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THESIS

USE OF COMMERCIAL IMAGERY CAPABILITIES IN SUPPORT OF MARITIME DOMAIN AWARENESS

by

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June 2015

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Maritime domain awareness (MDA) is a concern for all maritime countries. To know when ships are approaching their shores and what threats and hazards are forthcoming, MDA is imperative for protecting the homeland and its citizens.

As technology has improved in the world of commercial satellite imagery, those who perform MDA have realized they can utilize these capabilities to improve their common operational picture. As satellites continue to improve, it is more feasible to utilize their products within operations centers at the operational and even tactical level. With the added benefit that this imagery is unclassified and sharable, and with the United States' desire for coalitions and sharing with partners, commercial satellite imagery is moving into the forethought of many decision makers.

This research focuses on current operating procedures for MDA, the capabilities and limitations of today's commercial imaging satellites, and what ground stations are available to assist in the use of combatant commander-controlled tasking. Two major demonstrations of the use of commercial satellite imagery for MDA in this thesis provide lessons learned to be applied to future architectures and ways forward.

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USE OF COMMERCIAL IMAGERY CAPABILITIES IN SUPPORT OF MARITIME DOMAIN AWARENESS

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LIST OF ACRONYMS AND ABBREVIATIONS

ADSS	Analyst Detection Support System
AFB	Air Force Base
AIS	Automated Identification System
AOR	Area of Responsibility
CANES	Consolidated Afloat Networks and Enterprise Services
CAOC	Combined Air Operations Center
CENTRIX	Combined Enterprise Regional Information Exchange System
CMFP	Cooperative Maritime Forces Pacific
CMG	Control Moment Gyros
CNO	Chief of Naval Operations
COCOM	Combatant Commander
COP	Common Operational Picture
COTS	Commercial-off-the-Shelf
DCGS	Distributed Common Ground System
DCGS-A	Distributed Common Ground System–Army
DES	Data Exploitation System
DIB	DCGS Integration Backbone
DOD	Department of Defense
DVWF	Detection of Vessels, Wide, Far
EADS	European Aeronautic Defence and Space Company N.V.
EMCON	Emissions Control
EO	Electro-Optical
GCCS-M	Global Command and Control System–Maritime
GSD	Ground Sampling Distance
ISR	Intelligence, Surveillance and Reconnaissance
IP	Internet Protocol

MARPAC	Maritime Force Pacific
MDA	Maritime Domain Awareness
MOC	Maritime Operations Center
NCC	Navy Combatant Commands
NGA	National Geospatial–Intelligence Agency
NRL	Naval Research Laboratory
NTM	National Technical Means
OPAREA	Operation Area
OPSEC	Operations Security
ORS	Operational Responsive Space
OTH-G	Over the Horizon–Gold Message
PE	Polar Epsilon
QA	Quality Analysis
RGT	Remote Ground Terminal
RIMPAC	Rim of the Pacific
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communications
SCNB	Scan SAR Narrow B
SPAWAR	Space and Naval Warfare Systems Command
SWIR	Short Wave Infrared
UK–DMC	United Kingdom–Disaster Monitoring Constellation
U.S.	United States
USCG	United States Coast Guard
USN	United States Navy
VHF	Very High Frequency
VMOC	Virtual Mission Operations Center

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I. INTRODUCTION

Since the beginning of time, governments of coastal countries have had a need to know what is occurring at sea to protect their national interests and provide security for their citizens. To defend their territory against sea-borne threats, countries on and near the oceans have required at least general knowledge of who was operating in the maritime environment close to their shores and the nature of the operations being conducted. As threat technology has improved, governments have needed greater awareness of traffic on the oceans and have needed to see further and further out from their shores for a multitude of reasons. For instance, weapons ranges have increased, which requires the ability to see those threats further out. Besides the direct threats of weapons from naval combatants, with the amount of cargo that moves over the ocean and through the major shipping routes, threats can come in on any ship. Whether it is from personnel being carried by the ship any type of agents (biological, chemical, nuclear) or drugs being transported or any other type of hazard, the earlier a government can know about an impending threat the better it can prepare for the threat's arrival or potentially keep it out. For these reasons, countries need to know not only what activity is occurring near their shores, but also keep aware of targets over the horizon. Also, if a government can keep an eye on the waterways further and further out, it can watch ships for patterns and determine where they are heading to identify possible issues before those ships enter territorial waters. The ability to monitor the sea space surrounding a country's landmass and know what activity is occurring is known as maritime domain awareness (MDA).

With all the technology currently available, it has been possible to apply many more tools against the MDA problem, thereby improving awareness of potential threats in the maritime domain. However, the world's oceans are still very large, and having a full and complete knowledge of all the activities occurring on those vast seas is challenging. This thesis addresses some of those challenges by first reviewing the fundamental policies the United States has established regarding MDA. Following that review, this thesis provides background on various commercial space-based capabilities that might contribute to improving MDA, as well as some recent attempts to exploit those space-based capabilities. Finally, it provides recommendations for establishment of an architecture to exploit these capabilities on an operational basis.

A. U.S. MARITIME DOMAIN AWARENESS POLICY

Homeland Security Presidential Directive 13, Maritime Security Policy (HSPD–13), states:

> The United States, in cooperation with our allies and friends around the world and our State, local and private sector partners, will work to ensure that lawful private and public activities in the Maritime Domain are protected against attack and criminal and otherwise unlawful or hostile exploitation. These efforts are critical to global economic stability and growth and are vital to the interests of the United States. (White House, 2004)

HSPD–13 directs a coordinated and collaborative intelligence effort among the departments of Homeland Security, Defense, Justice, and the Director of Central Intelligence that uses existing capabilities to integrate all available intelligence to identify and prevent maritime threats (White House, 2004).

The Department of Homeland Security framed MDA as consisting of accurate information, intelligence, surveillance, and reconnaissance of all vessels, cargo, and people extending well beyond U.S. traditional maritime boundaries. The greatest challenge in securing the maritime domain is the vastness of expanse, the medium by which threats can move, and the "broad array of potential targets that fit the terrorists' operational objectives of achieving mass casualties and inflicting catastrophic economic harm" (United States Department of Homeland Security, 2005 p. 2). Three overarching principles guide the maritime strategy: 1) preserve the freedom of the seas, 2) facilitate and defend commerce, and (3) facilitate the movement of desirable goods and people across U.S. borders while screening out dangerous people and material (White House, 2005). To define this strategy further, The White House's *The National Strategy for Maritime Security* states that MDA consists of the following:

- all areas and things of, on, under, relating to, adjacent to, or bordering on a sea, ocean, or other navigable waterway, including all maritime related activities, infrastructure, people, cargo, and vessels or other conveyances, and
- the effective understanding of anything associated with the maritime domain that could impact the security, safety, economy, or environment of the United States (2005, p. 2).

To guide the maritime security activities of federal agencies and homeland security partners, the strategy also defines four critical objectives:

- Prevent terrorist attacks and criminal or hostile acts
- Protect maritime–related population centers and critical infrastructure
- Minimize damage and expedite recovery
- Safeguard the ocean and its resources (Westling, 2010)

B. CURRENT CAPABILITIES AND PROCEDURES

With MDA being so important to the United States, and such emphasis being placed on it, many branches of the Departments of Defense and Department of Homeland Security have become involved. Though a benefit, this can also lead to duplicating work and multiple efforts. In an effort to stop that from happening, the Secretary of the Navy was directed to be the Executive Agent for the DOD on MDA. The Secretary then went on to lay out a policy that delineated who was responsible for all aspects of MDA (Winter, 2009). MDA is attained through knowledge and, most importantly, being able to display that information to a decision maker in an efficient and timely manner. The Navy currently does this using the Common Operational Picture (COP). The COP is the main picture of all ongoing operations established by gathering information from multiple sources and displaying it in a format useful to operators and decision makers. Within the Navy, for the most part, Global Command and Control System–Maritime (GCCS-M) is used. SPAWAR defines it as a system that provides maritime commanders at all echelons a single, integrated, and scalable Command and Control system. GCCS-M fuses, correlates, filters, maintains, and displays location and attribute information on friendly, hostile, and neutral land, sea, and air forces, and integrates this data with available intelligence and environmental information to support command decisions (SPAWAR, n.d.).

While GCCS-M is the single overall command and control tool for the Navy, with multiple commands and each combatant commander (COCOM) and fleet focusing on their own area of interest, sometimes multiple COP's result. The addition of different units reporting to a MDA cell, with a wide range of available sensors, and various links in which they are participating, can sometimes cause information to become overloaded, or incorrect. Moreover, the numerous strike groups out on operations that will run their own picture, an independent deployer (ship operating on its own) that will run its own and try to gather information from anyone nearby, and finally an exercise COP in place anytime large-scale operations are being conducted, are not even considered. All these operations may be feeding into GCCS, and populating at higher levels, but depending on what is being fed in by multiple units from their multiple pictures, sometimes all the information can result in confusion. The issues of classification, which can mean three or more different pictures being run within one ship, and the feeding up and compounding of information, are also not considered. In this situation, a ground truth type system, one that could provide the exact location of any ship, would be of considerable assistance.

As previously mentioned, classification issues cause COCOMs and Navy Fleets to run multiple pictures at the same time as well. When participating in an exercise with different allies, it is possible a ship will need to use the Combined Enterprise Regional Information Exchange System (CENTRIX) and run an Allied Secret picture. In addition to the standard picture running through GCCS-M on SIPRNET at the Secret level, depending on ship type and resources, a Top Secret version can also be running in appropriate spaces.

CENTRIX is run as different networks around the world with different nets for Central Command, Pacific Command, Japan, or Maritime. CENTRIXS–M is the maritime network. SPAWAR describes it as a C2 communications network developed by the Navy that gives U.S. and allied ships the ability to communicate with each other. Answering one of the highest–priority COCOM requirements, the investment in CENTRIXS–M by the U.S. Navy has provided text chat, email, and voice data over secure channels with allied nations and their forces. CENTRIXS–M forms the network backbone and global infrastructure for coalition and multinational C4I interoperability, and is a key enabler of MDA (Kotner, 2009).

With multiple pictures up and running for even just one ship, duplicate tracks can result as that ship links and sends information to other ships and higher headquarters. As additional ships add their information, what was meant to provide the commander a quick overview picture quickly becomes confusing, especially as the compilation goes to higher command levels. While this work is not meant to be a thesis on data compilation or improvement of COP's throughout the Navy, it does present an issue that can be at least partially addressed by ground truth MDA systems. Satellite data can provide this ground truth. Sometimes, additional inputs to a system only cause more confusion and uncertainty in target location. However, depending on the source, satellite data can provide highly accurate location and identification information in a timely manner which can help clarify the operational picture. Once the data is provided, it only becomes a matter of seamlessly entering that data into the picture or fusing it with current tracks.

Information that is fed into the numerous COPs and GCCS is compiled from a multitude of sources. Each individual ship will have its own sensor tracks from radar, sonar, and visual contacts. Airborne assets, including helicopters and fixed wing, will normally enter a link through their controlling ship or via another aircraft forwarding data back to a ship. All the additional tracks from the aircraft's sensors will be input. Then, tracks and in some cases, placeholders for possible contacts based on intelligence gained from a multiple sources, are added. If data is obtained from any space-based sensors, then these tracks can also be input. Throughout this process, as more and more tracks are gathered from different sensors, then the tracks must be mated up to ensure that only one track for each contact exists, and that all the information available on that track is captured in its meta-data file. This process is very cumbersome, takes significant time and utilizes resources which could be allocated to other purposes.

MDA cells at the higher command levels will also have people assigned that can look through open source material to find ship logs, and port call requests to be able to help tag ships as they move around. That information is available in the public domain.

Additional sources at higher classification levels can be leveraged to compile even more information on contacts but these sources are not addressed in this thesis.

As the U.S. Navy continues to work with more countries in more coalitions, along with multiple U.S. agencies to complete maritime missions, is it essential to find ways to share data with these countries and agencies. To gather completely unclassified data is challenging depending on what sensors are used and in what manner. Thus, at times it can be difficult to provide or share quality data. Many countries want to engage in helping the larger MDA picture. Even those without ocean borders want to be able to understand the movement of vessels and cargo on the seas and the potential threats and hazards that could be riding along. To do so, they would like to be able to obtain relevant data from the United States and provide data when they have it. Thus, the use of unrestricted commercial systems makes sense in MDA.

C. THE ISSUE

Commercial satellite imagery can be purchased by anyone with the available funds by working through a dealer for one of the satellite vendors. The U.S. government has a well-established relationship with many of these companies, and has been using commercial imagery for many uses, especially over land for many years. However, in recent years, satellites have been able to provide data of adequate quality and timeliness down to the operational level to make them appealing for application to the MDA problem. Those that work in the MDA field are always looking for additional support and with satellites being able to offer that ground truth picture, commercial imagery is a field to investigate more.

In recent years, COCOMs have had the ability to request satellite imagery from national assets through the proper channels to obtain data supporting the MDA mission. One significant issue is that as those requests are routed higher and higher up the chain and are aggregated with other imagery requests, not all these needs can be satisfied—only so many images can be taken. With limited satellites and the fact that MDA is normally a lower priority when it comes to U.S. national assets, not all requests are filled. Thus, the commercial world is becoming an option.

Currently, all imagery purchase requests must go through the National Geospatial Intelligence Agency (NGA). This agency has contracts in place with a number of U.S. and foreign commercial electro-optical and radar imagery companies, which are introduced in Chapter II. However, they are also brokering between these companies, and searching their databases for images that may fit a request. While this process may be appropriate for a unit wanting imagery of a compound to be assaulted, where an image from three days before is fine, in the MDA problem set, actionable imagery is required as soon as possible. With ships moving 6–12 knots on average, as latency increases between image taken and data received in the Maritime Operations Center (MOC), ships have moved, but in what direction or at what speed is not always known. Thus, trying to send assets to investigate a target of concern can lead to wasted effort without timely information.

Nevertheless, a great opportunity becomes available. Commercial providers, such as DigitalGlobe and the commercial owners of RADARSAT, MacDonald, Dettwiler and Associates, have stated that MDA represents a sweet spot for changes in the business model (Middour, 2011). Commercial systems are woefully under tasked over water, and commercial companies are eager to sell excess shutter time. Discussions with vendors indicate they are willing to heavily reduce costs, specifically for over water imaging due to different business models and licensing. The wide area coverage capability of certain commercial systems allows for monitoring huge expanses of the Area of Responsibility (AOR), while not tripping operations security (OPSEC) concerns. Imagery ship detections in water allow for rapid conversion from qualitative imagery to quantitative data and direct insertion of that data to a COP (GCCS-M) displayed across the operational command and even to the tactical command level. A significant benefit of this new business model is derived from the notion that not all data needs to cached for historical purposes. By not paying to keep imagery only temporal in value (ship positions in an AOR's water), the cost can be reduced significantly due to decreased licensing constraints currently required for this data storage (Middour, 2011).

There are many complex issues to be addressed before this could fully be a reality, but the first area we should look at is the systems both in terms of overhead and ground systems that area available so we can make proper informed decisions.

II. COMMERCIAL IMAGERY SATELLITES

Many different types of commercial imagery satellites owned by a myriad of different companies are currently on orbit. These satellite systems all possess different capabilities and limitations. This chapter provides a breakdown of the current on orbit assets available and plausible for use by the United States in MDA.

A. ELECTRO-OPTICAL IMAGING SATELLITES

Electro-optical (EO) imaging satellites are digital Earth observation satellites designed to be placed in orbit around Earth, specifically to look down on it and take pictures. The size of the area imaged and the resolution of the picture varies across the different satellites. Some were built to provide wide area coverage to study large land masses, while others were built to obtain a very high resolution close look of a single point target. Thus, a broad spectrum of EO satellites exists, not only in an area versus resolution arena, but also in the type of images they can take. All EO satellites are capable of taking panchromatic (black and white) images, but recently, newer satellites have been capable of multi–spectral imaging to allow the satellite to use multiple bands with–in the electromagnetic spectrum to attain different images. This breakdown gives a description of these systems and some of their important specifications.

For the better part of 15 years, there were two main competing EO supplying companies: DigitalGlobe and GeoEye. These companies had all their own facilities, networks, and satellite constellations. The main business of these companies was selling to the U.S. government, namely the National Geospatial–Intelligence Agency (NGA). Both companies were able to thrive in capital investments (satellite building) and infrastructure upgrades while at the same time getting more public sales lines up and running.

In 2010, the NGA awarded EnhancedView contracts to both GeoEye and its direct competitor DigitalGlobe for a cumulative amount of $7.3 billion over 10 years (Foust 2012). Foust went on to say that this money would be split between the two companies and serve to provide for the purchasing of all needed U.S. government commercial imagery. With this contract, the NGA was also entering into a public/private venture to help finance the next satellite of each company as well, including GeoEye-2 for GeoEye and WorldView-3 for DigitalGlobe (Foust 2012). With the winding down of the wars in Iraq and Afghanistan and due to recent budget cuts across the DOD the NGA was forced to reduce its commercial imagery investment, GeoEye lost their contract in June 2012. Due to the loss of approximately 41% of its expected budget, GeoEye and DigitalGlobe began a merger process almost immediately that fall under the now parent company of DigitalGlobe (Foust 2012). The merger was completed and "Closed" on January 31, 2013 (DigitalGlobe, 2015).

1. IKONOS

IKONOS was the first sub–meter high–resolution commercial imagery satellite in orbit. It was launched in September 1999, originally by GeoEye, and is now owned by DigitalGlobe (DigitalGlobe, 2015). IKONOS started a revolution in what commercial imagery satellites could accomplish and bring to the table. The sub–meter resolution for panchromatic photos was a huge milestone to overcome and allowed the commercial providers to catch the eye of Defense and Intelligence agencies as a possible market. IKONOS, as seen in Figure 1, used an early satellite design and bus structure that was improved upon in later versions, including the incorporation of improved optics.

Figure 1. IKONOS EO Imaging Satellite (from DigitalGlobe, 2015)

Table 1 summarizes IKONOS performance. While it may seem outdated by some of the follow on imagers presented, IKONOS still provides higher resolution images than what some foreign governments can obtain from their systems. Until it ceases operation, IKONOS will be an important part of the DigitalGlobe constellation (DigitalGlobe, 2015).

