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THESIS

**ENHANCING ARCTIC SURVEILLANCE WITH
SPACE-BASED RADARS**

by

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June 2013

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**ENHANCING ARCTIC SURVEILLANCE WITH
SPACE-BASED RADARS**

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ABSTRACT

Recent evidence suggests that there are increasing levels of maritime activity in the Arctic Circle which requires new methods for meeting the Arctic maritime information needs of the United States and allies. Information needs are particularly acute in the most critical areas of the Arctic for the United States such as the U.S. Exclusive Economic Zone. Because the Arctic environment is inhospitable to lower atmosphere intelligence, surveillance, and reconnaissance methods with which to gather information, space-based surveillance such as synthetic aperture radar sensors are likely the best way to meet ever-increasing Arctic information needs. Modeling and Simulation was employed to determine a practical constellation design of space-based radars to remotely sense the totality of the Arctic Circle and the portion of the U.S. Exclusive Economic Zone that lies within it. Analysis of single orbital plane, Walker, and custom constellation designs determined that a constellation of three sensors strikes a balance between coverage and efficiency for Arctic surveillance. A constellation of radar sensors in sun-synchronous orbits with ascending node spacing of 50 degrees apart achieved optimality in coverage time, efficiency, and consistency in sequential 24-hour intervals.

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LIST OF DEFINITIONS, ACRONYMS, AND ABBREVIATIONS

Definitions

Access: visibility of one object from another object. For example, when a sensor can be seen from a point on the Earth (access does not necessarily imply that the sensor is collecting data) (Analytical Graphics Incorporated, 2006).

Altitude: the height above the surface of the Earth (Sellers, 2005).

Arctic Circle: the parallel of latitude that runs 66°33'44" (or 66.5622°) north of the Equator (Arthropolis, 2008).

Backscatter: the microwave signal reflected by elements of an illuminated scene from emitted radar energy back in the direction of the radar (Canada Centre for Remote Sensing, n.d.).

Bandwidth: a measure of the span of frequencies available in a signal distribution or the frequency limits of a system (Canada Centre for Remote Sensing, n.d.).

C-band: frequency band often used by synthetic aperture radar energy that has wavelengths at or near 5.6 cm (Canada Centre for Remote Sensing, n.d.).

Coverage: access among a group of assets (such as sensors in space) to a grid of points or area of Earth about which a sensor can collect data (Analytical Graphics Incorporated, 2006).

Dawn-to-Dusk Orbit: an orbit in which the satellite's orbital plane coincides with the plane that divides half of the Earth which is illuminated by the Sun from the half that is dark. This angle between the satellite and the sun remains constant for the duration of the satellite's life (Canada Centre for Remote Sensing, n.d.).

Detection (in context of radars): processing state at which the backscatter strength is measured for each pixel value of the detector (Canada Centre for Remote Sensing, n.d.).

Deterministic model: a model or simulation that will produce repeatable and consistent results (Rainey, Cloud & Crumm, 2004).

Digital Number: A number, between zero and 255 for example, assigned to each spatial grid position in the file representing the brightness levels of an image (Canada Centre for Remote Sensing, n.d.).

Duty Cycle: the use timeline for individual components of a satellite bus or payload (Sellers, 2005).

Exclusive Economic Zone (EEZ): the ocean surface and sub-surface area that extends seaward 200 nautical miles from the coastline of a nation (U.S. Navy, 2007).

Incident angle: angle between the line of sight of radar to an element of an imaged scene and the vertical direction characteristic of the scene. The larger the incident angle, the farther the viewing line of sight is away from the sensor nadir (Canada Centre for Remote Sensing, n.d.).

Inclination: the tilt of spacecraft orbital planes relative to the equatorial plane of the Earth (Sellers, 2005).

Low Earth Orbit: Circular or near-circular orbits with altitudes above the Earth's surface up to approximately 620 miles (1000 km) (Sellers, 2005).

Nadir: locus of points on the surface of the Earth directly below the radar as it progresses along its line of flight (Canada Centre for Remote Sensing, n.d.).

Objective function: the performance characteristic that mathematical or linear programming analysis seeks to maximize or minimize (Oxford Dictionaries, 2013).

Orbit height: the distance from the center or surface of the Earth (Sellers, 2005).

Parameter: a set of facts which establishes or limits how something can happen or be done (Cambridge Dictionaries, 2013).

Payload: the part of a spacecraft that performs the mission (Sellers, 2005).

Perennial: having a lifecycle or more than two years; continuing and recurrent (Dictionary.com, 2012).

Polar Orbit: a spacecraft orbit that travels over or near the North and South Poles of the Earth (Sellers, 2005).

Polarization: the orientation of the electric field as it is transmitted or received at a radar antenna. The electric field can be transmitted and/or received horizontally (H) or vertically (V). The four modes are (HH), (VV), (HV), and (VH) (Canada Centre for Remote Sensing, n.d.).

Radar: a sensor capable of transmitting and receiving microwave signals that can observe the strength and the time delay of the return signals (Canada Centre for Remote Sensing, n.d.).

Radar imaging resolution: the limit (in distance on the surface of the Earth) at which the sensor can differentiate objects detected from backscattered energy (Olsen, 2007).

Retrograde: a spacecraft moving in the opposite direction of Earth's rotation (westerly direction). A spacecraft in retrograde orbit has an inclination greater than 90 degrees but less than 180 degrees (Sellers, 2005).

Right Ascension of the Ascending Node: from a geocentric origin perspective, describes how an orbital plane is rotated in space with respect to the orbiting body's vernal equinox. It is a description of how an orbital plane is *twisted* longitudinally around the Earth (Sellers, 2005).

Satellite bus: the part of the spacecraft that performs the functions necessary for the payloads on the spacecraft to operate. Bus functions typically include power production and distribution, temperature control, data processing and storage, orientation control, and structural integrity (Sellers, 2005).

Satellite constellation: a collection of cooperating spacecraft (Sellers, 2005).

Field of view *or* swath width: linear width or diameter area of Earth the sensor can see (Sellers, 2005).

Spotlight mode: radar imaging mode in which the antenna pattern illuminates only a small area as the antenna passes overhead. The result is relatively fine resolution (Canada Centre for Remote Sensing, n.d.).

Sun-synchronous Orbit: retrograde, low-Earth orbits (LEO) typically inclined 95 to 105 degrees (Sellers, 2005).

Synthetic Aperture Radar: A type of radar that can produce images by transmitting radar pulses and recording the level of interaction with targets. The signal data is accumulated from strips of the surface that are illuminated both parallel and to the side of the flight direction. This azimuth and range digital signals are processed to focus the image thereby obtaining a higher resolution than can be achieved by conventional radar (Canada Centre for Remote Sensing, n.d.).

Telemetry: payload and spacecraft health and status information that ground-based space mission controllers receive (Sellers, 2005).

Temporal coverage: the duration of time that a sensor acquires data on the area of interest (Olsen, 2007).

Vernal equinox: the reference point found by drawing a line from Earth to the Sun on the first day of spring (Sellers, 2005).

Walker constellation: a constellation of satellites with multiple orbital planes (and possibly multiple satellites in each plane) of the same inclination but rotated about the pole with regular and equidistant right ascension of ascending nodes (Ellis, Mercury & Brown, 2012).

ACRONYMS AND ABBREVIATIONS

AIS	Automated Information System
AoA	Analysis of Alternatives
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CSA	Canadian Space Agency
DHS	Department of Homeland Security
DoD	Department of Defense
EEZ	Exclusive Economic Zone
EO	Electro-optical
FOM	Figure of Merit
FOV	Field of View
GHz	Gigahertz
GMTI	Ground Moving Target Indicator
IMO	International Maritime Organization
IR	Infrared
ISA	Italian Space Agency
ISR	Intelligence, Surveillance, and Reconnaissance
LEO	Low Earth Orbit
MHz	Megahertz
MODU	Mobile Offshore Drilling Unit
MOP	Measure of Performance
M&S	Modeling and Simulation
NATO	North Atlantic Treaty Organization
NM	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
NSC	National Security Cutter
NSSS	National Security Space Strategy
RAAN	Right ascension of the ascending node
RADAR	Radiofrequency Detection and Ranging
RCM	RADARSAT Constellation Mission (Canada)

SAR	Synthetic Aperture Radar
SBR	Space-Based Radar
STK	Systems Took Kit
UAV	Unmanned Aerial Vehicle
VMS	Vessel Monitoring System

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I. THE STRATEGIC IMPERATIVE FOR ARCTIC AWARENESS IN THE 21ST CENTURY

A. NATIONAL SECURITY AND THE ARCTIC

Increasingly common human activity in the maritime regions of the Arctic poses significant challenges for U.S. government executive branch departments charged with acting upon U.S. interests, legal frameworks, and national policy objectives. In the Arctic, the ability to focus finite resources among myriad existing and potential threats and hazards has become imperative as government resources become increasingly constrained and rely heavily on information to complete missions effectively and with minimal risk. The need for an information advantage in the Arctic has never been greater for the U.S. Department of Defense (DoD) and its executive agent for high latitude issues (U.S. NORTHCOM). The same can be said for the U.S. Department of Homeland Security (DHS) as the U.S. Coast Guard seeks to perform its duties in Arctic waters with little recent precedent for sustained missions in that part of the world.

Growing evidence suggests that activities that affect the Arctic maritime environment such as shipping, hydrocarbon extraction, fishing, and tourism activities (to name but just a few) are increasing in frequency, duration, and intensity and will continue to do so for the foreseeable future; particularly if perennial Arctic sea-ice continues to recede consistent with recent history (Office of Undersecretary of Defense for Policy, 2011). For government agencies that have responsibility (either through national policy objectives established by executive branch authority or federal statute) to respond and operate on, under, and above the Arctic waterways, possessing sufficient information, capacity, and capability to safely perform missions in the Arctic maritime environment are critical imperatives (Office of Undersecretary of Defense for Policy, 2011).¹

Given the harsh environmental conditions likely to be encountered above the Arctic Circle (notwithstanding the prospect of warmer temperatures and receding sea-ice

¹ U.S. Government agencies that typically have either or both executive branch authority and/or statutory responsibility and access to assets to carry out missions in the Arctic include the NORTHCOM Combatant Command of the Department of Defense and U.S. Coast Guard of the Department of Homeland Security.

in the future), it is clear that the Arctic will be a challenging area in which to operate military assets and therefore a timely and complete understanding of Arctic activities by DoD and DHS is paramount. Analysis of detected activity that informs strategic to tactical decisions regarding potential response options, resources, infrastructure investment, risk-mitigation, and related decisions begins with persistent, near-real time detection of activities in the Arctic regions of primary concern to the United States (Office of Undersecretary of Defense for Policy, 2011). Without continuous, regular, and accurate detection of maritime activities in the Arctic Circle ranging from relatively benign tourism ventures to adversary naval combatant maneuvers, the United States' ability to make well-informed strategic to tactical decisions is degraded.

As a natural extension of its strategic importance, the Arctic is clearly becoming a significant investment priority for U.S. executive branch departments and agencies. While national policies have begun to take shape from the recognition of an increasingly contested and disputed yet more navigable and habitable Arctic region, the operational and tactical level importance for the U.S. Armed Forces to possess the information, capability, and capacity to operate in the Arctic has rose commensurately. The U.S. Navy instituted an Arctic Roadmap to address such needs in 2009 to ensure plans of action and milestones were established for fiscal years 2010 to 2014. One focus area of the roadmap was investments in Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR). The Navy considered this focus area important for achieving a broad array of effects needed in the Arctic so that the right capability can be provided to the relevant Combatant Commander in support today's and tomorrow's strategic objectives in the Arctic (Greenert, 2009).

The DoD, through the NORTHCOM Combatant Commander, has made the Arctic region a key focus area. NORTHCOM predicts its responsibilities to offer support to search and rescue, law enforcement, humanitarian assistance/disaster response in the Arctic regions will steadily rise in the coming years (U.S. Northern Command Posture Statement, 2011). The U.S. Coast Guard, an agency of DHS, is facing even greater urgency to sustain operations in the Arctic. The Coast Guard has statutory responsibility to perform icebreaking, search and rescue, environmental protection, fisheries

enforcement, aids to navigation management, vessel safety, and waterways security in the Arctic maritime environment and particularly the littorals adjacent to U.S. territory. This responsibility includes but is not limited to the maritime Exclusive Economic Zone (EEZ) of the United States extending outward to 200 nautical miles from the coastline of Alaska (U.S. Coast Guard, 2009).

The U.S. Coast Guard is operating in Arctic waters today on sparse information in a compressed or arguably non-existent strategic planning time horizon. For agencies such as the Coast Guard, changing environmental conditions and activity levels in the Arctic is beyond strategically important with merely long-term implications. Arctic maritime information, capabilities, and capacities are important operationally and tactically right now (Papp, 2012). In 2012, the U.S. Coast Guard deployed one of its newest assets, the National Security Cutter (NSC), to the Arctic to provide capability for statutory missions such as search and rescue, fisheries enforcement, environmental protection oversight, vessel safety, and waterways security. This was necessary as exploratory drilling for hydrocarbons off the North coast of Alaska began in earnest (Papp, 2012). The importance of the Arctic to the U.S. Coast Guard is evident in its most recent posture statement:

The FY [fiscal year] 2013 Budget Request recognizes the criticality of the Arctic as a strategic national priority, given increasing presence and interest by other nations, the preponderance of natural resources available in this region, and increasing maritime commercial and recreational activity. (Papp, 2012)

To further illustrate the Arctic imperatives for the U.S. Coast Guard and the whole of U.S. government, the Coast Guard recently embarked on a new polar icebreaking asset capitalization program to prepare for increasing Arctic operational presence and mission requirements. This recapitalization has begun despite a budget that is flat or declining (Papp, 2012). As the need to build and deploy more icebreakers in support of Arctic operations demonstrates, the distances and conditions involved with performing military missions in the Arctic with ships and aircraft are very challenging. The successful case for more icebreaking capacity demonstrates the anticipated and growing complexity of future maritime operations in the Arctic environment. The

corollary to increasing complexity of Arctic maritime missions for the U.S. Armed Forces, particularly in the North Slope of Alaska in the U.S. EEZ, is that they are likely to require extensive planning owing to the limited military support infrastructure. Arctic missions will by their very nature be resource and personnel intensive and will involve more risk (Papp, 2012).

B. CHALLENGES IN ARCTIC MARITIME SURVEILLANCE

While there is a growing need to be able to conduct and sustain missions in the Arctic, the United States lacks complete awareness of expanding human activities there (U.S. Northern Command Posture Statement, 2011). Without awareness of human activities such as shipping, tourism, military operations, research and exploration, it is reasonable to assert that gaining an understanding of threats or hazards to the security of the United States and U.S. allies emanating from the Arctic region is unlikely. The relatively infrequent monitoring of the Arctic seas prevents U.S. Government agencies from achieving a decision-advantage through timely detection of sea-borne human activities that pose threats or constitute calamities at highest latitudes of the Northern hemisphere. In the maritime domain of the Arctic, developing capabilities that detect threats and hazards to focus necessary mitigation efforts in this harsh polar environment has never been more important (National Research Council, 2010). Better Arctic surveillance is particularly important for areas that are vital to U.S. sovereignty such as the EEZ surrounding Alaska where a U.S. Government response is most necessary and likely to occur in response to emergent hazards or threats. Current sensors are insufficient and sub-optimized to completely fulfill critical U.S. and allied government information needs relating to detection and characterization of maritime activity above the Arctic Circle.

C. HYPOTHESIS AND RESEARCH QUESTIONS

1. Optimizing a Space-Based Synthetic Aperture Radar Constellation for the Arctic

With current single payload commercial space-based radar systems offering limited coverage of the Arctic, one viable solution to remedy surveillance shortfalls in the

Arctic is a dedicated constellation of Synthetic Aperture Radars (SARs) to monitor the Arctic from space. The capabilities of space-based Synthetic Aperture Radar appear to match well with the information needs of the DoD and DHS because they provide dual capability for detection of vessels and hydrocarbons on the ocean's surface. These detection capabilities are potentially high-value to U.S. Navy and U.S. Coast Guard missions. Space-based SAR capabilities are not limited to detection of vessels and oil on the surface however. Varying the polarization of transmitted and received SAR waveforms can discern the extent of sea ice and provide indications of wind direction and speed from the roughness of the ocean surface (Olsen, 2007).

Furthermore, we can gain a sense of potential return on investment from current single payload SAR systems. Existing lone RADAR imaging payloads already process collected data and transfer it to vessels operating at sea (Vachon et al., 2000). Near real-time SAR imagery exploitation would be of extraordinary value to U.S. and allied maritime assets and agencies operating in or that are responsible for the Arctic. Although revisit to the Arctic occurs daily for current SAR systems, existing coverage, particularly in the time domain, is not significant for the totality of the Arctic region. Current SAR payloads cannot *persistently* monitor Arctic regions because the limited number of sensors available requires time-latent revisits to areas of interest.

To mitigate this shortfall, a dedicated polar, low Earth (LEO) orbiting constellation of satellites with SAR payloads may prove beneficial in mitigating surveillance shortfalls in the Arctic. A properly designed and dedicated satellite constellation configured to better satisfy U.S. and allied government Arctic information needs may justify development of a future dedicated space-based Arctic surveillance mission. Through illumination of trade-offs among the number of satellites and orbital planes and time available for surveillance of Arctic regions, forthcoming in-depth research and analysis will provide insight into the best constellation design of SAR payloads to close both broad area and focused Arctic surveillance shortfalls. Specifically, multiple SAR payloads will be optimally configured in number and orbital planes within a polar orbiting LEO constellation to maximize coverage performance of the Arctic for both broad and more focused area surveillance. Through understanding the resources

required to achieve an elegant Arctic surveillance solution through SAR sensors, space-based radar (SBR) Arctic surveillance options and investment decisions that must be evaluated in the future are better supported.

2. Research Questions

If the nation accepts the premise that synthetic aperture radars are the best surveillance technology and method for persistent and sustained surveillance of the Arctic, what is the optimal design of a constellation of SAR sensors to achieve the best temporal coverage performance? To answer this question, it must be determined what constellation design of SAR payloads can achieve the best temporal surveillance coverage performance of the Arctic writ large and the Arctic component of the U.S. Exclusive Economic Zone (EEZ)? Will a single orbital plane or Walker Constellation design provide the best coverage performance? If not, what is the most efficient constellation design?

D. LITERATURE REVIEW

Tracking Vessels on the Sea Surface with Space-based RADAR

A comparative review of two kinds of satellite constellation orbital regime models that accounted for trade-offs among revisit time, coverage, and gap-space between satellites found that a space RADAR constellation with 24 or more satellites (a.k.a 24 ball constellation) in 8 different orbital planes was likely to detect (and track with ground moving target indicator (GMTI) capabilities) 6800 surface ship targets traveling at 4 kilometers per hour at 35 degrees North latitude (Pegher & Parish, 2004).

This prior research demonstrates how space-based RADARs; particularly as part of an orbital regime, can be of use in detection of vessels. Detection of vessels transiting the Arctic Circle would be a primary functional capability required by the Department of Defense and Department of Homeland Security for a dedicated constellation of SAR payloads.

Use of Remote RADAR Payloads to Counter Maritime Terrorism

This research helped confirm that RADAR technology offers the capability to agencies that need to detect vessels or other indications of human activity on the ocean's surface—particularly at high latitudes since sensor coverage areas increase as latitude increases. As coverage area increases, the number of payloads required in a constellation to achieve continuous coverage decreases (Singh, 2010). The idea of combining SAR backscatter return geospatial data with Automated Identification System (AIS) was also discussed (Singh, 2010).

While combining AIS with SAR imagery could certainly help *identify* a vessel once a radar return detects a vessel, identification would be limited to vessels over 300 Gross Tons or approximately 100 feet in length (International Maritime Organization, 2012). Notwithstanding the limitations of AIS, combining inferred information from RADAR imagery with AIS data has very interesting implications. Since AIS data is nearly ubiquitous today and increasingly accessible, the combination of SAR geospatial imagery products combined with AIS would greatly enhance the ability to *sort* contacts between the known and unknown in a region of maritime interest such as the Arctic. The ability to sort contacts between those with correlating AIS data and those without would greatly assist reconnaissance assets (fixed/rotary wing, or Unmanned Aerial Vehicles (UAVs)) by enabling those assets to focus on unknowns (contacts or anomalies that are detected but unable to be identified or characterized). Beyond the persistence implied in a constellation of SAR payloads, space-based SAR could reduce risks and costs while increasing efficiencies for Intelligence, Surveillance, and Reconnaissance (ISR) operations. Perhaps nowhere in the world is it more essential to optimize ISR activities than the harsh maritime environment of the Arctic region.

