The Ability of a Small Satellite Constellation to Tip and Cue Other Commercial Assets

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ABSTRACT

Small satellite constellations could be utilized to tip-off or cue existing Electrical Optical (EO) satellite systems such as a GeoEye class satellite. This paper addresses a specific case of this capability for the current problem of maritime domain awareness. If a constellation of small Automated Identification System (AIS) satellites, a small Synthetic Aperture Radar (SAR) satellite, and a large EO satellite is used for both routine and ad hoc global satellite coverage of high-interest areas, that constellation could monitor ship activities in support of Maritime Domain Awareness (MDA). This could be achieved over larger areas than Coast Guard or other vessels can currently cover. This would require an AIS satellite flying in tandem with a SAR to automatically detect and locate ships. The AIS data (ship ID/location/ speed/course/heading) identifies the broadcasting vessels and that data is spatially merged with the SAR data to identify all the vessels in the SAR scan. This allows detection and location of non-broadcasting vessels' using the SAR and AIS fused data. Those non-broadcasting vessels target locations identified by the SAR image provides the tip-off target location to cue the high-res EO satellite ad hoc imagery collection to characterize these high interest vessels. This new EO imagery along with the fused AIS/SAR report could be delivered to a watch floor or an operations center to provide information on developing situations. This would enable shortened timelines for a tactical response related to the detected non-broadcasting vessels. This paper describes the specific case of utilization of small satellite capabilities in concert with existing on-orbit EO assets to address situational awareness of existing dangerous maritime conditions.

SATELLITE TECHNICAL BACKGROUNDS

In order to understand the constellation as a whole, each satellite and its capabilities needs to be described.

AIS

All ocean-going vessels, and vessels larger than 300 tons, are required by the International Maritime Organization to transmit AIS signals. In the past, the data has been collected primarily by shore-based and ship-borne receivers where range is limited to approximately 50 nautical miles line of sight. The Canadian company, exactEarth Ltd. has successfully demonstrated the utility of their space-based AIS technology. This AIS system offers global coverage of maritime activity.

The Nanosatellite Tracking Ships (NTS) mission, an eight kilogram nanosatellite orbiting every 90 minutes at an altitude of 630 km in a polar sun-synchronous orbit in 2008, was the first satellite to demonstrate the advanced processing capability necessary to decode messages from space in a way that approaches the kind of detection possible from shore-based or ship-based receivers. Since then the exactAIS™ service was initiated using satellites built by SpaceQuest of Fairfax, Virginia. An exactAIS™ payload was also hosted on India's ResourceSat-2 Earth observation satellite. Another exactAIS™ small satellite built by Surrey Satellite Limited (SSTL) is due to launch in 2012. In 2013, an exactAIS™ payload will be launched onboard the NovaSAR small satellite built by Surrey (see next section) facilitating simultaneous collection of AIS and SAR data, becoming operational in 2014.

The exactAIS™ payloads are detecting and decoding over 1 million AIS messages per day on ship identity, cargo, destination, location, speed, course and heading. The system – ultimately slated to comprise 8 low earth orbiting satellites -- detects messages from every International Maritime Organization (IMO) mandated vessel, and many smaller vessels that are not IMO mandated. Ground processing of the signals is accomplished via the exactEarth production system using advanced signal processing algorithms. This technology enables the highly accurate tracking and monitoring of maritime traffic from pole to pole and across the globe, even in areas of high shipping density where messages from multiple vessels interfere with one another. This patented technology is uniquely capable of reliably detecting and de-colliding large numbers of AIS signals in the antenna field of view. For example, off the East Coast of the United States, in a high vessel traffic area, 2,171 ships have been detected in 9 minutes of acquisition time with a detection rate of 241 ships per minute. This is a detection rate unmatched by any other space based AIS receivers. This is an important performance characteristic as AIS transmissions are being sent simultaneously from literally thousands of ships that could be in the field of view of a passing satellite at any one time.