Table 1. IKONOS Specifications (from DigitalGlobe, 2015)

IKONOS Imaging & Collection Specifications	Imagery			Satellite	
		Panchromatic	*Multispectral*	Swath Width	11.3 km
	Spatial Resolution	.82 meter	3.2 meters	Off-Nadir Imaging	Up to 60 degrees
	Positional Accuracy	15 meter CE90 (specification) 9 meter CE90 (measured)		Dynamic Range	11 bits per pixel
				Mission Life	12+ years
				Revisit Time	Approximately 3 days
	Collection Capacity	240,000 sq km/day (Pan + MSI)		Orbital Altitude	681 km
				Nodal Crossing	10:30 am

2. GeoEye-1

GeoEye-1 was launched in 2008, originally by GeoEye, and is now owned by DigitalGlobe. For over five years, it set the standard for providing the lowest commercially available Ground Sampling Distance (GSD) of any commercial satellite at 0.41 meters, for panchromatic imagery at nadir (DigitalGlobe, 2015). It is also capable of simultaneously acquiring 0.41–meter panchromatic and 1.65–meter multispectral imagery from its ITT Corporation camera, and creating a pan-sharpened image, which effectively provides a multi-spectral image with the resolution of the panchromatic image (DigitalGlobe, 2015). In the past, all imagery sold to non–U.S. government contracts had to be resampled to 0.5–meter resolution with which DigitalGlobe complied. In June of 2014 the U.S. Department of Commerce changed its policy and allowed for companies to apply for a new 0.25-meter black and white GSD and 1-meter color resolution (Ferster, 2014). GeoEye-1, as seen in Figure 2, looks as though it is mounted on its side, in that the solar arrays are mounted to the side of the telescope barrel. It was designed to allow it to gather larger collection sets with reaction wheels. With the follow–on satellite, DigitalGlobe has switched to control moment gyros (CMGs) to allow for quick transitions between targets, and thus, enable higher collection rates while still maintaining high geolocation and pointing accuracy (DigitalGlobe, 2015).

Figure 2. GeoEye-1 (from DigitalGlobe, 2015)

Table 2 summarizes GeoEye-1 performance. Incorporating necessary redundancy to enable a design life of seven years and fuel onboard for 15 years, GeoEye-1 will be able to continue providing imagery for years to come. With an imaging capacity of 700,000 km^2 per day of panchromatic or 350,000 km^2 per day of pan-sharpened multispectral imaging, it has an amazing capability for large area mapping projects (DigitalGlobe, 2015). GeoEye-1 products can be provided to meet a variety of needs, including everything from half–meter Geo and GeoProfessional images, to digital elevation models and digital surface models, to mosaics and feature maps.

Table 2. GeoEye-1 Specifications (from DigitalGlobe, 2015)

GeoEye-1 Imaging & Collection Specifications	Imagery			Satellite	
		Panchromatic	*Multispectral*	Swath Width	15.2 km
	Spatial Resolution	.41 meter	1.65 meters	Off-Nadir Imaging	Up to 60 degrees
	Positional Accuracy	5 meter CE90 (specification) 3 meter CE90 (measured)		Dynamic Range	11 bits per pixel
				Mission Life	Expected > 10 years
				Revisit Time	Less than 3 days
	Collection Capacity	350,000 sq km/day (Pan + MSI)		Orbital Altitude	681 km
				Nodal Crossing	10:30 am

3. GeoEye-2/WorldView-4

GeoEye-2 is the follow-on satellite for the now merged GeoEye Company. It was started under the original EnhancedView contract from NGA. Upon announcement of the merger there was much discussion on what would happen to the GeoEye-2 (EARSC Executive Secretary, 2012). With the development work complete, and production having already begun on GeoEye-2, for an expected launch in mid–2013, production will not stop. From the onset of the merger, questions were in the air since DigitalGlobe was also in the works of its own WorldView-3 with expected launch in 2014 (EARSC Executive Secretary, 2012). After completing the merger, it was announced in February 2013 that the new DigitalGlobe EnhancedView contract with NGA required the WorldView-3 satellite to be placed in orbit due to capabilities discussed later in this section (DigitalGlobe, 2015). Thus, DigitalGlobe made the decision to finish the GeoEye-2 and keep it as a ground spare to meet customer demand or as a replacement for other on-orbit satellites.

When the decision was made in June of 2014 to allow for the lower 0.25-meter GSD from the Commerce department, DigitalGlobe saw what would be a growing need for this new commodity. Knowing they had the GeoEye-2 completed, tested and ready to go with capability now grounded that couldn’t be produced by the rest of its entire constellation, a decision was made. Effective July 31, 2014, the name was officially changed from GeoEye-2 to WorldView-4 (DigitalGlobe, 2015). In order to meet demand from DigitalGlobe’s Direct Access and other commercial customers the launch for WorldView-4 has been accelerated to Mid-2016 (DigitalGlobe, 2015).

When it is launched, WorldView-4 pictured in Figure 3, will be a new top of the line EO bird in terms of GSD. It will allow for DigitalGlobe to take advantage of selling more 0.3-meter images and allow for faster revisit with an additional satellite in the constellation.

Figure 3. GeoEye-2/WorldView-4 (from DigitalGlobe, 2015)

DigitalGlobe has decided to go to control moment gyros on GeoEye-2 to give it more precise and faster slewing, which will allow for higher collection capability to the tune of 600,000 km per day in the pan-sharpened mode. Table 3 shows the expected and targeted performance values as of build time. It has been decided that prior to launch DigitalGlobe will update WorldView-4 to a panchromatic resolution of 0.30-meter and multispectral resolution of 1.20-meters, thus making it the highest resolution of any commercial imaging system (Satellite Imaging Corporation, 2015).

Table 3. Targeted GeoEye-2/WorldView-4 Specifications (from DigitalGlobe, 2015)

GeoEye-2 Attributes & Capabilities	Imagery			Satellite	
		Panchromatic	*Multispectral*	Swath Width	14.5 km
	Spatial Resolution	.34 meter	1.36 meters	Off-Nadir Imaging	Up to 60 degrees
	Positional Accuracy	5 meter CE90 (specification)		Dynamic Range	11 bits per pixel
		3-4 meter CE90 (expected)		Mission Life	Expected > 10 years
	Collection Capacity	600,000 sq km/day (Pan + MSI)		Revisit Time	Approximately 3 days
				Orbital Altitude	681 km
				Nodal Crossing	10:30 am

4. QuickBird

QuickBird, launched in October 2001, was the first satellite launched by the company DigitalGlobe. QuickBird, as shown in Figure 4, offers sub–meter resolution imagery, as well as a multispectral mode. QuickBird offers a .65 meter panchromatic GSD and has a four band multispectral capability (DigitalGlobe, 2015). Even as it aged and was degrading in its orbit, it still offered good performance against the newer satellites, but most important, was that Digital Globe had a constellation of three satellites, and thus, was able to obtain quicker revisits and more opportunities at different scenes, which was important to customers.

Figure 4. QuickBird EO Satellite (from DigitalGlobe, 2015)

As Quickbird degraded in its orbit a decision had to be made as to whether to let it end its life or do something to allow it more time. Thus, DigitalGlobe decided in April 2011 to use a large burn of fuel to raise QuickBird up to an altitude of 482 km to allow it to gradually descend back through its original 450 km altitude in 2013, and continue to be operational until early 2014 (DigitalGlobe, 2015). The burn worked and gave exceptional additional life to QuickBird. Table 4 gives the parameters and additional info from Quickbird's illustrious life. It took its last picture of Port Elizabeth, South Africa and re-entered the earth's atmosphere and burned up on January 27, 2015, ending over 13 years of service. During this time, it took over 636 million square kilometers of high-resolution earth imagery and completed 70,000 trips around the planet (DigitalGlobe, 2015).

Table 4. QuickBird Specifications (after DigitalGlobe, 2015)

Launch Information	Date: October 18, 2001 Launch Vehicle: Delta II Launch Site: SLC–2W, Vandenberg AFB, CA
Mission Life	Decayed in Jan 2015
Spacecraft Size	2400 lbs, 3.04 m (10 ft) in length
	Altitude 482 km
Orbit	Type: Sun–synchronous, 10:00 am descending node Period: 94.2 min.
Sensor Resolution and Spectral Bandwidth	Panchromatic: 65 cm GSD at nadir Black & White: 405–1053 nm Multispectral: 2.62 m GSD at nadir Blue: 430–545 nm Green: 466–620 nm Red: 590–710 nm Near–IR: 715–918 nm
Dynamic Range	11–bits per pixel
Swath Width	Nominal Swath Width: 18.0 km at nadir
Attitude Determination and Control	Type: 3–axis Stabilized Star tracker/IRU/reaction wheels, GPS
Retargeting Agility	Time to slew 200 km: 37 sec
Onboard Storage	128 Gb capacity
Communications	Payload Data: 320 Mbps X-band Housekeeping: X-band from 4,16 and 256 Kbps, 2 Kbps S–band uplink
Revisit Frequency	2.5 days at 1 m GSD or less

(at 40°N Latitude)	5.6 days at 20° off–nadir or less
Metric Accuracy	23 m CE90, 17 m LE90 (without ground control)
Capacity	200,000 km^2 per day

5. WorldView-1

WorldView-1, launched in September 2007 and, as seen in Figure 5, was the first next generation satellite launched by DigitalGlobe. With a GSD of 0.5 meters, it specialized in being solely a panchromatic sensor (DigitalGlobe, 2015). However, as it is equipped with CMGs, it is extremely stable and offers very high rate image collection capability. It offers in–pass stereo capability that can be utilized to generate change detection products. The CMGs offer extremely fast retargeting and a stable imaging platform once in position with speeds two times faster than reaction wheels. For this reason, it can collect 1.3 million km^2 per day of imagery compared to GeoEye-1 with 700,000 km^2 per day. The performance specifications of WorldView-1 follow in Table 5 (DigitalGlobe, 2015).

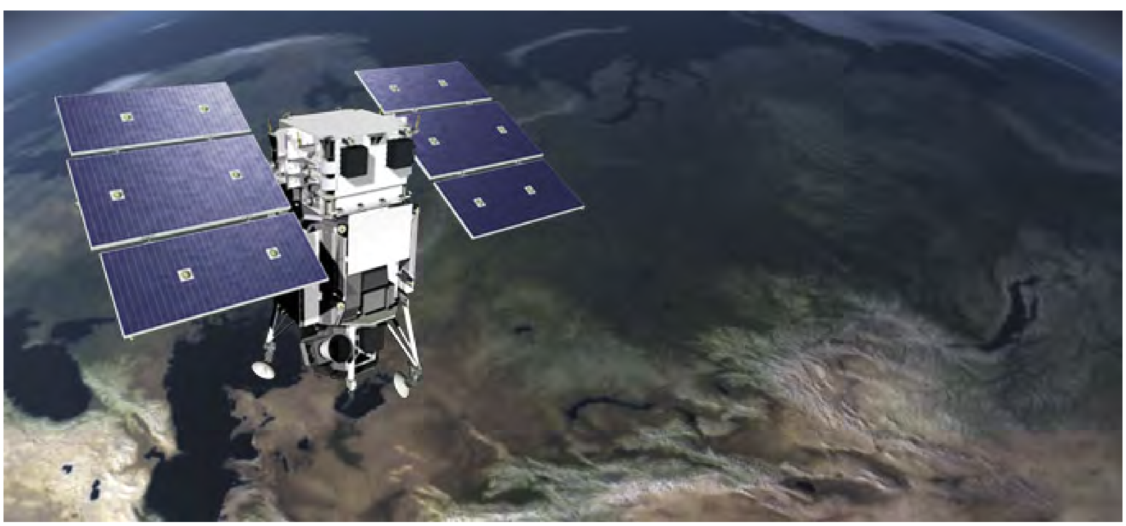

Figure 5. WorldView-1 (from DigitalGlobe, 2015)

Table 5. WorldView-1 Specifications (after DigitalGlobe, 2015)

Launch Information	Date: September 18, 2007 Launch Vehicle: Delta 7920 (9 strap–ons) Launch Site: Vandenberg AFB, California
Orbit	Altitude: 496 km Type: Sun synchronous, 10:30 am descending node Period: 95 min.
Mission Life	10–12 years, including all consumables and degradables (e.g., propellant)
Spacecraft Size, Mass and Power	3.6 m (12 ft) tall x 2.5 m (8 ft) across 7.1 m (23 ft) across deployed solar arrays 2290 kg (5038 lbs) 3.2 kW solar array, 100 Ahr battery
Sensor Bands	Panchromatic: 400–900 nm
Sensor Resolution	50 cm Ground Sample Distance (GSD) at nadir. 55 cm GSD at 20° off–nadir
Dynamic Range	11–bits per pixel
Swath Width	17.7 km at nadir
Attitude Determination and Control	3–axis stabilized Actuators: Control Moment Gyros (CMGs) Sensors: Star trackers, solid state IRU, GPS
Pointing Accuracy and Knowledge	Accuracy: <500 m at image start and stop Knowledge: Supports geolocation accuracy
Retargeting Agility	Time to Slew 200 km: 10 sec
Onboard Storage	2199 Gb solid state with EDAC
Communications	Image and Ancillary Data: 800 Mbps X-band Housekeeping: 4, 16 or 32 kbps real–time, 524 kbps stored, X-band Command: 2 or 64 kbps S–band
Max Contiguous Area Collected in a Single Pass (30° off–nadir angle)	Mono: 111 x 112 km (6 strips) Stereo: 51 x 112 km (3 pairs)

Revisit Frequency (at 40°N Latitude)	1.7 days at 1 m GSD or less 5.4 days at 20° off–nadir or less (0.55 m GSD)
Geolocation Accuracy (CE90)	Demonstrated <4.0 m CE90 without ground control
Capacity	1.3 million km^2 per day

6. WorldView-2

WorldView-2 is the first eight band multispectral commercial EO satellite on orbit (DigitalGlobe, 2015). Launched in 2009, it increased DigitalGlobe on-orbit capability by adding a third satellite to their constellation. When NGA had to reduce funding on its EnhancedView contract, it tested the capabilities of both the DigitalGlobe and GeoEye constellations. DigitalGlobe's three-satellite constellation was determined to be more robust, imaging the same spot of the earth more rapidly, and providing a more diversified sensor capability (EARSC Executive Secretary, 2012). For these reasons, it is speculated that DigitalGlobe captured a larger portion of the continued EnhancedView contract, which would eventually lead to the merger of the two companies under DigitalGlobe (EARSC Executive Secretary, 2012). WorldView-2 was also placed at a much higher altitude of 770 km and yet can obtain 0.46 meter GSD in the panchromatic. With the addition of the four new bands, namely coastal, yellow, red edge and near–IR2, as can be seen in Figure 6 that follows, the multispectral images are more detailed, able to fill in all the spectrum gaps, and permit for detailed exploration into areas these bands cover (DigitalGlobe, 2015).

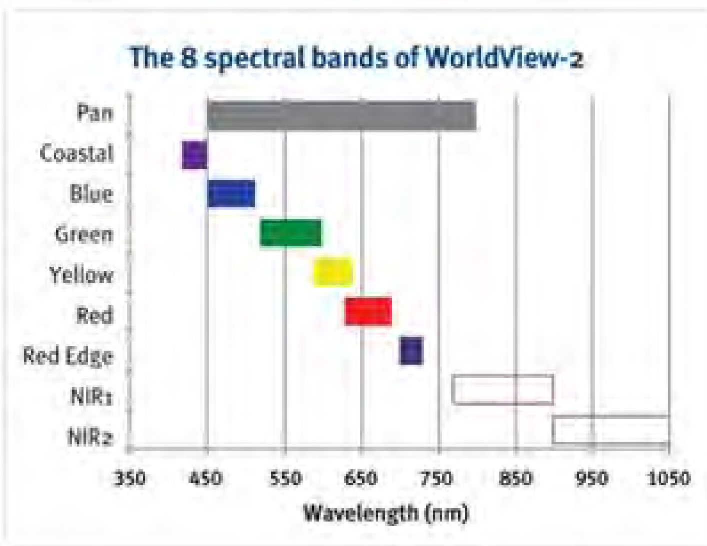

Figure 6. The 8 Spectral Bands of WorldView-2 (from Satellite Imaging Corporation, 2015)

WorldView-2 continued the use of CMGs, which once again allows for very fast retargeting and slewing. With its eight band multispectral imager, it provides robust change detection capabilities, as well as precise mapping and analysis (DigitalGlobe, 2012). Figure 7 shows WorldView-2. While not that noticeably different from WorldView-1, plenty of differences are very clear in Table 6, which shows its specifications.

