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Integrating Spaceborne Sensing with Airborne Maritime Surveillance Patrols

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Abstract: Airborne surveillance patrols are frequently employed to maintain situational awareness of large maritime border regions. Manned airborne platforms are typically used due to their inherent flexibility to detect vessels and also conduct classification and identification by flying in for closer inspection. For large and remote border regions, airborne surveillance patrols can be expensive in terms of personnel and platform resourcing. The unpredictability of vessel densities can at times impact on the robustness of the surveillance coverage. When a patrol encounters too many vessels to inspect, the limited flying hours mean that parts of its original flight plan may be curtailed, potentially leaving gaps in surveillance coverage. Extra flights can be added but this adds significantly to the resourcing costs.

Satellites, in contrast, are able to cover large remote areas and distances at short timescales, with predictable schedules. Imaging satellite constellations with payloads such as electro-optical (EO) sensors and synthetic aperture radars (SAR) can provide complimentary capabilities to that of airborne patrols. Traditionally, the use of imaging satellites in maritime border surveillance has been decoupled from airborne surveillance patrols due to their long tasking-delivery timescales. With the increasing availability of high-performance commercial EO & SAR satellites and the availability of satellite direct access capabilities offering improved tasking-delivery latencies, there are opportunities to integrate and leverage spaceborne sensing with airborne platforms in maritime border security applications.

This paper identifies and explores the potential roles of a selected set of imaging satellites to support airborne surveillance patrols for large maritime border regions.

Four potential roles are proposed:

- Surveying an area to determine likely vessel density and vessel types to aid in airborne patrol mission planning
- Surveying sections of the maritime region to free up airborne patrols
- Surveying areas missed by airborne patrols
- Supporting geolocation awareness of specific vessels in between airborne patrols

We present simulation results examining current commercial direct-access available EO & SAR satellites and provide early insights into their feasibility to support the proposed roles.

Keywords: *Maritime surveillance, integrated surveillance, satellites, airborne patrols*

1. INTRODUCTION

Airborne surveillance patrols are frequently employed to maintain situational awareness of large maritime border regions (ABPC, 2013). Manned airborne platforms are typically used due to their inherent flexibility to detect vessels and also conduct classification and identification by flying in for closer inspection.

For large and remote maritime border regions, airborne surveillance patrols can be expensive in terms of personnel and platform resourcing. The unpredictability of vessel densities can at times impact on the robustness of the surveillance coverage. When a patrol encounters too many vessels to inspect, the limited flying hours mean that parts of its original flight plan may be curtailed, potentially leaving gaps in surveillance coverage (Marlow et al., 2009). Extra flights can be added subject to availability but this adds significantly to the resourcing costs.

Satellites, in contrast, are cost effective in their ability to cover large remote areas and distances at short timescales. They have predictable schedules and geographic coverage which can be an advantage in terms of ease of planning and a disadvantage in being predictable by those being observed. Satellite constellations with Automatic Identification System (AIS), electro-optical (EO) or synthetic aperture radar (SAR) payloads can provide unique and complimentary capabilities to that of airborne patrols.
Satellite constellations with AIS receivers are providing global tracking of maritime vessels but only for those that carry and operate their AIS. Imaging satellites have varying performance in their ability to detect, classify and identify maritime vessels, either directly through imaging the vessel or indirectly by detection of ship wake. Imaging EO satellites can provide high resolution images during daylight hours sufficient for vessel identifications and are only limited by cloud cover. Imaging SAR satellites have some limitations in their ability to detect small and non-metallic vessels but have the advantage of being able to operate day or night and through cloud cover. In general, there is a trade-off between area coverage and the image resolution, in that smaller vessels requiring high resolution images will result in reduction of the area imaged.

Traditionally, the use of imaging satellites in maritime surveillance has been decoupled from airborne surveillance patrols due to satellites' typically long tasking-delivery timescales. Studies have examined the use of commercially accessible EO satellites for maritime domain awareness to provide an 'image history' rather than for responsive imaging applications (Bannister and Neyland, 2015).

In recent years, satellite direct access is a capability offered by several commercial satellite vendors (e.g. DigitalGlobe, Airbus DS) that enables customers with suitable ground receiving stations, to directly task an imaging satellite and directly receive imagery data, all within the same orbit pass over the ground receiving station. This provides best case tasking-delivery timescales over traditional satellite imagery acquisition approach that typically involves long lead time in submitting new imagery request and slower data delivery.

With the increasing availability of high-performance commercial EO & SAR satellites and the availability of satellite direct access offering improved tasking-delivery latencies, there are opportunities to integrate and leverage spaceborne sensing with airborne platforms in maritime border security applications.