Countries with vast coastlines such as the United States, Canada, Australia, Japan, India, Denmark (Greenland), have all been using exactAIS™ to enhance maritime domain awareness. Additionally, regions without significant shore-based infrastructure such as the Arctic, South America, and Africa have benefited by continuous coverage provided by exactAIS™. This technology makes possible tracking of ships within or approaching territorial waters. In addition, this operational system provides a comprehensive global AIS monitoring capability to maritime authorities around the world. The constellation provides near real-time information on the identity, location and movements of marine vessels that is being used worldwide to establish a vessel traffic management system, protect sovereignty and security interests, improve maritime safety, and enhance monitoring of fisheries and the environment.

SAR

Currently multiple SAR payloads are being flown on larger satellites which could support a MDA mission. These satellites utilize traditional performance approaches which limit their utilization. They are driven to provide for optimized higher resolution imaging with associated antenna sizes and power requirements. These are large institutional programs which also might not have the ability to redirect the satellite immediately to developing situations. They have shared missions, involving many different users with different priorities, and in some cases different countries. In addition, their swath widths are smaller and resolution higher than is required for a more complete Maritime mission. NovaSAR, a new small SAR satellite being developed in the United Kingdom (UK) by Surrey Satellite Technology Limited (SSTL) will provide the tasking agility required along with a 750km swath width of a 30meter resolution. The system is based on the SSTL heritage platform structure and avionics along with Astrium payload expertise. NovaSAR utilizes a 3.1-3.3 GHz S-band 3meter x 1meter phased array SAR payload designed by Astrium Ltd. The payload provides for multiple polarizations - HH, HV, VH, VV in single, dual, tri- or quad polar configurations. It has a design life of 7 years if placed in the optimal orbit of 580km with up to a 2.2Tbit data memory unit. With an X-band downlink of up to 800Mbps, NovaSAR can be operated from existing ground terminals. This Small unique SAR satellite is currently under construction and planned to be operational in 2014. An Astrium airborne SAR demonstrator trial was performed using a 1/3 size antenna to collect a series of S-band datasets. (See Figure 1).

Figure 1: Airborne Image Portsmouth Harbor.

With this type of smaller SAR system, flying in formation with the AIS system, makes it possible to identify vessels with their AIS activated, and to detect vessels that are not transmitting AIS. The SAR signature provides the link to determine any vessels which might be trying to avoid detection along with monitoring movements of many vessels in a traffic management system.

EO

Currently, multiple EO payloads are being flown which could support a MDA mission. Several of these payloads are in operations by GeoEye. GeoEye was formed in January 2006 when Virginia-based ORBIMAGE purchased the assets of Colorado-based

Space Imaging. Space imaging had launched IKONOS on Sept. 24, 1999 in a sun synchronous 681km orbit. IKONOS has been very long-lived and successful as it is still on-orbit today producing imagery. IKONOS was the world's first commercial satellite able to collect black-and-white (panchromatic) images with 82-centimeter resolution and multispectral imagery with 4-meter resolution. It has a three-day revisit, an 11.3km swath, and 60^{o} off nadir imaging capability.

On Sept. 6, 2008 GeoEye launched GeoEye-1(GE-1) into a similar orbit as IKONOS. GeoEye-1 simultaneously acquires 0.41-meter panchromatic and 1.65-meter multispectral imagery (4 band). At the time of launch, this was the highest resolution available commercially. GE-1has an electrical optical payload with a 15.2km swath width and a 60^{o} off nadir imaging capability.

While highly agile, due to the small swath width of these satellites, being in the right place at the right time to acquire a vessel is highly unlikely. This is similar to the same problems addressed in the SAR section concerning the larger SAR satellites. Shipping lanes can and are monitored as requested on a daily basis in certain areas of the world but these are only high traffic, usually well regulated areas. A method for "tipping-off" or cueing one of these high resolution satellites to collect the suspected location is necessary in order to ensure the vessel in question is acquired. GeoEye supports ad hoc ordering which is high priority tasking of the satellite at the last minute to support developing situations. This can be leveraged to support a cohesive coordinated effort to identify traffic, security, and safety conditions as the situation develops in a timely fashion.

PROCESS AND SCENARIOS

The scenarios described in this section all follow the same simple process flow. See Figure 2.