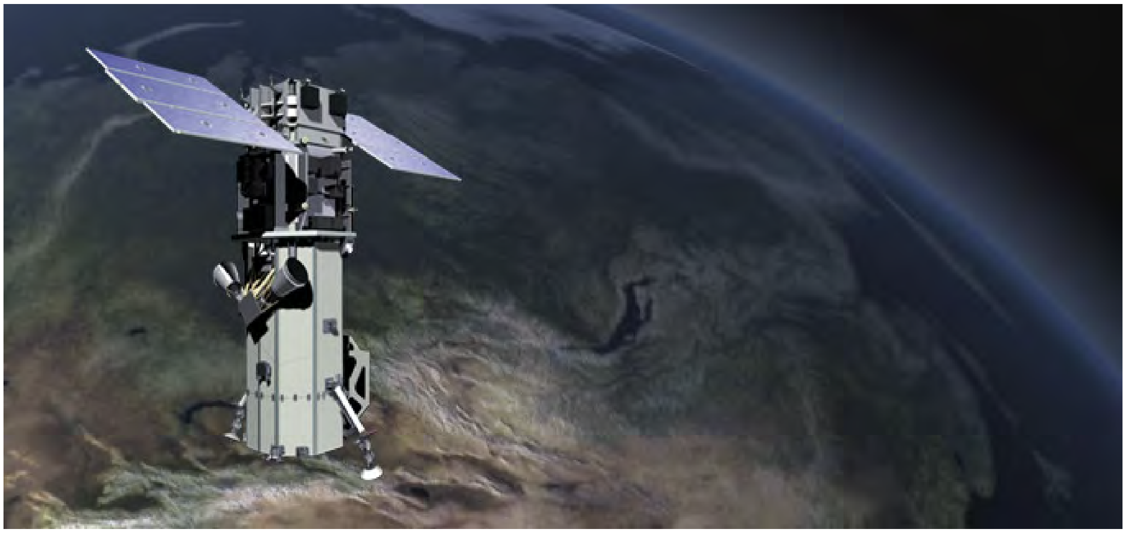

Figure 7. WorldView-2 (from DigitalGlobe, 2015)

Table 6. WorldView-2 Specifications (after DigitalGlobe, 2015)

Launch Information	Date: October 8, 2009 Launch Vehicle: Delta 7920 (9 strap–ons) Launch Site: Vandenberg AFB, California
Orbit	Altitude: 770 km Type: Sun synchronous, 10:30 am descending node Period: 100 min.
Mission Life	10–12 years, including all consumables and degradables (e.g., propellant)
Spacecraft Size, Mass and Power	5.7 m (18.7 ft) tall x 2.5 m (8 ft) across 7.1 m (23 ft) across the deployed solar arrays 2615 kg (5765 lbs) 3.2 kW solar array, 100 Ahr battery
Sensor Bands	Panchromatic: 450–800 nm 8 Multispectral: Coastal: 400–450 nm Blue: 450–510 nm Green: 510–580 nm Yellow: 585–625 nm

	Red: 630 –690 nm Red Edge: 705–745 nm Near–IR1: 770–895 nm Near–IR2: 860–1040 nm
Sensor Resolution	Panchromatic: 0.46 m GSD at nadir, 0.52 m GSD at 20° off–nadir Multispectral: 1.85 m GSD at nadir, 2.07 m GSD at 20° off–nadir
Dynamic Range	11–bits per pixel
Swath Width	16.4 km at nadir
Attitude Determination and Control	3–axis stabilized Actuators: Control Moment Gyros (CMGs) Sensors: Star trackers, solid state IRU, GPS
Pointing Accuracy and Knowledge	Accuracy: <500 m at image start and stop Knowledge: Supports geolocation accuracy
Retargeting Agility	Time to Slew 200 km: 10 sec
Onboard Storage	2199 Gb solid state with EDAC
Communications	Image and Ancillary Data: 800 Mbps X-band Housekeeping: 4, 16 or 32 kbps real–time, 524 kbps stored, X-band Command: 2 or 64 kbps S–band
Max Contiguous Area Collected in a Single Pass (30° off–nadir angle)	Mono: 138 x 112 km (8 strips) Stereo: 63 x 112 km (4 pairs)
Revisit Frequency (at 40°N Latitude)	1.1 days at 1 m GSD or less 3.7 days at 20° off–nadir or less (0.52 m GSD)
Geolocation Accuracy (CE90)	Demonstrated <3.5 m CE90 without ground control
Capacity	1 million km^2 per day

7. WorldView-3

WorldView-3 started as the follow-on satellite for DigitalGlobe under the original EnhancedView contract. As the contract changed, the capabilities of WorldView-3 were one of the reasons that DigitalGlobe was chosen. WorldView-3 will be the first simultaneous, high resolution, super–spectral imagery satellite and will feature a new Short Wave Infrared (SWIR) band that will provide the first ever-commercial space-based infrared sensor (DigitalGlobe, 2015). This capability is important, as it will provide limited penetration of haze, fog, smog, dust, smoke, and mist. The capability of WorldView-3 will allow for products never before available to the commercial world. This capability was essential and a requirement of DigitalGlobe keeping the entire EnhancedView contract. Thus, after the merger this was the main reason that WorldView-3 was launched and the then GeoEye-2 was stored (DigitalGlobe, 2015). Figure 8 shows an artist rendering of WorldView-3.

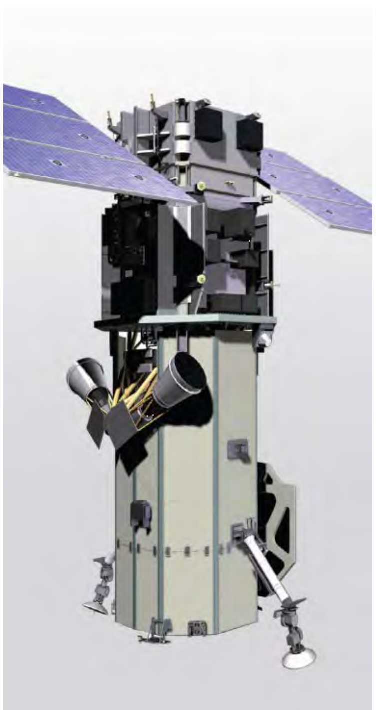

Figure 8. WorldView-3 (from DigitalGlobe, 2015)

WorldView-3 was launched on August 13, 2014 and by August 21 had opened the lens and achieved Initial Operational Capability, giving amazing pictures and new products back to Earth (DigitalGlobe, 2015). After its initial check out period and then starting in February of 2015 DigitalGlobe was able to start selling 0.30-meter resolution images from WorldView-3. Table 7 shows the specifications and amazing capability of WorldView-3 (DigitalGlobe, 2015).

Table 7. WorldView-3 Specifications (after DigitalGlobe, 2015)

Orbit	Altitude: 617 km Type: SunSync, 10:30 am descending Node Period: 97 min.
Life	Spec Mission Life: 7.25 years Estimated Service Life: 10 to 12 years
Spacecraft Size, Mass and Power	Size: 5.7 ms (18.7 ft) tall x 2.5 ms (8 ft) across 7.1 m (23 ft) across deployed solar arrays Mass: 2800 kg (6200 lbs) Power: 3.1 kW solar array, 100 Ahr battery
Sensor Bands	Panchromatic: 450–800 nm 8 Multispectral: Coastal: 400–450 nm Blue: 450–510 nm Green: 510–580 nm Yellow: 585–625 nm Red: 630–690 nm Red Edge: 705–745 nm Near–IR1: 770–895 nm Near–IR2: 860–1040 nm 8 SWIR Bands: SWIR–1: 1195–1225 nm SWIR–2: 1550–1590 nm SWIR–3: 1640–1680 nm SWIR–4: 1710–1750 nm SWIR–5: 2145–2185 nm SWIR–6: 2185–2225 nm SWIR–7: 2235–2285 nm SWIR–8: 2295–2365 nm
Sensor Resolution	Panchromatic Nadir: 0.31 m 20° Off–Nadir: 0.34 m

(or GSD, Ground Sample Distance; off–nadir is geometric mean)	Multispectral Nadir: 1.24 m 20° Off–Nadir: 1.38 m SWIR Nadir: 3.70 m 20° Off–Nadir: 4.10 m
Dynamic Range	11–bits per pixel Pan and MS; 14–bits per pixel SWIR
Swath Width	At nadir: 13.1 km
Attitude Determination and Control	Type: 3–axis Stabilized Actuators: Control Moment Gyros (CMGs) Sensors: Star trackers, precision IRU, GPS
Pointing Accuracy and Knowledge	Accuracy: <500 m at image start/stop Knowledge: Supports geolocation accuracy below
Retargeting Agility	Time to Slew 200 km: 12 sec
Onboard Storage	2199 Gb solid state with EDAC
Communications	Image & Ancillary Data: 800 and 1200 Mbps X-band Housekeeping: 4, 16, 32, or 64 kbps real time, 524 kbps stored, X-band Command: 2 or 64 kbps S–band
Max Contiguous Area Collected in a Single Pass (30° off–nadir angle)	Mono: 66.5 km x 112 km (5 strips) Stereo: 26.6 km x 112 km (2 pairs)
Revisit Frequency (at 40°N Latitude)	1 m GSD: <1.0 day 4.5 days at 20° off–nadir or less
Geolocation Accuracy (CE90)	Predicted <3.5 m CE90 without ground control
Capacity	680,000 km^2 per day

8. Spot 5

While many different companies and their respective countries possess plenty of other EO imaging satellites, one company, SPOT Imaging. Headquartered in France, has played a large role in the commercial satellite provider world because it has direct downlink with some U.S. military terminals and has been contracted by NGA as well (Eilenberger, 2011).

Spot 5 uses a unique stereo pair of imagers to provide a blend between large area mapping and high resolution. As seen in Figure 9, the images can gather swaths next to each other to provide a larger area or overlap one another to decrease the nominal GSD of 5 meters down to 2.5 meters (Astrium, 2012). While even 2.5 meters is much higher than some of the GSD's discussed earlier, it provides a very usable imagery capability, as well as the ability to look at larger areas for products, such as vegetation monitoring. Spot 5 is a follow-on satellite for the Astrium Company from its original Spots 1, 2, 3 and then Spot 4. With Spot 5, new capability was added, namely a High–Resolution Stereoscopic imaging instrument. It is continuing with these venerable satellites with Spots 6 and 7 launched in September 2012 and June 2014 respectively. The 10 year life span on these pushed Spot missions lasting into 2024 (Astrium, 2012). Figure 9 depicts how SPOT-5 uses its stereo imagers, while Table 8 describes performance parameters for SPOT-5.

Figure 9. SPOT 5 (from Astrium, 2012)

Table 8. Spot 5 Specifications (after Astrium, 2012)

Products	Panchromatic: 2.5m, 5m, 10m Multispectral: 2,5 m–5 m–10 m–20 m
Spectral bands	P (panchromatic) ; B1 (green); B2 (red) ;B3 (near infrared) ; B4 (SWIR : short–wave infrared, for SPOT 4 and 5)
Footprint	60 km x 60 km
Revisit interval	2 to 3 days
Tasking	Yes, standard or priority
Global archive	> 20 million images since 1986
Viewing angle	Cross–track : +/– 27° Forward / backward stereo viewing with SPOT 5
Location accuracy	< 30 m (1σ) with Spot 5 Ortho products : < 10 m (1σ) with Reference3D database Otherwise, dependent on quality of ground control points and DEM
Preprocessing levels	1A, 1B, 2A, 2B, Ortho

B. SYNTHETIC APERTURE RADAR (SAR) IMAGING SATELLITES

Synthetic aperture radar (SAR) imaging satellites image using the same principles of radar found on aircraft SAR systems. A very large energy pulse is sent out and reflects off the ground, water, or objects in the scene and returns back to the satellite. From this return, the satellite receiver and associated processor can generate an image. Depending on the transmitted power, reflectivity of the target, and other design aspects of the satellite, the resulting image can range from a resolution of 100 meters down to 2 meters. Sometimes this image has such good resolution it is mistaken for an EO image. Several companies operate a number of SAR satellites on orbit, such as RADARSAT-1 as depicted in Figure 10. Some major satellites used by the NGA and other U.S. government offices for imagery for which the U.S. military has downlink receive capabilities are discussed in the following sections.

1. RADARSAT-1

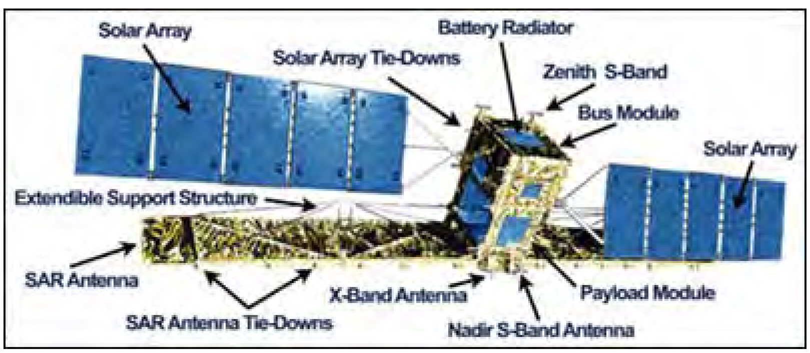

Figure 10. RADARSAT-1 (from Canadian Space Agency, 2006)

As compared to electro-optical satellites, radar satellites were originally not something widely thought of in the commercial world. When the Canadian Space Agency (CSA) decided it wanted to have rights to a radar satellite, it worked with MacDonald, Dettwiler and Associates to create a system to meet its needs and then launched it with enough capacity so that it would be able to sell the extra satellite availability to help cover costs. Thus, RADARSAT-1 was built and launched in November 1995 (Canadian Space Agency 2006). It was the first radar satellite for Canada and the first commercial operationally oriented radar satellite. RADARSAT-1 uses a microwave pulsed radar to image in all weather conditions, including through clouds and fog. It operates in the C–band at 5.3 GHz, and with its capability to change the shape of and steer its beams, it can provide a multitude of different coverage patterns, as well as resolutions (Canadian Space Agency 2006). As Figure 11 depicts, the system can conduct a large area search or focus in on a specific targeted area for higher resolution. Figure 12 shows how selecting a different imaging mode will affect the amount of the Earth covered in one swath. Finally, Table 9 shows what is gained with the swaps between large area and high resolution in a radar system.

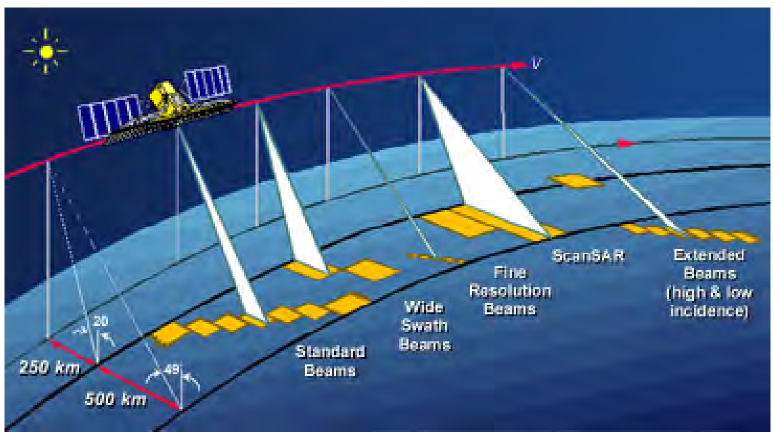

Figure 11. RADARSAT-1 Imaging Modes (from Canadian Space Agency, 2006)

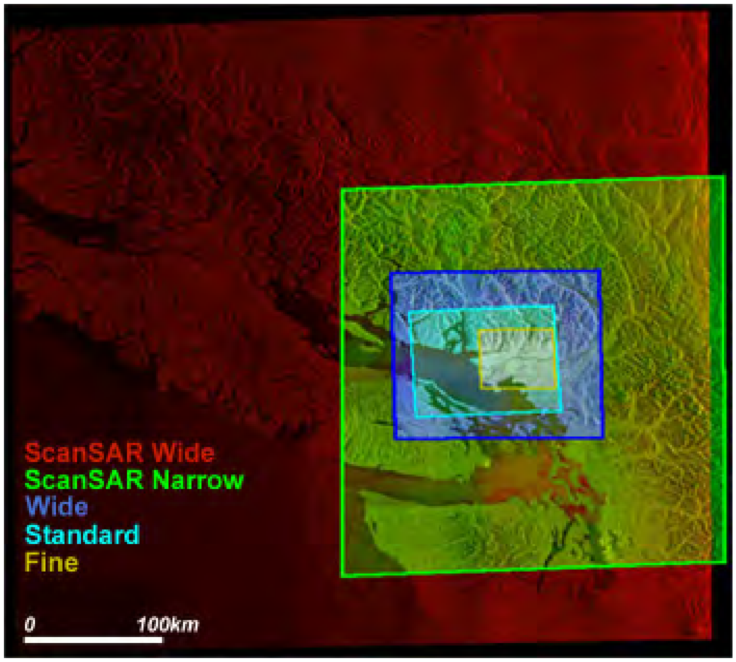

Figure 12. Beam Mode Ground Coverage (from Canadian Space Agency, 2006)

Table 9. RADARSAT-1 Imaging Modes (after Canadian Space Agency, 2006)

Mode	Nominal Resolution (m)	No. of Positions / Beams	Swath Width (km)	Incidence Angles (degrees)
Fine	8	15	45	37–47
Standard	30	7	100	20–49
Wide	30	3	150	20–45
ScanSAR Narrow	50	2	300	20–49
ScanSAR Wide	100	2	500	20–49
Extended high	18–27	3	75	52–58
Extended low	30	1	170	10–22

RADARSAT-1 has another advantage for the maritime domain awareness mission. It has a large number of available ground stations to downlink around the world, and thus, reduce the time between when the image is taken and able to be downlinked, processed and disseminated to the customer. Figure 13 shows the current number of ground stations plus six mobile downlinks that can be moved based on need. RADARSAT-1 is a great asset for open ocean search, as well as for many other uses (Canadian Space Agency 2006).

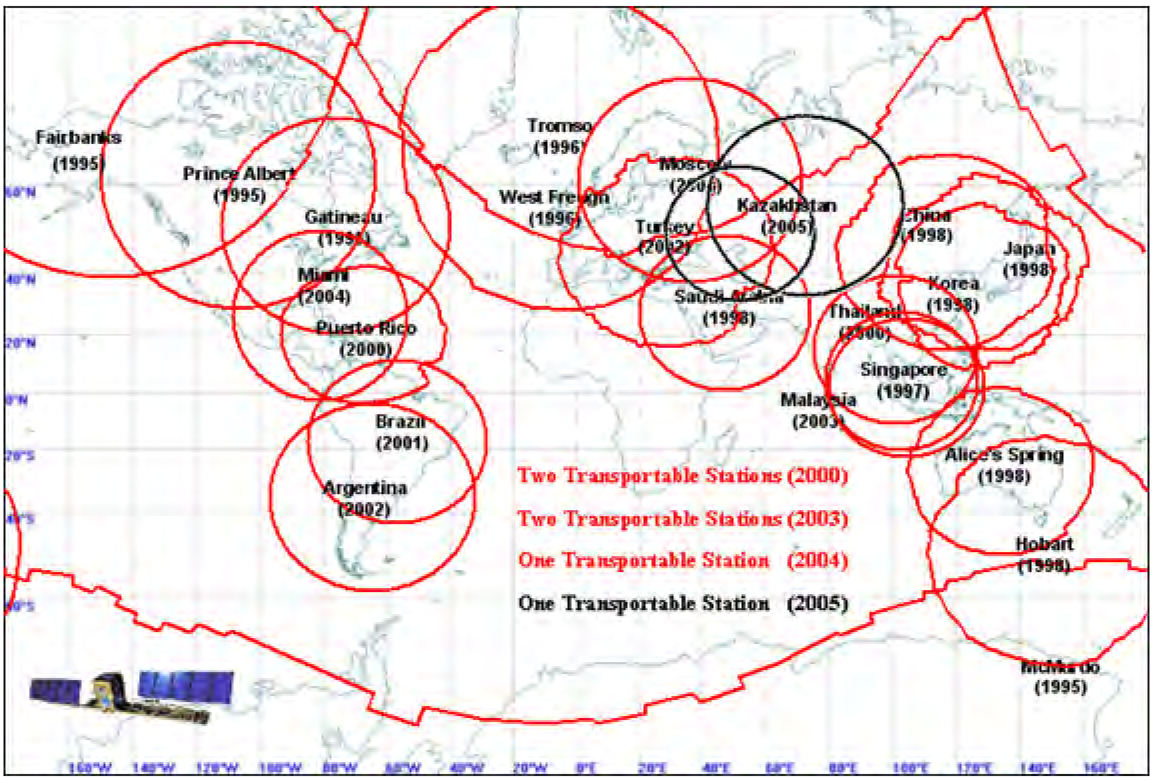

Figure 13. RADARSAT-1 Ground Segment (from Canadian Space Agency, 2006)

2. RADARSAT-2

Following the successes of RADARSAT-1, MacDonald, Dettwiler and Associates improved technology and in December 2007 launched RADARSAT-2 (Canadian Space Agency 2015b). The CSA looked to MacDonald, Dettwiler and Associates once again to leverage one of the most successful public/private partnerships. MacDonald, Dettwiler and Associates owns, built and operates RADARSAT-2, so it is fully commercialized, while the Canadian government helped with the upfront costs and will recoup its investment from radar imagery attained from MacDonald, Dettwiler and Associates (Canadian Space Agency 2015b).