2. IMAGING SATELLITE ROLES FOR SUPPORTING AIRBORNE MARITIME SURVEILLANCE PATROLS

Four potential roles of imaging satellites for supporting airborne maritime surveillance patrols are proposed in sections 2.1 to 2.4 where each role presents unique requirements for satellite imaging in terms of coverage, timing and quality. A summary of the roles is provided in Table 1.

2.1. Mission planning support

The mission planning support role involves imaging satellites surveying an area prior to being searched by airborne patrols. For a large maritime region that requires multiple airborne patrols, the support could be to image the whole region or just a section of the region. The acquired imaging data can be correlated with AIS data so as to estimate numbers and locations of vessels potentially needing to be inspected. This can aid in airborne patrol mission planning such as selecting the route pattern that better aligns with likely vessel locations, or choosing appropriate sensor swath size based on an understanding of likely minimum vessel sizes. The imaging should occur before the start of airborne patrols to provide input to the airborne mission planning process. The imaging quality should be sufficient for at least the detection and preferably classification of vessels of interest.

2.2. Coverage provider

The coverage provider role involves imaging satellites surveying sections of the maritime region in order to free up or reduce the workload of an airborne patrol and also to provide redundancy during airborne platform downtimes. Having imaging satellites survey remote parts of the maritime region can also enable airborne patrols to focus on areas closer to the mainland and thereby minimise transit time and hence increase surveillance efficiencies. The imaging should occur within similar time frames of the airborne surveillance patrols. The imaging quality should be sufficient for at least the detection and preferably identification of vessels of interest.

2.3. Coverage Redundancy support

The coverage redundancy support role involves imaging satellites surveying areas that were unable to be completed by airborne patrols. This can occur in situations where the patrol aircraft have too many vessels to inspect, leading to insufficient time or fuel to complete the planned route. To ensure gaps left by airborne patrols do not result in vessels transiting through the area undetected, imaging satellites can follow up with imaging of the gaps as they arise. The schedules and routes of airborne patrols will need to be aligned and designed to maximise the availability of satellites providing the coverage redundancy. The imaging quality should be sufficient for at least classification and preferably identification of vessels of interest.

2.4. Situational Awareness maintenance support

The situational awareness maintenance support role involves imaging satellites surveying specific areas identified by prior airborne patrols to maintain geolocation and behavioural awareness of vessels of interest in-between airborne patrol revisits. This requires multiple spot imaging spread over time. Each imaging opportunity must sufficiently cover the area that the vessel of interest can possibly move to by the time of the next imaging opportunity. The faster the vessel speed and the longer the time gap between revisits will require larger coverage in order to re-acquire the vessel position. The imaging quality should be sufficient for correlation with previous imaging data to locate the new position of vessels of interest.

Table 1. Roles of Imaging Satellites to support Airborne Maritime Patrols

Roles	Imaging Area Coverage Requirements	Temporal Requirements	Imaging Quality Requirements
Mission Planning Support	Survey sections of maritime region to be covered by airborne patrols	Imaging before airborne mission start time (Prior to airborne patrols)	Sufficient for detection
Coverage Provider	Survey sections of the maritime region not assigned to airborne patrols	Imaging within airborne patrol period (Synchronised with other airborne patrols)	Sufficient for detection, preferable for identification
Coverage Redundancy Support	Survey gaps in the maritime region left by airborne patrols	Imaging right after each coverage gap (Right after airborne patrols)	Sufficient for detection, preferable for identification
Situation Awareness Maintenance Support	Survey spot areas of the maritime region identified by airborne patrols to contain vessels of interest	Imaging spread across time in-between airborne patrol revisits (In-between airborne patrols)	Sufficient for identification with previous imaging data

3. SIMULATION STUDY

3.1. Scenario

A hypothetical maritime surveillance patrol scenario utilising an area of interest (AOI) 300NM deep by 600NM wide region with the upper left corner positioned at 160 degrees longitude on the equator is used for this simulation study. The maritime vessels of interest are small vessels seeking to transit through the AOI from the north.

A set of 11 commercial imaging satellites were simulated in Systems Tool Kit (STK v11.2) for the duration of 1 month (1 Jan 2017 00:00:00 UTC to 1 Feb 2017 00:00:00 UTC) to capture some of the variation caused by the interaction of the differing satellite repeat cycles. The satellites were selected based on their availability to provide direct-access and they include:

- 9 commercial EO imaging satellites (Geoeye-1, Pleiades-1&2, Spot-6&7, WorldView-1&2&3&4)
- 2 commercial SAR imaging satellites (TerraSAR-X, Tandem-X)

The coverage analysis in STK utilised a 0.2 degree resolution grid for the AOI and assumed coverage of the AOI grid points using the field-of-regard (FOR) of the satellites' primary imaging sensor. All subsequent data analysis and processing were performed in Matlab.