Maritime Uses and Tradeoffs for Space-based Synthetic Aperture Radars

Research in a John Hopkins University technical Journal emphasized the trade-off between resolution and field of view (FOV) or “swath width” of SAR payloads. The authors noted the best modes for vessel detection by SARs were those waveforms having large incidence angles. Decade old Statistics (2000) from the Canadian operated

RADARSAT-1 resulted in a detection rate for vessels of 84% for vessels ranging from 20 to 294 meters (65 to 965 feet). The research noted how RADARSAT-1 was able to detect oil slicks and more frequently, wind speed inferences, from the radar data. Using a transportable satellite receiver, RADARSAT-1 data was able to be processed and disseminated in quality-controlled geospatial information products directly to ships operating at sea in less than an hour on average (Vachon et al., 2000).

Given the reasonable performance for ship, hydrocarbon, and wind detection of RADARSAT-1 as indicated by data that is nearly 12 years old, the prospects for improved performance and capabilities of today's and tomorrow's SAR payloads is good. Acceptable detection capabilities and data transfer rates are key functional requirements that must meet high standards for SAR payloads to be worthwhile to government agencies with a responsibility to operate in the Arctic region.

An Evaluation of the Arctic—Will it Become an Area of Cooperation or Conflict?

Research completed at the Naval Postgraduate School in 2011 sought to predict whether the Arctic was headed for cooperation or conflict among Arctic nations; in particular among the nations of Norway, Russia, Canada, and the United States. The research concluded that while numerous countries with a long history of partnership such as Norway, Canada, and the United States will resolve disputes peacefully through international organizations such as the United Nations (UN), the International Maritime Organization (IMO), or NATO (North Atlantic Treaty Organization), Russia is not altogether predictable with respect to their intentions for dispute resolution (Trent, 2011).

Within this research, which analyzed a fraction of, yet the most significant, stakeholders in the Arctic region, there remains significant ambiguity about the future of the Arctic and how the actors will cooperate or choose to enter conflict among one another. This ambiguity can only be resolved through sustained methods of information collection about the intentions and activities of other nations. Uncertainty about the future actions of Arctic nations above the Arctic Circle, including those regions most vital to U.S. and allied interests, suggests that robust Arctic surveillance capabilities are necessary.

Surveillance of Canada's High Arctic

While multiple technologies are being explored to monitor the northern high-latitudes, SAR payloads offer unique advantages over other space-based surveillance from electro-optical (EO) or infra-red (IR) payloads. SAR surveillance is not inhibited by darkness, weather, or obstructed by clouds. Additionally, even single-payload SARs in LEO and high-inclination (polar) orbits offer daily coverage above 70 degrees north latitude instead of the 2 to 3 day interval coverage at the equator (Forand et al., 2007).

The advantages that SAR payloads offer for the monitoring of high latitudes are clear. Historical evidence indicates that adding payloads to an optimized SAR constellation can exceed daily coverage possibly providing near-real time or continuous access to the Arctic Circle and/or an Arctic area of interest.

Remote Sensing of Ocean Oil-Spill Pollution

As SARs have improved in their capabilities to vary polarization of waveforms, so too has the ability for SARs to detect oil on the ocean's surface. The wide area surveillance that space-based SARs offer coupled with the improvement in oil spill detection performance makes a compelling case for using SARs to detect both intentional and unintentional oil spill events. There is some evidence that suggests it is more cost effective for vessels to risk intentional hydrocarbon discharges at sea than comply with international rules and safeguards to prevent it (Schistad Solberg 2012).

Given the confluence of increasingly frequent transits by oil tankers and drilling operations in the Arctic Circle and that of improved oil spill detection capabilities from space-based SARs, there is a compelling argument that SARs provide needed capability to U.S. agencies responsible for preventing, responding to, and holding responsible parties to account for oil discharges at sea. The oil spill detection capabilities of SARs coupled with their informational capabilities relating to vessel detection and maritime environmental phenomena (wind, waves, and ice) help predict a highly positive operational return on investment for missionization of a SAR constellation.

Arctic Capabilities

The Government Accounting Office publication *Arctic Capabilities* noted the DoD's limited awareness across all Arctic domains because of "distances, limited presence, and the harsh environment." Specifically, the study noted that there is no forum in place to address medium and long-term capability gaps in communications, navigation, and awareness (Government Accountability Office, 2012).

The establishment of a SAR constellation may be what the nation (specifically the DoD and the U.S. Coast Guard) needs to close Arctic awareness gaps that are present. Continuous monitoring would support later investments in communications, navigation, and sensor capabilities as they lead to improved understanding of Arctic activities that would direct and justify further government investment.

Project Catch: A Space-Based Solution to Combat Illegal, Unreported and Unregulated Fishing

Beyond the clear need for the United States and allied agencies to detect vessels in the Arctic associated with hydrocarbon spills and adversary military vessels (among others), is the need to detect vessels illegally fishing. Existing systems such as Vessel Monitoring System (VMS) for overseeing fishing vessels worldwide are largely viewed as inadequate and easily compromised under the best of conditions. Moreover, the satellite systems upon which VMS architectures depend for timely data transfer to government agencies to monitor the status of fishing vessels are weak or non-existent at high latitudes (Detsis et al., 2012).

In the high latitudes about which we are researching the coverage benefits of a SAR constellation, SAR payloads can be part of the solution to the increasingly difficult challenge of countering illegal fishing. Current SARs have limited temporal resolution which will inhibit timely and sustained surveillance of vessels detected or suspected of illegally fishing in Arctic waters (Jha, Levy & Gao, 2008). This challenge of detecting illegal fishing is expected to only grow as more and more water becomes available for marine resource harvesting at higher and higher latitudes. The United States and allied EEZs are especially vulnerable to overfishing that, left unchecked, can deplete fisheries

stocks upon which nations depend. Supporting enforcement of fisheries regulations and treaties at high latitudes is yet another mission area beyond national defense and environmental protection for which SARs are well-suited.

E. BENEFITS OF RESEARCH

In the context that the Arctic is a clear strategic interest to U.S. government policy makers, this research employs state of the art modeling software to assess space-based radar options to cope with Arctic waterway surveillance gaps that have never been more important to U.S. executive agencies that need to protect and serve Arctic maritime interests. Improved Arctic monitoring will help satiate U.S. and allied government's ever-expanding appetites for continuous and weather independent monitoring of Arctic regions. Historical literature suggests Synthetic Aperture Radar (SAR) may be the best weather-agnostic, multi-hazard detection capability for remote sensing above the Arctic Circle that can detect indications of maritime threats and hazards. Improving temporal and spatial resolution of this capability for U.S. and allied stakeholders to near-real time such that decision makers are alerted and can use the information as expeditiously as possible is a critical need to enhance the value of surveillance with SARs. The research seeks to determine how we can best design space-based radar capabilities to meet expanding Arctic information needs. In this way, U.S. and allied policy-making, military, intelligence and myriad other government functions are better able to forge national, strategic, operational, and tactical responses to deal with emerging Arctic waterway challenges. Moreover, better surveillance of the Arctic will help indemnify the United States and U.S. allies against military, environmental, humanitarian, and economic risks. Analytical results will drive recommendations for space architecture mission configuration for both a high interest area in the Arctic (the U.S. EEZ) and the entire Arctic Circle based on optimal space resource requirements discovered through analysis of notional constellations of space-based Synthetic Aperture Radars.

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II. THE ARCTIC AND SPACE-BASED RADAR SURVEILLANCE

A. THE ARCTIC CIRCLE

The Arctic Circle marks the line of latitude where the sun does not completely set or rise for at least one day per year. Figure 1 illustrates the Arctic Circle from the perspective of the North Pole of the Earth (Arthropolis, 2008).



Figure 1. The Arctic with the Arctic Circle line of latitude illustrated (From Arthropolis, 2008).

Historically, maritime regions of the Arctic reaching the shores of Russia, Greenland, Canada, and Alaska were covered with ice in the colder seasons of the year. Figure 2 illustrates that partial or total coverage of water by perennial sea ice above the Arctic Circle has diminished on an average basis over the last 33 years. The extent of ice recession in August 2012 was a new record low since assessments began in 1979. The disappearance of multi-year sea ice in the Arctic has led to increased access to Arctic waters across a range of maritime activities driven by economics (Conley, Toland & Kraut, 2012).

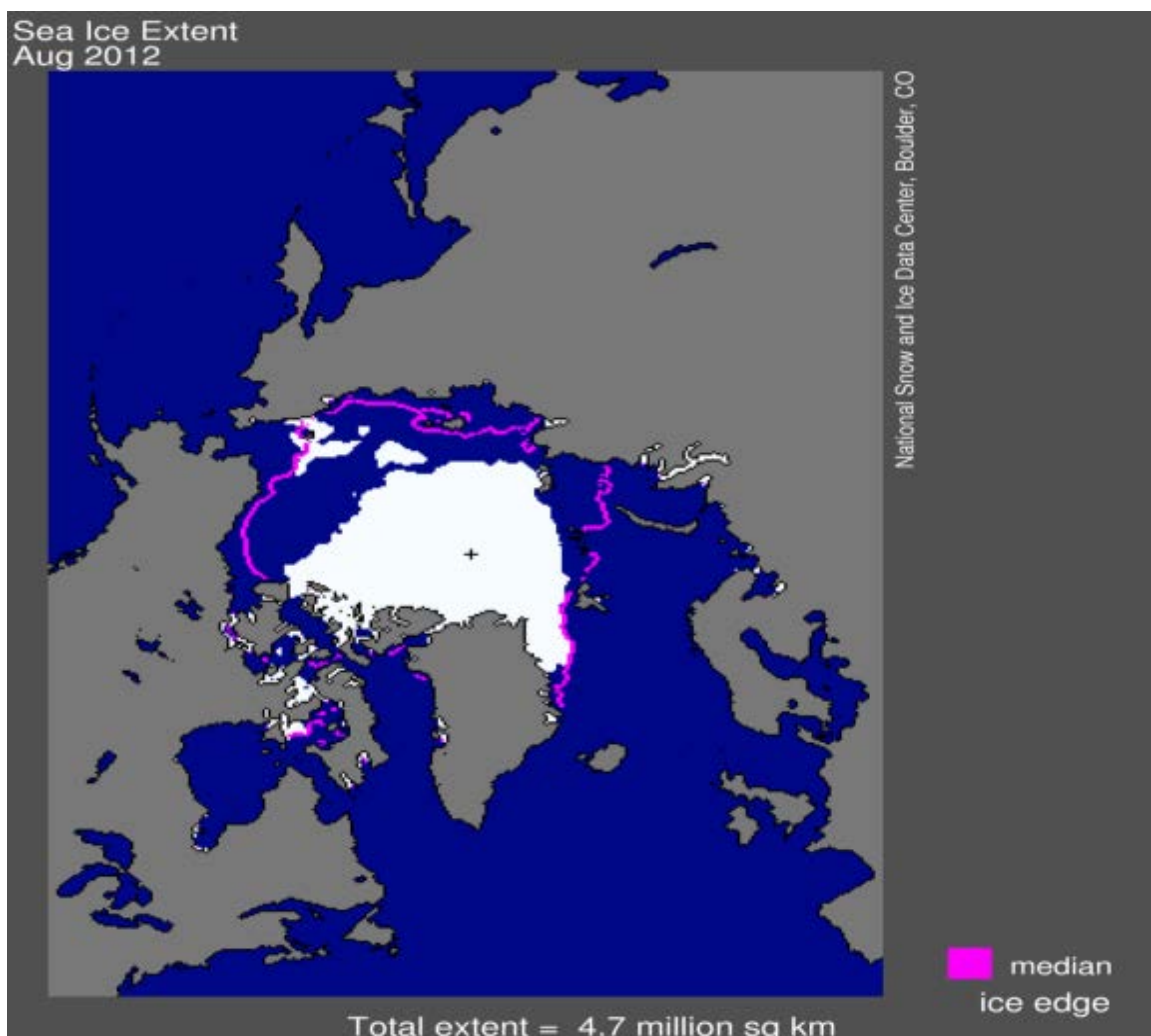


Figure 2. Arctic sea ice extent for August 2012 was 4.72 million square kilometers (1.82 million square miles). The magenta line shows the 1979 to 2000 median extent for that month. (From National Snow and Ice Data Center, 2012).

1. The U.S. Exclusive Economic Zone and the Arctic

Consistent with the Arctic region writ large, the United States lacks continuous surveillance in what is arguably the most sensitive area of the Arctic Circle for the United States. The U.S. Exclusive Economic Zone (EEZ) established in 1983 asserts U.S. sovereign rights to natural resources out to 200 nautical miles offshore from U.S. territory and recognizes other nations' exclusive rights to natural resources under the same framework (U.S. Navy, 2007). The EEZ underpins U.S. Arctic policy objectives and it is where requisite U.S. and international maritime law is enforced. It is the EEZ above the Arctic Circle in which the United States retains the most significant sovereign interests and why the EEZ can reasonably serve as the starting point for obtaining better insight into the increasingly frequent human activity in Arctic waters. Given the U.S. policy framework that places increasing strategic interest and importance in the Arctic, it is a reasonable assertion that maritime domain awareness of the U.S. EEZ above the Arctic Circle has become more important than ever before to U.S. and allied government agencies that are charged with protecting expanding Arctic interests. Figure 3 illustrates the U.S. Exclusive Economic Zone above the line of latitude delineating the Arctic Circle. The U.S. EEZ in the Arctic is bounded in the West by the U.S./Russia International Maritime Boundary, in the East by the U.S./Canada International Maritime Boundary and extends approximately 200 nautical miles seaward from the Alaskan Coast unless an international boundary limits the extension (National Oceanographic and Atmospheric Administration, 2012). The boundaries of the EEZ can be represented by the lines connecting the following coordinates (in degrees and minutes):

- 66 30 N; 169 W (southwest maritime corner that intersects the Arctic Circle)
- 72 48 N; 169 W (northwest maritime corner)
- 74 43 N; 156 34 W (uppermost maritime point in the Beaufort Sea approaching the Arctic Ocean)
- 72 53 N; 137 35 W (northeast maritime point that intersects the U.S./Canada international maritime boundary)
- 69 41 N; 140 56 W (southeast maritime point that intersects the land border between Alaska and Canada)

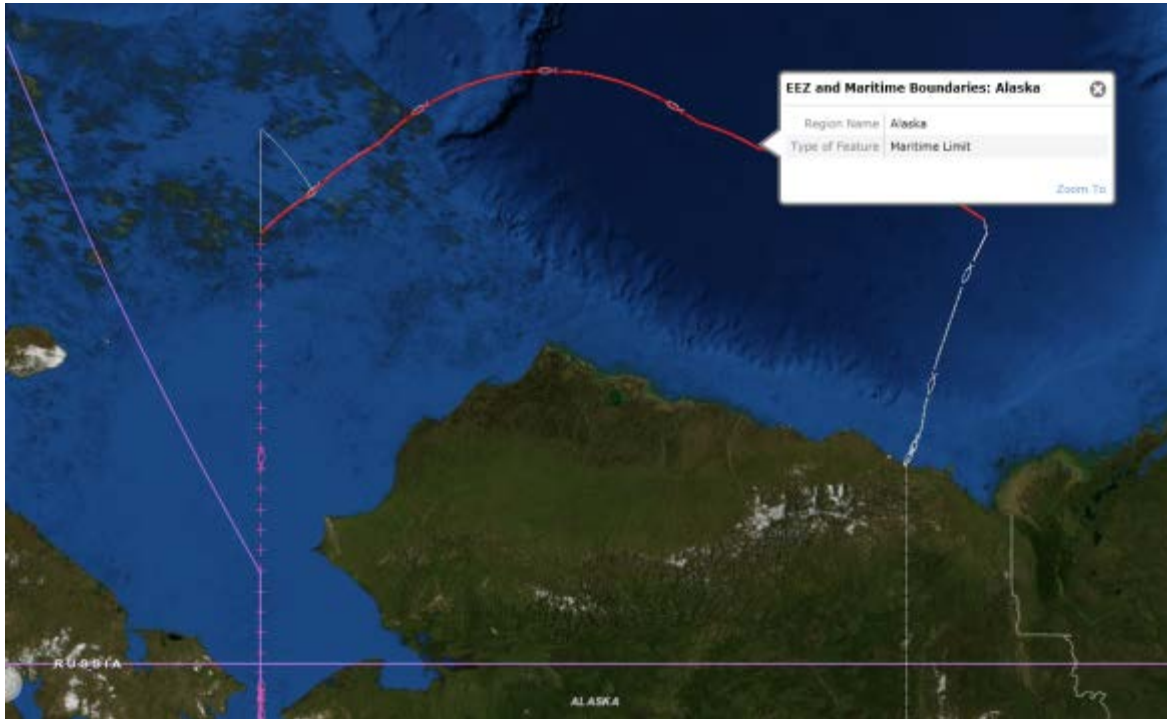


Figure 3. The U.S. Exclusive Economic Zone (EEZ) above the Arctic Circle line of latitude (From National Oceanic and Atmospheric Administration, 2012).

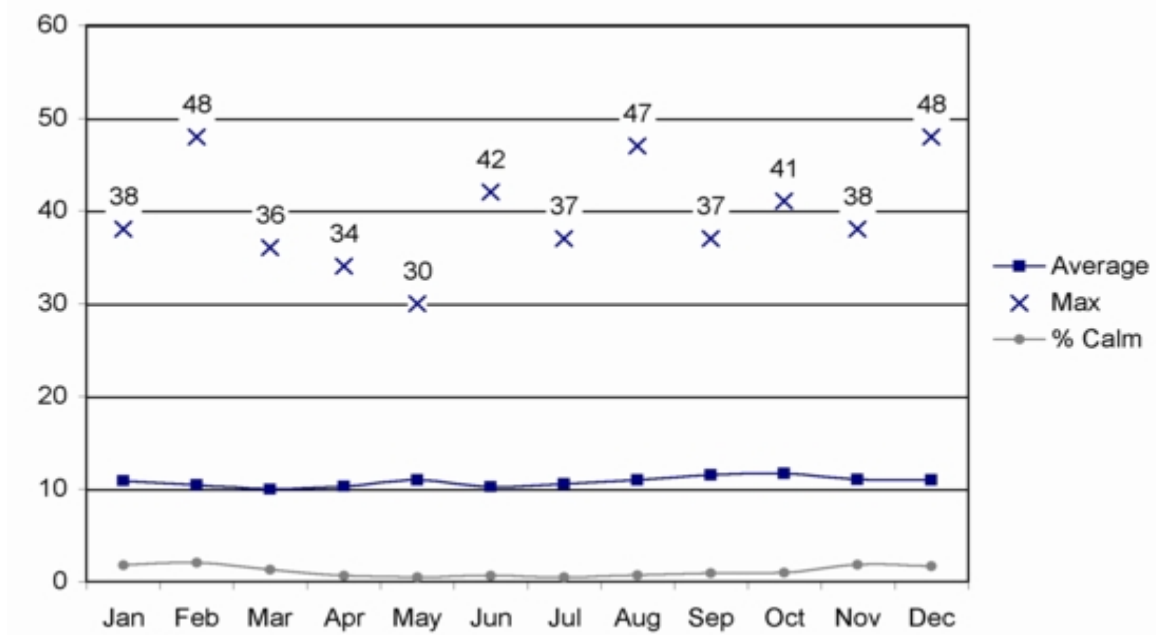
B. THE ARCTIC OPERATIONAL ENVIRONMENT

In the maritime environment of the Arctic in which U.S. and allied forces must conduct missions aboard ships and aircraft, information about weather conditions and natural hazards are critical for managing operational risk. Timely environmental information in this region is essential for saving lives, preventing undue hazarding of equipment, and providing insight to support difficult cost-benefit analyses faced by decision-makers fulfilling their duty to respond. In the harsh Arctic environment, there will almost certainly be times when tactical assets are unable to perform needed intelligence, surveillance, and reconnaissance (ISR) activities due to wind, waves, or temperatures exceeding safe operational limits; lack of resource availability; or the totality of risk factors exceed what is deemed acceptable by policy and/or decision-makers. A space-based, all-weather, day or night, persistent monitoring capability other

than personnel and equipment intensive aircraft and ship sorties may reduce or eliminate some manned tactical ISR activities along with the attendant risk these operations require.

