high-resolution hyperspectral satellites will be launched in 2018. The main customers will be U.S. Government intelligence services, the U.S. Department of Defense, international partner customers, as well as civil and commercial customers.

LiDAR Altimeters and DEM datasets

While there are currently no satellite-based LiDAR altimeter instruments, NASA is developing **ICESat-II** for launch in 2017. This is a follow-up mission from the original ICESat mission, which also carried a LiDAR – though the technology for ICESat-II makes use of a different laser wavelength. ICESat-II will be a research mission, with the current prospects for continuity limited.

There are a number of new public good global **DEM datasets** currently available – for more information, see Section 4.6. While continuity of satellite supply is less important for global-scale DEMs as they don't require frequent updating – current supply is strong, and in future finer resolution, higher accuracy, models can be expected. More localised DEMs (e.g. mine sites) do require frequent updating, and this is where airborne and commercial satellite solutions (e.g. TanDEM-X) can provide continuity. However, satellite LiDAR altimetry would enable quick and accurate updates.

Russian and Chinese Data Streams

Russian EOS has a long heritage, and including optical imagers across the range of low, medium, high, and very high resolution, hyperspectral, as well as SAR. These satellites are operated by the Russian space agency, ROSCOSMOS, in cooperation with the Russian meteorological agency, ROSHYDROMET.

RUSSIAN REMOTE SENSING ORBITAL CONSTELLATION

Spacecraft / Characters	Resurs-DK	Meteor-M №1			Elektro-L	Kanopus-V		Resurs-P			
Launch date	15.06.2006	18.09.2009			20.01.2011	22.07.2012		25.06.2013			
Life time	3 years	5…7 years			10 years	5…7 years		5 years			
Swath width, km	28.3 / 16	KMSS MSU-100	KMSS MSS U-50	MSU-MR	the visible part of the Earth	PSS	MSS	OEA	GSA	SMSA-VR	SMSA-SR
		900	900	2800		23	20	38	22	97	441
Spatial resolution, m: •panchromatic band	1 / up to 3	-	-	-	in the visible range – 1000	2.5	-	better than 1	-	12	60
•multispectral band	2 - 3 / 3 - 5	60	120	1000	in IR range – 4000	-	12	3 - 4	30	23	120
Number of sensors	3 / 1	3	3	6	10	1	4	7	up to 256	6	6
Revisit time, day	up to 6	2			30 min.	4		3 - 4			

Figure 12 – Russian remote sensing satellites (Image: ROSCOSMOS)

Due to historical difficulty in accessing data from Russian satellites outside of the WIS, its technical heritage and utility is not well understood in the Australian community, and so the potential does exist to evaluate whether data may be suitable, and how it might be accessed and integrated. Data from these satellites can be accessed a Russian-language web portal http://www.gptl.ru/. The announced data policy is free and open for data coarser than 30m, and commercial for data finer than 30m.

China's EOS program is broad and ambitious, with many different satellite and instrument types being developed. Historically the quality of the data has been low – however, there are signs that quality and reliability are improving, and may even rise to be on par with U.S. and European counterparts in future (2020 and beyond). The Chinese remote sensing community is complicated, with many different operators across meteorological, oceanographic, and land use application agencies, as well as commercial, governmental and space agency upstream hardware providers. Perhaps the most representative of the Chinese programs is the Gaofen (GF) suite of missions. The EO Portal (https://directory.eoportal.org/web/eoportal/satellite-missions/g/gaofen-1) reports that a number of GF missions are to be developed by 2020.

- *__GF-1__ employs the CAST-2000 bus, it is configured with two __2 m Pan/8 m MS camera__ and a __four 16 m MS medium-resolution and wide-field camera set__. GF-1 realizes an integration of imaging capacity at medium and high spatial resolution and with a wide swath, the design life is 5 years with a goal of 8 years.* **[high to medium resolution optical]**
- *__GF-2__ employs the CS-L3000A bus, it is configured with one __1 m Pan/4 m MS camera__, the design life is >5 years. GF-2 was launched on August 19, 2014 on a Long March-4B vehicle from TSLC (Taiyuan Satellite Launch Center), China.* **[high to medium resolution optical]**

- ***GF-3*** *employs the CS-L3000B bus, it is configured with a multi-polarized* ***C-band SAR (Synthetic Aperture Radar)*** *instrument at meter-level resolution, the design life is 8 years. GF-3 is scheduled for completion of development and construction in 2015.* **[C-band SAR]**
- ***GF-4*** *employs the GEO remote sensing bus, configured with a 50 m staring camera, operating from* ***GEO (Geostationary Earth Orbit).*** *GF-4 will provide an imaging area of 7000 km x7000 km with individual scene coverage (scenes of 400 km x 400 km), and with a capacity for high temporal resolution remote sensing monitor at minute-level. GF-4 has a design life of 8 years. GF-4 is currently well under development and construction and is scheduled to launch in 2015.* **[geostationary imager]**
- ***GF-5*** *employs the SAST-5000B bus [Note: SAST (Shanghai Academy of Spaceflight Technology)],configured with six payloads, including a* ***VIS and SWIR (Shortwave Infrared) hyperspectral camera, spectral imager, greenhouse gas detector, atmospheric environment infrared detector at very high spectral resolution****, differential absorption spectrometer for atmospheric trace gas, and a multi-angle polarization detector. GF-5 has a design life of 8 years and is scheduled to launch in 2016.* **[low resolution optical, atmospheric chemistry]**

There are many other Chines satellite series operating or under development with comparable capabilities to the GF suite – for example the CBERS series (Sections 4.5, 5.5), and the HY (Sections 4.6, 5.6, and 5.8) and FY series (Section 5.6, Tables 29 and 30). Indications are that GF are will be amongst the highest quality. As with Russian satellites, the technical heritage and utility of Chinese satellites is not well understood in the Australian community (with a few exceptions, mostly around weather, see Tables 29 and 30), and so the potential does exist to evaluate whether they may be suitable, and how they might be accessed and integrated.

Analysis

Overall, continuity of supply for the three main optical data types – low, medium and high resolution – appears to be strong. While there are some limited risks to supply of low resolution optical, these should soon be mitigated by the start of supply from Sentinel-3A.

A particular risk for **low resolution optical** – in particular users of MODIS – is the loss of direct broadcast mode, and the increased latency this may create. At present, with MODIS direct broadcast, data can be available to NRT applications within 30 minutes of acquisition.

While actual performance remains to be seen, Sentinel-3 data will not be available via direct broadcast – only via the global downlink and internet download. The mission requirement for the global downlink is to make data available within three hours. While it is possible that data may be available on the global downlink more (or less) quickly, three hours may limit some NRT applications.

It is worth noting that all data from the Sentinel-3 global downlink will be downloaded at the Svalbard ground station in Norway. Svalbard is approximately half way around the globe from Australia, and Sentinel-3's orbital period is 100 minutes – which means it will be some 50 minutes until Australian acquisitions are downlinked for processing. This would suggest that latency from Sentinel-3 for Australia will be at least 60 minutes, and most likely much longer – depending on how long ground processing in Norway and subsequent posting to the product download location takes, as well as the download time to reach Australia. While Sentinel Collaborative Ground Segments have presented the opportunity for direct downlink in Europe, initial discussions with staff at ESA indicate that there are satellite housekeeping constraints which likely limit the potential for direct downlink to an Australian ground segment.

The risk for **medium resolution optical** is low, with strong supply, public good data policies becoming the norm, and with commercial and other options available should supply from Landsat and Sentinel-2 falter. The main risk to supply here would be in relation to data distribution systems. Landsat has demonstrated a commitment to global distribution, and after an long development programme now has a system that can credibly service user demand world-wide.

However, the EC and ESA have yet to demonstrate how they will address, and also fund, the challenge of global data distribution for Sentinel-2 and the broader Copernicus missions, meaning there are significant technical and programmatic risks that remain to be addressed. With the added spatial and spectral resolution, data volumes from Sentinel-2 will be a significant increase relative to Landsat, which will only serve to amplify the challenge. It could be that mirror sites (i.e. other countries participating in the Copernicus programme, the U.S. or Australia, or even commercial actors) play a significant part in addressing these challenges.

The risk for **high resolution optical** is low, with commercial providers supporting strong supply, competition driving costs down, and new dense constellations of microsatellites opening up new applications driven by low latency and high revisit. These trends are all good for Australian users, and there is strong potential to open up new application areas.

The risk for **SAR** data varies from low to medium depending on the band. For Australian users, the significant boost underway in C-band supply and availability is positive, and holds the potential to drive significant adoption and application development. With free data flowing, new application areas may open up which were not previously possible – for example soil surface moisture monitoring at a spatial resolution of 20m nationally. (Current satellite-derived national-scale soil moisture measurements have a spatial resolution on the order of 10’s of kms.)

BENCHMARK COSTS

Introduction

For the purposes of benchmarking, cost information on the purchase of a payload (without launch, ground segment or operations), and the purchase of end-to-end turn-key solutions are examined.

The figures given are indicative only, and are based on information gathered from several sources including discussions with SSTL (UK), the Advanced Instruments and Technology Centre at Mount Stromlo Observatory, and other industry contacts.

Dollar figures included in this section are Australian currency unless otherwise noted, using an exchange rate of $0.77 AUD/USD as of June 2015.

Assumptions

This benchmark cost analysis is based on the assumption that Australia might take a business decision to invest in one or more payloads, or satellites, to secure data supply in light of perceived cost savings. It assumes that fixed costs for data storage and handling currently undertaken by the Australian government would be similar whether the current supply mix, or some future supply including Australian indigenous data streams were available.

As noted in Section 4.3 (current high resolution optical supply), the 2011 CEODA-Ops report estimated government expenditure on remote sensing data supply in Australia at approximately $100 million per annum. While there is some uncertainty around this figure, it will be taken as a current nominal annual supply cost – with all other data presumed to be flowing from sources free of supply cost. Supply cost includes both purchases from satellite data archives, as well as the procurement of new commercial acquisitions.

Instrument Development

SSTL provided indicative purchase costs for several different instrument types excluding the cost of satellite bus, launch, ground segment, and operations.

SSTL makes maximum efforts to leverage and re-purpose commercial off the shelf (COTS) components. This includes preferring to space qualify existing hardware (e.g. telescopes), rather than designing these components from scratch for use in space. Several common cost pressure points were identified – areas where the cost of components is traded off against performance, including:

- **quality of the primary mirror** including stability over a large variety of thermal conditions and over long focal lengths (i.e. 20m);
- **quality of star trackers determines** the tolerance to which images can be geolocated; as quality goes up, geolocation gets more precise, and instrument costs rise. While the highest possible precision covers the greatest range of applications, a performance-cost trade-off could result in reduced instrument costs while still serving certain classes of application;
- **the quality and performance range of the sensor and optics** in order to provide multiple bands, with performance into the thermal bands increasing cost; and
- in the case of SAR, **the cost of ensuring sufficient power systems** and the **cost of the antenna, especially at higher frequencies (finer resolutions)** tend to govern the overall cost-performance trade-off**.**

In addition to the cost of the instrument itself, several other costs would need to be considered.