Two-line element data for the satellites were sourced from STK data support website and all modelled imaging sensor field-of-regard and imaging mode specifications were obtained from satellite vendor websites.

3.2. Coverage Analysis

The scope of the analysis covered the following:

- Number of satellite passes over AOI per day – this examines the number of potential imaging opportunities per day over any part of the AOI.
- Timing of satellite passes per day – this examines the times when a satellite's sensor field-of-regard covers any part of the AOI.
- Percentage of the AOI within sensor coverage per day – this examines the percentage of the AOI that can fall within the sensor field-of-regard of one or more satellites within the day.
- Percentage of AOI imaged per day – this examines the extent to which the AOI can be imaged by satellites imaging as a group.

The analysis ignored data on both 1st Jan 2017 and 31st Jan 2017 to avoid incomplete data due to time zone offset of the AOI location. For EO satellites, only imaging passes during daylight hours were considered. All environmental effects such as clouds and sea states were not considered for this analysis.

4. RESULTS AND DISCUSSIONS

4.1. Satellite Passes per day

The number of satellite passes per day over the AOI by the selected satellites indicates a minimum of 6 passes and maximum of 13 passes with an average of ~11 passes (see Figure 1). Individual EO satellites such as WorldView-1 & 4 each provide normally one daily pass over the AOI, with the exception of 4 to 6 days in the month without a pass (see Figure 2 & Figure 3).

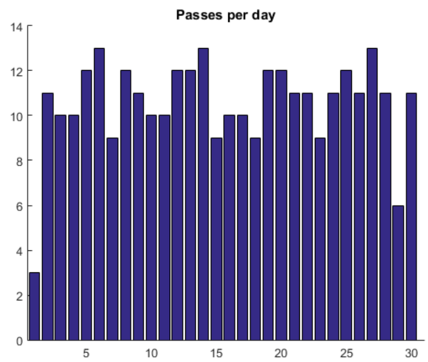

Figure 1. Number of Passes over AOI per day by selected satellites

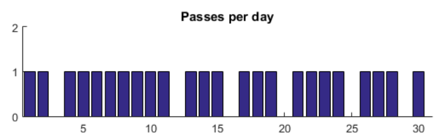

Figure 2. Number of Passes over AOI per day by WorldView-1

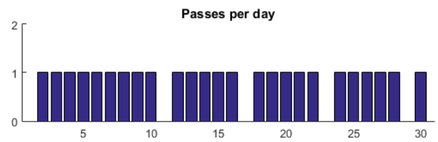

Figure 3. Number of Passes over AOI per day by WorldView-4

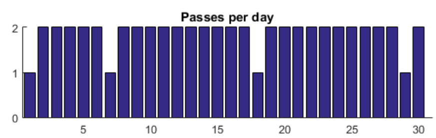

Figure 4. Number of Passes over AOI per day by TerraSAR-X/Tandem-X

Individual SAR satellites such as TerraSAR-X and Tandem-X each provide normally two daily passes over the AOI, with the exception of 3 days where only one daily pass is provided (see Figure 4).

4.2. Timing of Satellite Passes over AOI

The visualisation of the timing of daily passes over the AOI for the selected satellites shows four distinct timings groups (dawn, mid-morning, afternoon and dusk) as shown in Figure 5. The majority of EO satellite passes over the AOI are clustered around mid-morning. WorldView-1 is the exception with passes occurring in the early afternoon due to a planned orbit shift that completed in mid-2016. The SAR satellite passes over the AOI occur around dawn and dusk periods.