1. Environmental Conditions in the U.S. EEZ above the Arctic Circle

While temperatures can be characterized as mild in the maritime region of Alaska's North Slope relative to areas near the North Pole, weather conditions remain extremely harsh in the EEZ. Since the EEZ is less likely to be ice covered than areas near the North Pole, the weather is arguably more challenging as military assets, particularly surface vessels, would often face an ice-free environment where ocean currents and wind driven waves are environmental factors with which they must contend in addition to freezing temperatures. Figure 4 shows mean wind speeds in mile per hour (mph) at Barrow, Alaska (the northernmost population center in the United States from which the EEZ extends 200 nautical miles (nm) toward the Arctic Ocean) from data samples taken over a period of nearly three decades. Merely 1 percent of the calendar year are winds considered calm at Barrow. The mean wind speed is nearly 10 mph throughout the year while maximum wind speeds approach 50 mph (Alaska Climate Research Center, 2000). Moreover, the persistence of the wind along with stretches of high-speed wind can generate waves and swells that make the lower maritime reaches of the Arctic challenging if not impossible to operate surface and air platforms. Even if there existed infrastructure from which to support personnel intensive air and surface ISR assets, the Arctic maritime environment would severely hinder ISR assets if not prevent the sorties required to be effective; particularly for assets which have fatigue, duration, sensor, and speed limits that make surveillance of even a portion of the Arctic region such as the EEZ impractical under the best of environmental conditions.



Annual percentage of calm and non-calm observations	Non-Calm
1%	99%

Figure 4. Mean and maximum monthly wind speed (mph) and percent of calm observations for Barrow, Alaska (From Alaska Climate Research Center, 2000).

Figure 5 shows the mean daily low temperatures in Barrow, Alaska. The mean daily low temperature average is below zero degrees Fahrenheit annually from November to April. While average temperatures are milder from May to October, annual precipitation is greatest (Alaska Climate Research Center, 2000).

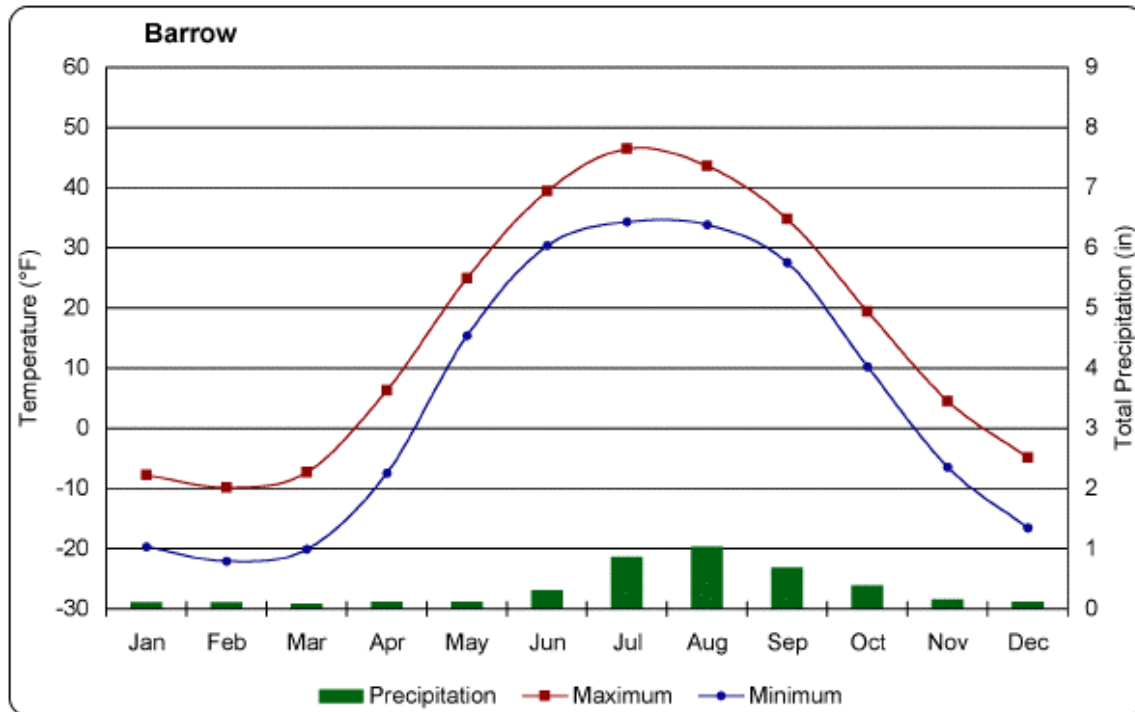


Figure 5. Mean maximum and minimum temperature and precipitation levels for the northernmost population center (Barrow) of Alaska's North Slope (From Alaska Climate Research Center, 2000).

C. REMOTE SENSING WITH RADARS

Space-based Synthetic Aperture Radars payloads (SARs) have proven their worth in supporting policy, diplomatic, security, military, scientific and economic decisions made in the course of projecting national maritime power and the resultant theatre actions. Equally useful, SAR payloads that can sense Arctic regions can help focus and tailor response actions by U.S. agencies operating in the vast and environmentally harsh Arctic realm. If SAR payloads can be operated from space in creative ways that minimize cost while maximizing coverage of an area of concern, U.S. government policy-makers, intelligence agencies, military forces, and researchers are better postured with the information required to support convicted decisions and actions in the Arctic frontier. Figure 6 depicts state of the art SAR payload components (the Canadian RADARSAT-2) and the satellite bus that supports them. Figure 7 illustrates current Synthetic Aperture Radar payloads on orbit over a portion of the Earth.

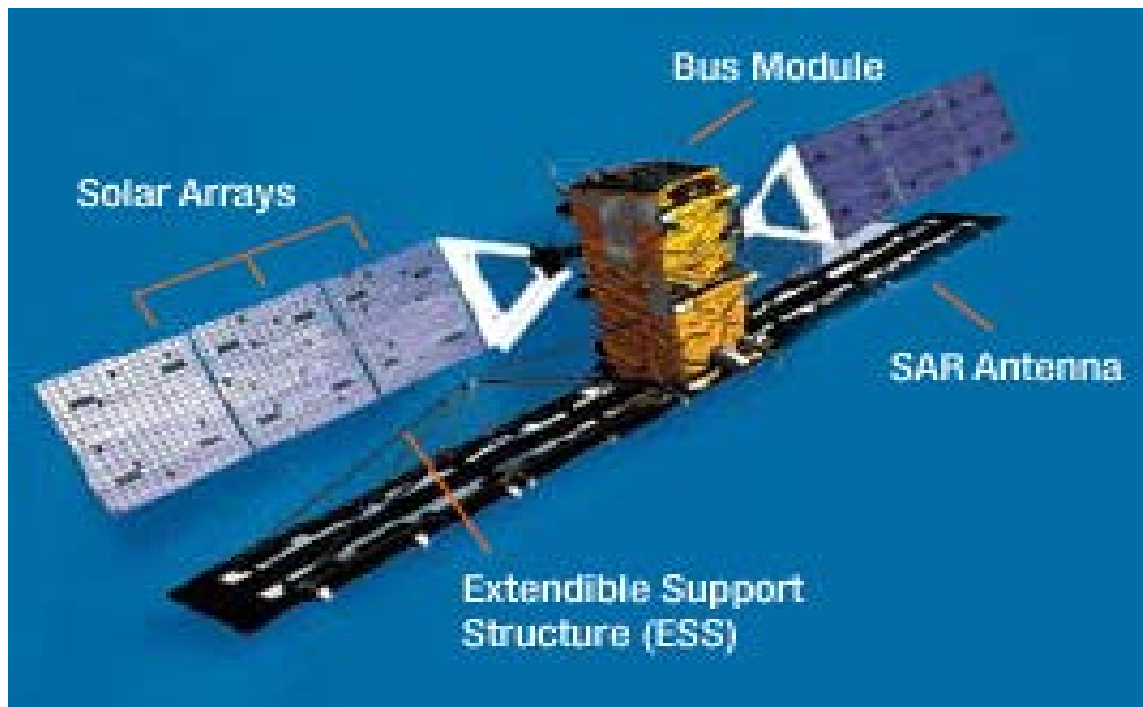


Figure 6. An illustration of the state-of-the-art in SAR technology: the Canadian RADARSAT-2 (From Canadian Space Agency, 2007).

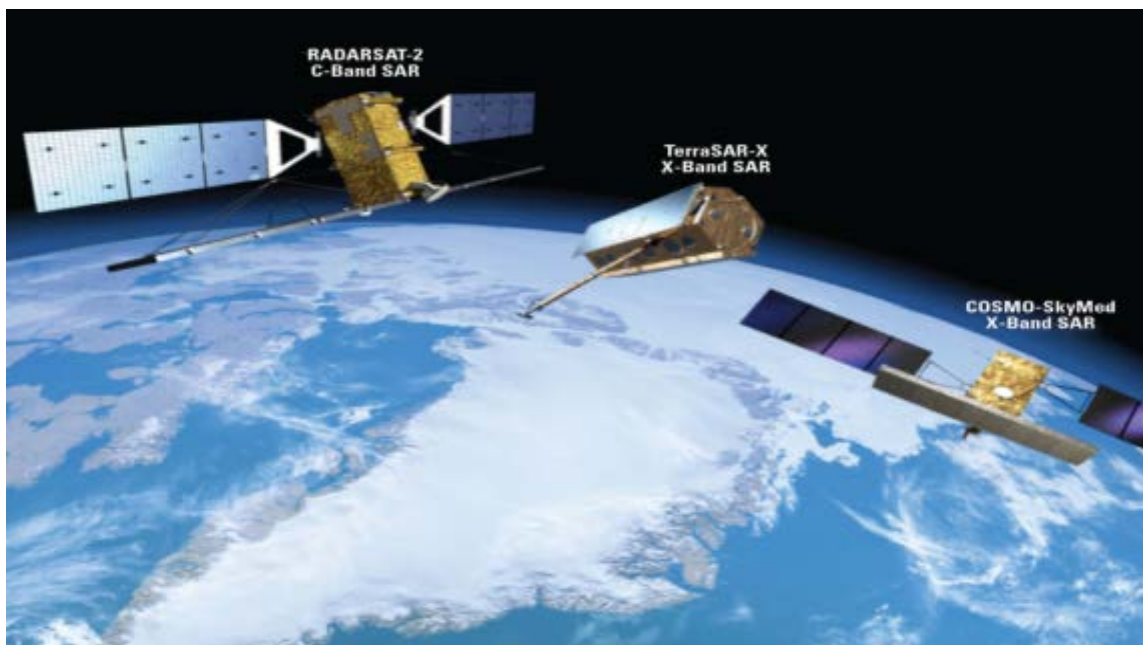


Figure 7. Depictions of SAR payloads currently orbiting the Earth (From Belton, 2012).

1. Space-Based Synthetic Aperture Radar Capabilities

a. Maritime Conveyance Detection

Advances in RADAR technology have enabled SAR payloads to detect boats with lengths as small as 1.5 to 3.5 meters (Da Silva, 2001). While identification of a vessel is not always certain from remote RADAR imagery analysis, the wakes of vessels are detectable at times which can provide indications of vessel course and speed (Olsen, 2007). Though data for identification and location of large vessels exists (such as that from the Automated Identification System (AIS)) which can provide the identity and location of large commercial vessels transiting around the globe), AIS is generally limited to vessels over 300 gross tons (equates to roughly 30 meters or 100 feet in length) (International Maritime Organization, 2012). So, while AIS may help with awareness of commercial vessels in the Arctic waterways, AIS data cannot provide insight to activities beyond large commercial vessels engaged in shipping. The need to detect vessels smaller than 30 meters, foreign military combatants or other government vessels, and mobile offshore drilling units (MODUs) that are not subject to AIS regulations are also key information requirements for the U.S. government agencies. Detecting these maritime activities through SAR payloads monitoring the Arctic are critical elements of information for decision support relating to asserting U.S. jurisdiction and protecting U.S. sovereign interests. Figure 8 shows a processed SAR image that produced returns from numerous contacts in the Straits of Gibraltar. SAR imagery is also capable of showing the wakes of vessels from which inferences about course and speed can sometimes be made (Ball, 2012).

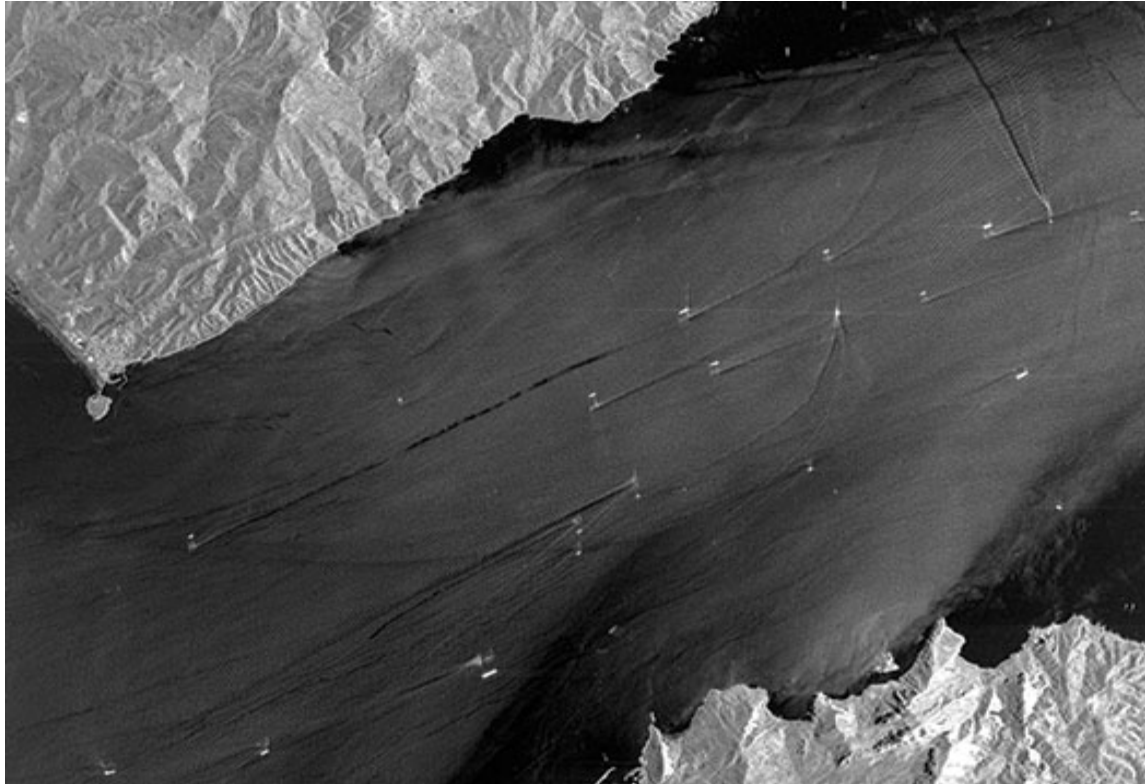


Figure 8. A processed synthetic aperture radar image of vessels and their wakes near the Straits of Gibraltar (From Ball, 2012).

b. Hydrocarbon Spill Detection

Additionally, SARs provide capability to detect hydrocarbons on the surface of the ocean (Olsen, 2007). This capability becomes particularly relevant since oil companies have started preparations (as of summer 2012) for hydrocarbon extraction on Alaska's North Slope (Joling, 2012). While there is risk of a hydrocarbon spill or leak (among other hazards and contingencies) from drilling operations by multi-national oil conglomerates, there is equal concern about oil spills from tanker vessels carrying crude oil that are transiting the U.S. Exclusive Economic Zone in the Chukchi and Beaufort Seas off or Alaska's North slope enroute to or from the Bering Sea. Near-real time sensor detection of oil slicks associated with crude carrying vessels or MODUs could provide indications of a spill that would enable a decision-advantage in mobilizing for a government response to ensure mitigation. SAR data that can be rapidly analyzed may also play a role in correlating hydrocarbons on the surface of the ocean with vessels that

intentionally or unintentionally discharge hazardous materials at sea. If sufficient evidence is produced relating to discharging of hazardous materials, shipping companies can be held accountable under national and international legal regimes for pollution at sea. Figure 9 shows the synthetic aperture radar signature of an oil slick on the water when SAR backscattered energy is reflected from the ocean's surface. The white spots are indications of a vessel on the ocean surface or a structure such as a MODU (Bauma, 2011).

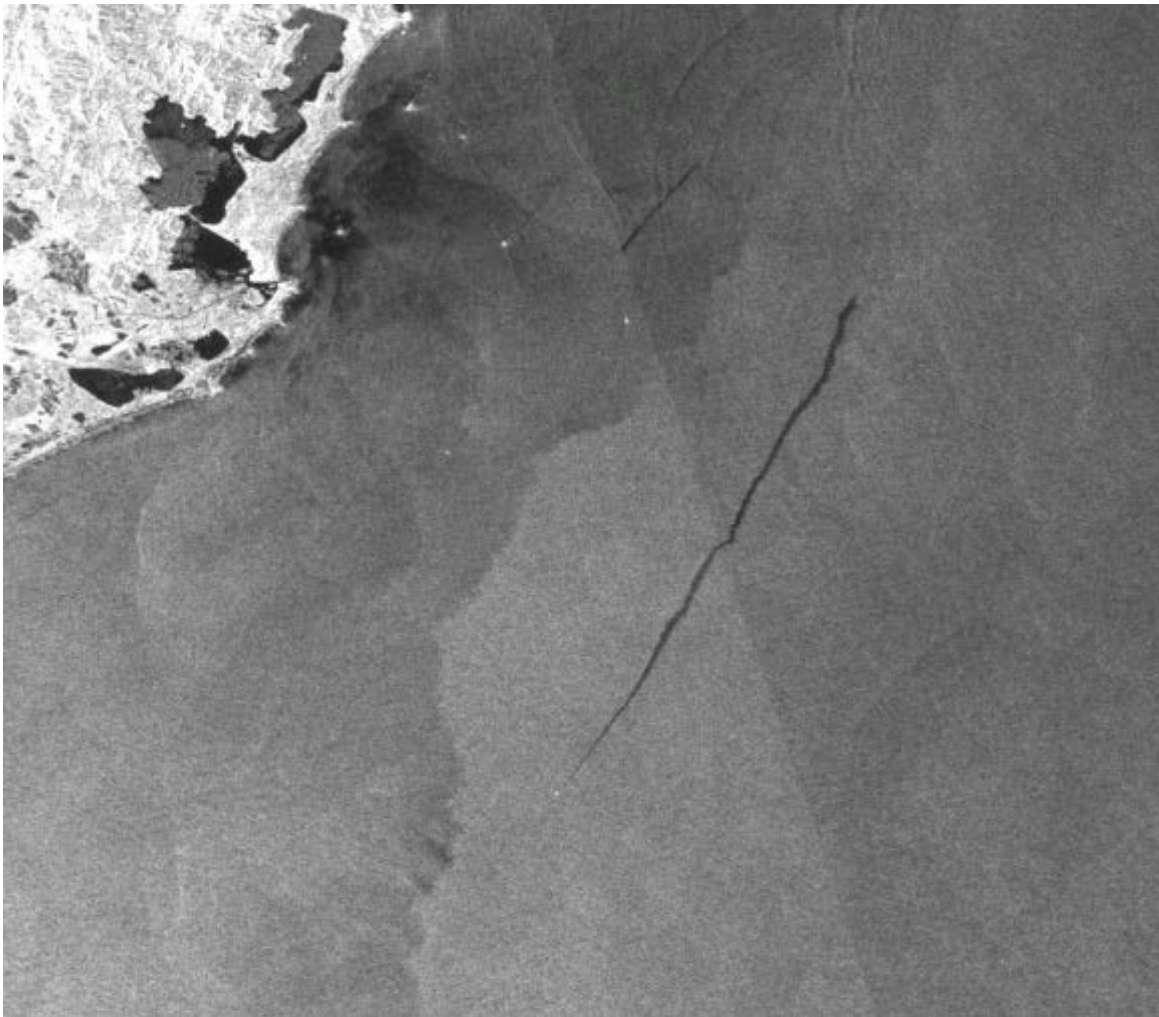


Figure 9. A processed synthetic aperture radar image of an oil slick (likely from the vessel indicated by the white spot at the end of the slick). The white spots indicate vessels or structures such as mobile offshore drilling units (From Bauma, 2011).

c. Weather inferences

As analysis methods have matured, SAR products have been able to enhance meteorological conclusions by corroborating or refuting data from weather sensors in the Earth's atmosphere while providing data over a much broader scale to support better regional weather updates and forecasts. Most recently, algorithms have been used to color code wind speed inferences from SAR imagery products. Figure 10 shows a SAR image to which the color coding algorithm has been applied that enables weather analysts interested in current weather or historical trends to ascertain wind speeds. Creative use of SAR data in this way provides a valuable independent and broader source of weather information beyond other marine wind speed sensors such as anemometers attached to weather stations, buoys, or ships (Canadian Space Agency, 2010).