– **Satellite bus cost** which varies depending on the power and data requirements of the payloads – in the case of a SAR instrument, which requires a great deal of power, the satellite bus could cost $259-$388M.

– **Launch cost** for a 100kg payload is generally about $3.8-5.2M – where 100kg and under would be considered "micro satellites".

– **Operations** include the cost of managing the day-to-day command and control, and tasking of the satellite.

– **Ground segment, command uplink and data downlink** includes the cost of issuing commands, and handling telemetry and imagery data to and from the satellite.

– **Data distribution** includes the cost of storing the imagery in a database on the ground, as well as providing search and discovery, and download or access to the user community.

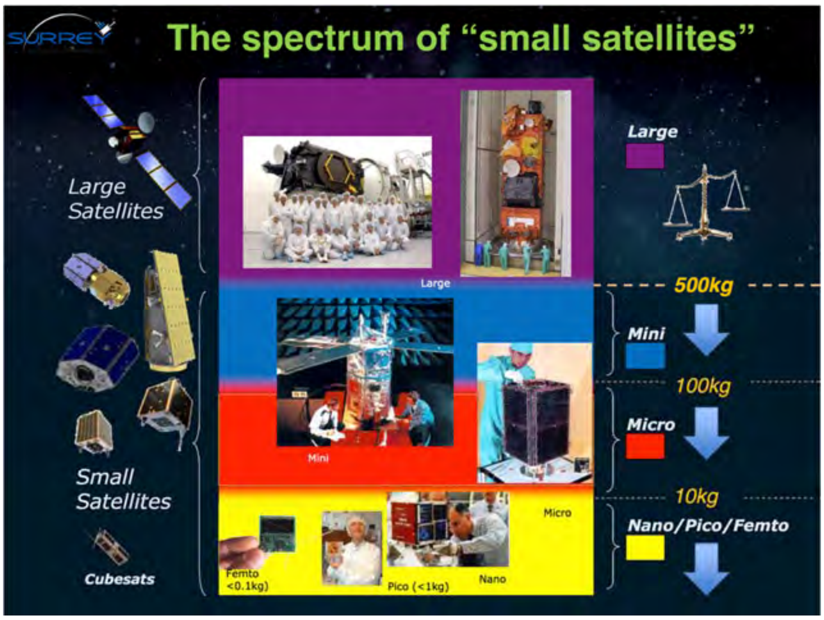


Figure 13 – Summary of small satellite sizes (Credit: SSTL)

Australian Capacity

The study team sought information on the domestic capacity to build satellite instruments from the Advanced Instruments and Technology Centre at Mount Stromlo Observatory, and received the following input.

> *When evaluating Australia's capability to manufacture space based instruments and satellites, it is important to consider our space manufacturing heritage, heritage with comparable technologies, access to relevant component suppliers and manufacturing supply chains, and access to essential infrastructure. It is also important to consider the benefit to the Australian economy and the broader impact of supporting advanced manufacturing in the space sector in Australia.*
>
> *In the 1990s Australia contributed significant hardware components to the European Space Agency Along-track Scanning Radiometer (ATSR) for the ERS-1 satellite, the ATSR2 for the ERS-2 satellite and the Advanced-ATSR (AATSR) for the Envisat satellite. Building on this experience the Australian National University (ANU) and Auspace designed, built and tested the Endeavour Space Telescope, which flew on the Space Shuttle in 1995, and the CRC for Satellite Systems was established to manage the specification, assembly, integration, test and launch of the FedSat satellite in 2002.*
>
> *The similarity between space-based systems and modern astronomical instrumentation, offered an opportunity to utilize expertise and infrastructure across these domains to produce precision instrumentation for some of the leading astronomical observatories around the world, including the Near-infrared Integral-Field Spectrograph (NIFS) for the Gemini Observatory in Hawaii. The ANU and the Australian Astronomical Observatory (AAO) have developed an international reputation for quality and reliability, which has culminated in Australia becoming a 10 percent partner in the $1 billion Giant Magellan Telescope (GMT) and being awarded two competitive contracts for first light instruments.*
>
> *The ANU GMT Integral-Field Spectrograph (GMTIFS) is a $30 million near-infrared, combined integral-field spectrograph and imager with diffraction-limited angular resolution. This cryogenic instrument operates in space-like thermal and vacuum conditions. It will be assembled in the clean room at the ANU Advanced Instrumentation and Technology Centre (AITC) and tested in the AITC Space Simulation Facility. The GMTIFS utilizes the most sensitive infrared detectors in the world, and managing the associated ITAR requirements is part of the regular operations of the AITC.*
>
> *To serve advanced manufacturing projects in space and astronomy, access to high-end component suppliers and international manufacturing supply chains are essential. This access is well established and often draws on supply chains that support other advanced manufacturing activities such as aerospace. This access is both essential to the success of the space and astronomy projects and important for supporting the viability of local companies by increasing their access to international supply chains and high value-add projects.*
>
> *The final critical component is access to essential infrastructure. The development of precision instrumentation for space and astronomy both require access to specialist infrastructure for assembly, integration and test. With the establishment of the AITC Australia's immediate and short-term requirements are met. The AITC provides the end-to-end facilities for the integration of precision instrumentation as well as their test and evaluation, including the launch certification of space systems.*

Australia is now well positioned to define, design, build and test an optical, infrared, or hyperspectral Earth Observation instrument that could be hosted on an international satellite and meet the needs of the growing geospatial industry. Based on experience with comparable astronomical instruments, and taking into consideration the materials, processes and tests needed to certify it for reliable space operation, it is estimated that a medium to high-resolution instrument could be delivered for approx. $30 million.

After considering Australia's ability to deliver an Earth Observation instrument that meets Australia's needs it is important to consider the impact on the Australian economy, the benefits to Australian industry and the development of skills in Australian that make it important to build it in Australia.

Since its establishment in 2006, the AITC has enabled instrumentation projects to the value of $117.8 million including export contracts to the value of $18.4 million.

This includes the successful delivery of five Australian Space Research Program (ASRP) projects with a total value of $16.8 million including: the Australian Plasma Thruster, the Automated Laser Tracking of Space Debris, Antarctic Broadband, Greenhouse Gas Monitor and the NASA GRACE Follow-on. It also includes $40 million for the Space Environment Research Centre, which further develops the use of adaptive optics for commercial space debris tracking, and supporting EOS Space Systems in the delivery of a commercial contract to provide a laser ranging telescope with adaptive optics for the Korean Astronomy and Space Science Institute (KASI) valued at $6.4 million.

The AITC supports Australia's future competitiveness by supporting: fundamental research; applied research; the translation of research into industry applications; test and evaluation services for industry; and the training of the future workforce. By working in partnership with industry on real projects, the AITC provides training programs to close the gap between industry, research and education, and ensure Australia's future workforce needs are met.

An investment in a geospatial instrument built in Australia would increase Australia's competitiveness in the global space and spatial market by connecting the value chain in Australia and connecting Australian industry with the international market. The astronomical community has a long and successful heritage of scientists and engineers working together to specify and build instruments that draw on bleeding edge technologies to deliver world-class research. The delivery of a geospatial instrument in Australia is the opportunity for the geospatial community to replicate this success by specifying an instrument that delivers economic returns along the whole value chain from advanced manufacturing, to ground station support, data collection and processing, data analysis, and the delivery of geospatial products and services.

Optical Instruments

Table 22 shows a range of model and cost scenarios for the build of optical instruments.

	Large Swath, Coarse Resolution	"Landsat Class"	High Resolution
Base Model	– 3-4 bands (i.e. DMC class), no IR – Wide swath – 1000's kms – COTS parts – **Low end cost $647K**	– 20m spatial resolution – 3 to 6 bands with wide swath – 0.5% radiometric accuracy – 7 year lifespan – **Low end cost $647K**	– 5-10m spatial resolution – Engineering tolerances and primary mirror drive costs up at finer resolution – **Low end cost $1.3-2.6M** **OR** – 1m spatial resolution – Rapid rise in cost 1m and under – Still a lower quality data stream (i.e. not Pleiades performance) – **Lowest cost $6.5-7.8M**
Enhanced Model	– 30-35 bands (i.e. MODIS class) – Higher quality "ESA build specification" – **Cost $26-39M**	– 9-13 bands (i.e. Landsat-8 / Sentinel-2A) – 185-290km swath – **Cost $26-39M**	
Mount Stromlo		– **Cost approx. $30M**	– **Cost approx. $30M**

Table 22 – Representative optical instrument only costs from SSTL and Mount Stromlo

The base model costs in Table 22 represent the most basic of functionality, but would address some of the requirements of the Australian user community. The expected quality of the data required would need to be well understood. Costs vary widely (40-60 times) between the base model and an enhanced model built to the quality standards of an agency like ESA. The early DMC instruments gives some indication as to the utility to be expected from the base model instrument.

SAR Instruments

SAR instruments are considerably more expensive to develop, though SSTL along with the U.K. Government are investing significantly to reduce cost through NovaSAR (see Section 6.4) – for example, employing COTS parts and performing the basic R&D to re-purpose key elements (e.g. generation of the radar signals by space qualifying communications equipment). Their objective is to be able to produce an S-band instrument for approximately $26M, but this price point is not likely to be achieved for several years. For an X-band instrument, this cost is likely to rise to $65-130M.

SAR instruments have higher power requirements from the spacecraft bus – which can drive the cost of the bus to a range of $259-388M.

Landsat Thermal Free Flyer

Section 5.5 describes the continuity options for the TIRS instrument (100m, low resolution optical) flying on Landsat-8, which until recently included potentially launching a thermal free flyer in 2019. While this free flyer is no longer being considered, based on U.S. Government budgetary submissions, the stand-alone cost of the development, build and launch of the satellite is $246M.

Satellite(s), Constellations and Turn-Key Solutions

Indicative costs for several different complete systems solutions were explored – including building the instrument and satellite, launch, and in some cases even the operations and downlink.

Indicative Microsats

One agency experienced in the development of microsats provided two sets of indicative cost figures based on implementation within a government framework.

A 75kg satellite carrying a low-to-medium resolution optical instrument, flown as a "third payload" on a shared launch with a 500km orbit and a likely 1 year operational lifespan would cost approximately $39M. While a 150kg satellite with a more advanced instrument, flown as a "second payload" on a shared launch with a 500-750km orbit and a likely 1-3 year lifespan would cost in the range of $65-$116M. It was noted that these costs are likely lower if the satellites were built and launched outside of a government framework.