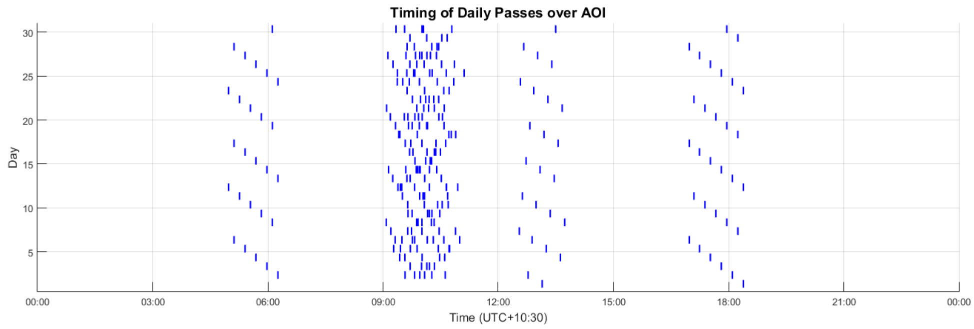

Figure 5. Timing of Satellite Passes for all selected satellites

4.3. Percentage of AOI within Sensor Coverage per Day

The daily percentage of AOI within sensor field-of-regard (FOR) coverage by the selected satellites shows that on most days any part of the AOI can potentially be imaged by at least one satellite (see Figure 6), with the exception of several days below ~85% coverage of the AOI. For individual EO satellites such as WorldView1&4, the coverage percentages vary cyclically from 0 to 95% from day to day (see Figures 7 & 8). Comparatively, individual SAR satellites such as TerraSAR-X & Tandem-X achieves slightly higher percentages varying cyclically from 10% to 98%, due in part to twice the daily imaging passes of individual EO satellites (see Figure 9).

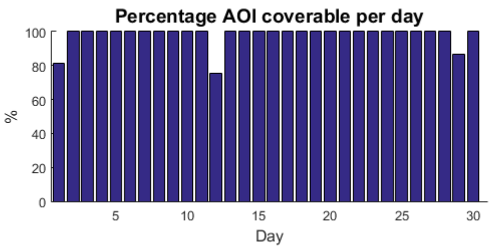

Figure 6. Daily % of AOI within sensor FOR coverage by selected satellites

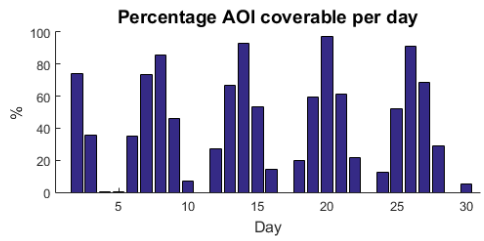

Figure 7. Daily % of AOI within sensor FOR coverage by WorldView-4

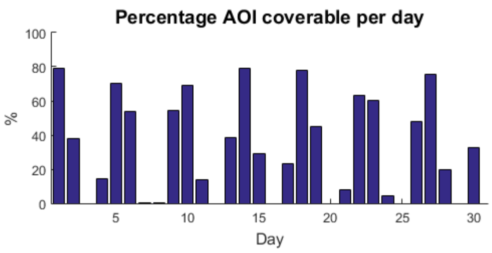

Figure 8. Daily % of AOI within sensor FOR coverage by WorldView-1

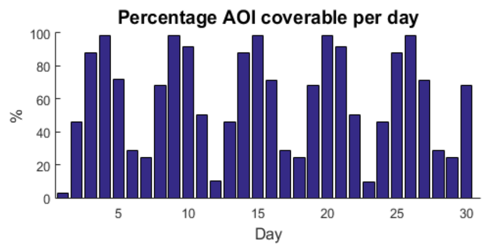

Figure 9. Daily % of AOI within sensor FOR coverage by TerraSAR-X/Tandem-X

4.4. Percentage of AOI Imaged per Day

We used the morning group of EO satellite passes to investigate the extent of AOI that can be imaged. For simplicity, we assumed each EO satellite pass utilises a high-resolution multi-strip imaging mode providing a fixed rectangular imaging boundary that can be shifted within the satellite sensor's field-of-regard. A sequential single-pass greedy algorithm was used to allocate each satellite's imaging coverage to provide indications on how much of the AOI can be realistically imaged. An example allocation of the morning group of eight EO satellites achieving ~37% AOI imaged on day 20 is shown in Figure 10. The percentage of AOI imaged for each day is similarly estimated and shown in Figure 11 with the average AOI coverage of ~25%.

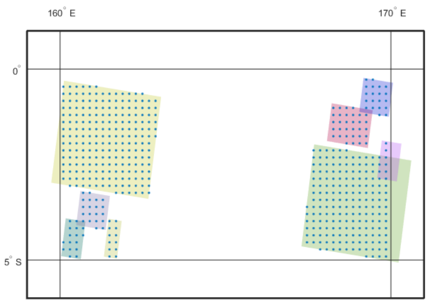

Figure 10. Example allocation of morning EO satellites' imaging to AOI on Day 20

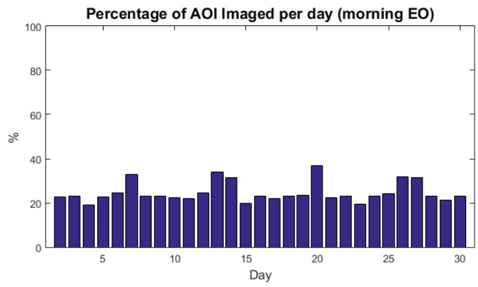

Figure 6. Daily Percentage of AOI imaged by morning group of EO satellites

4.5. Feasibility for Supporting Airborne Maritime Patrols

Based on the results of the satellite coverage analysis, we offer suggestions on how the selected satellites can support each of the four proposed roles and discuss some of the challenges.