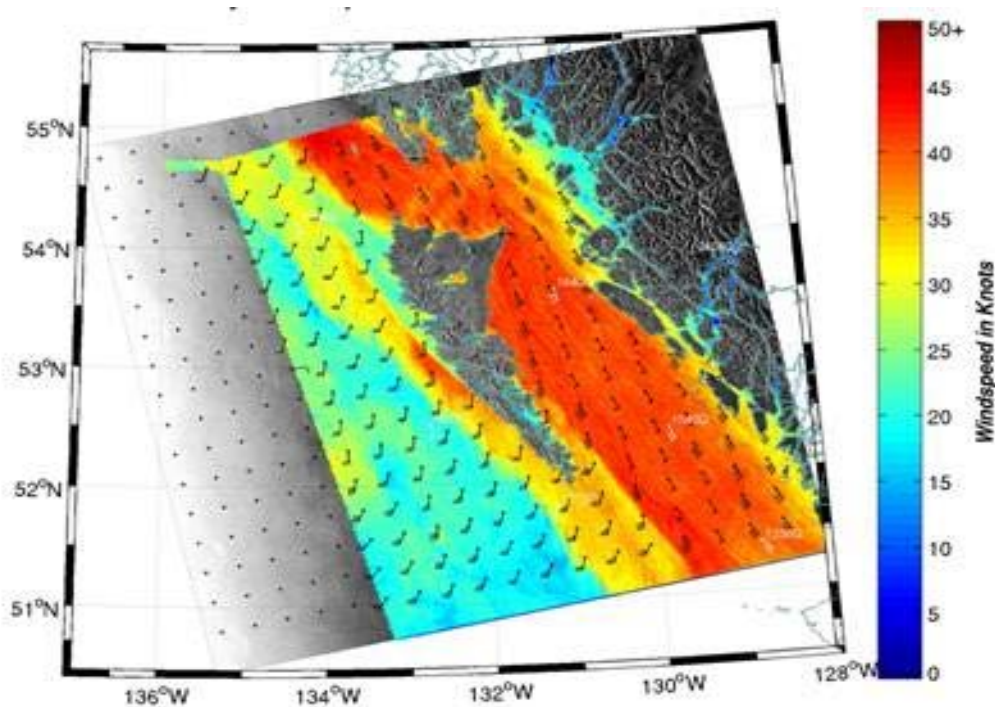


Figure 10. An algorithm applied to synthetic aperture radar imagery showing wind speed in the marine coastal zone near Queen Charlotte Island, British Columbia, Canada (From Canadian Space Agency, 2010).

While it is fairly well established that SARs have proven particularly useful for detection of threats on the ocean's surface such as vessels, oil slicks, and dangerous weather conditions, SARs can provide insight into other information needs as well. RADARSAT-2 has been utilized to track ice floes and collect information about maritime disasters. There are numerous science applications as well for SARs. RADARSAT-2 has been used for hydrology, cartography, geology, agriculture, and forestry. So, while some SARs provide capability to meet military needs, they also provide a wide range of secondary uses and benefits (Canadian Space Agency, 2007).

2. Synthetic Aperture Radar Payloads on Orbit

a. TerraSAR-X and TanDEM-X

TerraSAR-X and TanDEM-X are synthetic aperture radars sponsored and managed by German Aerospace Center (DLR) in partnership with private aerospace industries based there (German Aerospace Center, 2009). Table 1 shows basic technical data about TerraSAR-X. Table 2 shows basic technical data about TanDEM-X (German Aerospace Center, 2009).

Launch	June 15th, 2007
Orbit height	514 kilometers (319 miles)
Inclination	97.44 degrees
Satellite mass	1,230 kilograms (2712 lbs.)
Radar frequency	9.65 GHz
Revolutions around Earth per day	15.16
Operational life	at least 5 years
Orbital period	94.92 minutes
Duty cycle	18% (17.1 minutes)
Sensor minimum elevation angle (ScanSar mode to optimize detection)	45 degrees
Sensor maximum elevation angle (ScanSar mode to optimize detection)	70 degrees

Table 1. TerraSAR-X technical data (From German Aerospace Center, 2009).

Launch	June 21st, 2010
Orbit height	514 kilometers (319 miles)
Inclination	97.44 degrees
Satellite mass	1,330 kilograms (2932 lbs.)
Radar frequency	9.65 GHz
Revolutions around Earth per day	15.16
Operational life	at least 5.5 years
Orbital period	94.92 minutes
Duty cycle	18% (17.1 minutes)
Sensor minimum elevation angle (ScanSar mode to optimize detection)	45 degrees
Sensor maximum elevation angle (ScanSar mode to optimize detection)	70 degrees

Table 2. TanDEM-X technical data (From German Aerospace Center, 2009).

b. COSMO SkyMed

COSMO SkyMed is a constellation of four synthetic aperture radar payloads in approximately the same orbital plane phased (staggered) by 90 degrees within the plane. COSMO SkyMed is sponsored and managed by the Italian Space Agency (ISA) (Italian Space Agency, n.d.). Table 3 provides technical data about the 4 spacecraft that make up the COSMO SkyMed constellation.

Launches	August 6th 2007
	September 12th 2007
	October 25th 2008
	November 6th 2010
Orbit height	619.6 kilometers (385 miles)
Inclination	97.86 degrees
Satellite mass	1900 kilograms (4188 lbs.)
Radar frequency	9.65 GHz
Revolutions around Earth per day	14.8125
Operational life	at least 5 years
Orbital period	97.1 minutes
Duty cycle	10.3% (10 minutes)
Sensor minimum elevation angle	22 degrees
(ScanSar huge region to optimize detection)	
Sensor maximum elevation angle	52 degrees
(ScanSar huge region to optimize detection)	

Table 3. COSMO Skymed technical data (From Italian Space Agency, n.d.).

c. RADARSATs 1 and 2

RADARSATs 1 and 2 are Canadian sponsored synthetic aperture radar missions. RADARSATs 1 and 2 are managed by the Canadian Space Agency (CSA) (Canadian Space Agency, 2011). Tables 4 and 5 provide technical data about RADARSATs 1 and 2.

Launch	November 4th, 1995
Orbit height	793-821 km (493-510 miles)
Inclination	98.6 degrees
Satellite mass	2750 kilograms (6063 lbs.)
Radar frequency	5.3 GHz
Revolutions around Earth per day	14
Operational life	at least 5 years
Orbital period	100.7 minutes
Duty cycle	27.8% (28 minutes)
Sensor minimum elevation angle	30 degrees
(Extended high incidence to optimize detection)	
Sensor maximum elevation angle	41 degrees
(Extended high incidence to optimize detection)	

Table 4. RADARSAT-1 technical data (From Canadian Space Agency, 2011).

Launch	December 14th, 2007
Orbit height	798 km (496 miles)
Inclination	98.6 degrees
Satellite mass	2200 kilograms (4850 lbs.)
Radar frequency	5.4 GHz
Revolutions around Earth per day	14
Operational life	at least 7.25 years
Orbital period	100.7 minutes
Duty cycle	27.8% (28 minutes)
Sensor minimum elevation angle	30 degrees
(Extended high incidence to optimize detection)	
Sensor maximum elevation angle	41 degrees
(Extended high incidence to optimize detection)	

Table 5. RADARSAT-2 technical data (from Canadian Space Agency, 2011).

D. LIKELY SYNTHETIC APERTURE RADAR ORBIT CHARACTERISTICS

The logical orbit for multiple SAR payloads within a constellation that could provide optimal coverage and geospatial resolution of the Arctic is a Polar, Low Earth Orbit (LEO). A constellation of payloads is necessary because individual LEO payloads cannot maintain position over a specific location of the Earth (Wright, Grego & Gronlund, 2005). A LEO constellation of satellites is also necessary to support SAR payloads since these orbits are far more likely to achieve sensor performance requirements within the resolution and telemetry constraints imposed by a space-borne deployment (Wright et al., 2005).

Not only do SAR payloads require a LEO orbit to provide sufficient resolution and throughput, or data rates, they need to offer sufficient coverage of the area of interest. Polar orbits enable satellites to travel directly over every point on Earth over time. This feature of Polar orbits improves as you gain latitude making Polar orbits particularly suitable for monitoring the Arctic region (Singh, 2010).

While utilizing Polar LEO and orbits to meet mission requirements for resolution, communications, and coverage of high latitudes, there is also need to sustain power to the SAR payloads. To do this, an additional property often required in an orbit supporting a SAR payload is to make our LEO polar orbit sun-synchronous. The best sun-synchronous orbit to use is a special one that ensures the solar arrays of the satellite are constantly in view of the sun. This special sun-synchronous is called a *dawn-to-dusk* orbit (Wright et al., 2005).

So, to account for mission requirements including radar imagery resolution, communications links *and/or* telemetry, coverage of the area of interest, and onboard power generation, it should be apparent that the constellation of SAR payloads we seek to model will likely consist of some combination of Polar, Sun-synchronous, and Low Earth orbits. A constellation of sensors that possesses at least some of these characteristics is the most likely to continuously (or nearly so) sense high latitude regions of the Earth while providing data to consumers in the most efficient and timely way.

1. Low Earth Orbits

When energy must be used to create imagery of the Earth's surface with acceptable resolution in order to be useful, sensors such as synthetic aperture radar payloads must be deployed in low Earth orbit (LEO) (Wright et al., 2005). Satellites with altitudes above the Earth's surface less than 932 miles or 1500 km are generally considered in LEO orbit (Wright et al., 2005). LEOs enable SARs to receive sufficient energy from the features of the area being sensed to create an image from the properties of the energy received. The data collected and related image produced from the data will vary depending on the time difference between transmission and reception, wavelength used, and polarization of the energy among other variables (Canada Centre for Remote Sensing, n.d.). Nearly as important as the radar imaging resolution that only LEO orbits can provide, LEOs minimize communications latency for uplinking command and control communications and downlinking RADAR sensor telemetry for exploitation (Tomme, 2006). Generally, we can expect properly configured LEO constellations to require the least complexity in which to establish these critical communications links (Wright et al., 2005).

The disadvantages of LEO orbits are they can be seen from horizon to horizon from any point on Earth for only about 10 minutes. Intuitively, this limits the access that the sensor has to collect data from an area of interest on Earth. For this reason, to get continuous or at least persistent coverage of an area of Earth from a LEO orbit which we need for sufficient resolution, remote sensing of the Arctic with SAR payloads requires a constellation of satellites and SAR payloads working together (Wright et al., 2005).

2. Polar Orbits

In addition to having the advantage that the Earth rotates underneath the orbit allowing it to see every point on Earth at some point in time, the higher the latitudes of interest, the more frequently the point on Earth is revisited by a sensor in Polar orbit (Wright et al., 2005). These features of Polar orbits make them ideal for monitoring the Arctic region. Just as Low Earth Orbit provides the radar imagery resolution and

telemetry advantages which are useful for a SAR payload, Polar orbit provides the best coverage of the high latitude areas in which we are most interested.

3. Sun Synchronous Orbits

For reasons most directly related to power production and consumption by SAR payloads, SAR payloads can be powered most effectively by the satellite bus if the solar arrays of the satellite consistently face the sun. This allows the most effective generation of power for the relatively heavy power consumption of SARs. A special sun-synchronous orbit (96 to 98 degree inclination) called *dawn-to-dusk* provides the best orbit for power generation since there remains a constant angle between the satellite and the sun for the duration of the satellite's life. At the sun-synchronous inclination, the satellite orbital plane moves at just the right rate due to Earth's gravity so that the angle never changes with respect the Sun and the solar arrays are constantly illuminated. This allows the power required to energize the SAR payload throughout the duty cycles (when the payload is transmitting and receiving energy) with limited reliance on battery power. This is advantageous because batteries are more likely to fail over the lifetime of a satellite bus so it is best to limit their use to the extent possible (Wright et al., 2005). Figure 11 depicts a Polar and Sun-synchronous LEO orbit that is optimal for SAR payload mission requirements.

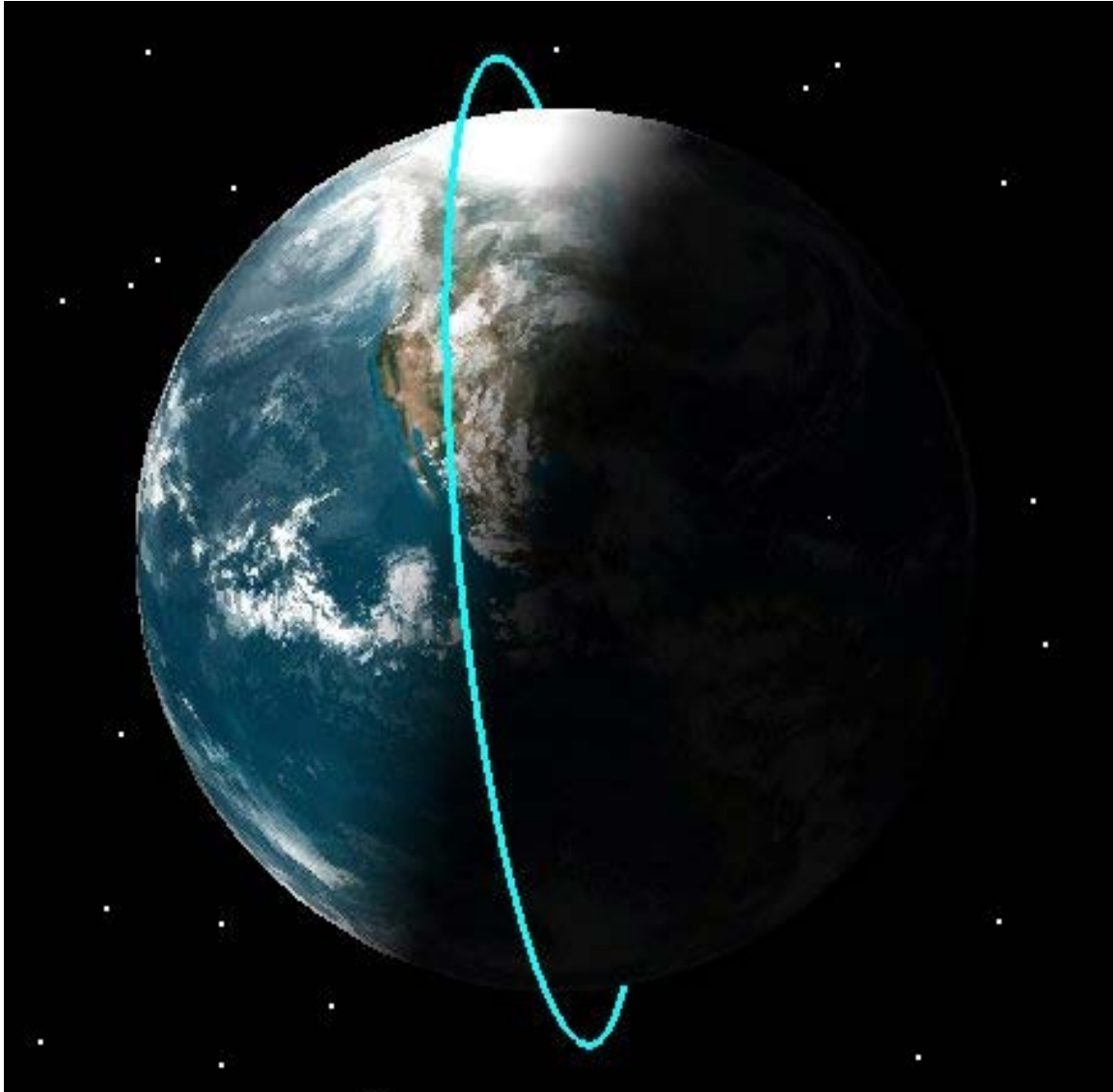


Figure 11. A depiction of a Polar Sun-synchronous LEO orbit. The offset from the terminus of the sun's light is intentional so that natural precession from the Earth will maintain a constant angle between the sun and the satellite's solar arrays (From Canadian Satellite Tracking and Orbit Research, 2010).

4. Walker Constellations

Walker Constellations are characterized by satellites systematically spaced in circular orbits having the same inclination, altitude, and period (Ellis, Mercury & Brown, 2012). Generally, satellite planes are spaced equally within a 360 degree circle of orbital plane possibilities around the Earth. Typically, if there are 2 orbital planes then their RAANs are placed nearly 180 degrees apart. If there are 3 planes, the RAANs are 120

degrees apart and 4 planes require 90 degree RAAN offsets (Ellis et al., 2012). There are four parameters that characterize a Walker constellation:

• Inclination	notated by the letter i
• Total number of satellites	notated by the letter T
• Total number of orbital planes	notated by the letter P
• Spacing between satellites in adjacent planes	notated by the letter F

While i , T , and P are somewhat intuitive and well-defined in this research, F is more subtle. $F = 360$ degrees divided by the number of satellites (T) multiplied by the phasing desired (P). Maximum phasing is signified by 1. If closer phasing is desired with satellites in adjacent planes you would increase F . So if we were to use Walker notation in the form $i\ T/P/F$ to describe a hypothetical constellation of RADARSAT-2 SAR payloads, it might look like the following:

98.6 4/4/1

This notation would mean there are four RADARSAT-2 satellites in four separate planes that are inclined at 98.6 degrees with $F = 1$ for the phase difference of 90 degrees $((360/4) * 1)$. The 1 indicates the satellite in the adjacent plane is maximally phased with the satellite in the plane next to it (i.e. as 1 satellite in a plane is reaching approximately 90 degrees latitude in the Northern hemisphere, the adjacent plane's satellite would be reaching the equator at 0 degrees latitude) (Massari, 2007). Figure 12 displays an 80 6/3/1 Walker constellation which translates to 6 total satellites in 3 orbital planes (2 per plane) at inclinations of 80 degrees with a phase differential of 1. This requires a phase differential in adjacent planes to equal 60 degrees $(360/6 * 1)$ (Cox, 2009).

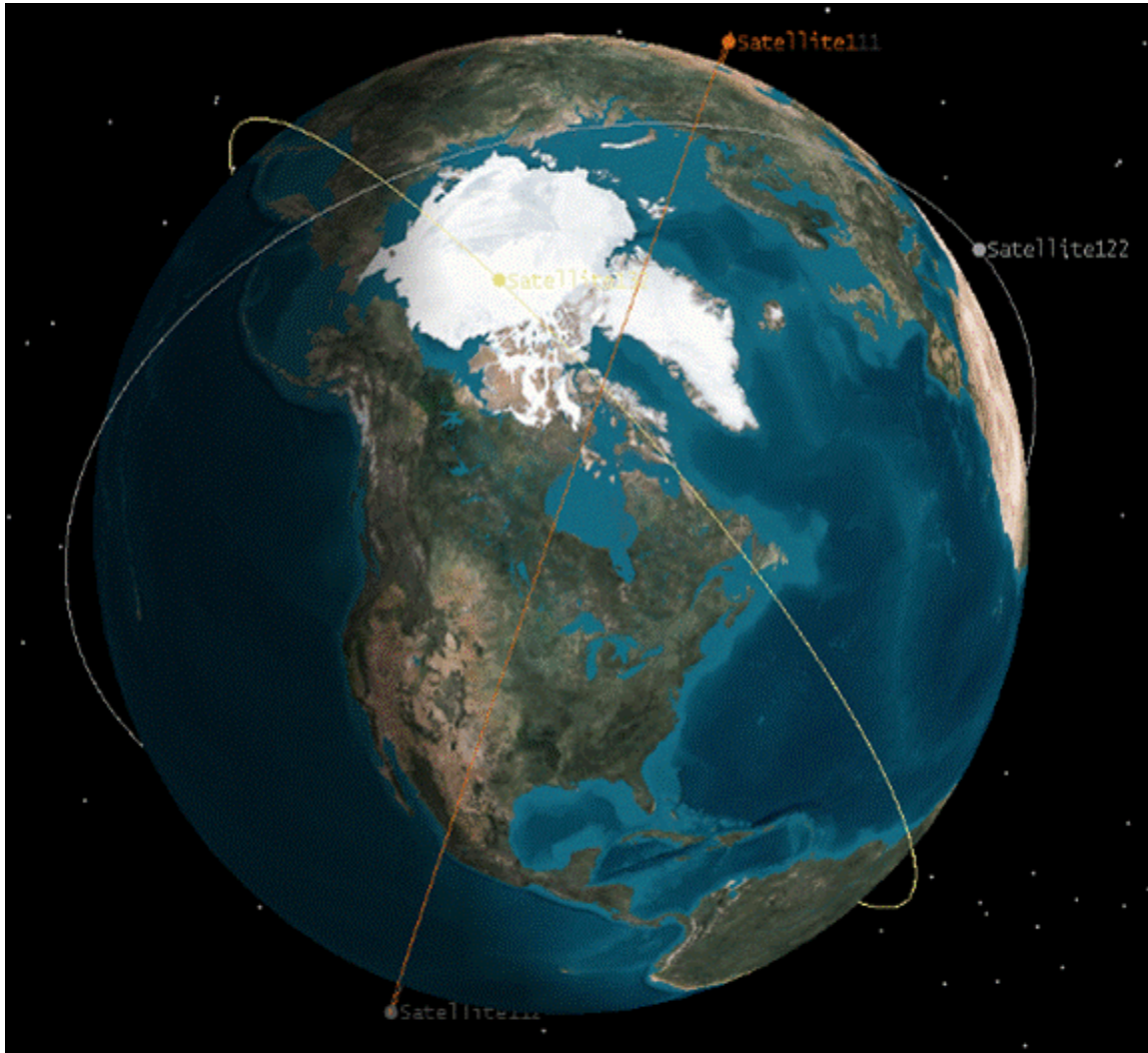


Figure 12. An example of an 80 6/3/1 Walker constellation where each satellite is inclined 80 degrees, there are 6 total satellites in 3 separate planes (2 per plane) with each satellite phased 60 degrees differently than the satellite in the adjacent plane (From Cox, 2009).