It was also noted that one of the cost drivers is the requirement to implement a de-orbit capability. By international convention, if the satellite is to be flown under 500km, then its orbit will decay sufficiently quickly that a de-orbit capability does not need to be implemented. If the satellite is to be flown above 500km, it will have a longer design life, but a de-orbit capability (i.e. sufficient fuel and thrusters to lower the orbit) needs to be built into the satellite, which drives up complexity and cost.

DMC-style 3-4 Satellite Constellation

SSTL provided cost information for several different overall solutions, including a DMC-style 3-4 satellite constellation, work they are doing on a DMC-3 / Beijing-2, and work on NovaSAR with the U.K. Government.

For a complete DMC-style 3-4 satellite constellation, the SSTL estimate is $26M, plus launch costs. The instruments would have a spatial resolution of 20m (medium resolution optical) with 3-4 optical bands, and the constellation would provide full coverage of continental Australia weekly. For a 5m instrument (high resolution optical) with additional SWIR bands, the cost rises to $39-52M plus launch costs, with full coverage of continental Australia provided every 3-4 weeks. Implementation is assumed to be to a commercial standard, rather than within the project and quality constraints typical of a government programme.

DMC-3 / Beijing-2 Constellation

SSTL is currently finalising the DMC-3/Beijing-2 three satellite constellation under contract to the Chinese company 21AT. The system including space and ground segment is built, launched, operated, and owned by SSTL, but 21AT has a seven year exclusive license to all data produced by the system globally – though the U.K. Government retains the right to 'shutter control'. The spatial resolution is 1m panchromatic (i.e. black and white) and 4m multi-spectral (i.e. 4-band colour red, green, blue and NIR), with daily revisit. The total cost to the customer of the seven year lease being $207M. It is expected that this constellation will be launched in June 2015.

NovaSAR

SSTL has entered into a public-private partnership (PPP) with the U.K. Government on the development of the S-band NovaSAR system. There is currently no customer, but it is expected to be ready for launch in 2016. Options to secure launch funding include via a partner (similar to DMC-3/Beijing-2), or via financing against a business plan for the sales of data.

The first NovaSAR system will be built and launched for a total cost of £45M (equivalent to $89M as of June 2015) and SSTL report that they are seeking to aggressively reduce this cost over the next few years – with the target of a payload cost as low as $26M. The design and build is being implemented to make maximum use of COTS parts, and also to re-purpose and space qualify key components (i.e. RF generators) for other applications.

Summary

The range of costs for Australia to purchase an instrument, satellite or turnkey solution in order to secure data supply varies significantly. Purchase options exist for the key instrument types of low, medium and high resolution optical, as well as SAR. Table 23 summarises the cost estimates for the build of instrument and/or satellite (as noted), as well as for end-to-end solutions which include launch and data downlink and handling as noted.

Instrument Type	Instrument / Satellite Estimate	Solution Estimate
Low Resolution Optical	Low-end instrument: $647K "ESA quality" instrument: $20-30M	Landsat Thermal Free Flyer satellite: $207M
Medium Resolution Optical	Low end instrument: $647K Mt. Stromlo instrument: $30M	1-year government: $39M 1-3 year government: $65-130M
High Resolution Optical	5-10m instrument: $1.3-2.6M 1m instrument: $5-6M Mt. Stromlo instrument: $30M	3-4 sat. DMC-style 20m: $26M* 3-4 sat. DMC-style 5m: $39-52M* 1m global 7-year lease: $207M
SAR	S-band satellite (target): $26M	

Table 23 – Cost estimate summary for instrument/satellite (excluding launch) and end-to-end solutions
*** Launch cost excluded- approx. $5-10M additional for DMC-style satellite**

The main driver of cost is the expected implementation standard. Typically, publicly funded government space programs have higher compliance, quality control, and build quality standards than commercial customers – and this drives costs up. This is illustrated in the difference between the cost of a low-end low-resolution optical instrument shown in Table 23 versus the cost of an "ESA quality" build.

Other significant drivers of cost include the satellite bus, which can run into the $100's of millions on top of instrument build cost for high-powered SAR instruments, as well as launch cost which can be in the range of $3.9-5.2M for a 100kg payload.

While it is not possible to compare all the cost estimate information gathered directly to the annual supply cost of $100M identified in the 2011 CEODA-Ops report, it is possible to compare this figure with the end-to-end DMC-3 / Beijing-2 solution being delivered by SSTL. This indicates that the cost of a daily global high resolution optical data supply could be as low as **$28M per year ($207M over seven years)**. This includes the purchase of the satellite, launch, operations, and data downlink to a database where the data can be accessed. The suitability and quality of DMC-3 / Beijing-2 data would need to be assessed based on the expected application.

Table 24 compares the cost for the DMC-3 / Beijing-2 arrangement with new acquisitions covering Australia (summarised from Table 10) from two optical, and one C-band SAR data stream.

Supply	Cost	Coverage
DMC-3 / Beijing equivalent	$28M annually over 7 years 7 year total $207M	Global 1m PAN, 4m 4-band Multi-spectral Daily revisit
SPOT-6/-7	$60M one time	Australia EEZ 1.5m 4-band Multi-spectral One-off coverage
Pléiades	$208M one time	Australia EEZ 0.5m 4-band Multi-spectral One-off coverage
RADARSAT-2	$2.5M one time	Australian Mainland C-band SAR One-off coverage

Table 24 – Data supply cost comparison
(EEZ = Australia's Exclusive Economic Zone mainland and surrounding oceans)

While the top level figures for a DMC-3 / Beijing-2-like arrangement are compelling, a more detailed and nuanced analysis of user requirements and the suitability of the data stream would be required to determine actual suitability. However, it does suggest that this arrangement could be cost effective relative to a $100M annual spend with the added benefit of helping to secure data supply. In order to compare costs fully, the fraction of the current annual spend on high resolution optical and SAR data would need to be known.

CONCLUSIONS

This supply risk assessment looked at a sample of requirements for Australian operational EOS applications. These requirements were derived from case studies performed as part of the companion economic study assessing the socioeconomic value of different EOS data applications. This study was performed by ACIL Allen, and is summarised in Section 2:

1. Agriculture;
2. Weather forecasting;
3. Ocean monitoring;
4. Water resource assessment;
5. Natural hazards and insurance;
6. Monitoring landscape change; and
7. Mining and petroleum.

Section 3 outlines the requirements identified for these case studies, and refined by experts in the application areas who provided further inputs, defining priority data sets (Table 1) and helping to establish the emphasis, from which four main instrument types were identified.

– **Low resolution optical data**: coarser than 80m spatial resolution (i.e. image pixel size).
– **Medium resolution optical data**: between 80m and 10m spatial resolution.
– **High resolution optical data**: finer than 10m spatial resolution.
– **Imaging radar (SAR) data**: C-, L-, and X-band radar spatial resolution 80m – 10m.

In addition, several other instrument types are needed to fully address the requirements from the case studies: sounders and limb scanners; radar altimeters and scatterometers; passive microwave; hyperspectral imagers; LiDAR Altimeters; and, DEM datasets which can be derived from a number of different instrument types. **The EOS data requirements identified are summarised in Section 3.3 (Table 4).**

Based on the requirements identified, current (Section 4) and future (Section 5) continuity of supply for the four main instrument types, and to a lesser extent the other types, was assessed. Based on this assessment, it appears as though **the EOS data requirements can be addressed to a significant extent**.

	Technical Continuity Risk	Programmatic Risk	Political/policy Risk
Low Resolution Optical	Low	Medium - JPSS delays, Sentinel ground segment, GCOM-C continuity, MODIS failure	Low
Medium Resolution Optical	Low	Low	Low
High Resolution Optical	Low	Low	Low
C-band SAR	Low	Low	Low
L-band SAR	Medium - One operational mission	High - ALOS continuity unclear, SAOCOM unproven at global scale	High - Japanese space policies uncertain
X-band SAR	Low	Low	Low
C-band SAR	Low	Low	Low

Table 25 – Summary of continuity risk for main instrument types

In future, specific requirements may not be fully met – with reduced spatial or spectral resolution, or increased latency being limitations. In some cases these limitations are caused by changes in programs and instrument specifications (e.g. loss of bands, reduced revisit frequency post-MODIS), and in other cases they are based on technology (e.g. some of the high resolution and hyperspectral requirements for mine monitoring cannot be addressed by currently available satellite technology).

Instrument Type	Overall Supply Risk	Key Supply	Notes
Low Resolution Optical	Low	– **NASA:** MODIS (current - 2017) – **NOAA/EUMETSAT:** AVHRR (current – 2021) – **NOAA:** VIIRS (current – 2027) – **EC/ESA:** Sentinel-3 (2015-2024+) – **JAXA:** GCOM-C (2016-2021)	– AVHRR coarse resolution than required in many cases. – MODIS well beyond its design life. – Some uncertainty around funding for 4th and 5th VIIRS units. – Sentinel-3 ground segment implementation needs to be confirmed. – GCOM-C programme continuity very uncertain.
Medium Resolution Optical	Low	– **USGS:** Landsat (current – 2023+) – **EC/ESA:** Sentinel-2 (2015 – 2025+)	– Sentinel-2 ground segment implementation needs to be confirmed. – Some other public good, and commercial supply options for this type.
High Resolution Optical	Low	– **<1m:** World View, GeoEye, Pléiades – **5m:** SPOT-6/-7, RapidEye, emerging constellations (SkyBox, Planet Labs) – **10m:** Sentinel-2	– Many commercial supply options in this type. – Possible emergence of new high-revisit applications with new data streams.
SAR			
C-band	Low	– **MDA (commercial):** RADARSAT-2 (current - 2015+) – **EC/ESA:** Sentinel-2 (current – 2023+)	– Strong continuity through Sentinel-1, though ground segment implementation needs to be confirmed. – RADARSAT Constellation planned for 2018 – 2025.
L-band	Medium	– **RESTEC / PASCO (commercial):** ALOS-2 (current – 2019) – **CONAE:** SAOCOM (2016 – 2025+)	– ALOS-2 is the only current option, and continuity planning is unclear. – SAOCOM (Argentina, 2016+) may bolster supply and continuity.
X-band	Low	– **Commercial:** TerraSAR-X, CosmoSkyMed	– A number of other commercial supply options. – Strong continuity via military supply contracts / interest. – A number of Asian countries implementing X-band SAR.

Table 26 – Summary of supply risk for main instrument types

In all cases, **adaptation is going to be required in order to make optimal use of supply options available**.