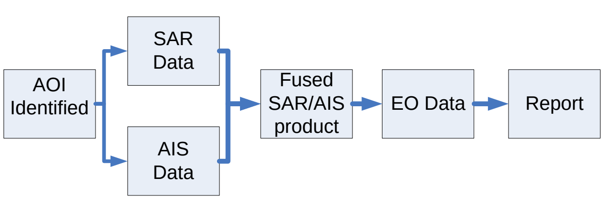


Figure 2: Process Flow

The AOI is identified at an initial Time = T_0. This is an area which some suspect activity has taken place in the past or some ongoing activity suggests that this is a area which should be monitored.

Because AIS data covers such a large FOV, AIS data already exists in the archive covering the AOI. The exactEarth© production system is run to retrieve previous AIS collections of that AOI. Since this AIS data is in the past, it can be considered that the acquisition of the AIS data is at time = $T_0 - x$, where x is some previous collection time.

The SAR data is scheduled to be collected over the AOI at the same time that the AIS data is being searched for past collections. Thus the SAR data is acquired at Time = $T_0 + y_1$, where y_1 is the time when the SAR satellite is over the AOI and can collect the imagery to be processed

Once the SAR is collected, the AIS data and the SAR data are fused to create a product that can be analyzed for additional information on whether an EO collection is required to provide a visual inspection for vessel identification.

At this point, the EO is tipped off for the projected location of the vessel in question and the visible imagery is acquired. This can be considered Time = $T_0 + y_2$, where y_2 is the time to task, acquire and process the EO imagery. If this was done correctly, the resulting imagery will contain the vessel in question.

The visible EO imagery is analyzed and merged into a single report using the pertinent details of the AIS information, the SAR information and the EO image. This report would include details such as the vessel general classification, including length and beam. If identifiable it would contain the vessel type such as tanker, container, bulk cargo, along with the actual vessel location and the correct AIS identification signal. This report would verify that the actual ship identity in the EO imagery is the same as the AIS information and include a chip of the imagery of the vessel to a report user.

Orbits

In order for the scenarios to work, the three satellites have to have coincident coverage of the shipping lanes and large areas of the Earth.

The AIS satellites and the GeoEye satellites are already in orbit and such their orbits and FOV are set. With the AIS 4600 kilometer field of view, this makes placement of the SAR satellite fairly straightforward. Using a 98^{o} sun synchronous orbit, the SAR satellite must simply ensure overlapping coincident coverage. While the SAR satellite can be placed in a ~58^{o} inclined orbit also, 98^{o} was chosen for its common orbit with the GeoEye satellites. See Figure 3 for potential overlapping coverage. In this Figure, overlapping coverage is shown between SAR and AIS at the equator (top picture), 45 deg North (middle picture) and 70 deg North (bottom picture).

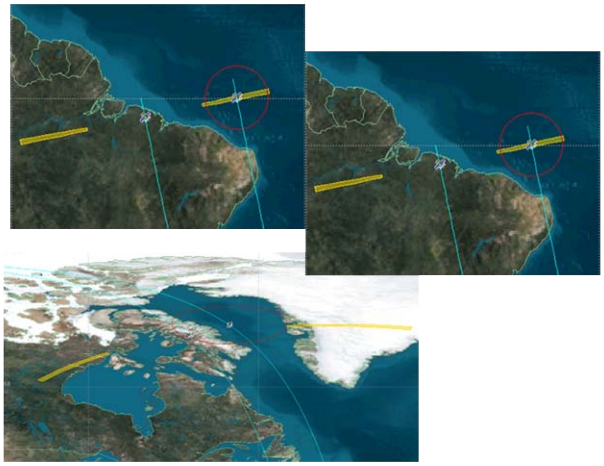


Figure 3: SAR/AIS Overlapping Coverage

A simulation was generated using the existing orbits of the exactEarth AIS satellite and GeoEye GE-1 satellite. A projected swath for the NovaSAR satellite once launched was added to this simulation. Figure 4 is a screen capture from that simulation showing a view of the overlap between the SAR satellite and the AIS FOV. Note that the AIS FOV was reduced in order to demonstrate the overlap coverage and is not indicative of the actual 4600 kilometer FOV. This indicates that the combined AIS and SAR overlap which is proposed is viable using existing and "soon-to-be-launched" satellites.