RADARSAT-2 was placed into the exact same orbit and trails RADARSAT-1 to allow for quicker revisit and perfectly aligned follow–up shots that greatly enhance the ability to provide change detection products and support many other applications (Canadian Space Agency 2015b). The RADARSAT-2 design was based on the successful heritage of its predecessor and was improved by adding new imaging modes and the ability to take images from either right or left look angles. CSA determined as RADARSAT-1 only images from the right side, it was determined that RADARSAT-2 should have the capability to move using its reaction wheels to be able to capture right and left looking images to improve revisit times if necessary. The only down side is that it takes 10 minutes to move from one side to the other, and the spacecraft must stabilize before it can resume imaging. However, if the image is needed on the current pass, this maneuver can be accomplished. It also upgraded the SAR transmitter to be able to select polarization from Horizontal (H) or Vertical (V). With 12 different beam patterns, the operator is given a multitude of transmit and receive options to provide the customer the best image possible depending on whether higher resolution, larger image size, or the new Quad–pol image is needed as described in Table 10 (Canadian Space Agency 2015b).

Table 10. RADARSAT-2 Beam Modes
(after Canadian Space Agency, 2015b)

Beam Modes		**Nominal Swath Width (km)**	**Approximate Resolution (m)**
Selective Polarization –Transmit H or V, receive H and/or V	Fine	50	10 x 9
	Standard	100	25 x 28
	Low Incidence	170	40 x 28
	High Incidence	75	20 x 28
	Wide	150	25 x 28
	ScanSAR narrow	300	50 x 50
	ScanSAR wide	500	100 x 100
Polarimetric– Transmit H and V on alternate pulses, receive H and V on any pulse	Fine Quad–pol	25	11 x 9
	Standard Quad–pol	25	25 x 28
Selective Single Polarization– Transmit H or V, receive H or V	Ultra–Fine	20	3 x 3
	Spotlight	18	3 x 1
	Multi–Look Fine	50	11 x 9

RADARSAT 1 and 2 have been huge successes, and with an eye to the future, CSA and MacDonald, Dettwiler and Associates are working on their next venture, RADARSAT Constellation. The three-satellite configuration, that is scalable up to six satellites, will provide complete coverage of Canada's land and oceans offering an average daily revisit, as well as daily access to 95% of the world to Canadian and International users (Canadian Space Agency, 2015a). The mission development began in 2005, with satellite launches planned for 2018. Also ensuring that the first satellite is launched to ensure no datagap is loss before end of life for RADARSAT 2. Table 11 details and shows the similarities and differences between RADARSAT 1, 2, and constellation (Canadian Space Agency, 2015a).

Table 11. Comparison of RADARSAT 1, 2, and Constellation Specifications (after Canadian Space Agency, 2015a)

General	**RADARSAT-1**	**RADARSAT-2**	**Constellation**
High Resolution	8m x 8m (stripmap mode)	1m x 3m (spotlight mode)	1m x 3m (spotlight mode)
SAR Antenna Dim	15m x 1.5m	15m x 1.5m	6.75m x 1.38m
Solar Arrays (each)	2.21m x 1.32m	3.73m x 1.8m	2.2m x 1.7m main power (one panel) 0.5m x 1.6m keep alive power
Bus	3.55m x 2.46m	3.7m x 1.36m	Canadian SmallSat
Look Direction	Right Looking	Routine left– and right–looking operation	Right looking, multiple satellites will eliminate need for left–right to increase revisit.
Radar			
Active Antenna	C–Band	C–Band	C–Band
Center Frequency	5.3 GHz	5.405 GHz	5.405 GHz
Bandwidth	30 MHz	100 MHz	100 MHz
Polarization	HH	HH,VV,HV.VH	HH, VV,HV,VH Compact Polarimetry
Aperture Length	15m	15m	6.75m
Aperture Width	1.1m	1.37m	1.38m
Mass	679 kg	750 kg	400 kg approx..
Peak Power	5 kW	2.3kW	
Orbit	Sun–synchronous		
Altitude	793–821 km	798 km	592.7 km
Inclination	98.6 degrees	98.6 degrees	97.74 degrees
Period	100.7 min	100.7 min	96.4 min
Descending Node	6:00 hrs	6:00 hrs	6:00 hrs

3. TerraSAR-X

In 2002, Germany recognized the advantage of commercial radar satellite capabilities and moved into a similar public/private venture to build a SAR satellite. The German Aerospace Center (DLR), Germany's equivalent of NASA, partnered with

Astrium, a European Aeronautic Defence and Space Company N.V. (EADS) (Fritz& Eineder, 2010). They built and launched TerraSAR-X with DLR maintaining ownership and control of the ground segment while Astrium would hold exclusive rights for the commercialization of the satellite and its imagery. TerraSAR-X was launched in June 2007 and was an immediate success. It utilizes a side looking X-band SAR radar as seen in Figure 14 that provides the ability for both stripmap images, as well as spotlight and ScanSAR (Fritz& Eineder, 2010).

Figure 14. TerraSAR-X (from Astrium, 2012)

In June 2010, TanDEM–X was launched. It is an exact twin of TerraSAR-X and it flies in formation a few hundred meters away from its twin to image at off angles and provide 3D imaging for high resolution mapping products (Fritz& Eineder, 2010). If the 3D mapping is not needed, then additional imaging can occur from TanDEM–X. TerraSAR-X has many of the same imaging modes as discussed with the RADARSAT satellites. Figure 15 shows these modes. Table 12 provides the specification of TerraSAR-X for a good comparison to the RADARSAT family.

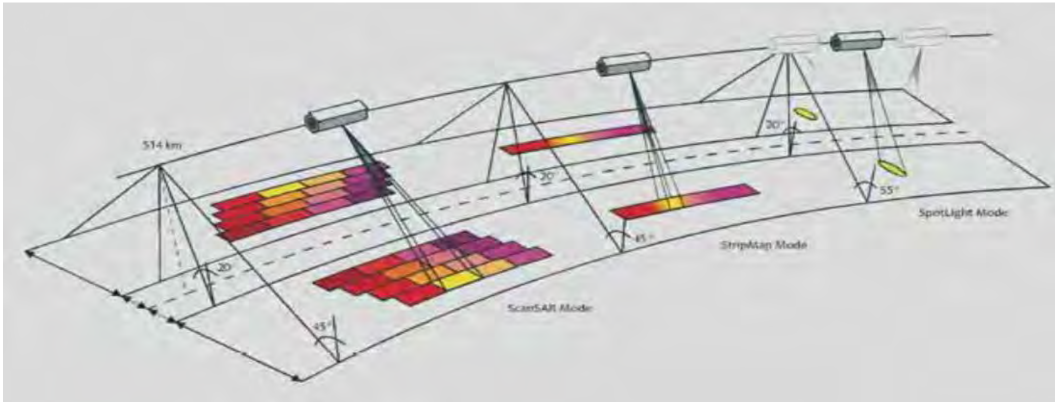

Figure 15. TerraSAR-X Imaging Modes (from Fritz & Eineder, 2010)

Table 12. TerraSAR-X Specifications (after Fritz & Eineder, 2010)

Orbit and Attitude Parameters	
Nominal orbit height at the equator	514 km
Orbits / day	15.182
Revisit time (orbit repeat cycle)	11 days
Inclination	97.44°
Ascending node equatorial crossing time	18:00 ± 0.25 h (local time)
Attitude steering	"Total Zero Doppler Steering"
System Parameters	
Radar carrier Frequency	9.65 GHz X-band
Radiated RF Peak Power	2 kW
Incidence angle range for stripmap / ScanSAR	20°–45° full performance (15°–60° accessible)
Polarizations	HH, VH, HV, VV
Antenna length	4.8m
Nominal look direction	Right
Antenna Width	0.7m
Number of stripmap / ScanSAR elevation beams	12 (full performance range) 27 (access range)
Number of spotlight elevation beams	91 (full performance range) 122 (access range)
Number of spotlight azimuth beams	229
Incidence angle range for spotlight modes	20°–55° full performance (15°–60° accessible)
Pulse Repetition Frequency (PRF)	2.0 kHz–6.5 kHz
Range Bandwidth	Max. 150 MHz (300 MHz experimental)

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III. GROUND SYSTEMS

All the aforementioned commercial satellites, as with all satellites, have at least one ground station. Most have entire ground system architectures with multiple downlink and uplink stations, as well as different networks for connection to all their systems. Most of the ground sites used for uplink and downlink are owned by the parent company. Sometimes a separate company will own the ground station, however, and lease time to satellite companies to allow more coverage or more chances of linking with their satellites. Such a network allows each company to control its spacecraft separately, as well as pull down the data or images collected and retask it for future orbits. Without a ground architecture with the capability to downlink data and send future commands to spacecraft, all the satellites on orbit provide no benefit. This being said, the military has its own ground networks for its specific satellites but they typically do not talk to or have linking capability with the commercial satellites. Thus, for a COCOM to be able to downlink data and imagery directly, if desired, it would have to possess its own downlink reception sites within its control. While it can wait for the imagery to come back from the multiple companies it deals with, this adds time to the equation vice having a downlink in theater and performing the processing locally. This need for direct downlink receive systems that interact with commercial satellites is one of the problems moving forward and some solutions are reviewed.

A. EAGLE VISION

In 1992, the Air Staff conceived an idea to create a direct downlink receive capability that would operate as a COCOM asset and provide the downlink data connectivity for commercial satellites to improve the timeliness of imagery delivery to customers (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010). In dealing with the NGA, the process is request, requirement validation, vendor tasking, and vendor delivery to NGA, and next, NGA delivery to the customer. In contrast, when utilizing a direct downlink, data is delivered directly to the customer for immediate exploitation. Thus, an experimental system was derived called Eagle Vision. Eagle Vision 1 was rolled out and operational by 1995. Another five were produced over the following years for a total of six. As of 2015, five are still operational. Eagle Vision was originally funded by the Air Staff and has never become a program of record. In other words, it does not have a specific funding line, training program, maintenance and upkeep budget or any of the other benefits afforded programs of record. Both active Air Force units as well as Air National Guard units man Eagle Vision. The capabilities of the system have been used with positive outcome in many demonstrations, as well as many deployments for operational use including during disaster relief efforts. Although it has never become a program of record, it continues to be used extensively, and has garnished support both in Congress, as well as by many top military leaders (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010).

Five Eagle Visions are currently in use (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010). The same report states that Eagle Vision 1 is stationed in Ramstein, Germany, is operated by the 24th Intelligence Squadron, and is the only active duty Air Force unit. While deployed in the EUCOM AOR, it is not specifically a EUCOM asset. Eagle Vision 2 was operated by the Army Space and Missile Defense Command and is now non–operational. Eagle Vision 3 is based out of San Diego, California and is operated by the 147th Combat Communications Squadron of the California Air National Guard. Eagle Vision 4 is stationed in McEntire, SC and is operated by the 169th Communications Flight of the South Carolina Air National Guard. Eagle Vision 5 is stationed at Hickam AFB, HI and is operated by the 293rd Combat Communications Squadron of the Hawaii Air National Guard. Finally, Eagle Vision 6 is stationed in Huntsville, AL and is operated by the 232nd Combat Communications Squadron of the Alabama Air National Guard.

These five operational Eagle Vision units are comprised of the same equipment (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010). As certain units have more money pushed their way, they may have more processors for exploiting data, and depending on which commercial providers those specific Eagle Vision units are dealing with, they may have updated downlink capability for certain spacecraft vice others. All have a minimum baseline of interoperability with a specific number of satellites. Other units have gained additional satellite link capability due to specific testing or events in which they participated. Eagle Vision utilizes an X-band downlink to receive data from commercial satellites.

Each Eagle Vision was designed as a fly away asset to be sent out for use at the COCOM level and to enable the given COCOM to be able to locate the system where it made the most sense for satellite visibility (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010). Thus, the entire system is broken down into segments and can be transported via either two C–130Hs or one larger aircraft. It is comprised of a data acquisition segment, the large 5.2 meter satellite dish on a portable trailer, and a 20-foot trailer that houses the Commercial Image Processing System seen in Figure 16, which provides the specific processors for each individual satellite that ingest the raw data and convert it into usable data. The Data Integration Segment, as seen in Figure 17, is comprised of six Windows–based Image workstations and four large format printers that need to be housed in some facility or brought in a trailer when operated out of garrison. Dissemination is handled through satellite communications via a USC–60A for a .mil connection and commercial SATCOM systems for commercial Internet production. The USC–60A is seen on the right in Figure 18 while a general commercial SATCOM dish is on the left. Generators and Environmental Control Units are also required for running all operations (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010).

Figure 16. Eagle Vision Data Acquisition Segment (from Deputy Chief of Staff USAF, ISR Innovations Directorate, 2010)

Figure 17. Eagle Vision Data Integration Segment (from Deputy Chief of Staff USAF, ISR Innovations Directorate, 2010)

Figure 18. Eagle Vision Satellite Communications (from Deputy Chief of Staff USAF, ISR Innovations Directorate, 2010)

Eagle Vision satisfies the minimum requirements for which it was designed, i.e., to provide a transportable downlink capability. However, since it is not a program of record, it does not have consistent manning, training, or funding across the five operational units (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010). Manning issues due to the end strength numbers of individual Air National Guard units mean that one unit may deploy with different capabilities than another unit. The funding and updating of equipment is also different for each unit. For example, if one unit was used in a specific operational demonstration, it may have received additional funding to upgrade servers, or was outfitted with processors for a specific satellite downlink. However, since no program office exists to track these changes or to ensure other units are maintained to the same level, as a customer, it is not possible to know the exact composition of a unit received for a mission. Also, while they have been utilized for fly away deployments, disaster relief has been a main focus. With National Guard units and different funding appropriation types involved, it can sometimes be hard to move different units around at will. Also, while compact and transportable in comparison to some ground stations, the 5.2 meter dish is quite large and with its entire footprint, it is not something that can be randomly picked up and moved. With its size constraints for aircraft, dedicated flights are necessary, using large aircraft which have specific runway length and surface constraints. Next, multiple trucks and equipment must be transported from the air facility to the specific operating location. Therefore, the choice of locations to deploy the system becomes limited. While the 5.2-meter dish is suited for allowing a large satellite view area or mask, as well as being able to close links with older satellites that have less transmit power, it is very large. As technology has improved, satellites have increased transmitter power to allow for smaller dishes on the ground. Recently, RADARSAT-2 stated that it could easily close with anything three meters and larger. Thus, with the COCOMs' desire for more capable assets that can stay in theater or be more easily transported, they are looking for both commercial systems they can easily purchase on their own, or for a future program of record, such as the capabilities of the Army Remote Ground Terminal discussed next (Deputy Chief of Staff USAF, ISR Innovations Directorate 2010).

B. FUTURE SYSTEMS FOR COCOM USE

(1) Army Remote Ground Terminal

The U.S. Army Corps of Engineers at the turn of the century saw how well direct downlinks were helping with commercial imagery sharing between coalition forces. The Army Geospatial Center set out to create a fully supported smaller version of Eagle Vision (Jank, 2011). It started with a demonstration product, the Remote Ground Terminal (RGT). This system leverages numerous lessons learned from the Eagle Vision system, and with new technology and faster processors, it has a much smaller footprint. It utilizes a smaller 2.4-meter trailer mounted direct downlink dish as seen in Figure 19, and is helicopter sling rated for transport vice requiring a dedicated aircraft. The Common Commercial Imagery Processor pictured in Figure 20 is able to exploit the data downlinked from a given satellite and produce usable data (Jank, 2011).

Figure 19. Remote Ground Terminal Downlink Dish (from Jank, 2011)

Figure 20. Commercial Common Imagery Processor in Four Transit Cases (from Jank, 2011)

Currently, downlink reception and processing capability exists for WorldView 1 and 2, GeoEye 1 and RADARSAT-2, with capacity for TerraSAR-X being finalized (Jank, 2011). Jank explains further that this equipment fits into four large transit cases, and one portable workstation. Transportability was a key area for the Army. After being unhooked from a tow vehicle, the transit cases are opened, which in turn, are the operating housings as well. Once power is applied and cable connections between the cases and dish are made, the system is ready for downlink. As further testing is completed and the system moves toward an operational capability, it will become part of the program called Distributed Common Ground System–Army (DCGS-A). This system offers huge possibilities for the future. COCOM staffs and Navy Fleets will be able to utilize this downlink capability as needed for MDA. The future of the DCGS system and its capabilities are discussed in Chapter VI (Jank, 2011).