Three broad conclusions can be drawn from the study:

- **The nature of the best available public good data streams for the four main instrument types will change.** Some of these changes will be positive (e.g. improved spectral/spatial resolution from Sentinel-2), and some will be negative (e.g. loss of direct broadcast from MODIS twice daily). But overall, supply for these four main types is expected to remain strong.
- **The additional data streams coming online in the 2015-2016 timeframe will greatly increase data volumes.** This is in part because of greater spatial and spectral resolution, in part because of more supply sources and more accessible archives, and in part because of greater revisit frequency. These factors mean that ground segment and data management solutions (e.g. the Australian Geoscience Data Cube, Google Earth Engine) will likely become more important in enabling users to be able to manage and make use of this new data. This also underscores the need for strong coordination with international partners, and potentially for new coordination frameworks (e.g. CEOS Virtual Constellations).
- **The cost of investing in a dedicated satellite space segment has reduced with advances in small satellite technology.** While public good data streams from overseas will continue to be the dominant supply, the business case for a dedicated Australian national Earth observing satellite or satellites, or contribution to an international partnership, looks increasingly attractive. Space segment investment would need to be supported by the ground segment, resulting in additional requirements to receive, standardise, and apply data in a common framework such as the Australian Geoscience Data Cube.

Evolution of Best Available Public Good Data Streams

The study has observed that **Australian EOS data requirements basically tend to reflect the best available public good data sources**. This is neither surprising, nor expected to change. What is likely to change is the nature of the best available data source. For example, MODIS users noted the reduced number of bands available from the continuity option VIIRS, and the removal of the direct broadcast mode from Sentinel-3.

The need to adapt is one of the consequences of relying on overseas sources for data supply. National users in the U.S. and Europe (key data providers) will also have to adjust, but the requirements of their applications would have been reflected during consultation in the space and ground segment design process. Supply from the freely available sources that Australia benefits from will always be subject to overseas programmatic and funding decisions.

The study concluded that there is a move away from Australia having all its EOS data supply “eggs in one basket”, with the **emergence of new operational data streams from Europe’s Copernicus programme (e.g. Sentinel-1, Sentinel-2, Sentinel-3)**. It is helpful that Australia and Europe enjoy a broad, open, and cooperative relationship – meaning that supply from these new data streams is well understood, and can generally be relied upon.

This also underscores the need for strong coordination with international partners, and potentially for new coordination frameworks. One example of a framework would be the Committee on Earth Observation Satellites (CEOS) Virtual Constellations, each of which is focused on delivering specific key product(s) from more than one data stream. (More information on CEOS Virtual Constellations can be found here: http://ceos.org/ourwork/virtual-constellations/.)

Continuing close **alignment with ongoing U.S. activities including missions from USGS (Landsat), NOAA (VIIRS), and NASA (MODIS, future technology) will help to ensure continuity of supply**. In particular, the relationship with operational programs like Landsat and VIIRS, but also with NASA's ongoing series of research missions which help to realise the potential of next generation technology.

Building the relationship with European agencies, and in particular **the emerging EC and ESA programmes will build supply and bolster continuity prospects**. Principally, this means links to the Copernicus Program and securing access to data from the Sentinel missions by proactive engagement. In addition, increasing research ties to ESA will, similar to engagement with NASA, help to ensure Australian users are well positioned to benefit from next generation technology. The recent CSIRO-ESA agreement on research is a good step, but needs to be supported by investment in the relationship.

The collaborative relationship with Japanese EOS data providers appears likely to continue to be complicated for non-geostationary data streams. Himawari-8 data will be distributed to the Australian community via the BOM. However, ALOS-2 (and the ALOS archive) are fully commercial at finer spatial resolutions, and while accessible for a price, ALOS continuity planning is not settled. Programs like GCOM-W (current) and GCOM-C (future) are promising, but funding is very uncertain with significant doubt around follow-on missions and continuity of supply under the new space policy priorities of the Japanese government – which emphasise national security and commercial development.

China and India are investing heavily in their EOS programs, have achieved some success, and report impressive ambitions. These two, along with Brazil, will continue to be backup sources in the short-to-medium term, but don't have a broad heritage of reliable supply and so should be evaluated on a mission-by-mission basis.

China's EOS programme is actively working on an option for almost every instrument type included in the study, and has a broad and deep EOS programme under development (by a multitude of different agencies and institutes). Actual performance is more variable, with technical quality sometimes being questionable, and data access outside of the WMO framework being restricted for some application areas. (E.g. radar altimetry data is made available months after observation, if at all, which means it is not useful for NRT applications.) Importantly, Australia often falls within the coverage footprint of geostationary instruments covering China, which means the possibility exists for Australian coverage.

India has chosen to invest in strong indigenous capacity to build and launch their own satellites with little outside support. But applications are largely focused on their particular national priorities, with most international data supply either sold commercially, or routed via WMO (in the case of the meteorological satellites only). Their development and launch scheduling is also somewhat variable, with plans often changing significantly from year-to-year.

The biggest changes in the supply profile are in the low and medium resolution optical types, with the **near term addition of Himawari-8 (low resolution) and Sentinel-2A (medium resolution)**. **Sentinel-3** is also expected to become a significant supply of low resolution optical data – providing comparable, and in some aspects improved, performance to MODIS and VIIRS.

Himawari-8 may enable new non-meteorological applications from geostationary instruments. It provides a significantly higher frequency of observations (i.e. every 10 minutes on a routine basis for Australia), a wider range and bigger number of wavebands, and finer spatial resolution than previously available from geostationary. However, to make use of this new data stream, product algorithms will need to be adapted, and in some cases, new algorithms and methods will need to be created – which requires investment.

Sentinel-2A will improve upon Landsat-8's performance in terms of spatial and spectral resolution, and coverage area, and will greatly reduce medium resolution optical supply risk. It will also greatly reduce revisit times. In coordination with Landsat-8, and soon after Sentinel-2B, combined the three satellites could deliver weekly or better revisit (currently 16 days from Landsat-8). Availability of Sentinel-2A data means that the 'best freely available' data resolution will be three times finer than with Landsat-8 only (10m vs. 30m) - and offers 13 spectral bands vs. nine.

Increasing Data Volumes

With increased supply, the increase in number of spectral bands, and finer spatial resolution, data volumes are also expected to increase greatly – which may move data processing beyond the technical means of some users as well as stretch the capabilities of the data suppliers. **While new supply options could provide a major boost to a number of application areas, ground segment and data handling systems will need to be improved to take best advantage.**

It appears that **platforms like the Australian Geoscience Data Cube (AGDC), in combination with the National Computational Infrastructure (NCI), can offer scalable solutions to data handling and processing challenges** by managing much of the data handling and processing on centralised infrastructure. Cloud computing is a "game changing" technology being pursued on a number of platforms including the AGDC, Google Earth Engine, Planet Labs, and Amazon Web Services – amongst others. The general philosophy is to bring the algorithms and processing capacity to the data, rather than to move large amounts of data across networks multiple times.

Cloud computing technologies hold the promise of removing much of the data handling burden, enabling the generation of products from time series that weren't previously practically feasible, and also help to streamline source switching - meaning that applications could start to make themselves "sensor agnostic". **The development of national-scale solutions and supporting infrastructure will require significant investment, will carry a continuing operating cost, and may increasingly become an essential piece of the nation's spatial data infrastructure.**

Planning for future Landsat standard products appears likely to lead to the generation of "analysis ready data", generally with atmospheric corrections applied (i.e. processed to surface reflectance). Other data providers like Sentinel-2 have indicated they are planning to move in the same direction for their standard products. If data providers handle processing to an "analysis ready" standard, and make products available to end users via a platform like the AGDC, users could focus on their applications and algorithms, rather than on data handling and pre-processing.

Space Segment Investment

Overall, commercial data supply is strong, growing, and diversifying - which is producing increased competition. But acquisition costs will continue to throttle access for Australian users not accustomed to having budgets for data purchase. While commercial providers are most active in the high and very high resolution optical data types, as well as in SAR, changes are anticipated around the 10m resolution mark with the public good Sentinel-2A providing data.

The emergence of lower cost platforms based on development with COTS components will result in significant cost reductions in deploying operational hardware in space. This may also provide a new growth axis for the commercial sector around extracting value from the rapid revisit enabled by larger low cost constellations. If these platforms (e.g. CubeSats) can reach a level of performance that makes them fit for purpose, they may potentially be disruptive. It is expected that many of these changes will play out over the next 2-5 years.

The cost of securing access to space infrastructure is getting lower, with the likes of SSTL offering turnkey solutions that provide daily high resolution optical (1m) global coverage for an average of $28M per year (for seven years). The costs for a turnkey solution that provides Australian-only coverage, and at reduced frequency could be expected to be less. The technical suitability of these data streams for current and future applications would need to be evaluated, but given the $100M estimated annual Australian spend for EOS data in the 2011 CEODA-Ops report, more detailed investigation may be warranted.

APPENDIX A: TABLES OF ACRONYMS

Acronym	Expansion	Organisation	Full Name
AGDC	Australian Geoscience Data Cube	ASI	Agenzia Spaziale Italiana
AUD	Australian Dollars	BOM	Bureau of Meteorology
BOS	Basic Observation Scenario (ALOS)	CEOS	Committee on Earth Observation Satellites
COTS	Commercial off the Shelf (components)	CONAE	Comisión Nacional de Actividades Espaciales (Argentina)
CSG	Coal Seam Gas (for mission, see Table 28)	CRCSI	Cooperative Research Centre for Spatial Information
DEM	Digital Elevation Model	CSA	Canadian Space Agency
EEZ	Exclusive Economic Zone	CSIRO	Commonwealth Scientific and Industrial Research Organisation
EOS	Earth observations from space	EC	European Commission
GPS	Global Positioning System	ESA	European Space Agency
GPS-RO	GPS radio occultation	EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
IR	Infrared	GA	Geoscience Australia
LEO	Low Earth Orbit	ISRO	Indian Space Research Organisation
LiDAR	Light Detection and Ranging	JAXA	Japan Aerospace Exploration Agency
MWIR	Microwave Infrared	JMA	Japan Meteorological Agency
NRT	Near Real Time	MDA	MacDonald, Dettwiler and Associates
OGRE	Optical, Geospatial, Radar, and Elevation Supplies and Services Panel	NASA	National Aeronautics and Space Administration
RGB	Red, Green, Blue	NGA	National Geospatial-Intelligence Agency (U.S.)
SAR	Synthetic Aperture Radar	NOAA	National Oceanic and Atmospheric Administration
SWIR	Short-wave Infrared	NSMC-CMA	National Satellite Meteorological Centre - Chinese Meteorological Administration
TIR	Thermal Infrared	NSOAS	National Satellite Ocean Application Service
USD	US Dollars	SSTL	Surrey Satellite Technology Limited
VIS	Visible (light)	VAST	Vietnam Academy of Science and Technology
WIS	WMO Information System	WMO	World Meteorological Organisation

Table 27 – Table of acronyms and organisations (agencies/companies)