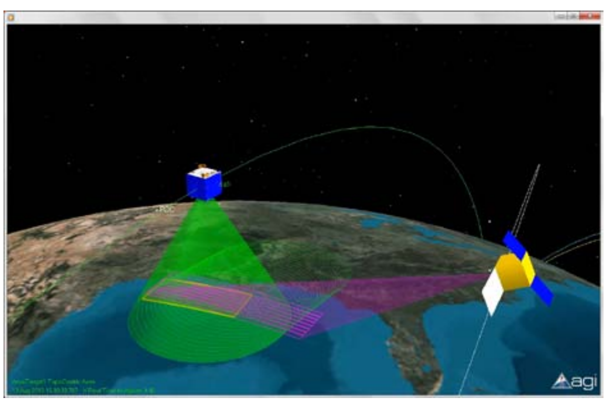


Figure 4: SAR/AIS Coverage Simulation

Figure 5 is a screen capture from that same simulation showing an overlap view once the GE-1 satellite footprint and orbit is added. This demonstrates that the GE-1 footprint size is much smaller and thus would need to be very accurately directed to the specific tasking location in order to capture the desired activity.

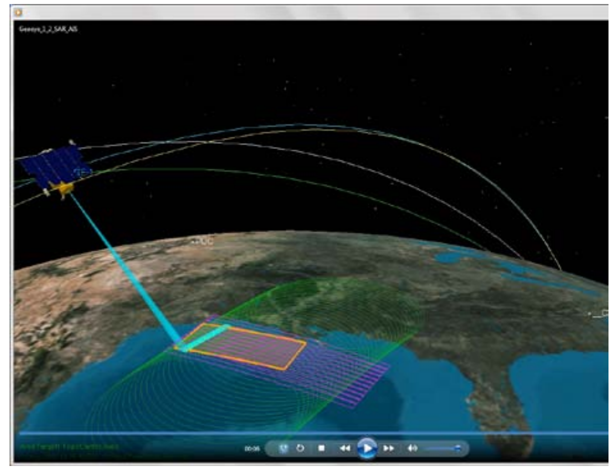


Figure 5: SAR/AIS/EO Footprint Coverage

As shown, a 98^{o} sun synchronous orbit works well to provide overlapping coverage for all three satellites, but highly accurate tip-off location information is required for GE-1.

Marine Protected Areas (Scenario #1)

As described before, the Field of Regard for the AIS is quite large versus the swath width of the SAR satellite. However, most situations are over a particular Area-Of-Interest (AOI) where problems regularly occur or contain a Marine Protected Area (MPA) such as the Tarium Niryutait Marine Protected Area in the Canadian Arctic on the coast of the Beaufort Sea. It was established by the Canadian government in 2010. See Figure 6.

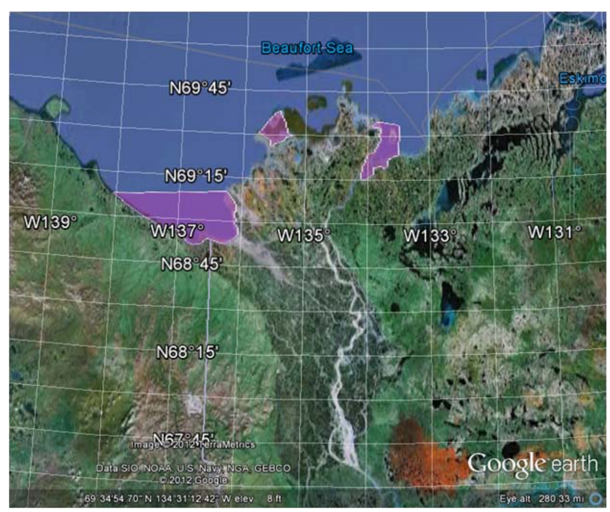


Figure 6: AOI Identified as Tarium Niryutait

These MPAs are protected from fishing and other activities yet cannot be adequately monitored well using ground based assets for violations. Using the large field of regard for AIS data already collected, an early warning of a vessel approaching the AOI can be reported. See Figure 7.

Figure 7: Analysis of Vessel Approach: 23:15 Day1

The AIS information provides the position, speed and course direction. This data is then projected forward in time so that the SAR can detect the vessel in its new position. See Figure 8.