(2) Commercial Systems

Commercial vendors are also producing smaller and more capable satellite communications dishes. Depending on the power transmitted from the satellite, which is increasing with newer satellites, it is possible to downlink with man–portable size dishes. While this may seem like only an issue for ground operating troops, antenna size carries over to those working with MDA. On ships, space is always at a premium, and trying to put another dish on the super structure of a ship would not only cause issues with actual space but also create signal interference issues. If a ship had a portable dish capable of receiving downlinked imagery, it could store this dish out of the elements and set it up only when needed, thus prolonging antenna life. If a ship was operating in a totally silent EMCON environment, or a degraded SATCOM environment as is possible in future conflicts, then the ship could employ its own commercial downlink for MDA purposes. To make this reasonable, it would have to be a fairly easy to operate, plug and play system, as well as small enough to break down and store. With possible future conflicts being fought in congested straights and waterways, a Special Operations team could set up ashore to monitor vessels travelling through a particular area. If a transportable dish was available to receive downlink from an imagery satellite they would then be in a position to investigate or strike on different profiles depicted by the current MDA picture. With no known acquisition programs looking at these small X-band downlink dishes, it makes sense to look at what commercial vendors have available.

As an example, Rockwell Collins manufactures a multitude of satellite dish systems. Its SWE-DISH CCT200 Fly Away fits the void described in the scenarios above. It features a 2.0 x 1.4 meter Gregorian offset antenna, shown in Figure 21. With multiple plug and play options for different modems and processing equipment, and the flexibility to operate in different bands, including X-band, it offers many of the desired capabilities. Being that it is a smaller dish with a compact footprint, it will have a slower downlink data rate capability. With the entire antenna and equipment contained within four cases capable of being carried by two individuals, this antenna system is a possibility for certain future operations (Rockwell Collins, 2012).

Figure 21. Rockwell Collins SWE-DISH CCT200
(from Rockwell Collins, 2012)

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IV. RADIANT POLARIS

A. RANDOM BEGINNING

Imagine if a ship got underway in the middle of the night from a port in Africa, and U.S. Naval Forces in the region had a critical need to know the whereabouts of this particular ship, yet unfortunately, it had slipped away and now needed to be relocated. The process may go something like this: The Commander, U.S. Naval Forces Europe-Africa (NAVEUR-NAVAF) would call his staff together and direct them to find the ship immediately. Unfortunately, after a few hours, it may still not be found using the traditional resources available for such a search. Then several members of the staff might recall that personnel in the U.S. Sixth Fleet MDA shop had been discussing how they could use radar satellites to find ships at sea and how that could help with MDA. Therefore, the NAVEUR-NAVAF staff members could ask the MDA shop if they could find a ship on the African coast that left in the middle of the night. The Sixth Fleet MDA shop subsequently would be able to arrange tasking via NGA for RADARSAT to cover the area of interest. Employing the RADARSAT wide field of view capabilities, NGA could be able to provide that image as requested in a short period of time. The imagery could be sent immediately to Sixth Fleet, and by overlaying and fusing multiple layers of GCCS and sensor data from all classification levels, it could be possible to find the designated ship operating under complete RF Emissions Control (EMCON).

A situation like this would provide a much needed springboard, for radar satellite's to really get into the fight for MDA, and allow for commercial space use within the military COCOM level of use.

B. MDA FROM COMMERCIAL SPACE

In 2009, Sixth Fleet decided to run an experiment utilizing commercial imagery assets to conduct MDA in the Mediterranean. Initially, the N3 (operations) shop and Maritime Operations Center (MOC) at Sixth Fleet, under direction of its MDA and Space Operations Officer, was able to work directly with multiple commercial vendors to design a streamlined sharing process that cut latency issues for delivery of imagery down to between 30–90 minutes. This process generated a substantial amount of overhead imagery-derived data for injection into the Sixth Fleet COP. In particular, radar data injected directly into the common operational picture in near real time provided a new level of ground truth for comparison to other data sets.

Based on this continued success, planning was conducted for an operational demonstration, named Radiant Polaris, of the direct downlink capability coupled with scheduling control and on–site processing. An Eagle Vision system was flown into Cape Verde. During this time, the U.S. Coast Guard (USCG) Cutter Legare was on station and working with the Sierra Leone, Senegal, and Cape Verde Coast Guards on maritime law enforcement. This environment provided an opportunity to demonstrate the capability and share ability of the products being created and the unclassified COP. Eagle Vision was able to provide downlink and processing of RADARSAT-2 and SPOT data. Eagle Vision operators tasked and received RADARSAT-2 passes every day as the satellite flew overhead at 6:00 am. This data provided ground truth for the location of all shipping within the satellite field of view. As seen in Figure 22, all the red circles are radar detections around Cape Verde. Once the data was downlinked, it would take between 25–55 minutes to have it input into the GCCS COP, with a final report from the imagery analysts within 90 minutes. This near real time information provided excellent over the horizon cuing of vessels in the area (Schgallis, 2010).

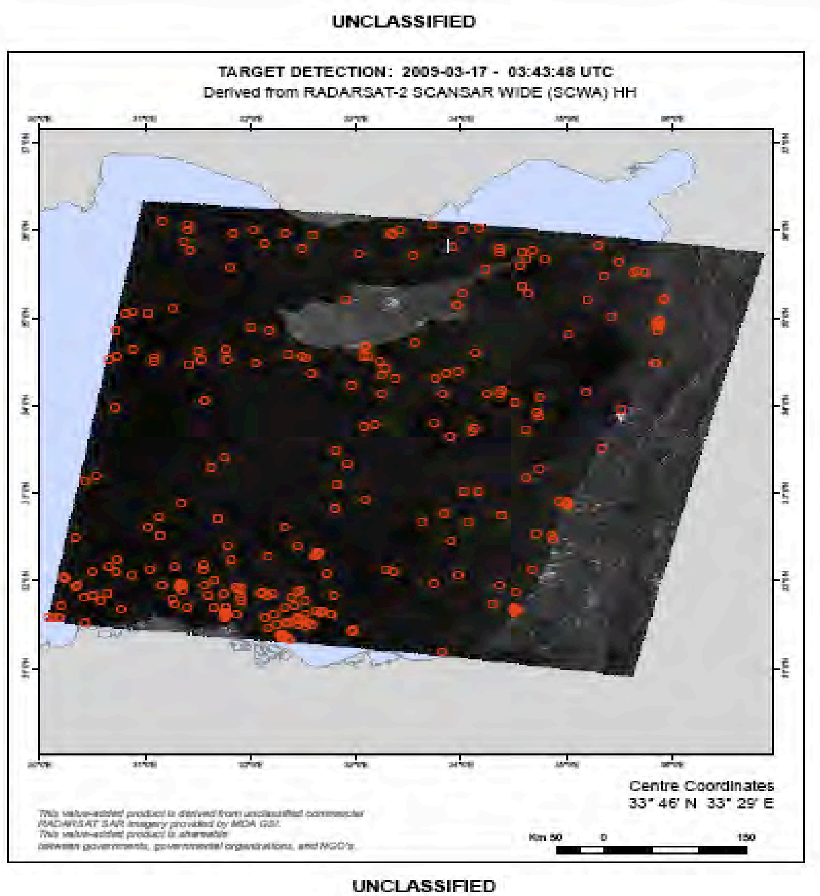

Figure 22. RADARSAT-2 Image with Ship Detection Algorithm Run (from Schgallis, 2010)

After the ground truth radar returns were analyzed, the Sixth Fleet MOC would fuse commercial Automated Identification System (AIS) data with the plots. AIS is a VHF transmission sent by a ship that provides identification and other information about the ship including position, course, speed, next port of call and last port of call. Additional information, such as vessel ownership, flagged country, draft, cargo, even contact phone numbers for satellite telephones, can be included. The IMO regulation requires AIS to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size. The requirement became effective for all ships by 31 December 2004 ("AIS transponders," 2003). However, many smaller vessels also utilize it as the information broadcast is gathered by all vessels in the area and allows for enhanced situational awareness, especially in collision avoidance. Some ports require it for entry of even smaller ships. This AIS signal can be collected by land stations or from receivers on certain satellites, like those from companies such as exactEarth, ORBCOMM, and Spacequest. Once the AIS data is overlaid on top of the radar returns, then it is possible to look for unidentified targets. The next step is to try to determine if those vessels are either small vessels not required to carry or operate AIS, if the ships are required to carry AIS but the systems are not functioning properly, or if the ships are what are called dark targets. These ships are not radiating anything at all in an effort to remain unobserved, trying to stay in the dark, and move about to where they want to go. With this knowledge and current operational picture in front of a commander, the proper orders can now be issued for how to go about using resources most effectively. As can be seen in Figure 23, the red circles are the radar detections, while the overlaid green dots are AIS returns. When red circles appear with no matching AIS information, the staff focuses its attention on ascertaining the identity of that ship (Schgallis, 2010).

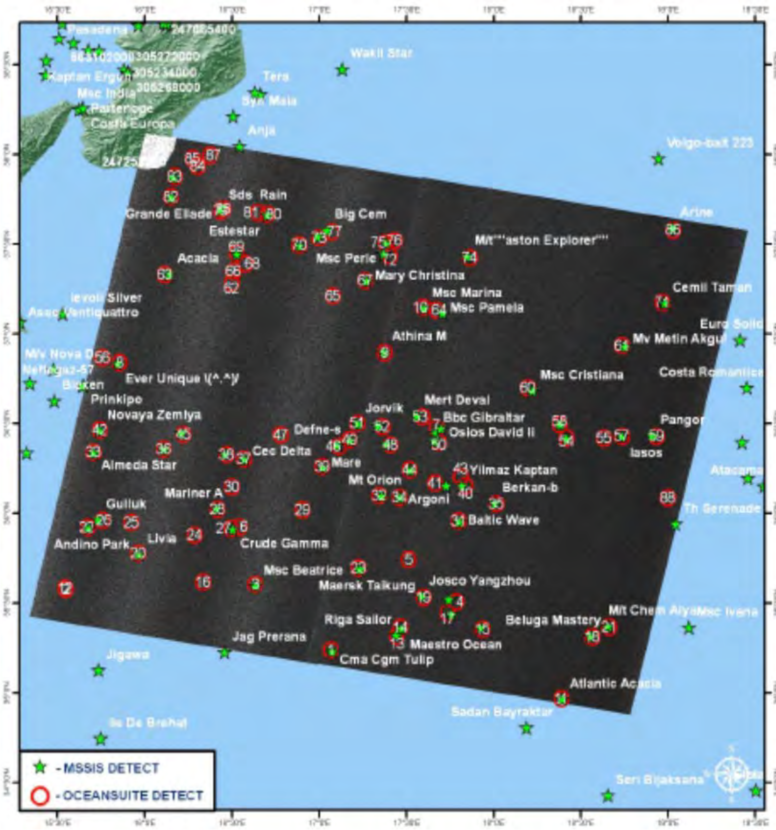

Figure 23. Radar Imagery Overlaid With AIS Detections (from Schgallis, 2010)

To help with determining the size of vessels, and even their intent, which is one of the greatest challenges for a commander, radar imagery can help. Imagery can provide relative vessel scales, assist with ship typing and classification, provide approximate length, and even help determine course and speed from wake detection. Figure 24 displays multiple satellite images chipped out to show how what appears to be a blurry image can actually give the analyst added information to help classify ships, even those not large enough to require AIS. If a ship's AIS states that its course is 180 degrees due south but from imagery it is possible to see its wake and it is actually headed 000 degree due north, then that ship may warrant further investigation.

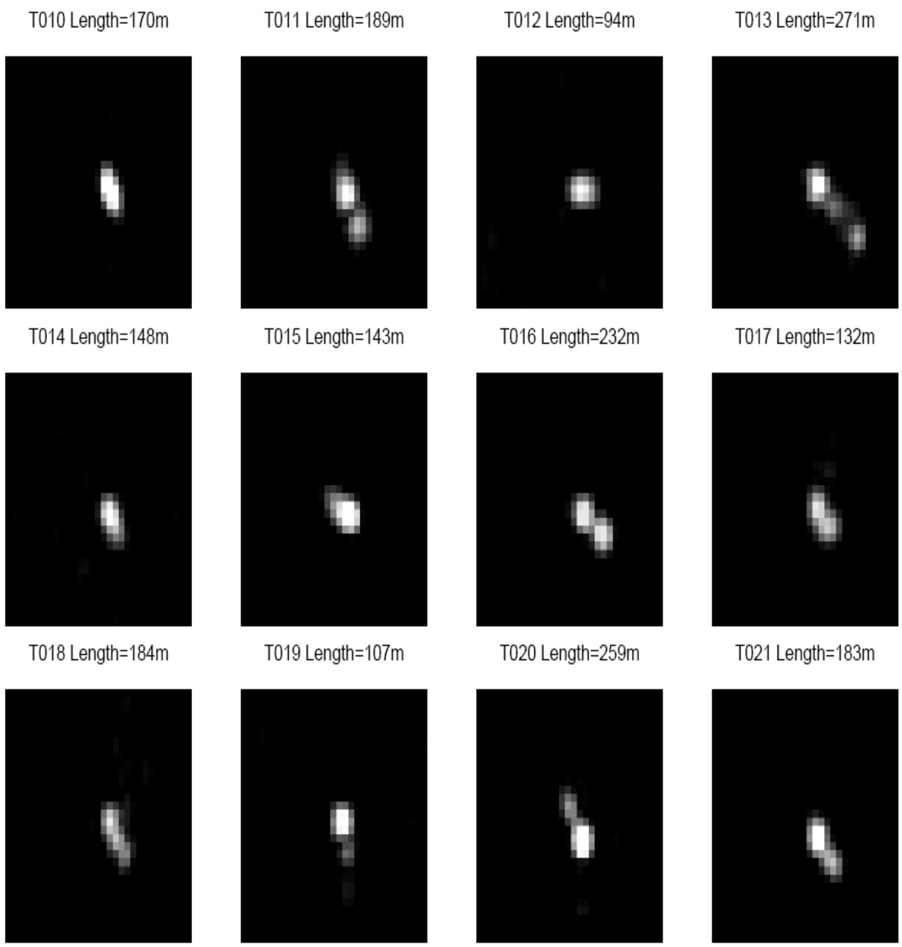

Figure 24. Chipped Out Radar Returns of Ships That Help Classify (from Schgallis, 2010)

With information being directly input into GCCS during this exercise via Over the Horizon–Gold (OTH-G) messages, the commander could see the entire maritime target set, allowing for better use of resources. OTH-G messages are specially formatted messages that are machine readable and utilized with the GCCS system. This allow for automated system or human typed messages to be automatically fed into one server, and populated on screen as tracks with appropriate symbols and data attached, which permits a better use of resources. Figure 25 shows an OTH-G message that was injected to help create the GCCS-M picture also displayed. The added information seen in the RMKS section of the OTH-G message will be populated into the RMKS section of the appropriate track and is accessible to the operator by clicking on the track symbol.

During the Radiant Polaris exercise, only the USCG cutter was available for tasking. Therefore, priority was given to prosecute the targets of interest within the cutter's range. Depending on available resources, potential exists for execution of a more complex scenario. For instance, based on the GCCS picture in Figure 25, the commander could task the USCG Cutter to prosecute the nearest targets, send the cutter's organic helicopter to identify two of the more distant targets, and then use a land-based Maritime Patrol Aircraft to view the larger group near the island. This would enable the commander to utilize the available resources in the most effective manner to fully cover the AOR vice arbitrarily tasking the assets with the hope of finding a target of interest.

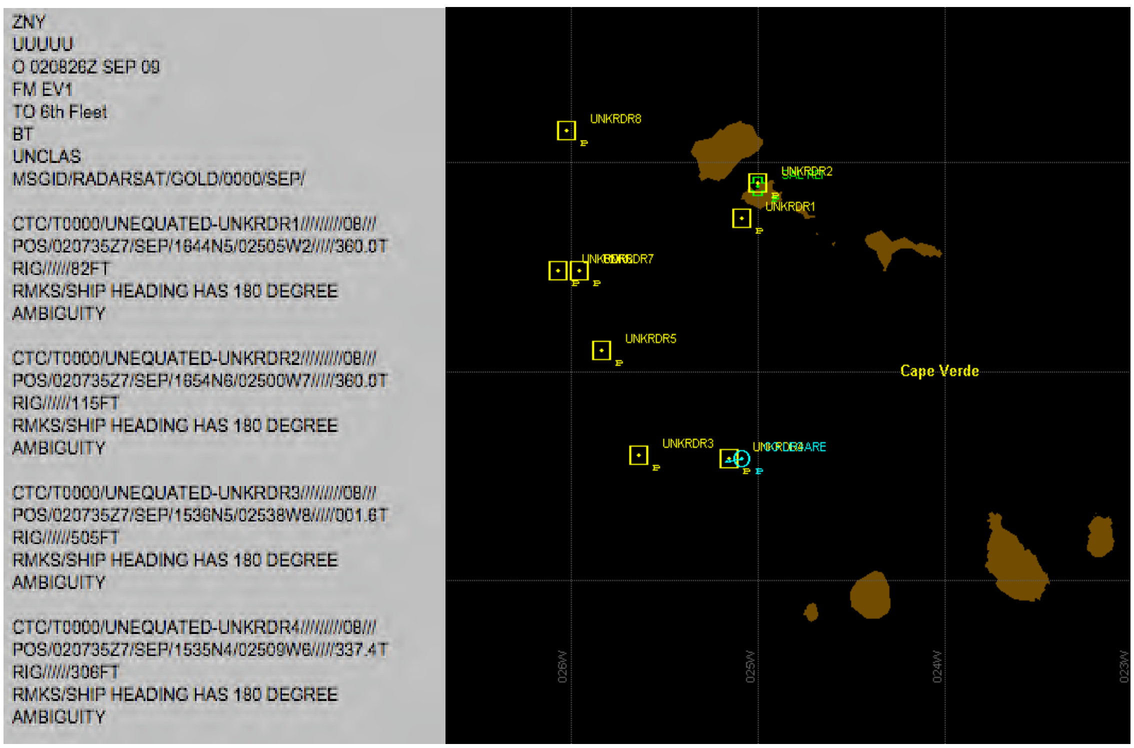

Figure 25. GCCS-M View During Radiant Polaris with Associated OTH-G Message (from Schgallis, 2010)

The architecture utilized during Radiant Polaris, as shown in Figure 26, was fairly straightforward and allowed for timely use of the radar data. It allowed for effective flow of information between all the key players and enabled all the data and displays to be maintained at the unclassified level, thus facilitating sharing with multi–national training partners (Schgallis, 2010).