Mission (*Agency*)	Full Name	Instrument (*Agency*)	Full Name (*Mission)*
ALOS (*JAXA*)	Advanced Land Observation Satellite	AHI	Advanced Himawari Imager (*Himawari-8 and -9*)
CSG (*ASI*)	COSMOS-SkyMed Second Generation	ASCAT	Advanced Scatterometer (*Metop*)
CSK (*ASI*)	Cosmo-SkyMed constellation	AVHRR	Advanced Very High Resolution Radiometer (*NOAA, Metop)*
DMC (*SSTL*)	Disaster Monitoring Constellation	ETM+	Enhanced Thematic Mapper Plus (*Landsat-7*)
ERS (*ESA*)	European Remote sSnsing Satellite	LISS-III	Linear imaging Self Scanner-III (*Resourcesat*)
GCOM-W and –C (*JAXA*)	Global Change Observation Mission-Water and -Climate	MODIS	MODerate-Resolution Imaging Spectroradiometer (*Aqua, Terra*)
GOES (*NOAA*)	Geostationary Operational Environmental Satellite	MSI	Multi-Spectral Instrument (*Sentinel-2*)
JPSS (*NOAA*)	Joint Polar Satellite System	OLCI	Ocean and Land Colour Imager (*Sentinel-3*)
PRISMA (*ASI*)	PRecursore IperSpettrale della Missione Applicativa	OLI	Operational Land Imager (*Landsat-8*)
RCM (*CSA*)	RADARSAT constellation mission	SGLI	Second-generation Global Imager (*GCOM-C*)
SMAP (*NASA*)	Soil Moisture Active Passive	SIRAL	SAR Interferometric Radar Altimeter (*CryoSat-2*)
SMOS (*ESA*)	Soil Moisture Ocean Salinity	TIRS	Thermal Infrared Sensor (*Landsat-8*)
SPOT (*CNES / commercial*)	Satellite Pour l'Observation de la Terre	VIIRS	Visible/Infrared Imager Radiometer Suite (*Suomi-NPP, JPSS*)
Suomi-NPP (*NASA*)	Suomi National Polar-orbiting Partnership		
TSX-NG (*DLR / commercial*)	TerraSAR-X Next Generation		

Table 28 – Table of mission and instrument acronyms

APPENDIX B: PRIORITY DATA SETS AND REQUIREMENTS SET BY EOS EXPERTS

This Appendix contains the templates completed by domain experts during interviews conducted by the study team.

National Crop and Land Use

Responder	Alex Held (CSIRO)	
Case Study	01 - Agriculture	
General Description of Dataset	National Crop and Land Use Dataset	
Derived Information Description	– National-, and regional-scale crop monitoring – Land cover/land use type products	
Data Type	Low and Medium Resolution Optical	
Coverage Summary	National / Whole of State / Wheat belt	
Regions of Interest	National / main cropping areas (rain-fed and irrigated) for each state	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	**Low resolution:** 100-250m **Medium resolution:** 20-30m	**Low resolution:** 100-250m **Medium resolution:** 20-30m
Repeat Frequency	**Low resolution:** 8-16 day MODIS composites for crop condition monitoring (NDVI) **Medium resolution:** 2-3 times per year during main growing season for crop type / land use	**Low resolution:** 8-16 day MODIS composites for crop monitoring (NDVI) **Medium resolution:** 8-16 days with combined Landsat-Sentinel-2 and Sentinel-1
Timeliness / Latency	**Low resolution:** 2-3 days after acquisition of last image in the composite **Medium resolution: same**	**Low resolution:** 2-3 days after acquisition of last image in the composite **Medium resolution: same**
Main Existing Data Streams	**Low resolution:** MODIS **Medium resolution:** Landsat-7, Landsat-8	**Low resolution:** MODIS + VIRS **Medium resolution:** Landsat-7, Landsat-8, Sentinel-1
Anticipated Data Streams	**Low resolution:** – VIIRS (some experimentation) – Sentinel-3A (integration work not yet started) – GCOM-C – Himawari-8 **Medium resolution:** – Sentinel-2A	**Low resolution:** – **Medium resolution:** – Blended Landsat / Sentinel-2 product available at higher frequency, complimented with Sentinel-1 (SAR) coverages once crop is fully grown, to help improve crop discrimination accuracy
Important Technical Characteristics	– For crop condition and growth monitoring, NDVI is the key variable being tracked, and this requires optical bands – SWIR is required to improve accuracy in crop type and and-use mapping (without SWIR discrimination is not sufficient for land use)	– Thermal useful if more frequently – will probably be used to measure water-use H-8 in that direction – will need R&D on how to extract useful water signal – Use of complimentary time-series SAR data (C-, S-band) to improve discrimination of key crop types requires R&D – Soil moisture may be in the mix – used to simulate crop performance – SMAP and SMOS sub 1km
Continuity and Coordination		

Responder	Alex Held (CSIRO)	
Archive Requirements	Longest-possible time series of MODIS and Landsat data helps in tuning models and correlate against historical crop yield statistics.	
Source Switching	Transition of mapping methods to new sensors is likely to require some R&D and possible funding by operational agencies. Continuity from MODIS to VIIRS, and MODIS to Sentinel-3A will be very important as VIIRS and MODIS are the main two operational continuity options in this class. It remains to be seen if either of these sensors could be a replacement for MODIS-class data streams. Similarly, continuity from Landsat-8 to Sentinel-2 will be critical.	
Nuances and Emphasis	– Soil moisture dataset from the likes of SMOS/SMAP could be integrated to improve crop yield prediction. – Time series for MODIS and LS accessible important – people use crop growth models, and so longer time series helps model tuning – Move to cloud computing / data cube approaches is anticipated to help users interact more effectively with time series	

Table 29 - National crop and land use

Atmospheric sounders

Responder	Agnes Lane	
Case Study	02 - Weather	
General Description of Dataset	Atmospheric sounder dataset	
Derived Information Description	Atmospheric temperature, water vapour/humidity	
Data Type	Atmospheric sounder data	
Coverage Summary	Global	
Regions of Interest	Global data for the global forecast model, Australian region data for the local forecast model	
Requirement	**Minimal**	**Optimal**
Spatial Resolution		
Repeat Frequency		
Timeliness / Latency	– Observations received via the Bureau's direct reception network have the lowest latency, and have the largest impact on model accuracy – Internet-received observations have a lower latency, but still have positive impact on model output	
Main Existing Data Streams	AMSU-A, IASI, AIRS	
Anticipated Data Streams	Continuity planned includes next generation systems like IASI-NG, CrIS, ATMS	FY-4 will provide soundings from geostationary, but for the China area only
Important Technical Characteristics	Temperature and humidity soundings in all-weather conditions, in LEO	Soundings from geostationary orbit
Continuity and Coordination	– Adequate data are expected to be provided by JPSS and MetOp – WMO has made recommendations regarding the addition of an early morning orbit, this is being investigated by China	

Responder	Agnes Lane	
Archive Requirements		
Source Switching		
Nuances and Emphasis	These data have the largest impact on BOM weather forecasting of any source of information.	

Table 30 - Atmospheric sounders

Geostationary imagery

Responder	Agnes Lane	
Case Study	02 - Weather	
General Description of Dataset	Geostationary imagery dataset	
Derived Information Description	– Atmospheric winds derived from movement of clouds & aerosols – Visible and IR imagery used by forecasters for nowcasting – Derived products for climate services (e.g. solar radiation) – Imagery for public website	
Data Type	Imagery derived from geostationary orbit	
Coverage Summary	Hemisphere	
Regions of Interest	Australian region	
Requirement	**Minimal**	**Optimal**
Spatial Resolution		
Repeat Frequency		
Timeliness / Latency	<10 mins	
Main Existing Data Streams	MTSAT-2, Fengyun-2	
Anticipated Data Streams	Himawari-8/9	
Important Technical Characteristics	16 channel data: 123TB (uncompressed) per year	
Continuity and Coordination	Adequate data are expected to be provided by Himawari, FY-4, and GEO-KOMPSAT-2	
Archive Requirements	Data will be archived on robotic terabyte tape storage facilities at the Bureau, at a cost of approx. $9k p/a.	
Source Switching	China FY-4 series (2016-2040), Korea GEO-KOMPSAT-2 series (2018-2029)	
Nuances and Emphasis		

Table 31 - Geostationary imagery

Ocean vector winds and height

Responder	Agnes Lane	
Case Study	02 - Weather	
General Description of Dataset	Ocean vector winds and height	
Derived Information Description	Sea level. Ocean vector winds	
Data Type	Scatterometer and Radar altimeter data	
Coverage Summary	Global	
Regions of Interest	Australian region	
Requirement	**Minimal**	**Optimal**
Spatial Resolution		
Repeat Frequency		
Timeliness / Latency		
Main Existing Data Streams	The Bureau receives validated, cross-calibrated satellite altimeter data from the Radar Altimeter Database System (RADS), Netherlands. It includes data from Jason-2, CRYOSAT2, SARAL.	Must have at least 3 altimeters but 4 would be best for ocean models
Anticipated Data Streams		
Important Technical Characteristics		
Continuity and Coordination	The RADS data stream is the only altimeter data stream into the Bureau. Single point of failure.	
Archive Requirements		
Source Switching		
Nuances and Emphasis	Altimeter data are an essential input to ocean forecast models and seasonal prediction models. High quality altimeter data are a priority, particularly in Australian coastal zones. UTAS is leading altimetry validation activities in Australia.	

Table 32 - Ocean vector winds and height

Global Sea Surface Temperature

Responder	Garry Brassington (BOM)	
Case Study	03 - Oceans	
General Description of Dataset	Global Sea Surface Temperature dataset	
Derived Information Description	Sea Surface Temperature (native observations as observed in the swath)	
Data Type	– Low resolution optical IR – Microwave	
Coverage Summary	Global coverage (0.1 degree global model)	
Regions of Interest	Primarily all adjacent ocean basins and seas: Indian Ocean, SE Asia, South Pacific, Southern Ocean	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	1km per available sensors is OK	– 1km fine for foreseeable – Coastal will be an issue – Himawari-8 is an important capability
Repeat Frequency	24-hour collection from U.S. Navy provider – whatever data has been collected	E-reefs will target higher frequency assimilation and modelling of the diurnal warming
Timeliness / Latency	Satisfactory, twice a day updates	– Temperature an issue for e-reefs and looking for finer spatial scale and low latency – Will move to real time assimilation
Main Existing Data Streams	– All AVHRR wide-swath operational – VIIRS – U.S. Navy Operational composite of 2-3 satellites in GHRSST L2P format – Windsat & AMSR-2 directly	Himawari-8 will have a dominant impact for e-reefs (and other coastal modelling applications)
Anticipated Data Streams		AVHRR, Himawari-8, Sentinel-3A (SLSTR)
Important Technical Characteristics	– Piggy back off global communities and take what is available – Don't push requirements – Day-night biases are the issue of concern – Data availability is key	– E-reefs and coastal requirements are more taxing in terms of resolution and S:N - precision will need to go up – Ocean Colour will be key in e-reefs (Sentinel-3) – Salinity ambitious and no missions – Sea-ice has not been included but would like to include in the future
Continuity and Coordination	GHRSST community has provided the coordination of these platforms	
Archive Requirements	– Don't throw anything away – Everything kept for reanalysis or study – Some is in deep storage	
Source Switching	– Multiple sources available – GHRSST community does the hard work on data formats – BOM software is compatible with all the providers – Himawari-8 will be in same format	
Nuances and Emphasis	Diurnal variations key, especially in tropical areas	