III. CLOSING ARCTIC SURVEILLANCE GAPS

A. ANALYSIS METHODS

Modeling and Simulation (M&S) enables representation of a system in the physical world while also experimenting with the system's output or results when varying input values to the system. Computational, or virtual, M&S software can help develop understanding and promote discovery of how systems may behave in the physical world. Moreover, M&S develops understanding and enables discovery in an efficient way and at a relatively low cost in resources (Rainey et al., 2004). The reference text Modeling and Simulation for Space Systems underscores this point:

Simulation and modeling are well accepted techniques for reducing time and cost. They have been used to improve the effectiveness of systems design, verification, and validation. (Rainey et al., 2004)

Since it is generally time and cost-effective, one of the primary uses of M&S is conducting Analysis of Alternatives (AoA) (Rainey et al., 2004). Alternatives discovered using M&S can be used to assess the trade-offs between the alternatives of continuing with current limit of coverage of the Arctic from SAR payloads on orbit and investing in new satellites and payloads that can monitor the Arctic more effectively.

To determine the optimal orbital regime required for SARs to conduct the best possible surveillance of the Arctic Circle and the U.S. EEZ within it, advanced M&S software is used. Systems Tool Kit (STK) software enables an analyst to model and then simulate a variety of satellite orbital regimes with an almost infinite number of configurations. STK will be used to assess what coverage of the Arctic could be expected from a constellation of SAR payloads placed on orbit with a dedicated, or at least primary, mission to conduct Arctic surveillance.

Future SAR systems can be expected to meet or exceed the performance standards that have long been established by RADARSAT-2. Therefore, it is sensible to make RADARSAT-2 act as a representative SAR capability for orbital analysis. By using RADARSAT-2 as the model sensor with the same parameters, an *apples-to-apples* comparison and analysis can be accomplished with respect to coverage performance by a

given constellation design. Thus, RADARSAT-2 key performance standards and characteristics will be used as input data into STK M&S software. The RADARSAT-2 data M&S output will be used to assess the coverage performance of notional constellations for a dedicated SAR mission to provide optimal persistence for surveillance of the U.S. EEZ in the Arctic Circle and the totality of the Arctic Circle.

Among many possible outputs, optimization of an objective function, or a measure of performance in terms of decision variables, is a goal of M&S. The objective function of M&S in this context is coverage of the Arctic and the EEZ above the Arctic Circle within the fixed parameters of altitude and inclination. The experimental variables or *factors* are quantitative and consist of the number of payloads and their orbital planes (uniquely characterized by the right ascension of the ascending node (RAAN) parameter). Through the iterative process of varying the payloads within an orbital plane and the planes themselves, an optimal satellite constellation configuration with which to support SAR payloads to provide the best coverage of the Arctic and the EEZ within it will be determined.

1. Modeling and Simulation and Space

a. Using Modeling and Simulation for Space Challenges

Modeling and Simulation (M&S), particularly in a computational or virtual environment, represents a complex system such that analysis can be conducted that would otherwise be impossible or nearly so. Some of the more common uses of M&S for space systems are analyzing communications links, sensor access, spatial resolution, and temporal resolution (Rainey et al., 2004). Since M&S can be effective in analyzing sensor access and resolution in a very complex environment such as space, it is the method of choice for optimizing the characteristics of an orbital regime that will provide maximum coverage of a chosen area of interest on Earth. Furthermore, DoD directives now require the use of M&S for new programs:

To reduce the time, resources, and risk of the acquisition process and to increase the quality of the systems being acquired. (Department of Defense, 2008)

In addition to saving precious resources in solving material solution challenges in space systems, M&S tools take into account the myriad and complex forces that affect satellites in orbit. Relatively small forces beyond gravity such as orbital perturbations and other celestial objects can affect orbiting bodies over time. M&S helps account for even the more insignificant forces beyond gravity that are acting on orbiting objects that will affect satellites and their sensors over time (Rainey et al., 2004).

b. System Insight and Understanding

M&S is very practical in examining space systems as the systems being analyzed must obey fairly consistent physical laws which make deterministic modeling, or producing repeatable and consistent results, particularly likely. While M&S can be used for many purposes such as training and safety, when conducting M&S through a computational model such as with software, the goal is often understanding and discovery (Rainey et al., 2004). M&S is an effective way to examine a continuous system that will vary over time. Applying M&S to space systems analysis using quality inputs can provide the insights desired and enable exploratory analysis (what if?) that are essential to adjusting factors (or variables) such that an objective function is optimized. This type of exploratory analysis allows hypothesis testing in a near-real time way and enables a way to evaluate trades in satellite numbers and orbital planes to achieve the maximum coverage with the fewest resources (Rainey et al., 2004).

One of the key attributes of M&S is the benefit it provides in exploring solutions for user's (such as warfighters) needs in the concept and technology development phases for major government acquisition programs (Rainey et al., 2004). Researching the coverage potential of a dedicated or primary SAR capability for Arctic surveillance is an effort to support solution exploration to meet the Arctic awareness needs of U.S. government agencies while also conducting in-depth analysis of a proven surveillance method to meet those needs.

2. Modeling Software: Systems Tool Kit

Systems Tool Kit (STK) is an independent commercial software M&S package that is widely used for aerospace missions across their lifecycles (Rainey et al., 2004). STK works well for aerospace because it can propagate orbits using a variety of time-tested gravitational models. With STK, you can model time, assets, the environment, and constraints and visually see outputs dynamically, graphically, and statistically (Analytical Graphics Incorporated, 2013). Since STK was originally developed to predict access areas and/or coverage of Earth orbiting sensors, the algorithms within the M&S capabilities of the software are robust and relatively mature for space orbit analysis purposes.

a. STK Features

STK enables a user to model a variety of system components in order to run simulations with them. Satellites can be created using tools within STK to establish the exact orbital elements you desire to include altitude, inclination, right ascension of ascending node (RAAN), and so on. STK also contains a database of existing satellites and sensors which enable a user to design a constellation of satellites that are currently on orbit. To best visualize how a satellite is orbiting the Earth, STK offers both a two-dimensional and three-dimensional graphical user interfaces (Analytical Graphics Incorporated, 2013).

When simulating an orbit of a satellite, the two dimensional graphical user interface can display the ground track of the orbiting satellite(s). While the ground tracks can be informative to get a sense of where the satellite's nadir path would be as it orbits, there are additional features of STK that offer even greater insight into how a satellite, (along with any associated sensors), or a constellation of satellites, will behave in a given configuration. Perhaps one of the most valuable for estimating coverage is the ability for STK to use colors to display differences on the surface of the Earth that signify a sensor's access area or time that the area can be covered by the sensor. This feature can provide an idea of what ground can be covered by the sensor under analysis as it flies in its orbit (Analytical Graphics Incorporated, 2013).

On a broader level, STK enables a user to propagate a *Walker Constellation* which is a constellation of satellites systematically spaced in circular orbits having the same inclination, altitude, and period (Ellis, Mercury & Brown, 2012). This functionality, along with the aforementioned features of STK, will be extensively used as part of an iterative analysis process to determine the best coverage of the Arctic with the least number of sensors (Analytical Graphics Incorporated, 2013).

b. Modeling and Simulation Boundary Conditions

To conduct analysis and discover new insights about the system under study, M&S requires bounding the problem so that possible solutions or results are not infinite. In the case of optimizing an orbital regime of SARs to monitor the Arctic, we place reasonable and advisable constraints on the orbital characteristics of the satellites that would carry the SAR payloads by constraining the orbits to those with consistent low Earth and polar properties. Therefore, the altitude and inclination characteristics, or parameters, of the notional satellites carrying the SAR sensors will be held constant for analysis.

Conversely, despite RADARSAT-2 exhibiting this orbital characteristic, we will not hold the dawn-to-dusk sun-synchronous orbit as a required orbital property. While dawn-to-dusk orbits would be beneficial to battery-life of the satellite bus, it is reasonable to subordinate the issue of battery-life to coverage. Maximizing constellation coverage may require the ability to change right ascension of ascending nodes (RAANs) for orbital planes. This may preclude placing multiple satellites at the same altitude and inclination into a dawn-to-dusk sun-synchronous orbit. Limiting M&S analysis to sun-synchronous dawn-to-dusk orbit properties would likely overly constrain orbital flexibility particularly when altitude and inclination are held constant. The intent of exploration in the research is to not limit its usefulness due to excessive restrictions on possible orbital planes.

The most advanced and effective SAR systems on orbit today possess altitude and inclination characteristics to achieve a balance between the oft-competing performance standards of sensor resolution and coverage. This is why constant altitude

and inclination parameters of the constellation of SAR sensors under study are necessary. The objective of the research is to ensure the aforementioned constraints are reasonable, yet not overly so while providing sufficient flexibility to configure multiple constellations. Since reasonable constraints are applied to analysis, the research focuses on which orbital regime is optimal for resolving the problem of insufficient Arctic surveillance coverage at altitudes and inclinations that are proven to be effective for remote sensing with SARs.

c. Assumptions

Assumptions may or may not limit solution sets as do constraints, but they are specific to a particular research project (Rainey et al., 2004). In the context of determining temporal coverage performance of a sensor such as a SAR payload, it is assumed the sensor can sample energy from an illuminated area of interest while the area of interest is in view of payload. Effective SAR remote sensing is predicated on this concept so that data can be collected and processed.

Since temporal coverage performance of the sensors for areas of interest on the Earth is the most important analytical factor for this research, the capacity of the entire space architecture that would support the SAR constellation is not explored. Analysis assumes that a satellite bus supporting a SAR sensor payload can telemeter collected backscattered energy that has been processed back to ground stations in a timely way for analysts to use and disseminate the processed and analyzed information to clients.

d. Constraints

For the purposes of analysis, eight SAR sensors is the limit that can be placed on orbit in any one constellation. This constraint is viewed as reasonable because it is the same number of SAR sensors currently on orbit and the objective of the research and analysis is to determine the best constellation design for performance and *efficiency*. The most advanced constellation designs discovered so far for *global* missions limit the number of sensors to nine (Los Angeles Air Force Base, 2013). Practically, there is little chance the number of SAR sensors utilized for a mission in which only a *region* of the

Earth is the primary surveillance mission could match or exceed that which is designed for a global mission.

3. Inputs

a. Model Sensor Characteristics: RADARSAT-2

Recall from Chapter II that space-based radars are arguably the best space-based sensors for penetrating clouds and other atmospheric phenomena and are not hindered by darkness. All of these environmental phenomena may exist in the Arctic (sometimes for months at a time in the case of darkness) (MacDonald, Detweiller and Associates, 2012). The fact that SARs are particularly suited to sense the Arctic despite atmospheric hindrances that would otherwise prohibit electro-optical (EO) sensors from conducting surveillance is the primary reason for which we are using a SAR sensor to model a constellation to survey the Arctic region.

Equally important is the ability for space-based radar to monitor a far larger area with more frequency, particularly above the Arctic Circle, than any airborne or terrestrial sensor (MacDonald, Detweiller and Associates, 2012). The Arctic Circle is a vast area which requires a sensor to be able to collect data from a relatively large swath of the region and rapidly provide the data to analysts. Only a space-based platform and sensor that revisits the area frequently and can efficiently provide data to analysts can provide value toward understanding the range of maritime activities in the Arctic.

Notwithstanding future missions that are likely to offer more advanced services than those on orbit today such as the Canadian Radar Mission (RCM), RADARSAT-2 offers a wide variety of services to clients. As such, it is the ideal combination of satellite bus and sensor characteristics and performance to use as inputs to M&S efforts with the STK software suite. Table 6 delineates the orbital and performance characteristics of RADARSAT-2 that will affect the coverage of the variety of constellations that are modeled in order to find the optimal configuration:

Spatial Resolution Range	3 to 100 meters
Orbit height	798 km (496 miles)
Inclination	98.6 degrees
Look direction	Left and right-looking imaging
Orbital Period	100.7 minutes
Duty cycle	27.8% (28 minutes)
Swath width (average ground coverage) (Extended high incidence beam mode with 20 meter resolution)	75 km (46.6 miles)
Center frequency of RADAR energy	5.4 GHz (C-band)
Bandwidth of RADAR energy	100 MHz
Sensor minimum elevation angle (Extended high incidence to optimize detection)	30 degrees
Sensor maximum elevation angle (Extended high incidence to optimize detection)	41 degrees

Table 6. RADARSAT-2 orbital characteristics that affect coverage (From MacDonald, Detweiller and Associates, 2012).

It is important to note that because the primary use for Arctic monitoring is for detection of potential threats, marine vessel detection is the operating mode of the SAR for which a constellation will be modeled and simulations run. Generally, the ability of SAR to detect maritime surface vessels is dependent on sea state, incident angle, and the vessel's characteristics such as size, orientation and speed. Fortunately, energy from SARs can be optimized to best detect vessels even when the sea state and vessel's properties are otherwise challenging (Canada Centre for Remote Sensing, n.d.). The energy variance is determined by the operating mode of the SAR sensor.

The best operating modes for detection of ships are those modes that have relatively large radar beam incidence angles (Vachon et al., 2000). RADARSAT-2's Extended-high Beam Mode with an incident angle of up to 59 degrees possesses this

property. With resolutions up to 20 meters, Extended-high Beam Mode is currently the optimal mode for marine vessel detection and potential classification. Extended-high Beam Mode limits the swath width or ground coverage of the RADARSAT-2 to an average 75 km or 46.6 miles (Canadian Space Agency, 2007).

While any future SAR sensors will almost certainly be able to shift modes to best meet the need of the client whether the sensing is done for weather, hydrocarbon marine vessel detection, or any other scientific purpose, the assumption is that surface vessels constitute the most time-sensitive information as the threat they can present can evolve rapidly relative to other challenges or threats that can materialize in the Arctic Circle. Thus, the SAR constellation for which we are modeling has a primary mission to detect surface vessels encroaching or infringing on the sovereign interests of the United States and/or allies. For this reason, the Extended-high Beam Mode is used for SAR sensor coverage analysis to ensure the constellation could achieve its primary mission of monitoring the Arctic for surface vessel contacts as they represent the most dynamic and greatest Arctic threats to U.S. interests.

4. Analysis

a. Procedure

To identify the optimal configuration of SAR sensors with respect to their number and assigned orbital plane while maximizing temporal coverage performance, the following procedures will be used to assess coverage performance:

- i. The number of SAR payloads within a single orbital plane (the same plane as that of RADARSAT-2) will be increased to the limit of sensors that can be placed on orbit (eight) for both the Arctic Circle and the Arctic component of the EEZ. Maximizing the number of sensors to eight limits *simultaneous* coverage overlap. It is intuitive that more sensors will provide better temporal coverage performance. The intent of the analysis is to try and determine what constellation design will provide the best return on investment or *efficiency* of coverage. For instance, if an alternate constellation design can offer as good or better temporal coverage performance efficiency with less than eight sensors, then that is a more optimal constellation design for improving Arctic

surveillance. Hence, the meaning of efficiency in the context of this research is to maximize temporal coverage performance with the minimum number of sensors (to save costs).

The Arctic Circle latitude line of approximately 66 degrees implies that the necessary latitudinal coverage of the Arctic Circle is 2×24 degrees (90 degrees latitude – 66 degrees latitude = 24 degrees $\times 2 = 48$ degrees). This accounts for both the polar ascent and descent of the spacecraft. The time to transit 48 degrees of latitude on the ascent and descent of the sensor is determined by converting degrees in the following way:

$$48 \text{ degrees} / 360 \text{ degrees} = 13.3\% \text{ of a complete orbit.}$$

Since we know the orbital period for a full 360 degree orbit is 100.7 minutes, we can estimate the time to cover the Arctic for each spacecraft will be:

$$.133 \times 100.7 \text{ minutes or } 13.4 \text{ minutes.}$$

Theoretically, this is how long the Arctic Circle will be *in view* of a SAR payload (which does not imply the entire Arctic is being *sensed* by the payload. By dividing the total orbit time by the *in view* time, we obtain a theoretical *minimum* number of payloads to persistently monitor the Arctic from an orbital plane that is optimized for resolution and coverage (such as that of RADARSAT-2):

$$100.7 \text{ minutes} / 13.4 \text{ minutes} = 7.5$$

This result means that 8 SAR payloads are theoretically necessary to constantly view at least part of the Arctic Circle from a single orbital plane. This supports limiting our constellation to eight sensors as redundancy, while desirable, is just not affordable and practical for modern space-based missions.

ii. Once temporal coverage performance has been assessed in a single plane, Walker Constellation designs will be examined up to the maximum number of sensors (eight). This is consistent with maximizing coverage while minimizing the payloads necessary. While generally, Walker Constellations produce favorable coverage compared to other constellation designs, the emphasis on coverage of the Arctic and sub-regions within it is not a traditional way of assessing coverage as historical studies focus on coverage area for the entire globe or specific areas of interest at lower latitudes (Johnson, n.d.). The analysis will help determine if the general rule that Walker constellation designs provide the best coverage for Earth surveillance holds true for the Arctic Circle and the areas within the Arctic Circle that are of most interest to the United States.

iii. In the third step, findings about a single orbital plane and the various Walker constellation designs will be used to design ad-hoc constellations to determine if the temporal coverage performance demonstrated by single orbital plane and Walker Constellation designs can be improved upon.

b. Outputs and Discovery

As an M&S tool, STK is able to provide measures of performance (MOPs) from running simulations. MOPs quantitatively measure a system output such as coverage by latitude and total or average coverage over fixed time durations (Rainey et al., 2004). STK can provide these MOPs using statistical methods such as raw values and graphs that can make coverage based on a particular set of inputs apparent. These analytical outputs will provide insight into the relationship between number of payloads in various numerical and planar configurations (the explanatory or independent variables) within the constellation and collective temporal coverage performance (the response or dependent variable) among all payloads that the area of interest is observed in a 24-hour period.

STK's deterministic outputs from models of notional single-orbital plane, Walker, and ad-hoc constellation designs will provide evidence of the relationship among coverage and required payloads that will reveal the best numerical and planar

configuration of SAR payloads within a dedicated constellation to conduct surveillance at high latitudes. From the analysis, the resources required to monitor the entire Arctic Circle effectively and what is required to monitor the U.S. EEZ more effectively will become clear. Ultimately, analysis will reveal the number, planes, and phasing of payloads to achieve temporal coverage performance optimality. To find the most efficient coverage, the average coverage time per sensor is found by dividing the average coverage time by the number of sensors to obtain an efficiency factor for each sensor. Once the best efficiency factor is determined, an orbital configuration will be designed around the configuration that provides the most efficiency per sensor at the lower latitudes of the Arctic Circle.

IV. AN OPTIMIZED SYNTHETIC APERTURE RADAR CONSTELLATION FOR ARCTIC SURVEILLANCE

A. SPATIAL COVERAGE PERFORMANCE OF THE ARCTIC AND SUB-REGIONS

Analysis begins by ensuring the areas of interest can be spatially covered by our model sensor. The mode of RADARSAT-2 with the highest incidence angle was selected for this baseline analysis since this mode has the greatest likelihood of surface vessel detection (Canada Centre for Remote Sensing, n.d.).