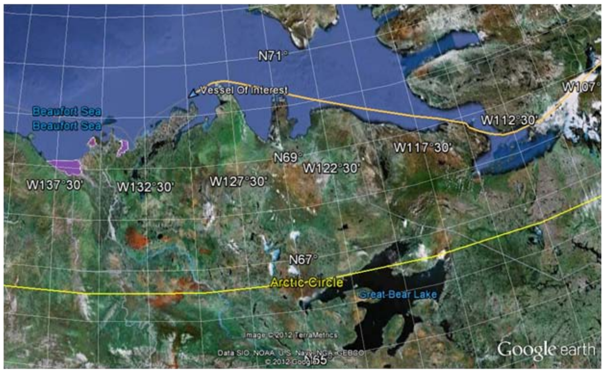


Figure 8: SAR Image: 1:45 Day2

The SAR is maneuvered to acquire this location. The SAR data is downlinked and analyzed with the AIS data. Using SAR imagery, the vessels in the MPA can be detected and their exact location located. Using the then coincident AIS information and the SAR data, the specific vessel can be identified. See Figure 9.

Figure 9: SAR Image and AIS: 6:35 Day2

This analysis precisely locates the vessel and uses vessel-specific details to determine the appropriate estimate of movement and precise tasking required for a 16km EO imaging swath. The EO satellite is then tasked using this information and images the vessel in question in order to characterize and identify the vessel. See Figure 10.

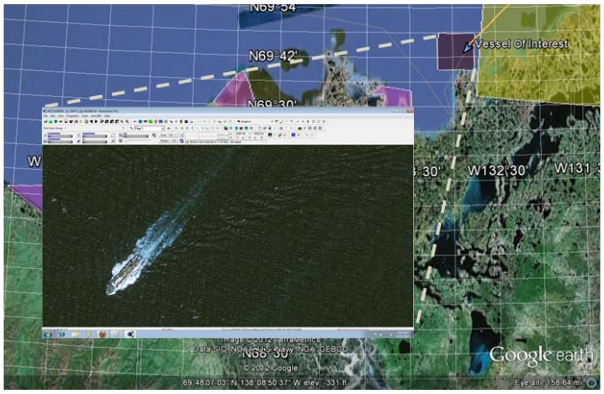


Figure 10: EO Image: 10:52 Day2

This total scenario time was less than 12 hours of when the vessel was first detected and identified as something of interest.

This Marine Protected Areas (Scenario #1) is an example of how this tip-off process could be exercised for environmental protection efforts. It allows identification of a possible oil-carrying vessel to determine if it is trespassing in a MPA. Oil carrying vessels are required to avoid MPAs however, trespassing occurs often due to the increased trip length when going around the area. Being able to perform this identification within a 12 hour period is useful in enforcing and fining environmental violations. These types of violations currently occur in the world's largest MPA surrounding the Northwestern Hawaiian Islands in the United States. These islands have been described as "America's Galapagos" and are now the largest intact tropical marine region under U.S. jurisdiction.

Environmental Safety Violations (Scenario #2)

In this hypothetical environmental regulatory violation scenario, the AIS detects a "suspicious" vessel in port, perhaps a vessel which previously is known to not perform maintenance and has earlier been fined for leaking oil in the shipping lanes. See Figure 11.

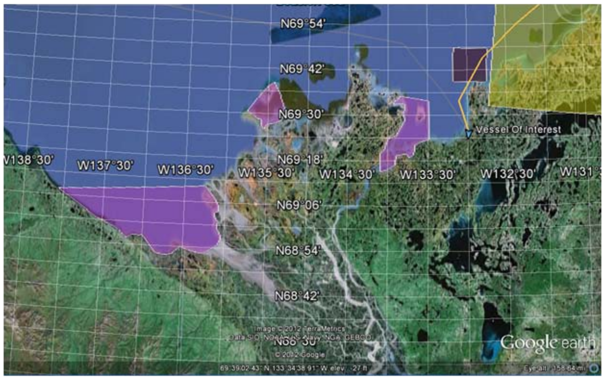


Figure 11: AIS Vessel in Port: Time = 16:48 Day1

Then 24 hours later, the AIS detects the vessel movement from the port and this vessel has already been tagged as a known or possible violator. See Figure 12.