Table 33 - Global sea surface temperature

Global Sea Level

Responder	Garry Brassington (BOM)	
Case Study	03 - Oceans	
General Description of Dataset	Global Sea Level dataset	
Derived Information Description	Sea Level Height Anomaly – highly derived.(3rd party (RADS) does the compilation and correction)	
Data Type	Precision Altimeter packages	
Coverage Summary	Global coverage (0.1 degree global model)	
Regions of Interest	Primarily Indian Ocean and SE Asia, South Pacific	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	Adequate – need wide swath	– Reduction in latency would have the largest impact – Repeat orbits and nadir instruments mean some parts of the ocean are never observed – Wide swath would provide improved spatial continuity
Repeat Frequency	Daily observations with groups of 3-4 days of data assimilated	Same as SST – daily or better
Timeliness / Latency	– Jason is 10-day repeat – Beyond forecasts. Need minimum of 4 nadar altimeters in operations – Currently around 3 – 3-day latency best available for IGDR now	4 satellites or more, and wide swaths to get up to daily or better to improve ocean current forecasting
Main Existing Data Streams	Jason series, Cryosat-2, SARAL	
Anticipated Data Streams	Sentinel-3	– SWOT great for global and coastal forecasting – Continue use of Jason and other current sources – Use RADS as 3rd party
Important Technical Characteristics	– LATENCY/Coverage #1 – Data quality is essential and reduces choice of systems – JASON is the reference	
Continuity and Coordination	3rd party provider handles these issues	
Archive Requirements	– Don't throw anything away – Everything kept for reanalysis or study – Some is in deep storage	
Source Switching	RADS takes care of this as the current 3rd party supplier.	
Nuances and Emphasis		

Table 34 - Global sea level

Water Resource Assessments

Responder	Luigi Renzullo (CSIRO)	
Case Study	04 – Water	
General Description of Dataset	Water Resource Assessments	
Derived Information Description	– Irrigation projection, planning and management information products – Catchment characterisation – National water reporting – Water resource modelling – Estimated future water requirements from estimates of land under cropping	
Data Type	Medium and low resolution optical	
Coverage Summary	National wall-to-wall, down to catchment level for local authorities	
Regions of Interest	Australia, down to specific catchments	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	– 250m down to 25m	– Very high resolution optical for catchment characterisation – 50cm
Repeat Frequency	– BoM annual – Local authorities *ad hoc*	
Timeliness / Latency		– Flood mapping down to hourly data.
Main Existing Data Streams	– Landsat and MODIS	– WorldView-2 and -3
Anticipated Data Streams	– Sentinel-2A, Sentinel-3A, VIIRS	
Important Technical Characteristics		
Continuity and Coordination		
Archive Requirements	– Archive required to put observations in historical context – BoM publishes the most recent year's WRA in the context of the past 100 years.	
Source Switching		
Nuances and Emphasis	– In some cases a legal obligation has arisen to revisit archive data to ensure all available data is being used for resource management. – Future constellations and/or geostationary assets may be able to enable products in an hourly timeframe. – River flow predictions use *in situ* stream gauges rather than satellite EOS. – In general BoM works to ingest operational data streams, rather than historical (other than for historical assessment).	

Table 35 - Water resource assessments

Soil Moisture

Responder	Luigi Renzullo (CSIRO)	
Case Study	04 – Water	
General Description of Dataset	Soil Moisture	
Derived Information Description	Soil moisture maps of the top 5cm of soil. Other moisture parameters are inferred including water available at the roots.	
Data Type	Microwave passive and active	
Coverage Summary	National wall-to-wall, ideally down to paddock level for individual land owners.	
Regions of Interest	Australia	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	10's of kms (passive)	Sub-10km (passive-active) As fine as 3km sharpened product discussed for SMAP. Paddock scale for Sentinel-1A derived products (30m)
Repeat Frequency	Weekly composite	Weekly or better. Hours needed for operational meteorology applications (extreme weather and flooding modelling).
Timeliness / Latency	Composite products for national assessments are not urgent. Smaller scale work, e.g. paddocks, will need much more current info – hours latency.	Hours needed for operational meteorology applications (extreme weather and flooding modelling).
Main Existing Data Streams	ASCAT	SMAP (active-passive) Sentinel-1
Anticipated data streams	SCA on EPS-SG series	The derivation of products from **Sentinel-1A** remains a work in progress, but it could be expected to be a valuable data stream.
Important Technical Characteristics		
Continuity and Coordination		
Archive Requirements	Archive required to put observations in historical context – BoM publishes the most recent year's WRA in the context of the past 100 years.	
Source Switching		
Nuances and Emphasis	Given the importance of soil moisture as an ECV, there will always be a need for these data sets. However, it remains to be seen what the ideal mix of active-passive sensing might be to address this need. SMAP capability is yet to be proven.	

Table 36 - Soil moisture

National Fire Monitoring

Responder	Norman Mueller (GA)	
Case Study	05 - Hazard and Risk Management	
General Description of Dataset	National fire monitoring	
Derived Information Description	– Grassland fuel loads – Sentinel hotspots programme – Burn scar assessment	
Data Type	Medium and Low resolution optical	
Coverage Summary	National and occasional SE Asia regional	
Regions of Interest	– Australia – Some infrequent work with PNG and Indonesia, generally environmental	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	– Low resolution: 1000 m – Medium resolution: 25 m	– Low resolution: 100 m – Medium resolution: 10 m
Repeat Frequency	– Low resolution: twice daily – Medium resolution: weekly	– Low resolution: multiple daily (Himawari-8 will provide coverage every 10 minutes, with potential applications to be assessed) – Medium resolution: daily
Timeliness / Latency	– Low resolution: 30 mins – Medium resolution: 24 hours	– Low resolution: 10 mins – Medium resolution: 2-3 hours
Main Existing Data Streams	Low resolution: – MODIS – AVHRR – VIIRS Medium resolution: – Landsat	Low resolution: – MODIS – AVHRR – VIIRS – Sentinel-3 – Himawari-8/9 Medium Resolution: – Landsat – Sentinel 2 Commercial data streams from: – DMCii – Airbus Defence and Space – Digital Globe
Anticipated Data Streams	Low resolution: – Sentinel-3A as a true continuity option for MODIS – Himawari-8 Medium resolution: – Sentinel-2A	Medium resolution: – The combination of two Landsat and two Sentinel-2 units will drop revisit time significantly, down to approximately every three days.
Important Technical Characteristics	– The central requirement is thermal detection of fires, and the ability to measure fire severity through change in vegetation characteristics. Multi-resolution satellites with sensors providing detection capabilities across visible, near infra-red, short-wave infra-red and thermal are desirable. – VIIRS has fewer bands, and so is more limited, but can do some of the job. It also does not provide the same revisit frequency as MODIS.	

Responder	Norman Mueller (GA)	
Continuity and Coordination	Low resolution: – Currently planning for Sentinel-3A build out, as well as Himawari-8 – First priority for Himawari-8 will be hotspots algorithm, which may be able to provide a national product as frequently as every 10 minutes. – Himawari-8 has enough spatial and spectral character that it may be able to support MODIS-level –burn scan mapping, and possibly grassland fuel load and surface reflectance.	
Archive Requirements	– Time series observations of fire can inform modelling of fire frequency, trends in burn severity and recovery. – The longer the archive the better for model tuning and anomaly assessment – currently maintaining Landsat back to 1987 and MODIS back to 1999.	
Source Switching	– Himawari-8, Sentinel-2 and -3 being investigated.	
Nuances and Emphasis	– Can turn around the processing of a single MODIS image in 2-3 hours for emergency, but QA requires full processing chain approximately 4-5 hours from acquisition. – Hotspots are generated much faster than a full scene analysis using a very fast conversion algorithm which produces a small file containing just hotspot information for web service delivery. Detected hotspots are thus available within about 30 minutes of a MODIS pass on the Sentinel web site.	

Table 37 - National fire monitoring

National Flood Monitoring

Responder	Norman Mueller (GA), Craig Arthur (GA), Martine Woolf (GA)	
Case Study	05 - Hazard and Risk Management	
General Description of Dataset	National flood monitoring	
Derived Information Description	– Flood extent maps – Inundation frequency information	
Data Type	Low and medium resolution optical	
Coverage Summary	National and slightly broader – some work with neighbors PNG and Indonesia, but not very often (generally more in environmental)	
Regions of Interest	Australia	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	Low resolution: 500 m Medium resolution: 25 m	Low resolution: 100 m Medium resolution: 10 m
Repeat Frequency	– Twice-daily low resolution – Weekly medium resolution	– Low resolution: multiple daily (Himawari-8 will provide coverage every 10 minutes, with potential applications to be assessed) – Medium resolution: daily
Timeliness / Latency	– Low resolution: 6 hours – Medium resolution: 24 hours	– Low resolution: 1 hour – Medium resolution: 3 hours

<table>
<tr><th>Responder</th><th colspan="2">Norman Mueller (GA), Craig Arthur (GA), Martine Woolf (GA)</th></tr>
<tr><td>Main Existing Data Streams</td><td>– MODIS
– Landsat</td><td>– Landsat
– Sentinel-1
– MODIS
– VIIRS
Commercial data sources
– Hi-res optical (Airbus DS, Digital Globe)
– DMCii
– SAR (COSMO-SkyMED, TerraSAR-X, Radarsat-2)</td></tr>
<tr><td>Anticipated Data Streams</td><td>– Sentinel-3A
– Himawari-8</td><td>– Sentinel-2A</td></tr>
<tr><td>Important Technical Characteristics</td><td>– Automated water detection from optical sensors is heavily dependent on the sensor having SWIR bands as well as visible.</td><td>– Sentinel-1 provides operational SAR acquisition over large areas, now becoming particularly useful for broad flood detection.
– DMC has only three bands, but it has a wide swath and can do the job required.
– SPOT, World View and similar sensors can complete with aerial capabilities, and is useful over urban areas and town centres.</td></tr>
<tr><td>Continuity and Coordination</td><td>Low resolution:
– Currently planning for Sentinel-3A build out, as well as Himawari-8
– Himawari-8 has enough spatial and spectral character that it may be able to support MODIS-level products.
Medium resolution:
– Currently planning for Sentinel-2A. Increased revisit frequency, spatial resolution and swath could provide a doubling in the effectiveness of medium resolution, automated flood mapping from optical sensors.</td><td>SAR:
– Sentinel-1A acquisition is now in progress, demonstrating an effective instrument for flood mapping. Currently implementing acquisition and archive systems and planning for automated product generation.</td></tr>
<tr><td>Archive Requirements</td><td>– Continuous archive of low and medium resolution data. Now adding SAR archiving with Sentinel-1A data being made available.
– AGDC hosts the Landsat archive from 1987 to present (soon to include MODIS and other sensors) as a live data access and analysis system. Provides ability to analyse environmental information (such as surface water history) through time. AGDC imagery batch updated quarterly.</td><td></td></tr>
<tr><td>Source Switching</td><td colspan="2">Sentinel-1, -2 and -3 being investigated.</td></tr>
<tr><td>Nuances and Emphasis</td><td colspan="2">– Australia is sunny and flat, so in many cases optical data streams have enabled effective flood monitoring. However, during times and over areas of interest where flooding is acute, clouds and high relief landscapes tend to be important factors which SAR data can help to overcome.
– Securing SAR data generally requires specific supply arrangements to be in place, where optical data streams like MODIS and Landsat are “always available”, even though may be heavily cloud affected. Sentinel-1A wil provide the first SAR data stream offering comparable coverage.</td></tr>
</table>