1. Spatial Coverage of the Arctic Circle

Using RADARSAT-2 as our model sensor, the red colored area in Figure 13 indicates the potential spatial coverage of the Arctic Circle of merely one SAR sensor on orbit at present. Throughout a 24-hour period, the entire Arctic Circle has the potential to be remotely sensed. Even just one RADARSAT-2 SAR sensor in Extended-high Beam Mode provides complete spatial coverage of the entire Arctic Circle owing to the 14 revolutions per day by RADARSAT-2 as the Earth rotates underneath the orbit. From a spatial coverage performance perspective, this is the desired coverage. It is not probable that systems on orbit today, including RADARSAT-2, could apply their duty cycle for sensing over the Arctic on a daily basis. Arctic surveillance is not the primary or only mission of current SAR systems on orbit. So while the spatial coverage performance potential is there to remotely sense all of the Arctic, it is highly improbable that current systems could achieve 100% spatial coverage performance of the Arctic Circle on a daily basis owing to duty cycle limitations and competing missions. Despite this likelihood, one can get a sense of the spatial coverage performance *potential* of current systems from this analysis.

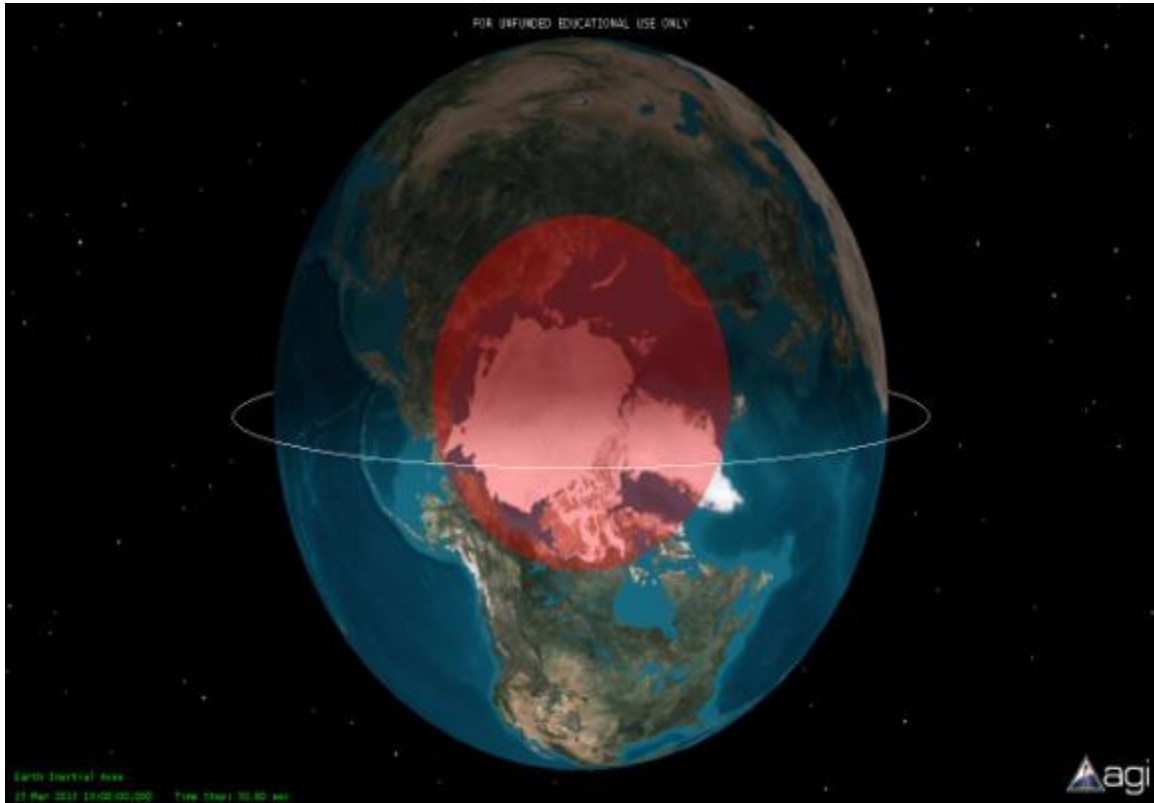


Figure 13. The red coloring indicates the potential spatial coverage of RADARSAT-2 during a 24-hour period.

2. Spatial Coverage of the Arctic U.S. Exclusive Economic Zone

The area of primary spatial surveillance interest for the United States in the Arctic is the EEZ shown in green outline in Figure 14. This area is often characterized as the North Slope of Alaska. The area encompasses nearly 245,885 square miles. Despite the graphic's depiction of ice, it often recedes much farther to the North towards the North Pole. Previous M&S shows that the EEZ, as a sub-region of the Arctic Circle, will be spatially covered by RADARSAT-2 over a 24-hour period of time.



Figure 14. The green polygon shows the U.S. Exclusive Economic Zone area of significant Arctic interest which lies North of the Arctic Circle.

B. ARCTIC TEMPORAL COVERAGE PERFORMANCE FROM SENSORS IN A SINGLE ORBITAL PLANE

Now that it is established that the spatial coverage performance potential of the Arctic Circle (and therefore the Arctic EEZ) for a 24-hour period is likely acceptable with merely 1 existing SAR sensor, it is assumed and highly likely that additional sensors that are polar and low earth orbiting will provide even better spatial coverage of the Arctic Circle. Therefore, additional analysis will focus on temporal coverage performance differences among notional SAR sensor constellation designs rather than spatial coverage. To achieve the greatest granularity in temporal analysis that will enable meaningful insights, the temporal coverage performance differences among notional SAR sensor constellations will be analyzed at various latitudes within the Arctic Circle and U.S. EEZ as well as the total time of coverage in a 24-hour period. Figures 15 and 16

depict partial and full models of the eight SAR sensors orbiting the Earth respectively in the single polar orbital plane that will be utilized for initial temporal coverage analysis.

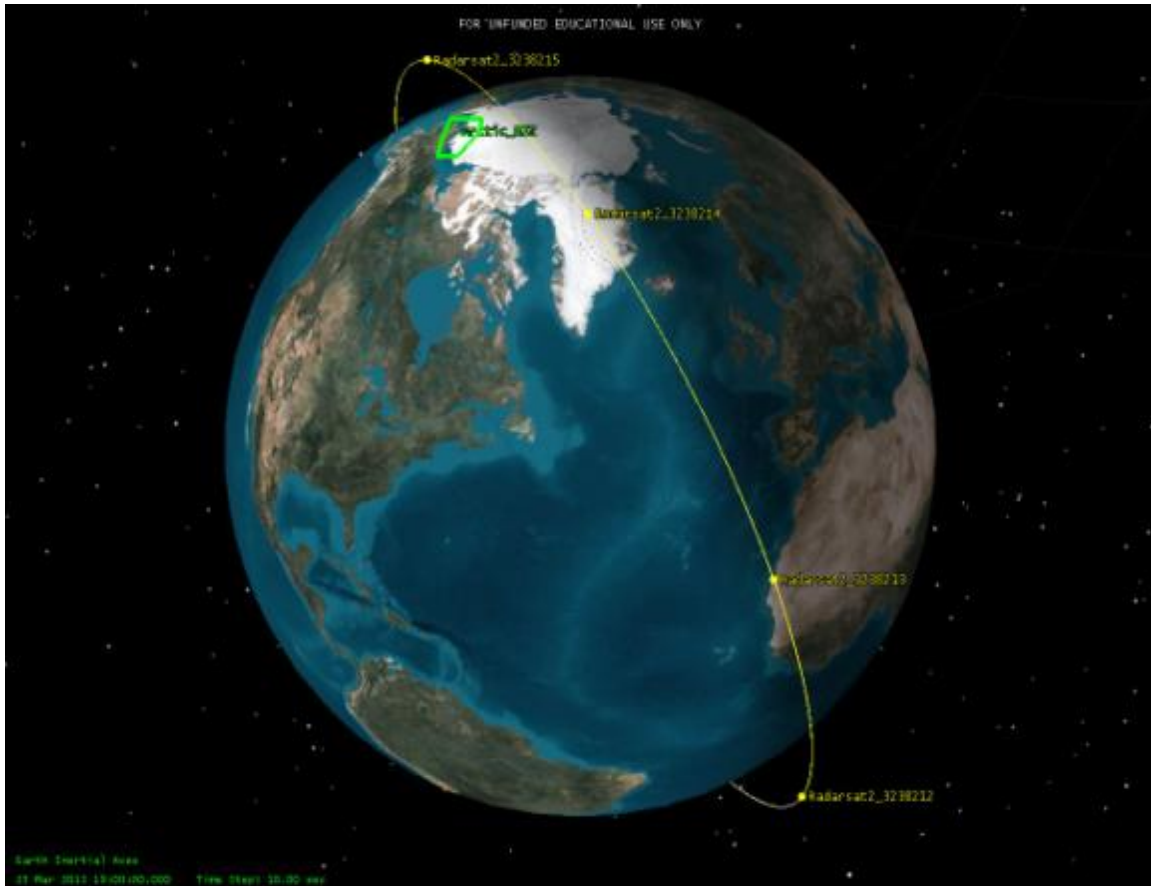


Figure 15. A view of the EEZ and half of the constellation of SAR sensors in a single polar orbiting plane.

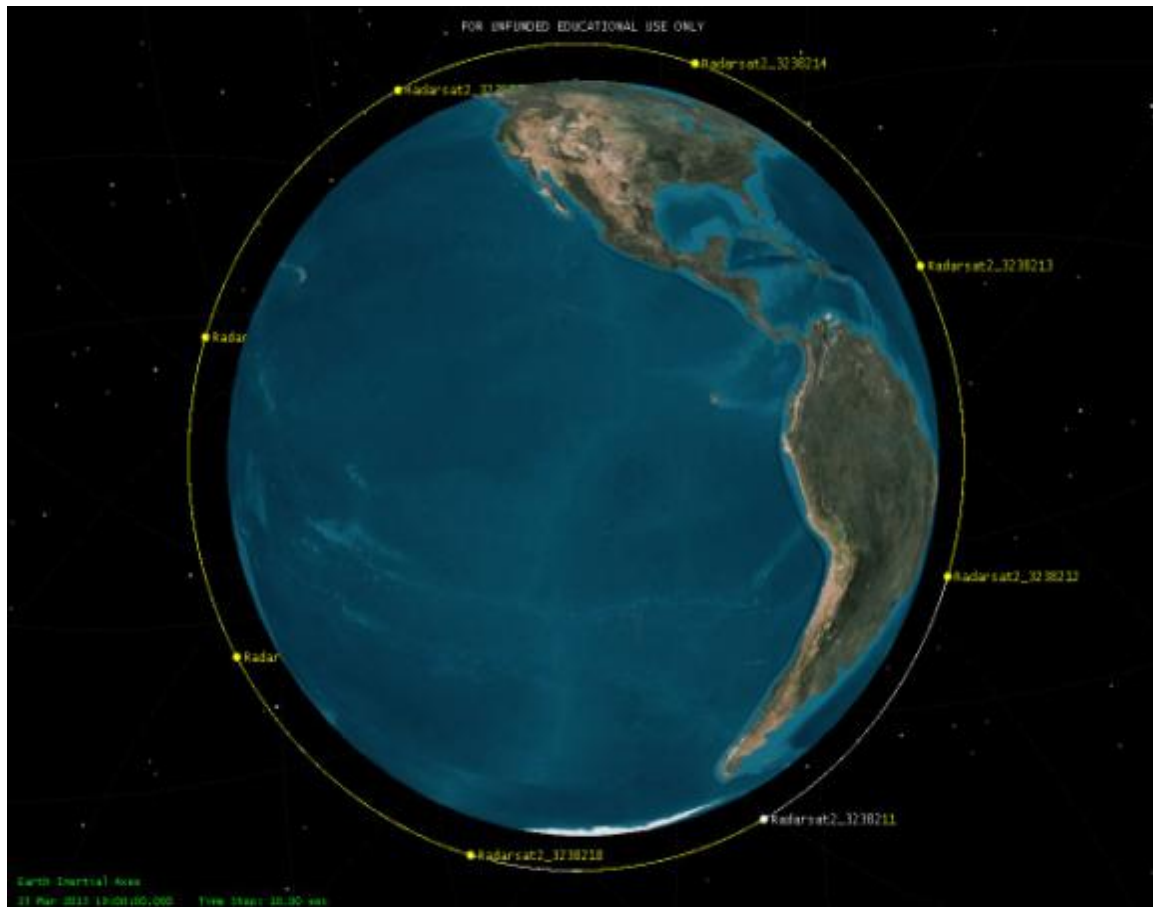


Figure 16. View of all eight SAR sensors placed in a single polar orbital plane from which temporal performance coverage is analyzed.

While it has been established that spatial coverage performance is clearly promising from existing and notional SAR sensors, temporal coverage performance of the Arctic Circle is another matter. Figure 17 confirms that the latitudinal temporal coverage performance of a constellation of sensors in a single orbital plane ranges from merely an hour to a maximum of just under six hours over a 24-hour period depending on the latitude—even if the maximum numbers of eight sensors are used. On these graphs, the y axis has the hours of coverage provided by the constellation while the degree of latitude of the coverage is shown on the x axis. The y axis, which is labeled FOM, represents the Figure of Merit. In all of the graphs, the FOM is the hours covered of the region of interest by the particular constellation design.

At times there is variation that exists between the maximum and minimum coverage among successive 24-hour periods. Where this variation does occur, the maximum is represented by a red line and the minimum is represented by a blue line. The average coverage in successive 24-hour periods is represented by a green line. In the case of the single orbital plane constellation construct, there is very little variation from period to period resulting in the red, blue, and green curves merging into practically a single curve to show coverage by latitude.

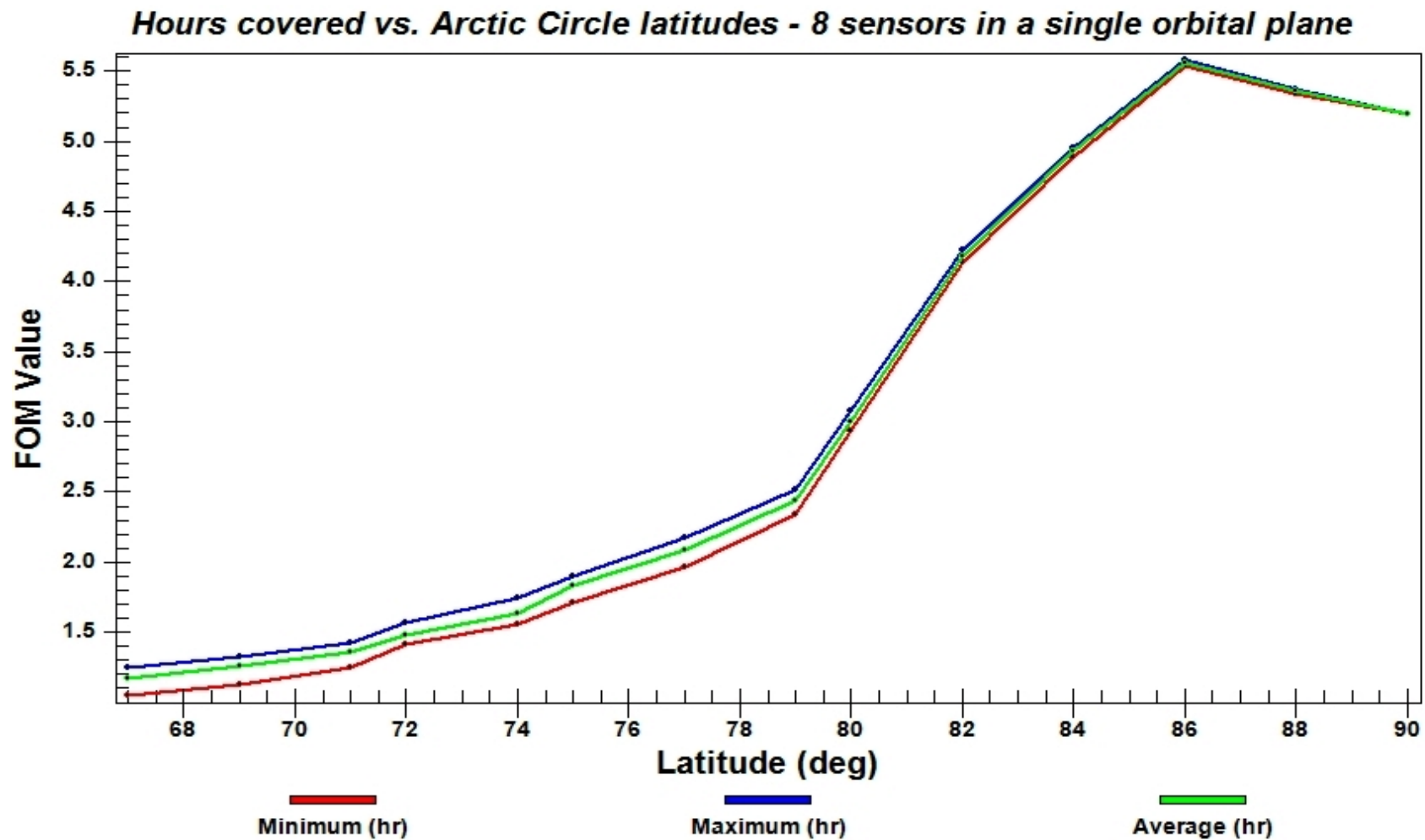


Figure 17. The cumulative hours covered within a 24-hour period by latitude from eight SAR sensors in a single orbital plane monitoring the Arctic Circle.

Advancing the analysis, the RADARSAT-2 sensors populate a constellation of SAR sensors cooperating within a single orbital plane until the maximum allowable number of sensors is reached (eight). Table 7 shows the average coverage time and the efficiency of adding additional sensors (hours covered per sensor) of the Arctic Circle by an increasing number of SAR sensors in a single orbital plane.

Number of SAR Sensors in Single Orbital Plane	Average Coverage time of Arctic Circle in a 24-hour period (hrs.)	Arctic Circle efficiency (hours monitored per sensor deployed)
1	.281	.281
2	.556	.278
3	.840	.280
4	1.120	.280
5	1.387	.277
6	1.652	.275
7	1.917	.274
8	2.168	.271

Table 7. The average coverage times and the efficiency of monitoring the Arctic Circle of an increasing number of SAR sensors deployed in the same orbital plane.

Finding 1: The most important latitudes (the lower latitudes within the Arctic Circle where maritime threats are most likely to occur) are monitored the least with a single orbital plane constellation design.

Finding 2: One, three, and four sensors within the single orbital plane constellation design appear to provide the best temporal coverage efficiency for the Arctic Circle.

1. The Arctic U.S. Exclusive Economic Zone

Since analysis so far accounts for the entire Arctic Circle when analyzing spatial and temporal performance coverage by SAR sensors in a notional single orbital plane, reasonable inferences can be made about coverage performance for the U.S. EEZ. Figure 13 shows that the U.S. EEZ will be covered entirely over the course of a 24-hour period

by RADARSAT-2 in its current orbit and certainly if additional sensors were added to the plane. Figure 17 suggests only an hour to less than two hours of data collection is likely in the U.S. EEZ (66 to 74 degrees latitude) in the Arctic with a full octet of SAR sensors in a single orbital plane. Figure 18 confirms this result.