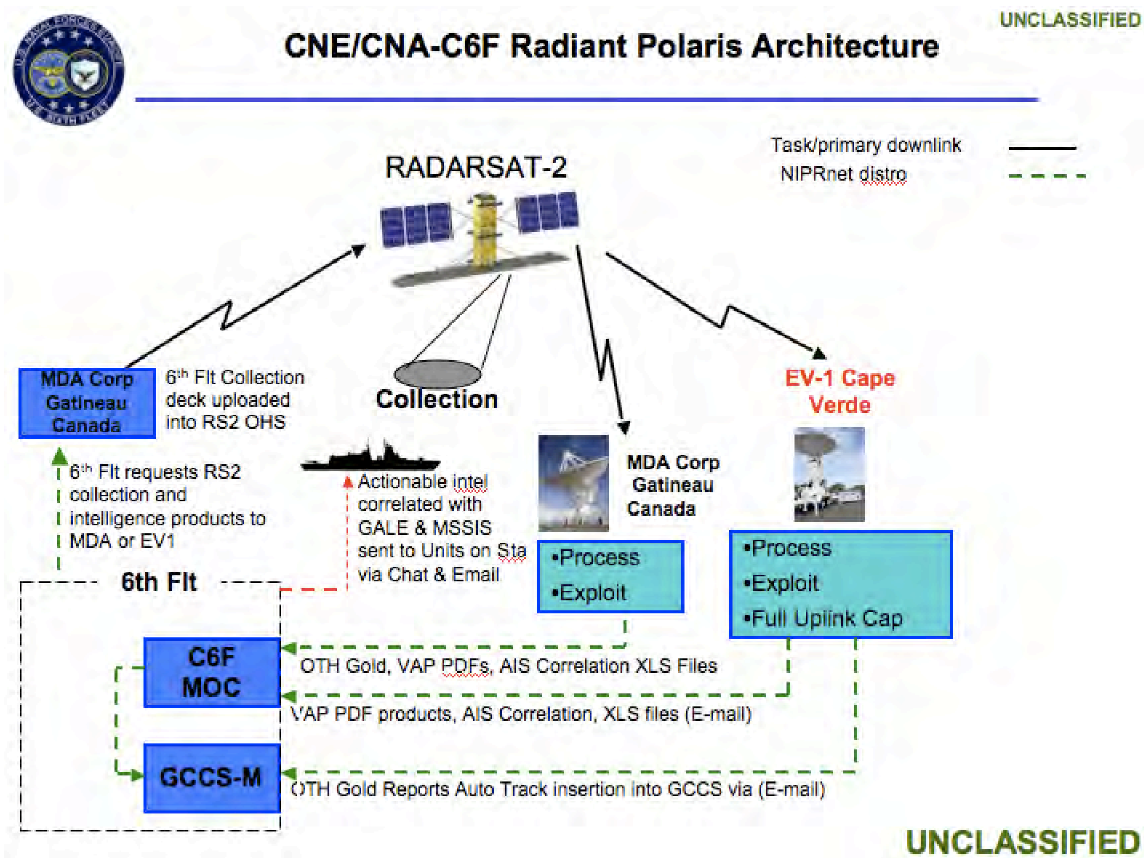

Figure 26. CNE/CAN-C6F Radiant Polaris Architecture (from Schgallis, 2010)

C. CONCLUSIONS AND OBSERVATIONS

Radiant Polaris was a success for Sixth Fleet, MDA organizations, and the commercial space-based remote sensing industry. Admiral Fitzgerald, Commander, U.S. Naval Forces Europe during 2010, stated, "the key enabler for the operational commander is the ability to task for products and receive them directly" (Middour, 2011). Moreover, specifically, Radiant Polaris "enabled us to obtain an operationally useful product in the required timeframe."

Once Sixth Fleet operators decided they wanted this direct downlink capability to support their MDA efforts, they worked with NGA to ensure the correct procedures were followed. The NGA's commercial imagery program worked with all parties involved to create a working template for this venture. After coordination, a special arrangement was made for Sixth Fleet to allow it to work directly with the commercial satellite vendors.

Sixth Fleet has a large area of the maritime domain for which it is responsible. As imagery from national systems is a limited commodity, commercial overhead remote sensing systems can be a valuable source of additional data (Middour, 2011). It also must deal with a large number of allies, especially in its African partnership missions. Since these nations are going to benefit the most from the ability of the United States to share imagery, this AOR presented the perfect opportunity to test this capability.

Tasking of the satellites was worked through the parent companies' offices as authorized under the special agreement with NGA. The commercial companies were very easy to work with, and for the most part, were very expedient with any re-tasking requests. While it can be argued that if the COCOM had direct uplink and tasking authority, turnaround times could be improved and even more data could be collected, the corresponding trade that would need to be addressed is that additional expertise would be needed at the COCOM level to support spacecraft command and control. This line of thinking has led to the idea of having an automated tasking system as discussed in Chapter VI.

Over the 40 days of the experiment, it was possible to gather maritime imagery of over eight million square kilometers during 200 satellite passes, which is an incredible amount of added value in the information age. Had a mature program been in place from the beginning, closer relationships with the commercial companies could have been established, resulting in improvements in tasking, processing and delivery times and delivery of even more information. Radiant Polaris was well-received throughout the Navy, and more importantly, it opened the door to future experiments and operational tests. Admiral Fitzgerald was favorably impressed with the program, stating that it "provides us with a timely and valuable ship detection capability to employ when operations require intel that is shareable with our maritime partners" (Middour, 2011 p. 5). In an email to the Chief of Naval Operations (CNO) he went on to say, "We have been experimenting with unclassified commercial imagery…the key enabler for the operational commander is the ability to task for products and receive them directly." To which the CNO replied, "Great work…looking at getting it to the other [Navy Combatant Commands]" (p. 2).

V. POLAR EPSILON

Following the success of Radiant Polaris and other experiments, the Canadian government and Royal Canadian Navy decided to create the Polar Epsilon (PE) system. The Polar Epsilon system was designed to fuse RADARSAT-2 imagery with an AIS input to enhance MDA. To see how the system works in an operational environment, the Canadian government worked with the Naval Research Laboratory (NRL) to include the system in the recent Rim of the Pacific (RIMPAC) 2012 exercise. RIMPAC is the largest recurring multi–country naval exercise and provides a highly realistic testing environment for a maritime awareness system given the availability of ground truth on the many ships participating, as well as a realistic operational environment and tempo.

A. RIMPAC SET–UP AND PLANS

RIMPAC is conducted in the waters to the north of Hawaii, with as many as 40 ships and numerous merchant or non-participating ships in the same waters, which provides an opportune testing environment. However, due to the distance of Canada's satellite downlink terminals from the operating area (OPAREA), another downlink was needed. Eagle Vision 5 garrisoned at Hickam AFB in Hawaii was the perfect choice. The depiction in Figure 27 shows that the available downlink coverage from the Canadian ground station would not have been adequate to receive imagery from the OPAREA near Hawaii (Heruth & Petrick, 2012).

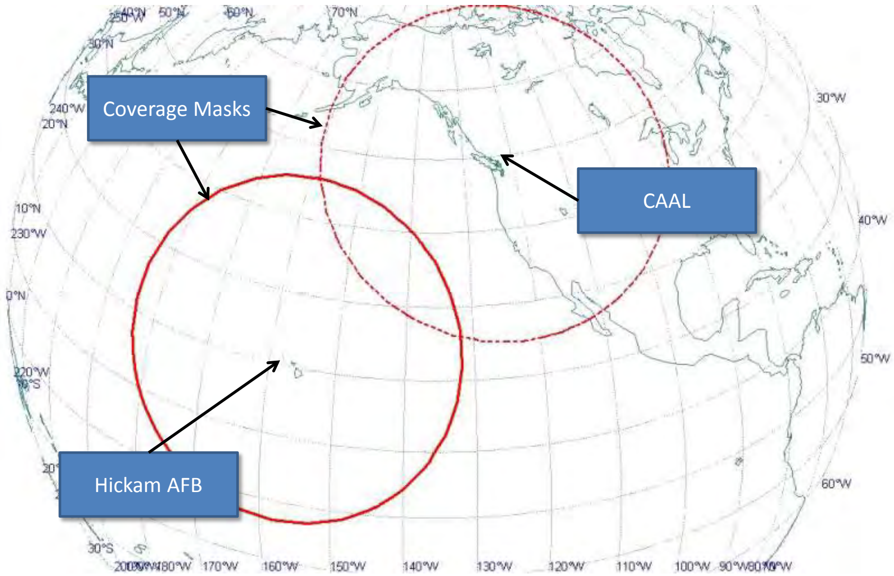

Figure 27. Coverage Masks for ground station at Hickam and Canadian Government ground station in British Columbia (from U.S. Naval Research Laboratory, 2012)

Thus, the Polar Epsilon data exploitation system (DES) was flown to Hawaii and collocated with Eagle Vision 5. The DES, depicted in Figure 28 includes the computers and processors that can input the processed radar data from the Eagle Vision and perform the AIS fusion, as well as the creation of the OTH-G messages. AIS information can be attained in many different ways; Polar Epsilon was developed using space-based AIS. Multiple companies provide space-based AIS from different constellations. ORBCOMM, COMDEV (through its subsidiary company exactEarth), SpaceQuest and LuxSpace all provide space-based AIS. The differences depend on the number of on–orbit satellite receivers available to each company, how their data is received, and the price charged. Polar Epsilon chose to use exactEarth based in Toronto, Canada for its exactAIS data. Previous exercises with the Canadian government had shown that exactEarth was capable of providing AIS data with the necessary timeliness. This data is provided from a constellation of three satellites with AIS receivers: Aprizesat-3, Aprizesat-6, and Resourcesat-2 (Heruth & Petrick, 2012).

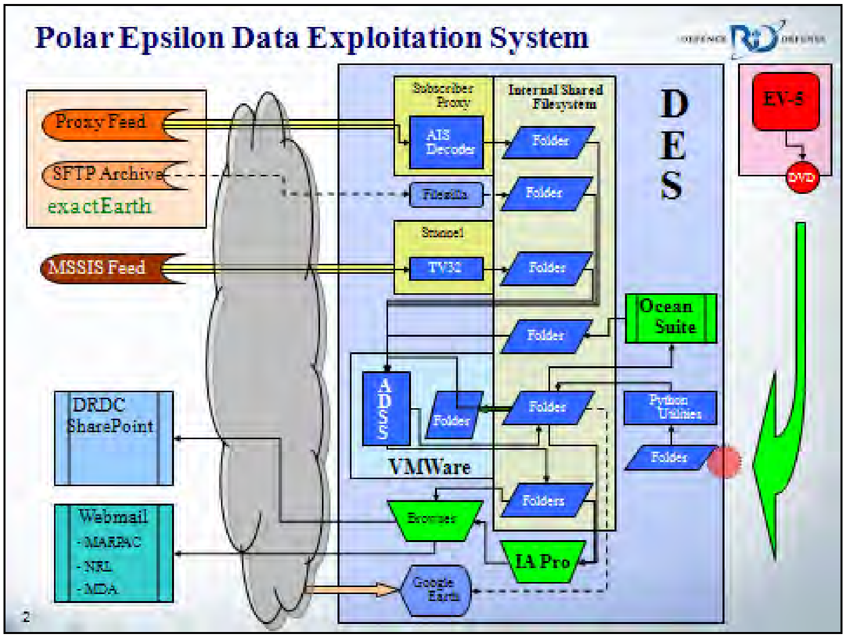

Figure 28. Polar Epsilon Data Exploitation System (DES) (from Heruth & Petrick, 2012)

Prior to the start of RIMPAC, an order was placed for all possible RADARSAT-2 right looking passes that fell within a 600 km radius of Hickam AFB. All passes were tasked with the SCAN SAR narrow (300km x 300km) imaging mode to provide the optimal mix of ship detection over a large area of open ocean. Also, tasking was ordered for coverage by the exactEarth AIS constellation with feeds to both the DES at Hickam and directly into the RIMPAC GCCS picture.

With the Polar Epsilon DES in place next to Eagle Vision in Hawaii, the data flow was designed to be quite simple. As RADARSAT-2 transited the area, it would conduct collection operations and downlink directly to Eagle Vision 5. The Eagle Vision team would process the raw satellite data through a dedicated RADARSAT processor to create usable radar data. This data would be passed to the DES that would also be receiving AIS data from exactEarth. The DES would then fuse the AIS reports with radar returns and the operator would be required to manually verify the low probability fused products. Next, OTH-G messages would be fed directly into the RIMPAC GCCS servers. The DES would send both raw radar tracks that had AIS correlation, as well as fused radar/AIS tracks. ExactEarth would send non–associated AIS reports directly to the RIMPAC

GCCS server to ensure full coverage. The basis for whether a radar track is fused with AIS data or not is due to latency, and the follow-on movements of a ship. If the position and course/speed of a ship is determined by radar and the ship continues to follow that same course and speed, AIS information collected at a later time will correlate well with the position projected using the earlier radar information and the data from the two sources can be fused. However, should that ship change course and slow down, and it is much later when the AIS information is collected, then the projected track developed from the radar data will be in error and an association between the two data sources will not be made. Table 13 shows a breakdown of latency between RADARSAT-2 and space-based AIS over flight. The number of R2 hits is the number of times that RADARSAT-2 would overfly the indicated point with-in the area of interest during the execution phase of RIMPAC 12. SCNB (Scan SAR Narrow B) and DVWF (Detection of Vessels, Wide, Far) refer to the types of imaging modes RADARSAT-2 could employ. The following rows show the minimum, mean, and maximum times between the RADARSAT-2 contact and the AIS collection occurring either before or after the radar detection. Points at the northern latitudes of the operation area would experience less latency due to the ground tracks of the four different polar orbiting satellites.

With the intended straight–forward data flow coupled with the co-located downlink and DES as seen in Figure 29, it was expected that processing through dissemination times would be reduced (U.S. Naval Research Laboratory, 2012).

Table 13. Coincidence of RADARSAT-2 SAR and SB–AIS Coverage (after U.S. Naval Research Laboratory, 2012)

Point at Hickam AFB		
	SCNB	**DVWF**
Number of R2 hits	8	15
min	02:41:22	02:41:22
mean	03:38:52	03:50:26
max	04:37:09	05:03:18
Point at edge of 600 km AOI (~5° north of Hickam AFB)		
	SCNB	**DVWF**
Number of R2 hits	10	16
Minimum time difference	01:58:48	01:44:12
Mean time difference	02:53:49	02:49:47
Maximum time difference	03:45:53	03:45:53
Point at edge of 2700 km EV–5 mask (~25° north of Hickam AFB)		
	SCNB	**DVWF**
Number of R2 hits	12	20
Minimum time difference	00:54:37	00:54:37
Mean time difference	02:12:38	02:18:12
Maximum time difference	03:30:09	03:30:09

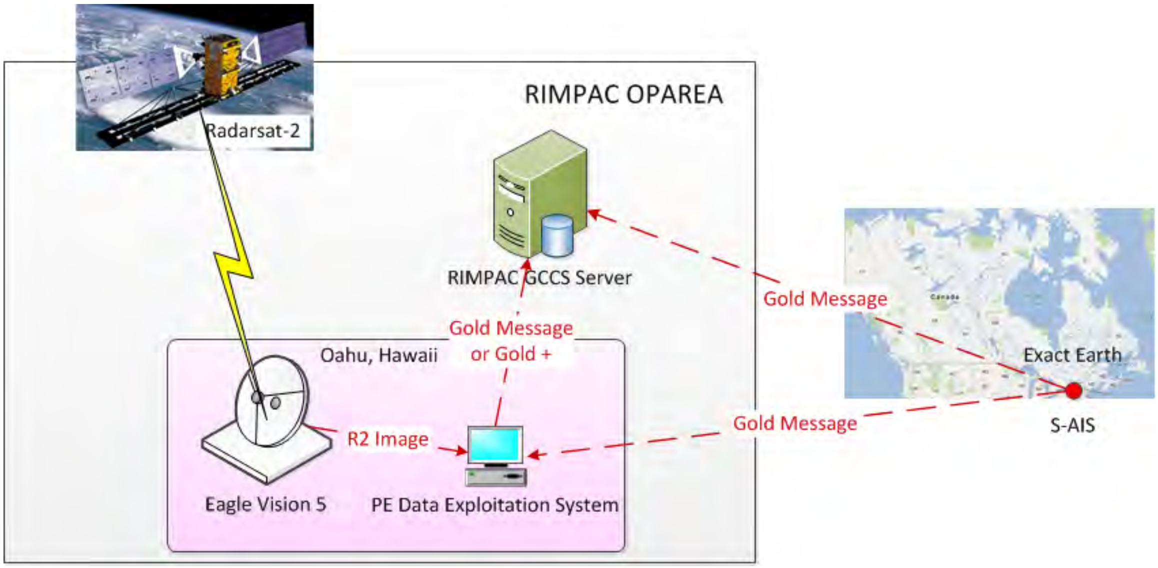

Figure 29. Polar Epsilon Intended Data Flow for RIMPAC 2012 (from U.S. Naval Research Laboratory, 2012)

B. RIMPAC OPERATIONS AND CONCLUSIONS

1. Processing and Exploitation

As RIMPAC got underway, connectivity and coordination issues were prevalent throughout many phases of the process. The downlink to Eagle Vision worked fine but for the number of specific RADARSAT processors that Eagle Vision 5 had, it would take approximately 18 minutes per frame for a total of 90 minutes of processing time for the nominal 5-frame pass. The Eagle Vision team, unfortunately, had many server crashes and process restarts in the first week due to server instability resulting from the high data loads and the lack of processors. Other Eagle Vision units have more RADARSAT processors and the Canadian PE team mentioned that its home system processed data much faster since it has more processors and stable servers. Once the data was processed, it was put on a DVD or hard drive, and passed over to the DES team for exploitation and fusing.