Responder	Norman Mueller (GA), Craig Arthur (GA), Martine Woolf (GA)
	– Optical imagery is intuitive, and EMS personnel are happy to look at even a MODIS image, where they can immediately and visually understand the extent of flooding. – In the past, EOS data use was more directed at the response phase, but the trend is moving towards preparedness and mitigation. – The modified SRTM 1-second product gives hydrologically consistent DEM, with most vegetation artefacts effectively removed. This makes it quite suitable, even though SRTM is not necessarily the highest accuracy or resolution DEM available. Both WorldDEM and iDEM (from DLR) are looking like strong contenders to replace SRTM, but there aren't any current plans. – The national land information group maintains the definitive DEM for Australia (National Elevation Data Framework), including airborne LiDAR – the aircraft dataset is slowing being built up.

Table 38 - National flood monitoring

Queensland Land Cover

Responder	Christian Witte (QLD DSITIA)	
Case Study	06 - Landscape	
General Description of Dataset	Queensland **land cover** dataset for natural resource management by government	
Derived Information Description	Products derived include: – Tree clearing products [Annual] (compliance support, expert evidence); – Persistent green trend using Landsat time series [Seasonal mosaics] (woody thickening / fractional cover / ground cover); – Crop frequency [twice annual]; – Fire scars/burnt areas (aka "land cover change"). – Water body mapping – All products generally from 1987 to current and then systematically updated	
Data Type	Medium resolution optical	
Coverage Summary	State wall-to-wall	
Regions of Interest	Queensland state wide	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	25m	25m
Repeat Frequency	– Frequency depends on application – Minimum 4-6 coverages per season	– Push from landholders to access ground cover data more frequently – Weekly would be ideal
Timeliness / Latency	– Latency not time critical – weeks	– Days to weeks
Main Existing Data Streams	– Landsat-8 is the core source – Landsat-7 also still in use – MODIS adequate for some applications, for example, monitoring general ground cover patterns in extensive grazing area and fire scar mapping outside of intensive coastal land use areas	– ALOS and ALOS-2 data accessible via K&C initiative for research purposes
Anticipated Data Streams	– Sentinel-2A – Sentinel-3A (for some applications, as a MODIS continuity option)	– A blended Landsat / Sentinel-2 mosaic could be ideal, and with 3-4 units in operation could achieve sub-weekly coverage – If ALOS archive and ALOS-2 were more affordable for operational purposes the integration of L-band SAR into the optical data archive

Responder	Christian Witte (QLD DSITIA)	
		could result in significant further automation in mapping tree clearing – SAOCOM L-band SAR could provide a public good ALOS/ALOS-2 alternative
Important Technical Characteristics	– Time series are critical, and the longer the better in order to tune and optimise algorithms – Landsat mosaics comprising 2 seasonal images used for crop frequency – Coastal zone (i.e. up to 100km inland) fire scars require Landsat scale, but inland MODIS scale is fine	
Continuity and Coordination	– Archive and future continuity essential	
Archive Requirements	– The tree clearing algorithm currently uses the archive of dry season Landsat images (but will probably move to the full archive) – The fractional cover algorithm is based on seasonal Landsat mosaics (each mosaic uses multiple dates to get the most representative values and infill cloud & shadows) – The ground cover algorithms is based on the fractional cover data, – The seasonal persistent green trend also uses fractional cover data	
Source Switching	In the event of a Landsat-8 failure, Landsat-7 mosaics could be used. Previous backup would have been SPOT-5, but with its demise, they would likely look to European options (in particular Sentinel-2) and explore Chinese, Indian and any other alternatives	
Nuances and Emphasis	– The Northern Territory and Victoria are using the same system through collaborative agreements. Tasmania and Queensland are about to commence a three year agreement for collaborative land cover mapping as well. – NT, VIC, NSW and QLD use Landsat fractional cover and derived products such as ground cover. There are also national fractional cover demonstration datasets available through TERN, but not for the full Landsat time-series. OK to say these produced national scale. NSW undertakes annual tree clearing mapping at Spot5 scale in addition. – The huge advantage of these collaborations is the initial sharing of knowledge and algorithms which then tends to develop into the joint enhancement or development of new algorithms. That results in efficiencies and greater national consistency. – Victoria derives fractional cover data and ground cover data. However, not tree clearing at this stage. There is particular interest in fire scar mapping New South Wales does tree clearing using SPOT – Time series products, for example for detecting tree clearing, require the final image in the series to be acquired before they can be finalised	

Table 39 - Queensland land cover

Queensland Land Use

Responder	Christian Witte (QLD DSITIA)	
Case Study	06 - Landscape	
General Description of Dataset	Queensland **land use** dataset for natural resource management by government	
Derived Information Description	Products derived include: – Residential and rural residential expansion [Approx. every five years] – Various crop, seasonal and perennial horticultural classes [Approx. every five years] – Broad range of other classes (see grey shaded classes: http://www.agriculture.gov.au/abares/aclump/Documents/ALUM_Classification_V7_May_2010_summary.pdf) – Immediate / responsive Pre- and Post-disaster imagery [*ad hoc*] (e.g. floods, storms)	
Data Type	High resolution optical	
Coverage Summary	Sub-State sites/regions	
Regions of Interest	Sites/regions across Queensland	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	10m	Sub-10m
Repeat Frequency	– Driven in part by availability of imagery – Don't require the whole state in one coverage – Aiming for a complete update every five years – Opportunistic, in coordination with other Queensland government functions; – no strategic state-wide acquisition/purchase plan for imagery currently in place	– Funded acquisition strategy is required
Timeliness / Latency	– Latency not time critical – weeks	– Latency not time critical – weeks
Main Existing Data Streams	– SPOT-5, -6, -7 – Partnership with China on ZY-3 used for research, not commercial – In coastal areas uses aerial photography when available	– Many coastal intensive land use areas photographed by aircraft every 1-3 years at 10-30cm with 30 agencies $30K each year (quite cost effective)
Anticipated Data Streams	– Sentinel-2A 10m optical bands would be OK for non-intensive/non-coastal regions	– Space borne LiDAR GEDI from NASA of interest, 2018-2020 timeframe – The likes of Planet Labs or SkyBox imaging could be of interest if an affordable subscription service and/or downlink station were available
Important Technical Characteristics	– Typical mapping units of 1Ha (100m x 100m)	
Continuity and Coordination	– Need to maintain five year currency	
Archive Requirements		
Source Switching		
Nuances and Emphasis	Uses satellite and aerial imagery, various other data sources and is largely based on manual expert image interpretation. Hence fairly resource intensive.	

Table 40 - Queensland land use

Mineral Exploration

Responder	Thomas Cudahy (CSIRO), Cindy Ong (CSIRO)	
Case Study	07 - Mining and Petroleum	
General Description of Dataset	Mineral exploration	
Derived Information Description	Mineral maps that assist in mapping the nature of any regolith cover, composition of the primary geology and any superimposed alteration effects that could be used as vectors towards economic mineralization from the regional (1:5M) to the prospect (1:50K) scales.	
Data Type	Satellite: – ASTER with its multispectral VNIR (15 m pixel), SWIR (30 m pixel) and TIR (90 m pixel) capability (see publicly assessable Australian ASTER geoscience products developed by CSIRO, Geoscience Australia and collaborators). – New possibilities emerging with the recent launch of the commercial WV-3 and its <5 m pixel multispectral VNIR and SWIR data. – Limited role for hyperspectral Hyperion imagery largely because of limited SWIR signal-to-noise and spatial coverage. Airborne: – Commercially available hyperspectral VNIR-SWIR systems with a <5 m pixel footprint (e.g. HyVista's HyMap and the DeBeer's AMS sensor).	
Coverage Summary	Satellite: – National Version 1 ASTER geoscience maps span the Australian continent. These were generated using 3500 individual ASTER from an archive of 35,000 over Australia spanning 2000-2007 – ASTER SWIR module was switched off in 2008 – WV-3 was launched in August 2014 and has yet to begin full commercial operations. Even so, its small spatial footprint means that it more suited to smaller area of coverage. Airborne: – HyMap/AMS have been used extensively by government and private organisations for local (~250 km2) to regional (~25,000 km2) surveys since 1998.	
Regions of Interest	Exposed areas (most of Australia) including "brownfield" areas around known mineral occurrences as well as more distal "greenfield" areas	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	30m pixel resolution (effective for better than 1:100,000 scale geological mapping)	5 m pixel resolution with a 10+ km swath
Repeat Frequency	Once after cloud free, high-sun angle, minimal vegetation cover scene has been acquired.	
Timeliness / Latency	Imagery (mineral maps) available prior to start of the field exploration programme	
Main Existing Data Streams	– Satellite: ASTER, Landsat, Hyperion – Aircraft: HyMap/AMS, Hawk/Eagle/Owl (SpecTIR, U.S.); CASI/SAI/MASI/TASI (ITRES, Canada)	
Anticipated Data Streams	– WV-3 (DigitalGlobe, 2015) – EnMAP (DLR, 2018) – HISUI (Japan Space Systems, 2018) – HyspecIQ (Boeing, 2018) – Ecostress (NASA-JPL, 2020)	
Important Technical Characteristics	– Wavelength range: 0.4-1.0 microns (VNIR) + 1-2.5 microns (SWIR) + 7.6-12.0 microns (TIR)	