Mission planning support role

For the mission planning support role, imaging will need to occur prior to the airborne mission planning process. The gap between satellite imaging and the aircraft flight should be kept to a minimum to reduce the potential vessel movement. For example, the timing of the daily SAR satellite passes at dawn can suit airborne patrols that begin operation in the morning.

The specific area of the AOI that will be covered by a SAR satellite (at dawn or at dusk) can vary from day to day, so the utility of the role will vary accordingly.

The large numbers of daily morning EO satellites passes provide on average around a quarter of the AOI coverage on a regular basis.

The afternoon EO satellite passes are more limited in their potential coverage due to there being only one satellite in the chosen set.

In practical terms, the support from satellites under this role is best suited to airborne patrols that begin operation just after the dawn or dusk SAR passes or after the morning EO passes.

Coverage provider role

For the coverage provider role, imaging will need to be synchronised around the timeframe of the airborne patrols.

Airborne patrols that operate at dawn, morning, afternoon and dusk periods can exploit the availability of satellite passes during these periods. As in the previous section, the extent of AOI coverage provided by the available satellite passes can vary within the different timing periods. The morning period with large numbers of EO satellite passes can potentially support coverage of a quarter of the AOI on a daily basis. The dawn, dusk and afternoon periods with limited EO or SAR satellite passes is constrained on which day and which part of the AOI can be supported.

A challenge will be how to best stitch coverage from the various satellites together with the aircraft coverage. To take most advantage of the satellite contribution, the location of the aircraft search area will need to be adjusted for each patrol.

Coverage Redundancy support role

For the coverage redundancy support role, imaging will need to occur after the airborne surveillance coverage gaps arise. As the timing may not be predictable upfront, airborne patrols will need to be scheduled such that the latter part of the airborne mission is aligned with the timing of available satellite passes.

The timing of the morning EO satellite passes is suitable for early morning airborne patrols. The large number of satellite passes can provide maximum flexibility to support coverage gaps in any part of the AOI.

The satellite passes at dawn, afternoon and dusk, can be utilised by airborne patrols scheduled around these periods but the limited numbers of satellite passes will constrain their support to only parts of the AOI. Airborne patrol routes that place the latter part of their planned route to match the coverage of the available satellite passes can also improve the utility of this role.

In this use case, the satellites act as a reserve and may not necessarily be utilised. It may be possible to combine this role with the coverage provider role at the same time.

Situation Awareness Maintenance Support

For the situation awareness maintenance support role, imaging will need to spread across time in a manner that ensures the positions of vessels of interest can be re-acquired.

The timing of available EO satellite passes in the morning and afternoon as well as the SAR satellite passes at dawn and dusk can provide a spread of imaging opportunities over the day.

The morning group of EO satellite passes offers the most opportunity to monitor vessels of interest on a daily basis, covering most of the AOI. The afternoon EO satellite pass can provide a single situational awareness update on an irregular basis with constraints on AOI coverage. The SAR satellite passes at dawn and dusk can provide situational awareness updates on a daily basis with constraints on AOI coverage.

5. SUMMARY AND CONCLUSIONS

The daily satellite passes from the selected set of direct-access capable commercial EO and SAR satellites fall within four distinct timing groups. The bulk of the selected EO satellites provide imaging opportunities that are clustered in the morning period. WorldView-1 is the only EO satellite to provide imaging opportunities in the afternoon period. The two SAR satellites provide imaging opportunities during dawn and dusk periods.

The preliminary results indicate that the selected satellites have the potential to support each of the four proposed support roles to airborne maritime patrols but only opportunistically due to the limited numbers of satellites and the constrained timings of available imaging opportunities. Correctly sizing the AOI and the need for tight integration in mission planning between satellites and airborne patrols will be essential. The increasing entry of multiple low-cost high-performance small satellites into the commercial imaging market will improve the feasibility of the roles.

Future work will look at modelling detailed multi-satellite & airborne mission planning to improve our understanding of the feasibility of each proposed role and to identify any challenges in implementation.

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