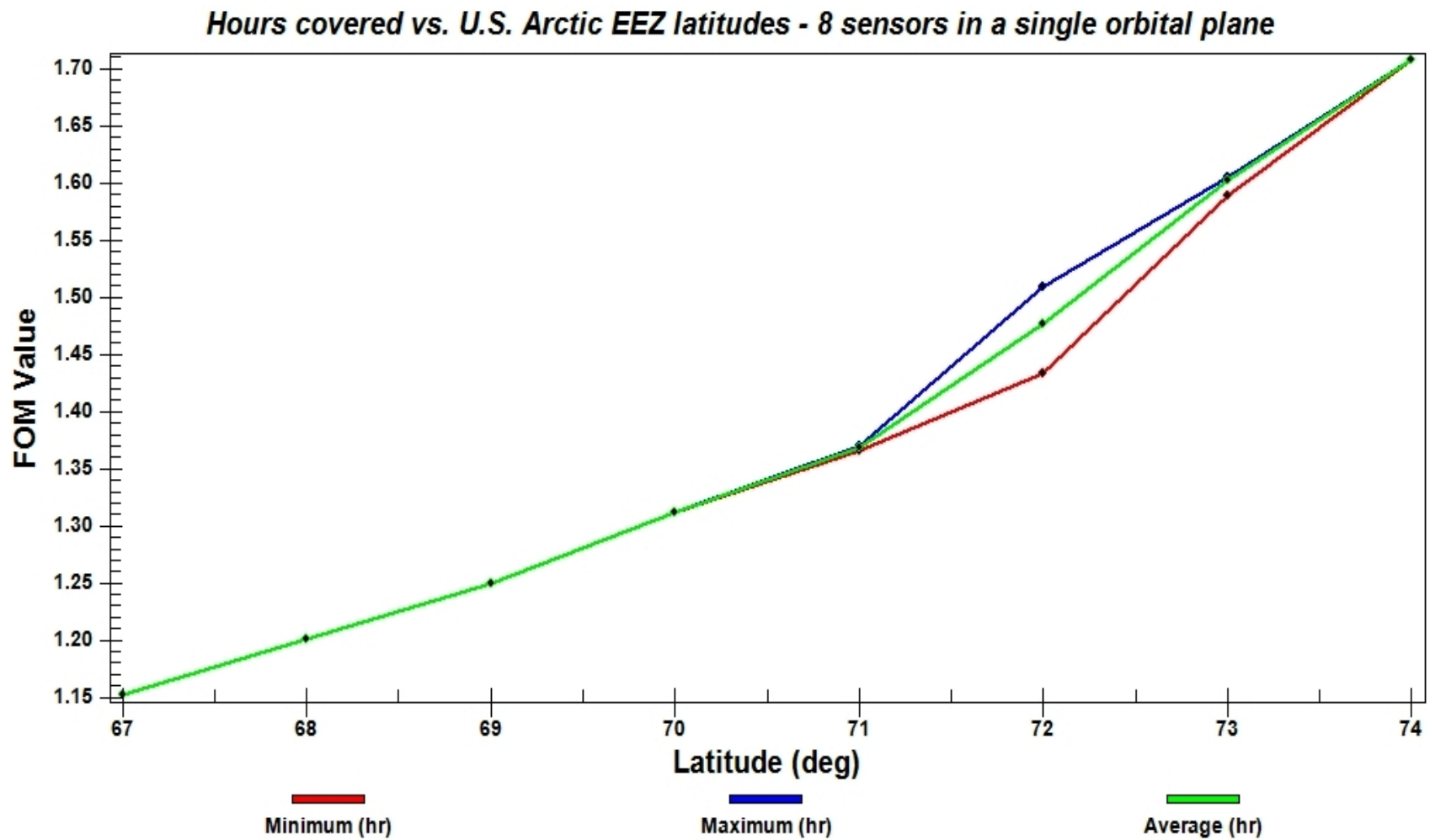


Figure 18. The cumulative hours covered in a 24-hour period by U.S. Arctic EEZ latitude from eight SAR sensors in a single orbital plane.

Number of SAR Sensors in Single Orbital Plane	Average Coverage of the U.S. EEZ in the Arctic Circle in a 24-hour period (hrs.)	U.S. Arctic EEZ efficiency (hours monitored per sensor deployed)
1	.191	.191
2	.368	.184
3	.544	.181
4	.720	.180
5	.897	.179
6	1.075	.179
7	1.257	.179
8	1.428	.179

Table 8. The average coverage times and the efficiency of monitoring the EEZ within the Arctic Circle of an increasing number of SAR sensors deployed in the same orbital plane.

Finding 3: The fewer the sensors within a single orbital plane constellation design, the more efficient monitoring of the Arctic and regions within it.

Finding 4: One, two, and three sensors within the single orbital plane constellation design appear to provide the best temporal coverage efficiency for the EEZ.

C. OPTIMIZING ARCTIC TEMPORAL COVERAGE PERFORMANCE WITH WALKER CONSTELLATION DESIGNS

1. The Arctic Circle

The possible Walker Constellation design configurations for a maximum of eight model RADARSAT-2 sensors are modeled for temporal coverage performance of the Arctic Circle. Table 9 delineates the 12 distinct Walker Constellation designs that were evaluated for the coverage time of the Arctic Circle and the EEZ within the Arctic Circle in a 24-hour period. Instead of plotting the coverage time by latitude for each of the 12 Walker Constellation designs, the minimum and maximum potential coverage times of the Arctic Circle by latitude for Walker Constellation designs are graphically displayed. The minimum coverage time in a 24-hour period of the Arctic Circle is provided by the 2/2/1 Walker Constellation (shown in Figure 19). The maximum coverage time of the Arctic Circle is provided by the 8/4/1 Walker Constellation (shown in Figure 20).

Inclination	Total Satellites	Orbital Planes	Adjacent Plane Spacing	Walker Notation
98.6	2	2	1	98.6 2/2/1
98.6	3	3	1	98.6 3/3/1
98.6	4	2	1	98.6 4/2/1
98.6	4	4	1	98.6 4/4/1
98.6	5	5	1	98.6 5/5/1
98.6	6	2	1	98.6 6/2/1
98.6	6	3	1	98.6 6/3/1
98.6	6	6	1	98.6 6/6/1
98.6	7	7	1	98.6 7/7/1
98.6	8	2	1	98.6 8/2/1
98.6	8	4	1	98.6 8/4/1
98.6	8	8	1	98.6 8/8/1

Table 9. Walker Constellations designs that are tested for temporal coverage performance against the Arctic Circle and Arctic EEZ

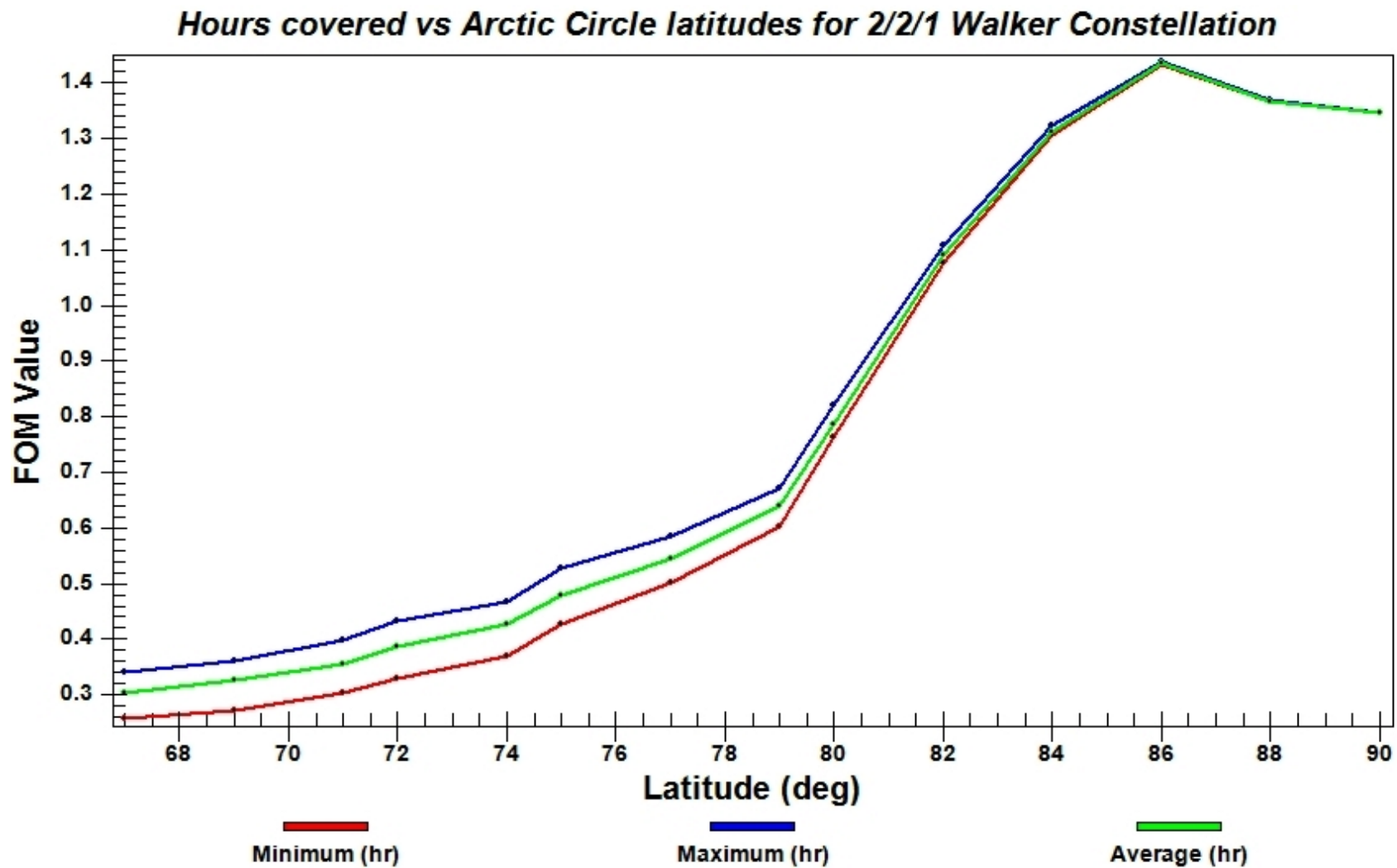


Figure 19. The cumulative hours covered within a 24-hour period by Arctic Circle latitude for a 2/2/1 Walker Constellation of SAR sensors.

Hours covered vs. Arctic Circle latitudes for 8/4/1 Walker Constellation

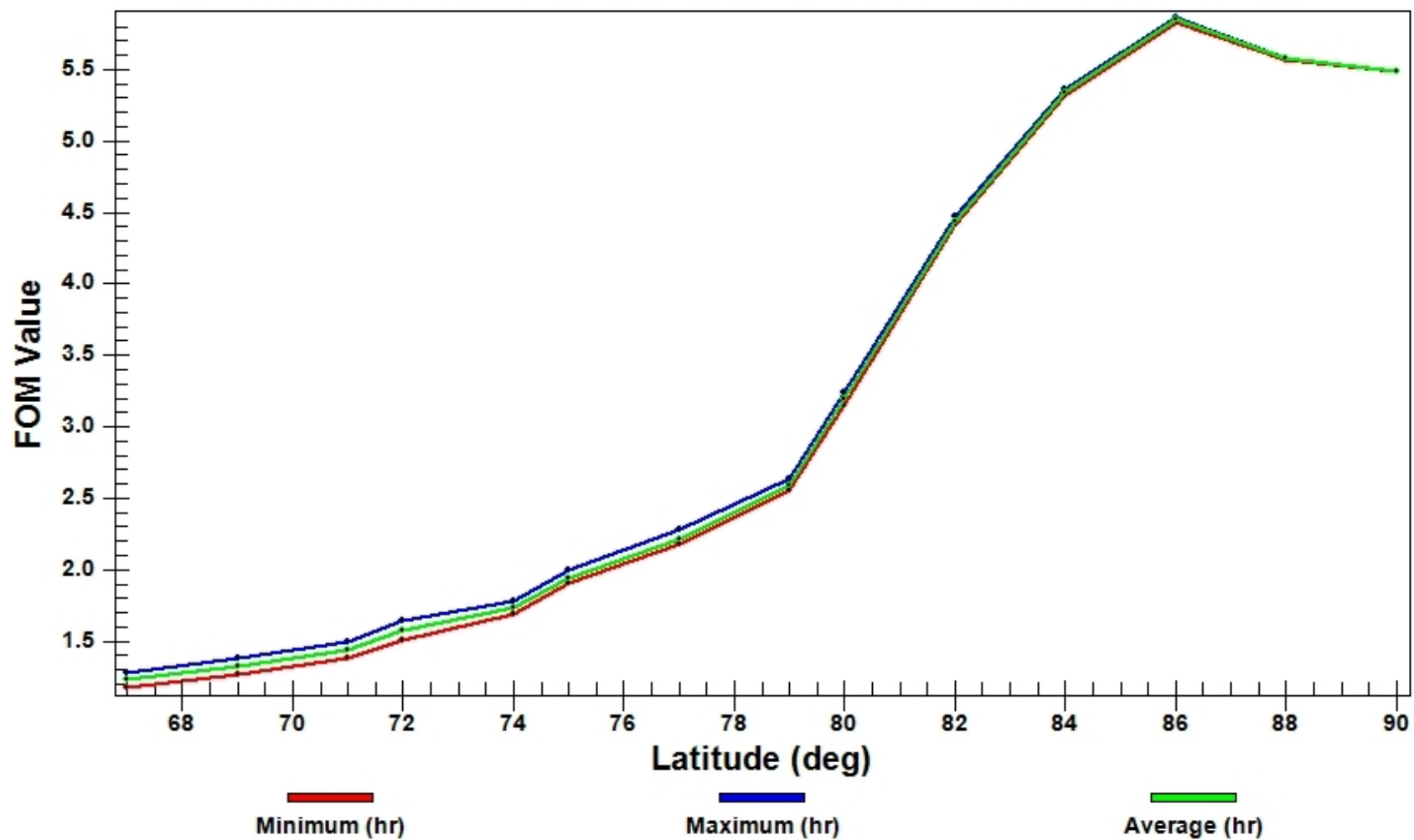


Figure 20. The cumulative hours covered in a 24-hour period by Arctic Circle latitude for an 8/4/1 Walker Constellation of SAR sensors.

Walker Constellation Design	Average Coverage of Arctic Circle in a 24-hour period (hrs.)	Arctic Circle coverage efficiency (hours monitored per sensor deployed)
Walker 2/2/1	0.563	0.282
Walker 3/3/1	0.86	0.287
Walker 4/2/1	1.143	0.286
Walker 4/4/1	1.143	0.286
Walker 5/5/1	1.431	0.286
Walker 6/2/1	1.666	0.278
Walker 6/3/1	1.716	0.286
Walker 6/6/1	1.716	0.286
Walker 7/7/1	2.001	0.286
Walker 8/2/1	2.176	0.272
Walker 8/4/1	2.288	0.286
Walker 8/8/1	2.287	0.286

Table 10. The average coverage times and the efficiency of monitoring the Arctic Circle of Walker Constellation designs.

Finding 5: There exists little latitudinal coverage variation among Walker Constellation designs for monitoring the totality of the Arctic Circle. In all designs, coverage does not accelerate until about 79 degrees latitude which is well above the latitudes of most significant interest in the Arctic Circle and above the U.S. EEZ latitudes.

Finding 6: The 3/3/1 Walker constellation design provides the most efficient temporal coverage performance for the Arctic Circle.

2. The Arctic U.S. Exclusive Economic Zone

The possible Walker constellations using a sensor limitation of eight are modeled against the U.S. EEZ in the Arctic Circle for temporal coverage performance. Instead of plotting the coverage time of the EEZ by latitude for each of the 12 Walker Constellation designs, the minimum and maximum potential coverage times of the EEZ by latitude for Walker Constellation designs are graphically displayed. The minimum coverage time in a 24-hour period of the EEZ is provided by the 2/2/1 Walker Constellation (shown in Figure 21). The maximum coverage time of the EEZ is provided by the 8/4/1 Walker Constellation (shown in Figure 24).

In contrast to the Arctic Circle writ large, the lower latitudes that constitute the U.S. EEZ in the Arctic have much more variation in maximum and minimum coverage by latitude from successive 24-hour periods. Figures 22 and 23 show how varied coverage can be at certain latitudes within the EEZ, particularly at 70 degrees, for the 3/3/1 and 5/5/1 Walker Constellation designs. The other ten Walker Constellation designs exhibit much less variation from period to period in coverage by latitude.

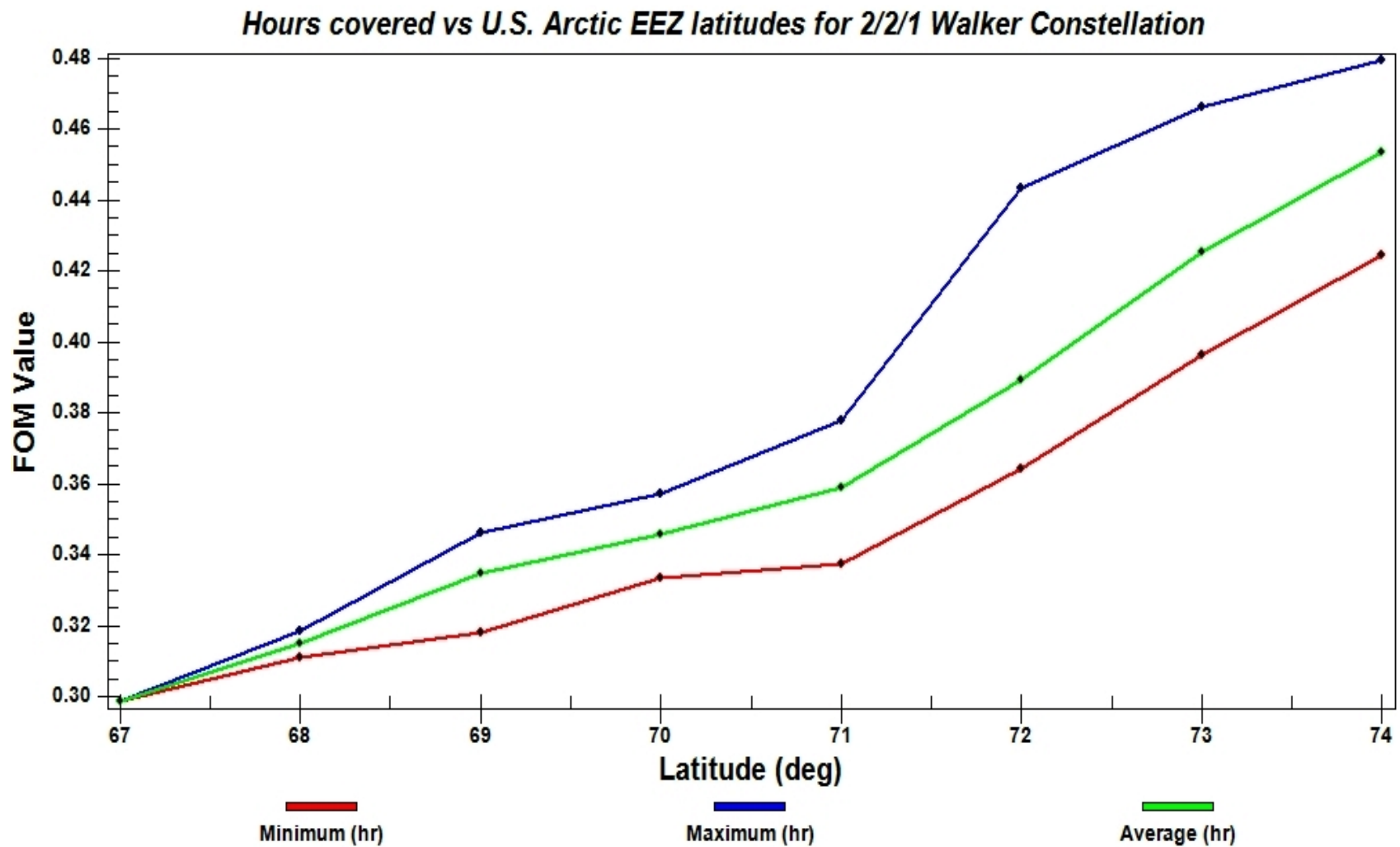


Figure 21. The cumulative hours covered in a 24-hour period by Arctic EEZ latitude for a 2/2/1 Walker Constellation.