Responder	Thomas Cudahy (CSIRO), Cindy Ong (CSIRO)	
	– Number of bands: Multispectral @ ~40 nm spectral resolution = ~10 bands across VNIR and SWIR; Hyperspectral @~20 nm resolution (e.g. HyMap/AMS) = ~120 bands across VNIR-SWIR; Hyperspectral @~10 nm resolution (e.g. EnMap/HISUI/HyspecIQ) = 240 bands across VNIR-SWIR – S/N: >150:1 across VNIR-SWIR	
Continuity and Coordination	With failure of ASTER SWIR module in 2008, then new WV-3 data is a possible replacement for ongoing multispectral SWIR data. ASTER systems will soon be de-commissioned with the only planned/secured (funding) TIR multispectral replacement data stream being NASA's Ecosstress mission in 2020. Continued access to high spatial resolution hyperpsectral VNIR-SWIR data from airborne providers will depends on their ongoing commercial viability. Coordination with emerging satellite and airborne instrument development teams is essentially conducted by CSIRO.	
Archive Requirements	National ASTER data archive is on NCI and Pawsey (CSIRO managed). Public airborne hyperpsectral survey data is on Pawsey (CSIRO managed).	
Source Switching		
Nuances and Emphasis		

Table 41 - Mineral exploration

Mineral Mining and Environmental Monitoring

Responder	Thomas Cudahy (CSIRO), Cindy Ong (CSIRO)	
Case Study	07 - Mining and Petroleum	
General Description of Dataset	Mineral mining and environmental monitoring	
Derived Information Description	High spatial resolution (<5 m pixel), accurate (traceable and reproducible) measurements of biophysical and mineralogical properties suitable for baseline mapping and monitoring mine operations and related infrastructure (<100 km2).	
Data Type	High quality hyperspectral and potentially LiDAR/SAR (include interferometer) data	
Coverage Summary	Targeted (<100 km2) and multi-temporal	
Regions of Interest	Mining operations and related infrastructure including transport corridors and bulk ore handling facilities	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	Depends on application, e.g. <5 m (optical) for open pit mine and stockpile ore characterization as well as related dust mapping/monitoring	~2 m optical
Repeat Frequency	Depends on application, e.g. ~3 days (optical) for open pit mine and stockpile ore characterization as well as related dust mapping/monitoring	Daily
Timeliness / Latency	Depends on application, e.g. <1 day access to information products for open pit mine and stockpile ore characterization as well as related dust mapping/monitoring	
Main Existing Data Streams	Airborne: HyMap, Specterra. Others available but not yet used (e.g. U.S.'s SPECTIR's Hawk/Eagle/Owl; and Canada's ITRES CASI/SASI/MASI/TASI) Satellite: WorldView-2 (commercial) – does not deliver required biophysical properties.	No current optical satellite EOS sources with sufficient spectral-spatial-radiometric resolutions
Anticipated Data Streams	– Satellite: Optical hyperspectral VNIR-SWIR HyspecIQ system (Boeing, 2018) – No MIR or TIR sensor yet in development	
Important Technical Characteristics	– Different biophysicochemical properties have different, diagnostic hyperspectral VNIR-SWIR-MIR-TIR properties – For example, vegetation water-stress can be estimated using the NIR water band while jarosite associated with the development of acid drainage is associated with very narrow absorptions in the visible and SWIR	
Continuity and Coordination	– Establishment of any new legislated environmental regulations based on EOS data will depend on assured continuity of suitable data – Coordination required between State Government regulators, industry and data providers as well as researchers for establishing appropriate products	

Responder	Thomas Cudahy (CSIRO), Cindy Ong (CSIRO)	
Archive Requirements	Archives to be held by State government regulators for use in mine closure criteria and possible legal dispute resolutions.	
Source Switching		
Nuances and Emphasis		

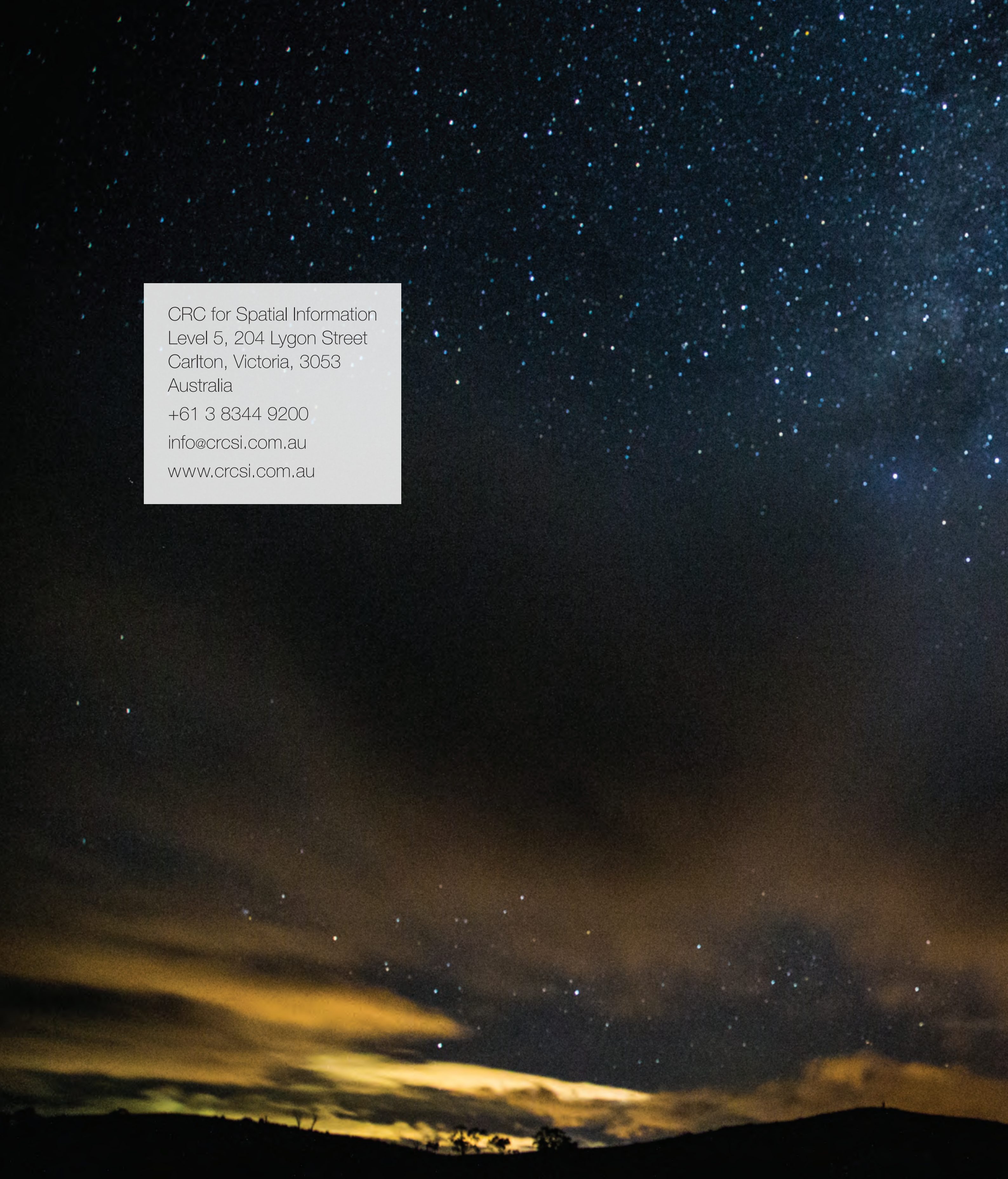
Table 42 - Mineral mining and environmental monitoring

Coal Seam Gas Monitoring

Responder	Cindy Ong (CSIRO)	
Case Study	07 - Mining and Petroleum	
General Description of Dataset	Coal Seam Gas (CSG) Monitoring in the vicinity of extraction areas	
Derived Information Description	– Measurements of fugitive gases, primarily methane and their associated impacts on agriculture crops – Measurement of actual subsidence and it's impacts related to plant physiology or other impacts such as erosion – Impacts of CSG operations such as dust and or related impacts on agriculture crops;	
Data Type	– Very high resolution optical – LiDAR/laser – Hyperspectral – Multi-spectral – SAR	
Coverage Summary	One or more sites	
Regions of Interest	CGS fields are predominantly in the Surat Basin (QLD, NSW) but capabilities equally required for fracking areas	
Requirement	**Minimal**	**Optimal**
Spatial Resolution	– **Fugitive gas leakages:** very high resolution optical or LiDAR/laser data <5m – **Fugitive gas regional trend:** atmospheric soundings <30m – **Dust, plant physiological impacts:** medium resolution optical or hyperspectral <30 m – **Subsidence and Micro-erosion**: SAR interferometry or other that can detect subsidence at sub-cm	– **Fugitive gas leakages:** very high resolution optical <2m – **Fugitive gas regional trend:** atmospheric soundings <30m – **Dust, plant physiological impacts:** medium resolution optical or hyperspectral <5 m – **Subsidence and Micro-erosion**: SAR interferometry or other that can detect subsidence at sub-mm
Repeat Frequency	– **Fugitive gas leakages and trend:** daily to monthly – **Dust, plant physiological impacts:** at least twice a year capturing end of wet and dry – **Subsidence and Micro-erosion:**	– **Fugitive gas leakages and trend:** daily – **Dust, plant physiological impacts:** monthly – **Subsidence and Micro-erosion:**
Timeliness / Latency	Weeks	Days
Main Existing Data Streams	– **Fugitive gas regional trend:** a range of atmospheric sounding satellites such as GOSAT, ACE-FTS, AIRS – **Dust, plant physiological impacts:** Airborne hyperspectral	

Responder	Cindy Ong (CSIRO)	
	– **Subsidence:** SAR (e.g. Sentinel 1, TerraSAR-X, TanDEM-X), or high resolution photography – **Micro-erosion:** high resolution photography	
Anticipated Data Streams	– **Fugitive gas regional trend:** Sentinel 5 – **Dust, plant physiological impacts:** satellite hyperspectral such as EnMap, HISUI – **Subsidence:** SAR – **Micro-erosion:** high resolution photography	
Important Technical Characteristics	– Very high resolution optical has to be spectral sub-nm and spatial sub 5m. – Very high spatial resolution optical detailed enough to identify micro changes in the topography. – LiDAR/laser data of sufficient sensitivities to measure "leakages". – Hyperspectral must be able to detect the mineralogical dust and the associated plant physiological impacts. – Multi-spectral must have bands that described the spectral features related to plant physiology/biochemical to identify the impact. – SAR data sensitive enough to measure subsidence at the cm-mm scale.	
Continuity and Coordination	Needs to be underpinned by independent validation and coordinated with other associated studies	
Archive Requirements	Need traceability back to level 0 data if possible	
Source Switching	Cross calibration of sensors and products	
Nuances and Emphasis		

Table 43 – Coal seam gas monitoring



CRC for Spatial Information
Level 5, 204 Lygon Street
Carlton, Victoria, 3053
Australia

+61 3 8344 9200

info@crcsi.com.au

www.crcsi.com.au

Australian Government
Geoscience Australia

Australian Government
Bureau of Meteorology

CSIRO

Symbios Communications

crc•si