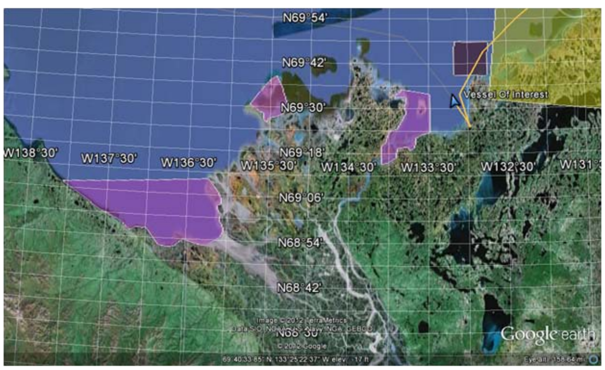


Figure 12: Vessel Movement: Time = 16:19 Day2

The SAR satellite is cued and images the vessel in question. The data is downlinked and analyzed. See Figure 13.

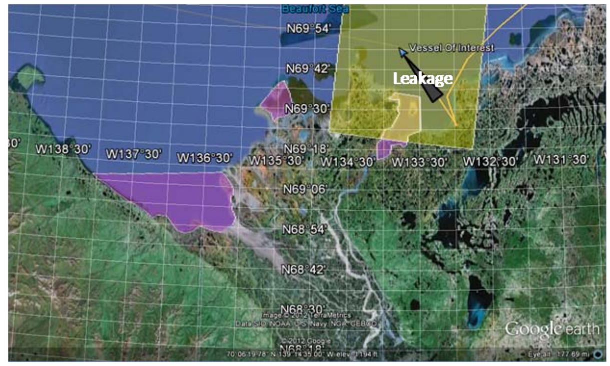


Figure 13: SAR Image: Time = 18:33 Day2

It can be seen on the SAR image that a large oil slick is forming behind the vessel in question. This of course, is not an actual oil spill but rather a hypothetical situation to demonstrate the utility of this approach. The vessel can be identified from its AIS signature and fined. In addition, the oil slick information from the SAR detection can be used as an input to models predicting its movement, and the appropriate oil spill response can be formulated and implemented.

Figure 14: EO Image: Time = 22:40 Day2

Subsequent EO imaging can validate model predictions and document response activities.

USERS AND DATA UTILIZATION

The previous section has discussed some scenarios which address primarily environmental protection applications. However, this data could be utilized for many other applications such as:

- Detecting piracy, tracking pirates and pirated vessels, and providing support for piracy response,
- Detecting illegal, unregulated and unreported (IUU) fishing and providing support for response,
- Detecting anomalous movements of vessels that may indicate illicit trafficking in goods, drugs or human cargo,
- Supporting humanitarian and disaster relief efforts which may involve vessels of many types flagged to many different nations.

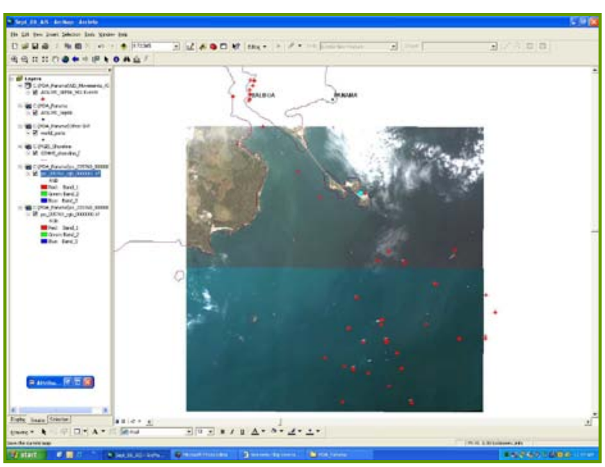
Reporting

Fusing SAR, EO and AIS with other data can provide more information including maritime intelligence. For example, SAR and EO data can detect all vessels in a given area of interest. AIS can identify those vessels that are voluntarily complying with AIS transmission rules. The vessels are either purposefully not transmitting, even though they should, or vessels that are too small to transmit. Most illicit trafficking occurs via small vessels. The satellite based data can cue shore based radar, cameras, patrol aircraft and patrol boats to follow up on suspicious cases.