The DES team would first download the updated exactEarth AIS files for fusion with the radar data. The AIS tracks for the OPAREA had to be pulled from the worldwide database on the UNCLASS network, which thus slowed down the local processor; unfortunately, the team could not directly downlink the AIS data to Eagle

Vision. The DES would then download the radar images received from the Eagle Vision team for processing on a laptop through the OCEAN SUITE software. OCEAN SUITE is a software program developed jointly by the Canadian government and McDonald, Dettwiler & Associates that chips out the radar return of a ship from the ocean surface to produce target positions. The Analyst Detection Support System (ADSS) handled the correlation between radar and AIS tracks. The ADSS is a multi–INT fusion software partnership between Canada, the United States, Australia, and the United Kingdom (UK). ADSS was designed as a framework to enable multiple ship detection and classification algorithms to be brought to bear against a large sample of imagery. It provides a structure within which the algorithms can function over arbitrarily large images. It commonly analyzes images up to a gigabyte; terabyte images are feasible if supported by the computing platform. The ADSS framework automatically makes efficient use of multi–processor platforms and provides for synchronization and monitoring of the available imagery in near real-time applications (Redding et al., 2003, pp. 448–453).

Current ship position and velocity data, as well as historic track information, is gathered during AIS overflight and used to plot where the ship should be when RADARSAT-2 flies over. Then, the ADSS system attempts to correlate the two positions and when a high confidence occurs between the two data points, the radar detected ship position is matched to the AIS ship data. Manual intervention is used to approve the high confidence factor matches. If confidence is low or no correlation exists, the radar target is named "UNKNOWN/RS2." For RIMPAC, each target was renamed "SFC PENDING#/RS2." An actual number for each target replaced the #. The DES then generated target reports in Over–the–Horizon–Gold (OTH-G) text format. The OTH-G messages contained either 1) AIS identified ship information updated with a more current RS2 ship position, or 2) "SFC PENDING#/RS2" ship position and length information. Since AIS ship information was already being reported to GCCS, the OTH-G message did NOT contain AIS-only ship identified information. Currently, manual intervention to QA, or conduct quality analysis, by a radar image analyst is required for OCEAN SUITE.

Midway through the exercise, it was determined that with RADARSAT-2's capability to image on left hand passes, it would be beneficial to have a mix of right and left hand passes for better coverage during the final battle problem over the last week of RIMPAC. Three left hand passes were subsequently approved for collection during that period. The OPAREA was covered each day by different passes from RADARSAT-2 based on its ground track. As seen in Figure 30, over three days in late July, the OPAREA was fully covered with certain passes going right through and others providing grazing views (Heruth & Petrick, 2012).

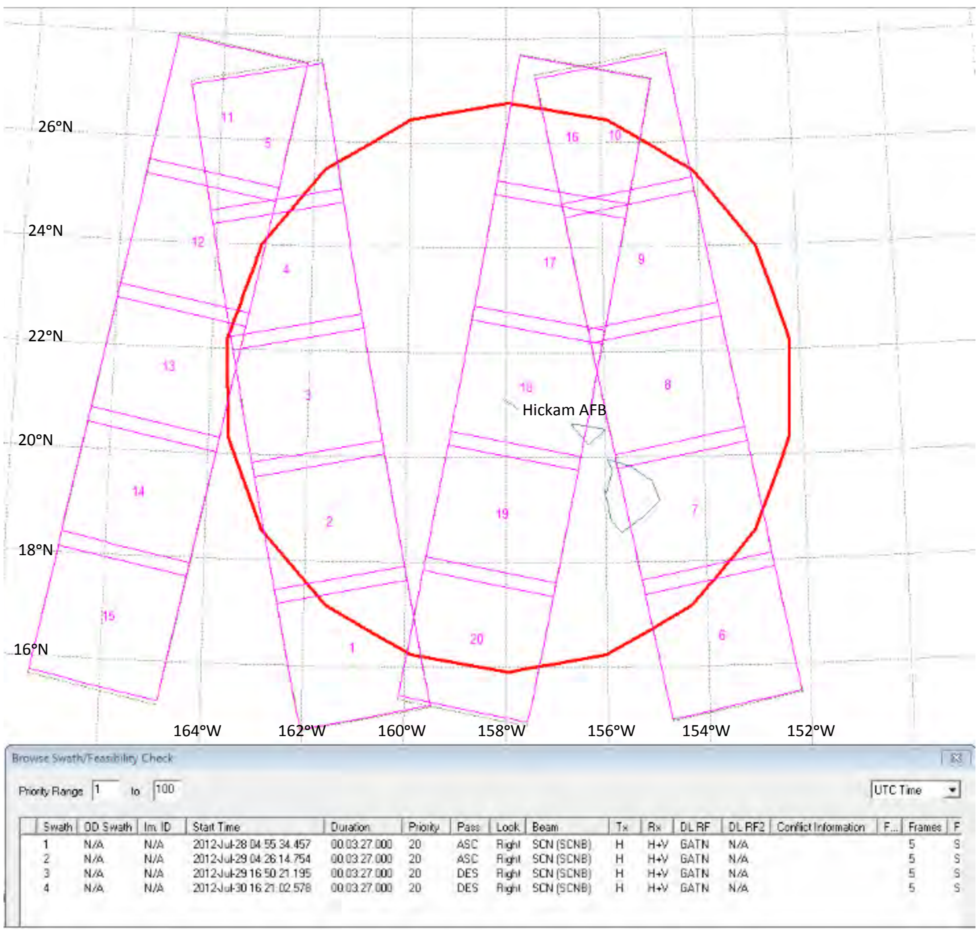

Figure 30. RADARSAT-2 Passes from 28–30 July, 2012
(from Heruth & Petrick, 2012)

2. Dissemination

Dissemination ended up causing the most problems for the Polar Epsilon team. The largest issue was that the RIMPAC common operation picture was being run on a special Cooperative Maritime Forces Pacific (CMFP) SECRET network and the PE team was sitting in an unclassified, unsecure facility. Thus, a different data path was needed to inject the PE data into the GCCS servers. After correlation, the PE team would email its unclassified OTH-G messages to Maritime Forces Pacific (MARPAC), Canada in Esquimalt, British Columbia. Once in Canada, operators would type the data into a new email on the CMFP network, and then that email was sent back down to the RIMPAC Combined Air Operations Center (CAOC), Hickam AFB. The GCCS watch stander in the CAOC copied and pasted the file into a text document and uploaded it into the CMFP GCCS. This information path is visually depicted in Figure 31. Unfortunately, this process was required due to the different networks involved, the limited ways in which connections and injects to those networks could be made, and also to the load on current watch standers in the CAOC and elsewhere in the Pacific Warfighting Center because of RIMPAC operations.

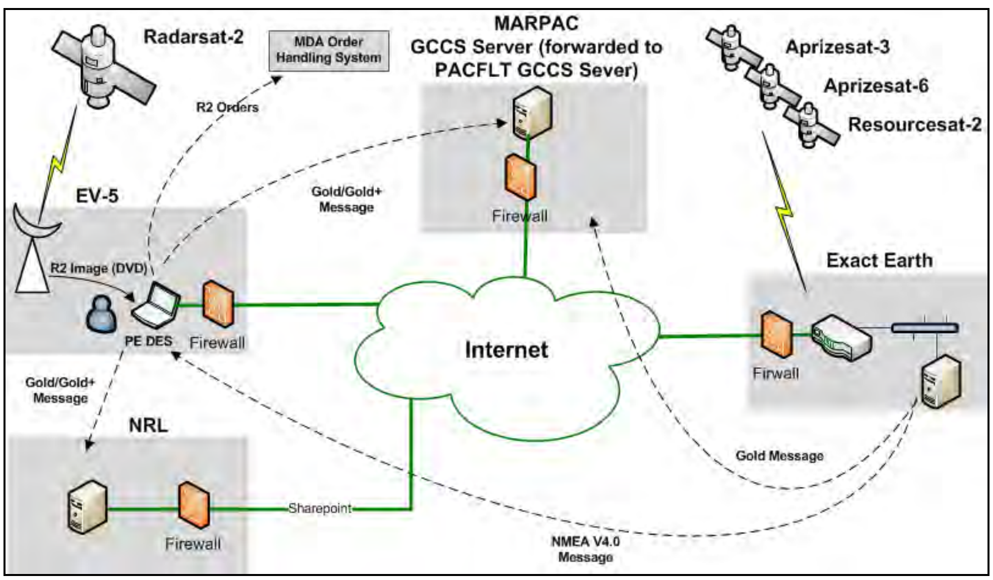

Figure 31. Actual Polar Epsilon Information and Data Flow (from Heruth & Petrick, 2012)

The process had a slow start, with personnel unsure of what to do with information, and training needed in dealing with the normally computer read OTH-G messages and their transcription into the system by hand. Within the first five days, a data handling procedure was written and training was conducted with watchstanders to ensure everyone knew the process and understood the common issues to address throughout the process. Finally, training was conducted with the intelligence and tactical watchstanders to ensure they knew that additional information was being added to tracks, such as the AIS and RADARSAT-2 data. As the teams were trained, times for processing decreased, fewer mistakes were made, and watchstanders understood the new data available to them.

By the second full week of operation, procedures were smoothed out and running easily. Eagle Vision 5 was taking 1.5 hours to process data directly off the satellite. The Polar Epsilon DES team was complete with full analysis and creation of OTH-G messages within 30 minutes of data receipt. Thirty minutes total were required for emails to go to MARPAC in Canada, be transcribed over and sent back down to the CAOC on the CMFP network. The final step for the GCCS operator to identify the email and upload the OTH-G into the GCCS server was 10 minutes. Two hours and 40 minutes passed between overflight and the download appearing in the COP on the watch floor. The final product of this chain is seen in Figure 32. While faster times are desired and possible with future systems, the added value of the information versus never having it was invaluable (Heruth & Petrick, 2012).

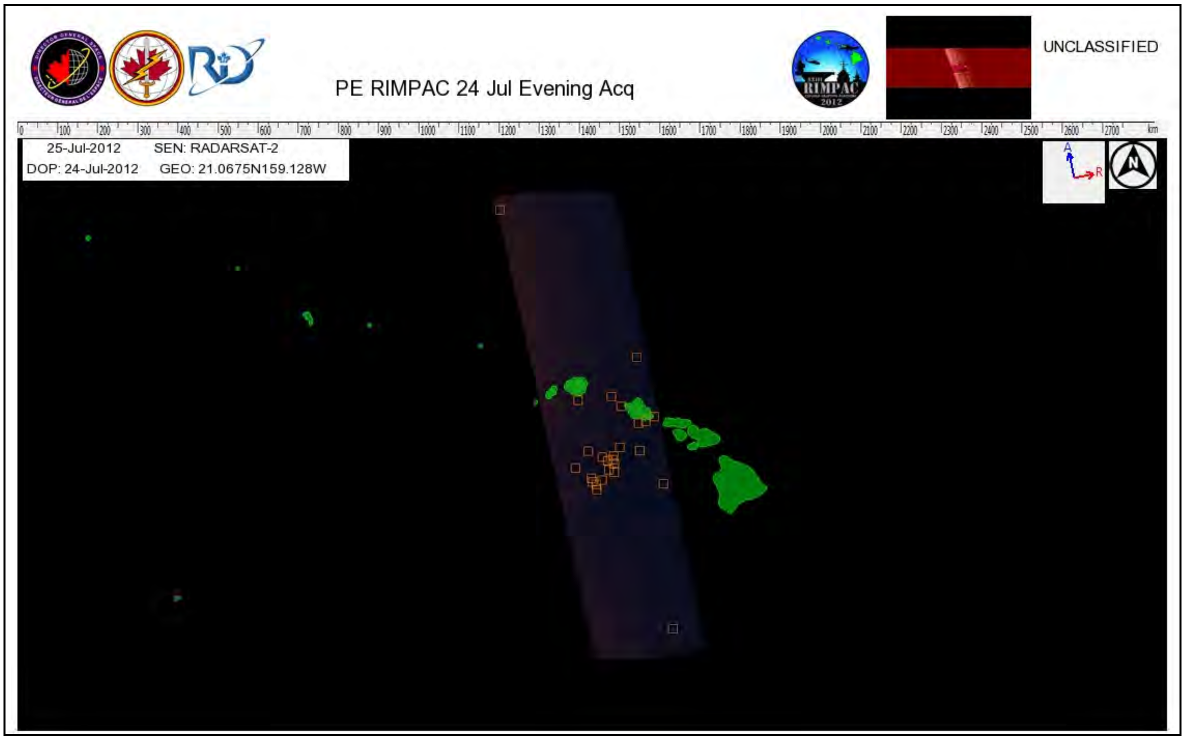

Figure 32. RADARSAT-2 Track after AIS Fusion
(from Heruth & Petrick, 2012)

C. CONCLUSIONS

Use of the Polar Epsilon system during RIMPAC was a realistic training exercise and operational demonstration of the system. The ability to bring the system in, get it running, and work through the issues to complete the mission and submit a product was an accomplishment. Also, the visibility gained on the capabilities of space-based radar, and how it can help with MDA within the intelligence and operations shops, as well as at the higher levels of leadership, to include the Flag level, was a substantial victory. The initial planning conferences that allowed NRL to directly brief capabilities to decision makers, as well as the introductions and working relationships that occurred during RIMPAC, provided an immeasurable contribution to encourage the future employment of other types of commercial imagery MDA systems. This "face time" allowed many people to learn and gain an appreciation for what could be done with commercial imagery.

Many lessons were also learned, for both the use of the particular systems involved, as well as for using space as a MDA tool in general. The processing times and obvious time delays in emailing and retyping of data were evident, which leads to a larger question. With the continued use of commercial electro-optic and radar imagery data, a completely unclassified COP will be required so that data can be directly injected into, and then shared with ease to all coalition partners. If multiple pictures will be running at different levels of classification, then a pre-established guard system or simple retype of info may be required but such implementations must be set up onsite to reduce emailing the files around the world to be placed on different networks.

Processing times depend on the downlink station and its capability. As discussed previously, the different Eagle Vision units do not have the same hardware and software configurations. While one unit may have a certain number of processors for a certain downlink, another may not. As a recommendation, it would beneficial for all the Eagle Vision units to maintain a document listing what downlink capabilities they have, the number of processors for that downlink, and average processing times for each specific downlink. Thus, a commander would be able to either shop around for the best unit to fit a certain need, or if assigned a specific unit for an operation, know what to expect, and if desired, to improve the system with operational funds obtained ahead of the event.

The use of ADSS for fusion of the radar tracks with AIS also caused some tracks to never be correlated due to high latency. Two future events will help with this problem. The exactEarth constellation of satellites with AIS receivers currently stands at three, but within the next few years, will increase to seven satellites. With the addition of more satellites, more passes will be made overhead a given location and at closer times to RADARSAT-2 passes. AIS service could also be contracted for from one of the other providers, such as ORBCOMM, to gain data from multiple providers and continue to cut the latency times. Second, the follow on to RADARSAT-2, under construction by the Canadian government, is RADARSAT Constellation. Each of the three satellites will have their own AIS receiver onboard that will be able to correlate AIS to radar returns automatically through onboard processing. This step will remove an entire step from the process additionally lowering the probability of false matching due to latency.

Finally, the use of one satellite was deemed to not be effective for complete MDA coverage of an area. During the 24 days of operation, only six swaths provided repeat coverage over the OPAREA, and the passes utilized only right-hand side collects. Since RADARSAT is a commercial satellite, and business issues needed to be considered for switching to left–hand collects, contingencies must be planned out in advance to include the use of different imaging modes to cover an area fully. That level of in–depth planning requires knowing the capabilities of the satellite and planning based on the mission. If the capability for uplink and tasking of the satellite directly from the AOR existed, as well as the direct downlink, more time sensitive tasking trades could be made. Since commercial tasking normally requires 72 hours pre-planning, tasking processes must be significantly streamlined. Through establishment of more automated and networked architectures, commercial companies could retain tasking authority but create a more responsive system. While one satellite was able to provide needed data to the decision maker, any increase would be an added benefit. It would be necessary to ensure that the proper hardware, software and procedures were in place to handle the additional information and processing requirements to support multiple satellites before implementing an expanded architecture (Heruth & Petrick, 2012).

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VI. FUTURE ARCHITECTURE AND CONCLUSIONS

A. FUTURE ARCHITECTURE

The future ability to make robust use of space-based commercial imagery assets to support DOD missions such as MDA depends on establishment of an architecture that facilitates efficient and effective tasking, processing, dissemination and exploitation of the vast amounts of data that can be generated by these systems. Multi-level classification issues are a significant factor in the establishment of an effective architecture. The various gateways, firewalls, and guards implemented and/or available for the different classified and unclassified systems have their pros and cons. While it may be possible to keep out data that is not supposed to be in the system, timely dissemination and access to various operators who can benefit from a more open architecture is also often prevented as a result. Given that the maritime environment covers the largest expanse of area and involves the most players and countries across which sharing of data is highly critical, this future architecture is extremely important. It must be kept completely unclassified and provide a sharable COP by leveraging commercial data, but also be able to pull this information seamlessly into the other classified COPs at the operations center to obtain the full benefit of that additional data.

Utilizing as many available commercial imagery assets as possible for MDA is also very important. While most of the time in both the Radiant Polaris and Polar Epsilon exercises was spent looking at application of SAR spacecraft, the EO birds can be a true help if provided with cuing data to help them image in the correct location. As imaging with the small telescopes of the EO birds would be like looking at the ocean through a straw, it is necessary to have an idea of where to look vice trying to search with such a system. A commercial EO spacecraft, such as WorldView 1, in a large area collect mode can average 10,000–15,000 square kilometers in a single pass at a nominal off-nadir angle, but in a spot collect mode that would be needed for higher resolution images, it would average only 225–290 square kilometers. The ability to have SAR cued EO would be a big step forward since most radar satellites are established in orbits that bring them overhead a given location at approximately 0600 and 1800 local time. Commercial EO satellites will normally fly over the same area at 1030 local, or have an equatorial crossing at 1030. If it were possible to establish a timeline to be able to downlink the SAR pass at 0600, process the image and get the data into the COP within 30 minutes, then the operations staff and commanding officer could devise a plan on how to allocate both organic and non-organic resources. After this had happened, if any targets of interest existed that could not be searched for by organic assets, or if an EO image was desired before approaching a target, then a future collection management and tasking systems such as the Virtual Mission Operations Center (VMOC) or other tasking platform could send a request to the EO tasking authority to have those projected target locations imaged. Then, after the EO pass at 1000, actionable imagery would be available, and hopefully a more fully understood maritime domain would result. An example of SAR cued EO is seen in Figure 33.

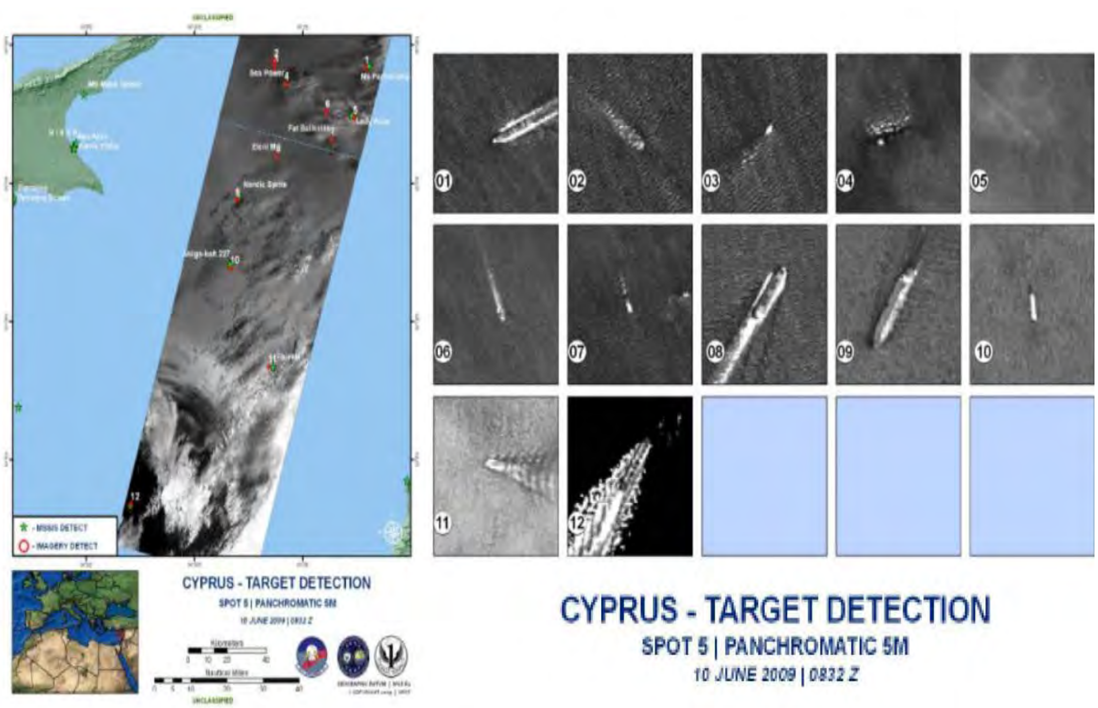

Figure 33. Use of SAR Cued EO Imaging during Radiant Polaris (from U.S. Air Force, 2010)

1. Virtual Mission Operations Center

The VMOC is a system designed to use Internet Protocol (IP) routing to provide satellite tasking capability over any Internet connection, which creates many interesting options for a future architecture. The VMOC allows the use of any device with an Internet browser to input tasking requests for imagery satellites. Initial testing of the system was completed on the United Kingdom's Disaster Monitoring Constellation (UK–DMC). This satellite (UK_DMC-1) was flown with a commercial Cisco router on board to implement the IP routing that made possible testing of the IP routing concept in space as well as providing for payload interaction. The initial testing was successful and the VMOC concept has been sustained and improved upon. The initial web-based tasking protocol was very simple as seen in Figure 34 (Wood et al., 2005, pp. 3052–3058).

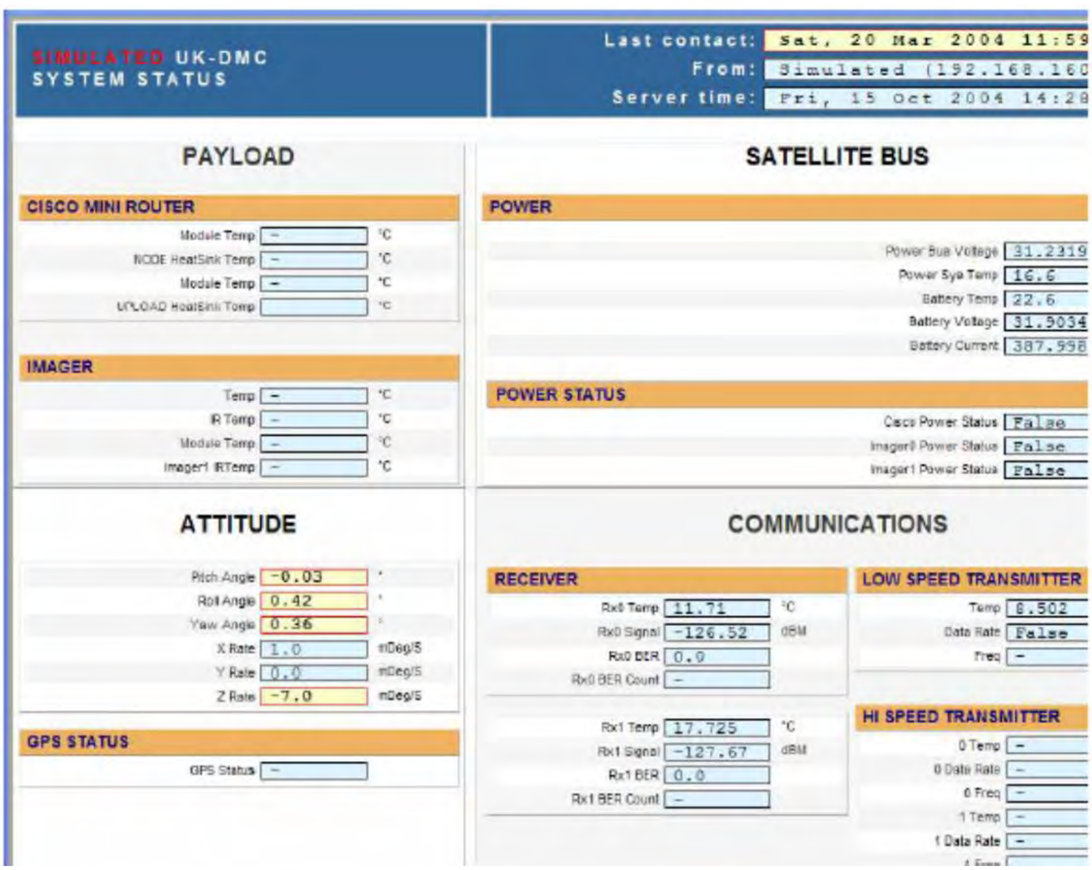

Figure 34. Initial VMOC Web Interface (from Wood et al., 2005, pp. 3052–3058)

When the Operationally Responsive Space (ORS) office began launching small satellites to include TACSAT–2 and TACSAT–3, and finally ORS–1, it decided to use VMOC as its scheduling and tasking architecture. VMOC allows access for the right person, to send the right command, at the right time. Thus, first of all, although any terminal on the unclassified standard Internet can access the VMOC, it is necessary to login properly, using secure authentication. Once a cleared person is logged in, then a certain number of authorized commands are offered. Different profiles are created for each individual who can login. At this point, it is possible to set which commands the individual is allowed to issue, what priority that individual gets for imagery requests, and what capabilities for bus and payload control an individual is authorized, which is all seamless to the user who sees the allowed tasks. Once the desired imagery request is selected, the system takes over, handles any de-confliction of inputs, and takes those priority rankings, as well as ephemeris data from the satellite to decide which tasks will be accomplished when and then sends those tasks to the satellite at the right time. Figure 35 shows how the user interface has improved and offers complete control of imagery tasking for ORS–1 (Conner, Dikeman, & Osweiler, 2004).

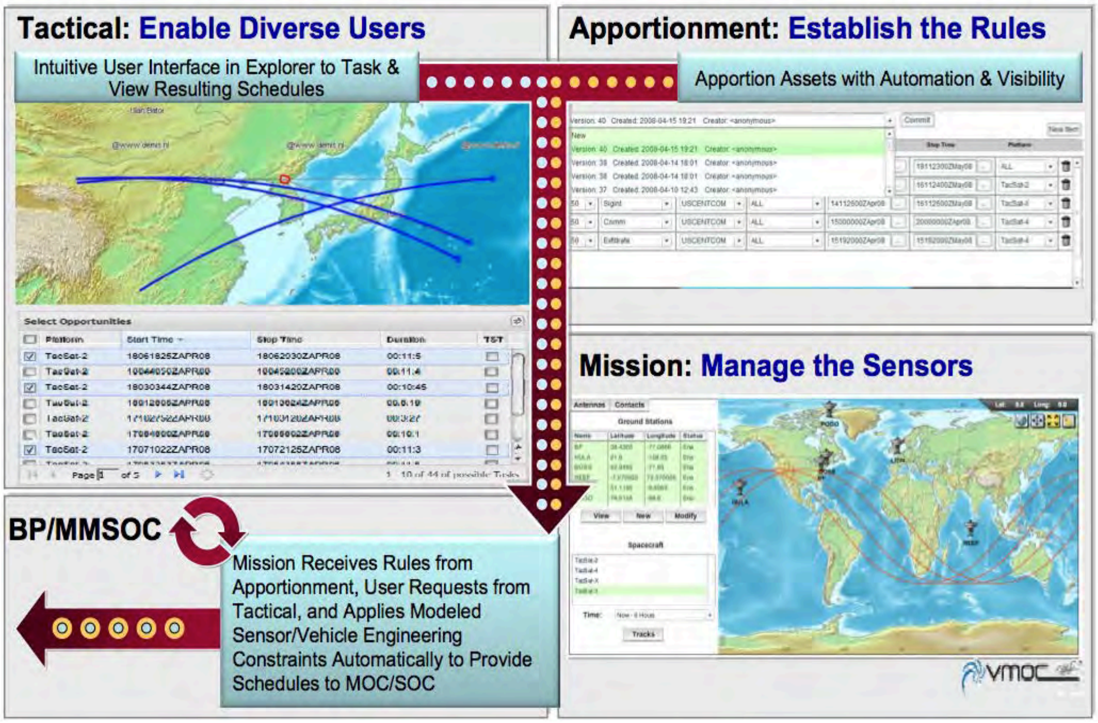

Figure 35. VMOC Tasking Screen for ORS Constellation (from Conner, Dikeman, & Osweiler, 2004)

The capability that VMOC has brought to other systems provides a framework for a possible commercial imagery tasking system. Operating on the unclassified Internet, with the proper controls, users could access a database requesting imagery for MDA purposes that could be automatically routed into the commercial company's tasking system. With the proper image priority codes, it can allow for machine-automated decision making for task scheduling conflicts. With such an architecture, the COCOM and MDA staffs could request the imagery they need, while still allowing the NGA to provide necessary oversight. With addition of the VMOC into the Distributed Common Ground System, robust commercial imagery architecture is beginning to look like more of a possibility.

2. Distributed Common Ground System

The Distributed Common Ground System (DCGS) was a concept initially discussed after the first Gulf War in 1991 (NCOIC, 2005). After action in Iraq, the Department of Defense (DOD) realized how dependent it was on Intelligence, Surveillance and Reconnaissance (ISR) capabilities, and the potential for information dominance. Thus, the DOD initiated a program to unify the ISR architectures across all the services, to allow for more rapid sharing of data throughout. This architecture became the DCGS, with each service having its own branch. Each service is responsible for building, procuring and fielding its own system components to allow for integration into its specific systems and programs. A fully funded program of record, the DCGS Integration Backbone (DIB), which provides the backbone to the network, is used to integrate all the services' systems.

The DCGS allows for all ISR data to be pulled in from NTM sensors, UAV and manned reconnaissance flights, commercial imagery, theater and tactical sources, and even the warfighter, to be put on one network and available to all the services. The individual services then have different systems to assist their commands best. Figure 36 depicts how the DIB holds the four service components together and pulls in data from all the other sources to distribute it to all the services (NCOIC, 2005).

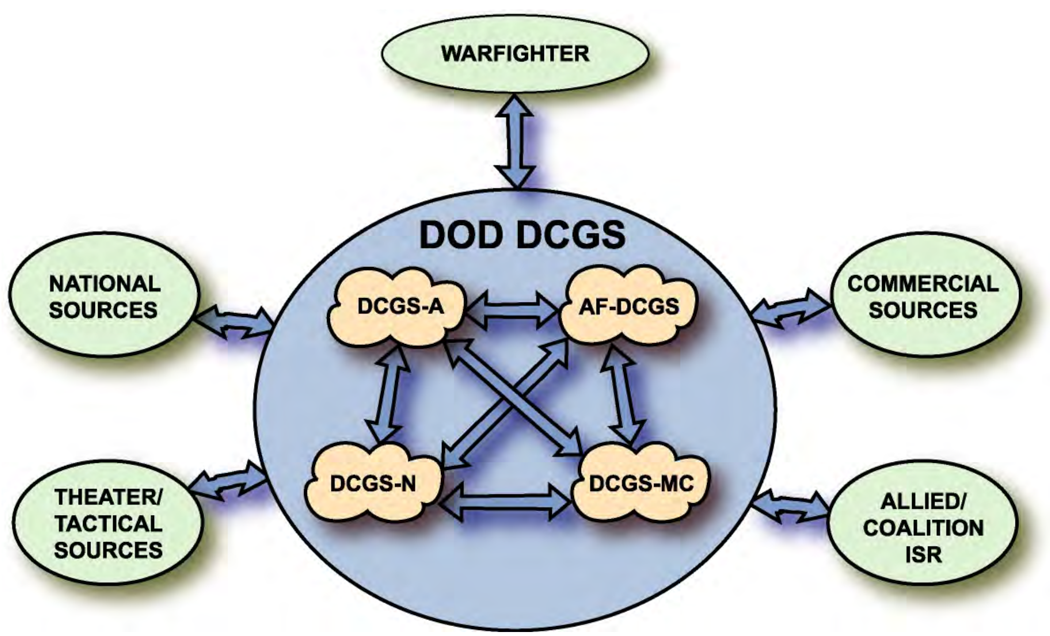

Figure 36. Distributed Common Ground System (DCGS) (from NCOIC, 2005)

As mentioned in the ground systems chapter, the Army Remote Ground Terminal will be transitioning into a component of the DCGS-A as it becomes operational. As part of the Army's system, it will provide a direct downlink capability wherever these dishes are deployed, and if coastal and not interfering with Army tasking, it would be possible to gather overwater imagery to aid in MDA. Since the RGT is a program of record, it should be possible for a COCOM to request in theater for whatever is needed.

The DCGS-N, the Navy version, is being fielded in multiple increments to Navy units (SPAWAR, 2011). As the Navy transitions to the Consolidated Afloat Networks and Enterprise Services (CANES) architecture for its next generation tactical afloat network, the DCGS-N will reside inside this framework, which is how it will eventually be fielded to all ships and submarines. In the initial increment, it is outfitting MOCs, training houses, the Office of Naval Intelligence (ONI), and other shore installations. The second half of the first increment will be the big deck ships, to include the command ships, aircraft carriers, and amphibious assault ships. As the architecture is installed on these ships and at shore commands, their ISR needs will be available via a single source. It will be interesting to see the future of this architecture and how commercial imagery will be made available through this service (SPAWAR, 2011).

B. CONCLUSIONS AND FUTURE WORK

To bring the use of commercial imagery to the forefront, three main issues must be fixed. First, a completely unclassified tasking, processing, dissemination and exploitation system is needed for use by coalition forces, first responders during natural disasters, and even law enforcement to disseminate the gathered data quickly. The second is the need for faster processing capability for all satellite data and subsequent insertion into the COP. Finally, a much smaller, more easily transportable and fully supported downlink receive capability would be necessary. None of these issues are out of reach; many, as discussed, are already being used or worked on.

Another major issue that has surfaced repeatedly is the need to streamline the commercial imagery collection management and tasking process. As more and more staffs learn of the capabilities of commercial imagery, how it can assist them in the MDA fight and how advances in downlink systems have improved accessibility to commercial imagery data more staffs will want to utilize this resource. As more users want to have their imagery directly downlinked for faster operational level support, tasking of commercial imagery systems will need to be much more efficient. If the SAR cued EO architecture is to become a reality, then more streamlined tasking processes, or even the ability to task locally, must be developed. One option is the use of an automated tasking architecture, such as the VMOC discussed in this thesis.

Additional issues common to many DOD programs include availability of funding as well as responsiveness of execution. Given the capabilities offered by commercial imaging systems for the MDA mission, a review should be conducted to determine the potential for special contractual arrangements with the various commercial imagery providers to obtain ocean surveillance imagery at reduced cost. If the commercial providers are serious about selling their product at a discount for MDA products under the understanding that the standard NGA contracting does not control it, then it would a mistake not to undertake a complete review into the possibilities available. Alternatives should be considered to provide more flexibility in the commercial imagery purchasing process. Options exist to spread the commercial imagery budget out to the separate COCOMs or allow the COCOMs to budget their allowed amount from a given funding code that NGA would control. While fully understandable for the NGA to control over land tasking at which it past or recent imagery may exist that fits the order, and thus save money for all involved, in the maritime environment with hourly changes, a more fast acting mechanism is then needed.

Future work into the testing of new systems needs to be conducted in target rich environments. The Polar Epsilon system is taking the lessons learned and creating a PE 2. With the new RADARSAT constellation having its own onboard AIS for immediate fusion to radar returns, time lines could be decreased, and with the constellation having three satellites working together, more assets on orbit would be available to pull data from shortening revisit times and increasing coverage area. The Philippine government has requested assistance and training in monitoring its maritime domain, which would provide a superb opportunity for testing in a true operational and daily environment. With this system being able to stay unclassified and shareable, it does not come with the added layers of security or cost of using national systems.

Another area would be to gather more information on the Distributed Common Ground System, how all systems will be deployed under it and how adding VMOC to it could create an optimal MDA/commercial imagery architecture. Also to follow is the development of the Army RGT and its fielding to active units and how it can be integrated into the DCGS and whether any units could be purchased by COCOM or Navy Fleet staffs.

Outside the classification of this thesis, a multitude of work needs to be done in reviewing the trade–offs compared to National Technical Means (NTM) and the possibilities and implications of using commercial imagery capabilities as a backup to NTM in an A2AD environment. Also to be examined is if commercial imagery was helping with the MDA problem, as well as how other assets could be made available.

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