However, being able to provide a electronically available fused report to a watch floor or an operations center would assist in getting information on a potentially dangerous developing situation to the people most likely to utilize it quickly. A fused report would shorten timelines for enforcing agencies for tactical responses of detected non-broadcasting vessels, vessels with violations and trespassing while it was occurring.

This fused report would not necessarily contain the full resolution imagery but rather the specific information derived from the AIS, SAR and EO collections. Some screen shots of electronic sample report pages is shown in Figure 15. This report should at a minimum contain:

- Vessel identification information or lack of, along with vessel details such as type of vessel, country of origin and cargo (if known).
- An imagery chip of the vessel for identifications purposes or indicating the violation in process.
- A summary of the issue or threat posed by the vessel along with detailed location information, heading, and speed. Next known port of call.



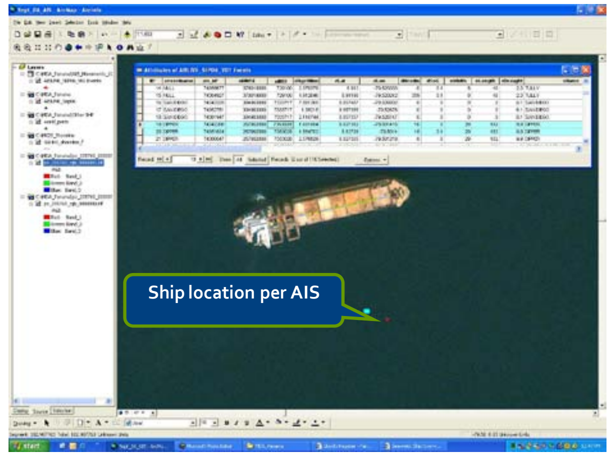


Figure 15: Sample Electronic Report Pages

Users of the Data

It is envisioned that this type of consolidated report would be used primarily by the Maritime Safety Agencies, Coast Guard or Navies of national governments. However, this data would be sharable with State, Local and Tribal/Native/Aboriginal entities along with Coalition partners and other international entities. Figure 16 is a notional view of the sharing of the data.

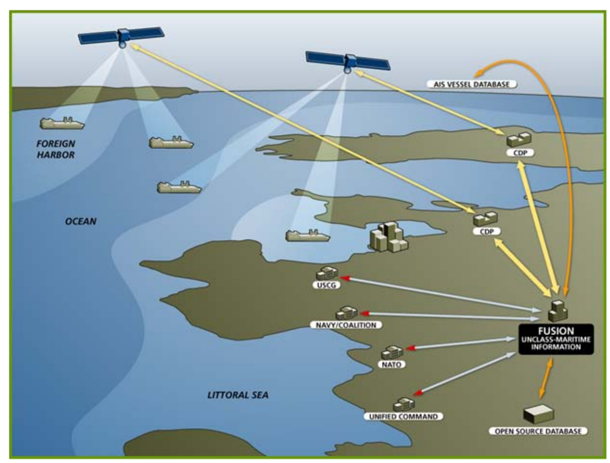


Figure 16: Concept of Data Sharing

A data sharing architecture enables a full range of users for the data which will amplify the usefulness, and thus the demand for this reporting service.

Data Archiving

The dissemination and archive of the reporting information and raw full resolution imagery should reside in a data warehouse. This data warehouse could support vessel imagery, port infrastructure orthorectified base layer imagery, image support data, automated text alerts/warnings. It would utilize industry standards, USG standards, and Web services for delivery and discovery of the data to allow the many types of users to access it. The data would be discoverable by implementing MDA Common Operating Infrastructure (COI) data sharing vocabulary along with metadata models and messaging services to provide a historic archive service of all vessel/port imagery and text data.

SUMMARY

In conclusion, the timeliness and accuracy of commercial satellites can be harnessed to support the MDA mission. By using a constellation of AIS, SAR and EO satellites in the Maritime Domain Awareness arena violations and other Maritime activities can be identified and made available to a user community. This leverages existing capabilities such as exactEarth's AIS and GeoEye's EO satellites in concert with the new NovaSAR satellite to better meet user timelines and Maritime needs.