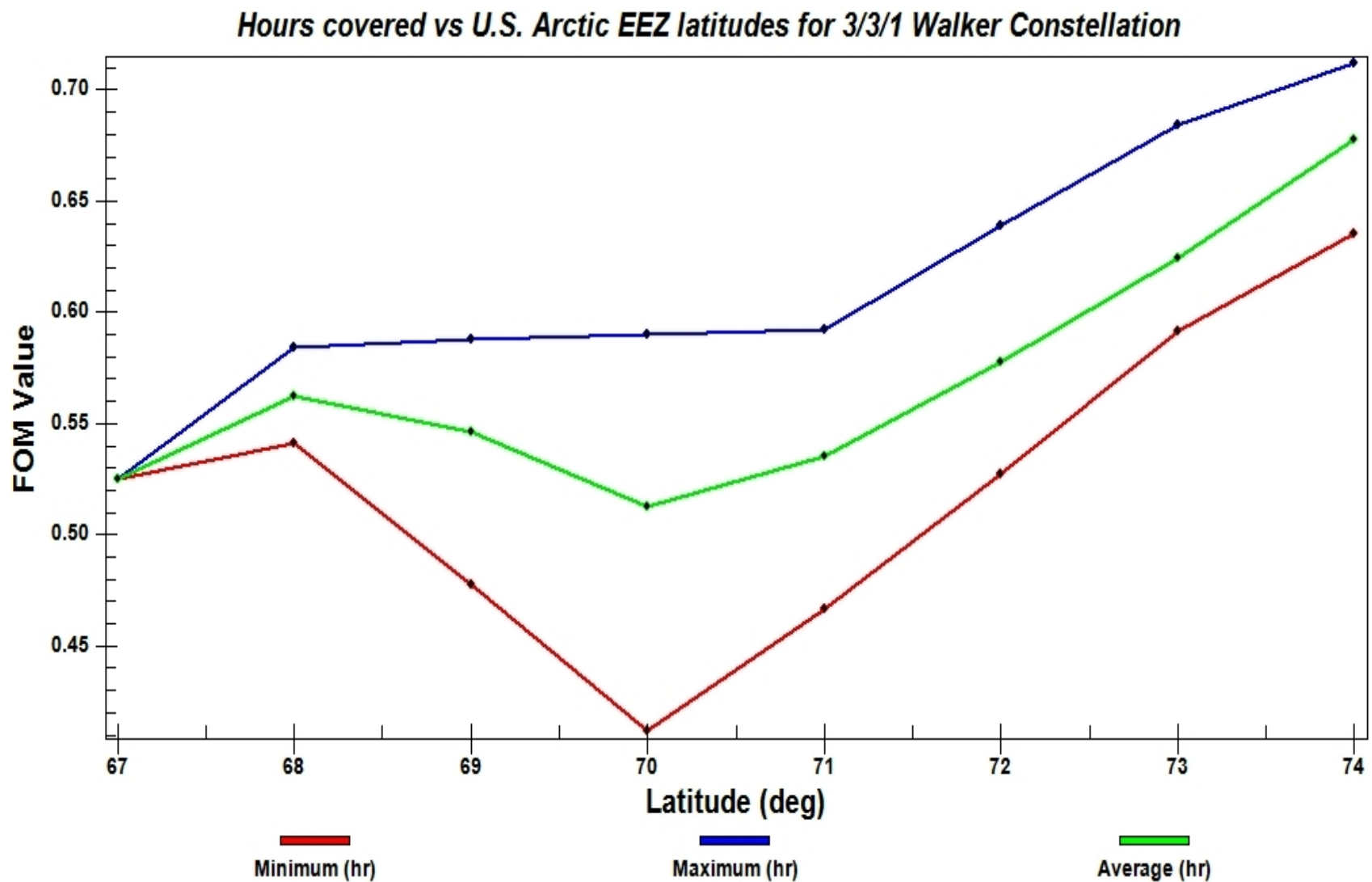


Figure 22. The cumulative hours covered in a 24-hour period by Arctic EEZ latitude for a 3/3/1 Walker Constellation.

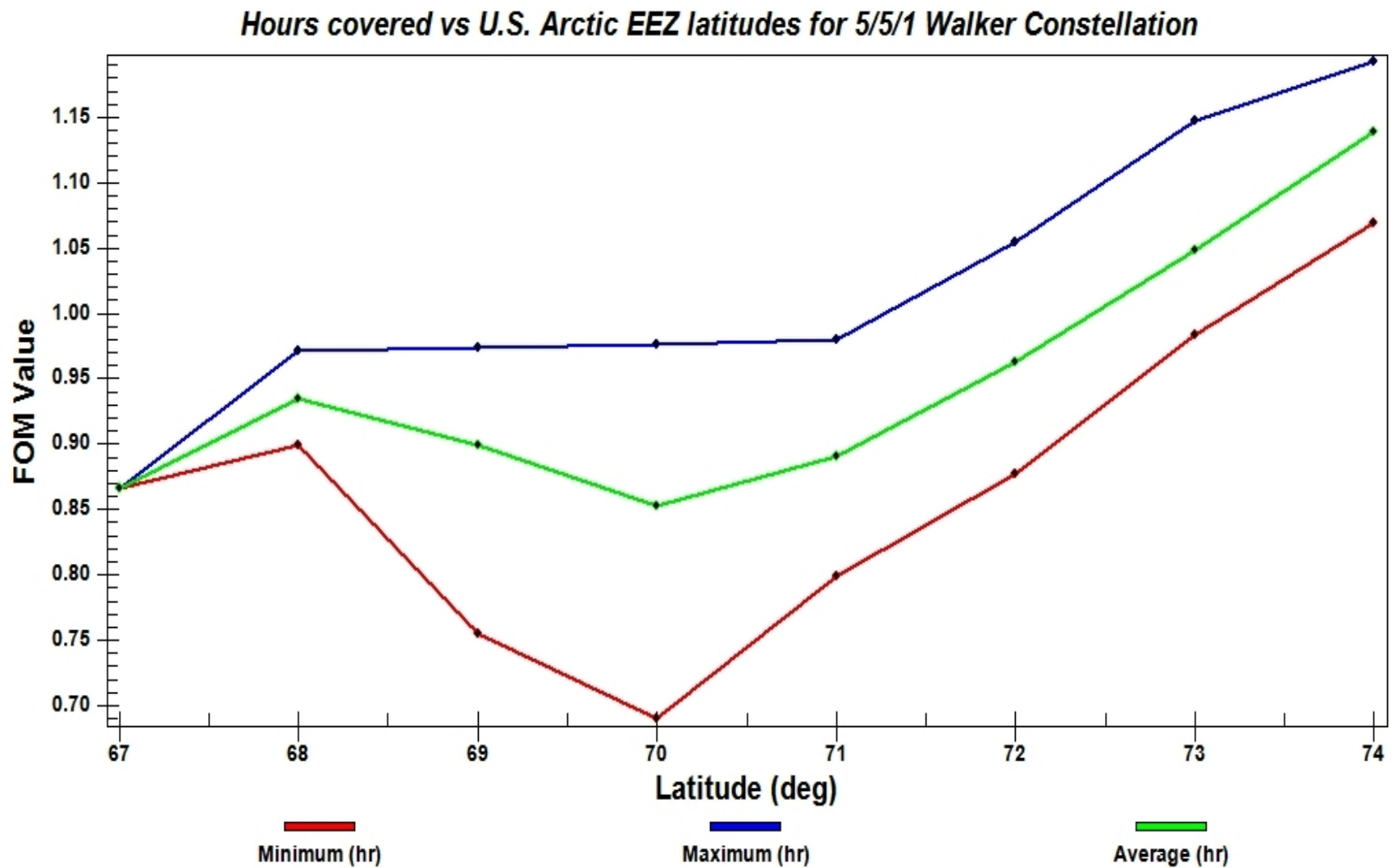


Figure 23. The cumulative hours covered in 24-hour period Arctic EEZ latitude for a 5/5/1 Walker Constellation.

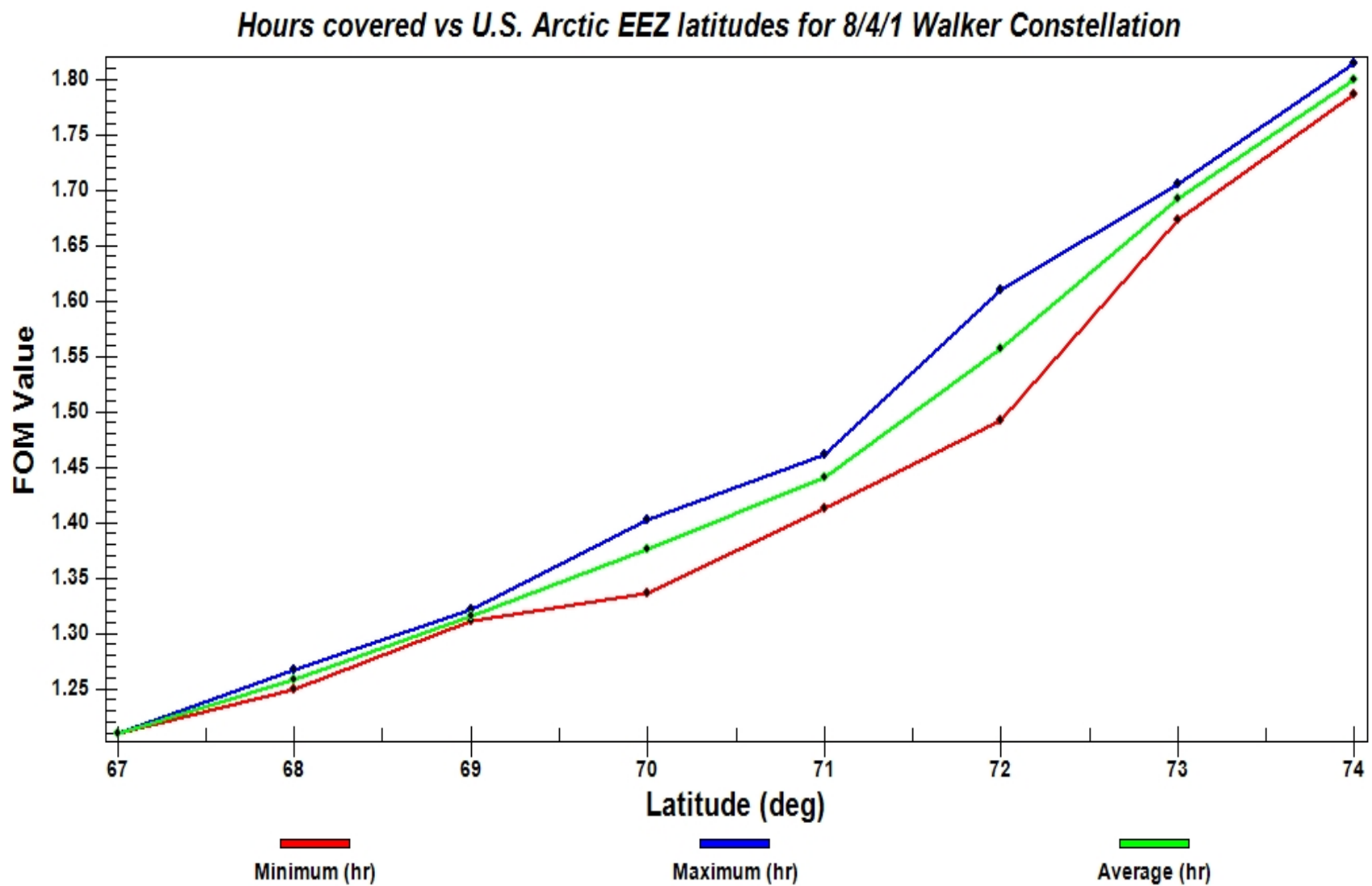


Figure 24. The cumulative hours covered in 24-hour period by Arctic EEZ latitude for a 8/4/1 Walker Constellation.

Walker Constellation Design	Average Coverage of the U.S. EEZ in the Arctic Circle in a 24-hour period (hrs.)	U.S. Arctic EEZ efficiency (hours monitored per sensor deployed)
Walker 2/2/1	0.377	0.189
Walker 3/3/1	0.568	0.189
Walker 4/2/1	0.751	0.188
Walker 4/4/1	0.752	0.188
Walker 5/5/1	0.947	0.189
Walker 6/2/1	1.06	0.177
Walker 6/3/1	1.131	0.189
Walker 6/6/1	1.139	0.190
Walker 7/7/1	1.305	0.186
Walker 8/2/1	1.406	0.176
Walker 8/4/1	1.504	0.188
Walker 8/8/1	1.478	0.185

Table 11. The average coverage times and the efficiency of monitoring the EEZ of Walker Constellation designs.

Finding 7: The most inconsistent coverage (widest coverage by latitude variation among distinct 24 hour coverage periods) across the EEZ is from the 3/3/1 and 5/5/1 Walker Constellation designs.

Finding 8: From an EEZ coverage efficiency perspective (hours monitoring the EEZ per sensor), the 6/6/1 Walker design appears to be the best design followed by the 6/3/1, 5/5/1, 3/3/1, and 2/2/1.

D. AN OPTIMAL AND BALANCED SPACE-BASED RADAR CONSTELLATION DESIGN

Given the cost in resources for launching SAR sensors, coverage efficiency for both the broad Arctic and U.S. EEZ is given primacy in selecting the number of sensors that have the best cost-benefit. *The best temporal coverage efficiency between the Arctic Circle and U.S. Arctic EEZ based on evidence from the single orbital plane and Walker Constellation M&S efforts are those consisting of three sensors.* Three sensors ranked #2, #3, #1, and #2 for efficiency ratings among the single orbital plane and Walker Constellations when tested against the Arctic Circle and Arctic EEZ respectively. Four sensors ranked #2, #4, #2, and #3 in efficiency.

While one or two sensors fared well in efficiency, the aggregate coverage and opportunity for sensing by only one or two sensors is less than half of one hour in any 24-hour period. Three sensors provides *at least* one half of one hour per day in the Arctic and the EEZ. In sum, given the launch costs and surveillance needs of the nation, three sensors appears to be the best balance between cost, coverage, and efficiency with which to design a constellation for Arctic surveillance optimality. Therefore, additional analysis will focus on improving temporal coverage efficiency from constellations consisting of three sensors to determine if different designs of tri-sensor constellations can improve upon temporal coverage performance of typical single orbital plane or Walker Constellation designs.

Having controlled for inclination, altitude, and sensor package variables in previous analysis, other changes to variables in a three sensor package are made to determine if a better constellation for SAR sensors can be found. The following variables are modeled and simulated to support this objective:

- Relationship of the three sensors within single orbital planes (tandem and modified tandem satellite positions within the orbital plane).²
- RAANs of different orbital planes in which the three sensors are orbiting.
- Combined Walker and RAAN differential constellation designs (hybrid between similar orbital plane and Walker Constellation design).

The intent is to identify if any of these independent variables can drive improved sensor temporal coverage efficiency of the lower latitude areas of the Arctic Circle where Arctic maritime activity is most likely to occur. Table 12 describes the constellation designs that were analyzed by changing one or more of the independent variables to determine optimal efficiency and consistency of Arctic EEZ coverage.

² A tandem construct in the context of this research is where satellites in the same orbital plane are separated by 15 degrees within their 360 degree orbital plane. This is the same separation of the TanDEM and TerraSAR sensors that are on orbit today.

Constellation	# of sensors	RAAN between Planes (Walker only)	RAAN offset of sensors in similar planes (Similar plane only) (degrees)	Separation between sensor in same orbital plane (degrees)	Separation between sensors in different orbital planes (degrees)	Arctic Circle coverage in 24- hour period (hrs.)	Arctic Circle Efficiency (hours covered per sensor deployed)	U.S. EEZ coverage in 24- hour period (hrs.)	U.S. EEZ Efficiency (hours covered per sensor deployed)
Single orbital plane – 2 satellites in tandem	3	N/A	N/A	15	180	0.839	0.28	0.561	0.187
Single orbital plane – 3 satellites in tandem	3	N/A	N/A	15	N/A	0.814	0.271	0.546	0.182
Similar orbital plane	3	N/A	1	N/A	120	0.86	0.287	0.566	0.189
Similar orbital plane	3	N/A	5	N/A	120	0.86	0.287	0.568	0.189
Similar orbital plane	3	N/A	10	N/A	120	0.86	0.287	0.568	0.189
Similar orbital plane	3	N/A	30	N/A	120	0.86	0.287	0.573	0.191
Similar orbital plane	3	N/A	40	N/A	120	0.86	0.287	0.61	0.203
Similar orbital plane	3	N/A	41	N/A	120	0.86	0.287	0.611	0.203
Similar orbital plane	3	N/A	42	N/A	120	0.86	0.287	0.611	0.204

Similar orbital plane	3	N/A	43	N/A	120	0.86	0.287	0.613	0.204
Similar orbital plane	3	N/A	44	N/A	120	0.86	0.287	0.612	0.204
Similar orbital plane	3	N/A	45	N/A	120	0.86	0.287	0.609	0.203
Similar orbital plane	3	N/A	46	N/A	120	0.86	0.287	0.606	0.202
Similar orbital plane	3	N/A	47	N/A	120	0.86	0.287	0.604	0.201
Similar orbital plane	3	N/A	48	N/A	120	0.86	0.287	0.603	0.201
Similar orbital plane	3	N/A	49	N/A	120	0.86	0.287	0.602	0.201
Similar orbital plane	3	N/A	50	N/A	120	0.86	0.287	0.602	0.201
Similar orbital plane	3	N/A	60	N/A	120	0.86	0.287	0.593	0.198
Similar orbital plane	3	N/A	90	N/A	120	0.86	0.287	0.571	0.19
Similar orbital plane	3	N/A	119	N/A	120	0.86	0.287	0.568	0.189
Hybrid Walker (mix of similar plane and Walker)	3	120	1	N/A	120	0.86	0.287	0.567	0.189

Table 12. The characteristics and temporal coverage efficiency of ad-hoc constellation designs modeled and simulated based on the best performing constellation of SAR sensors from single orbital plane and Walker Constellation designs

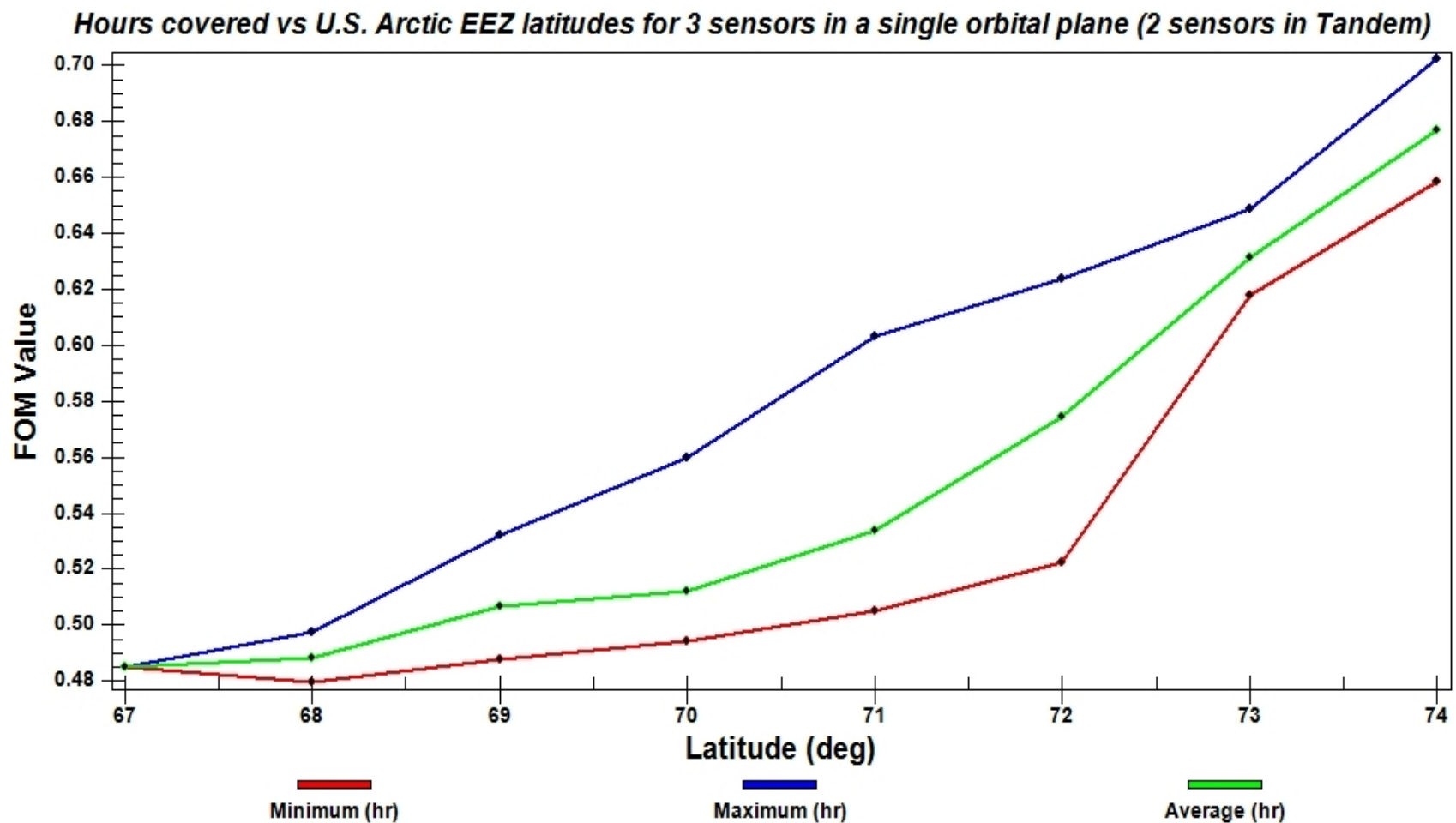


Figure 25. The cumulative hours covered in a 24-hour period by Arctic EEZ latitude for 3 sensors in a single orbital plane with 2 sensors in tandem.

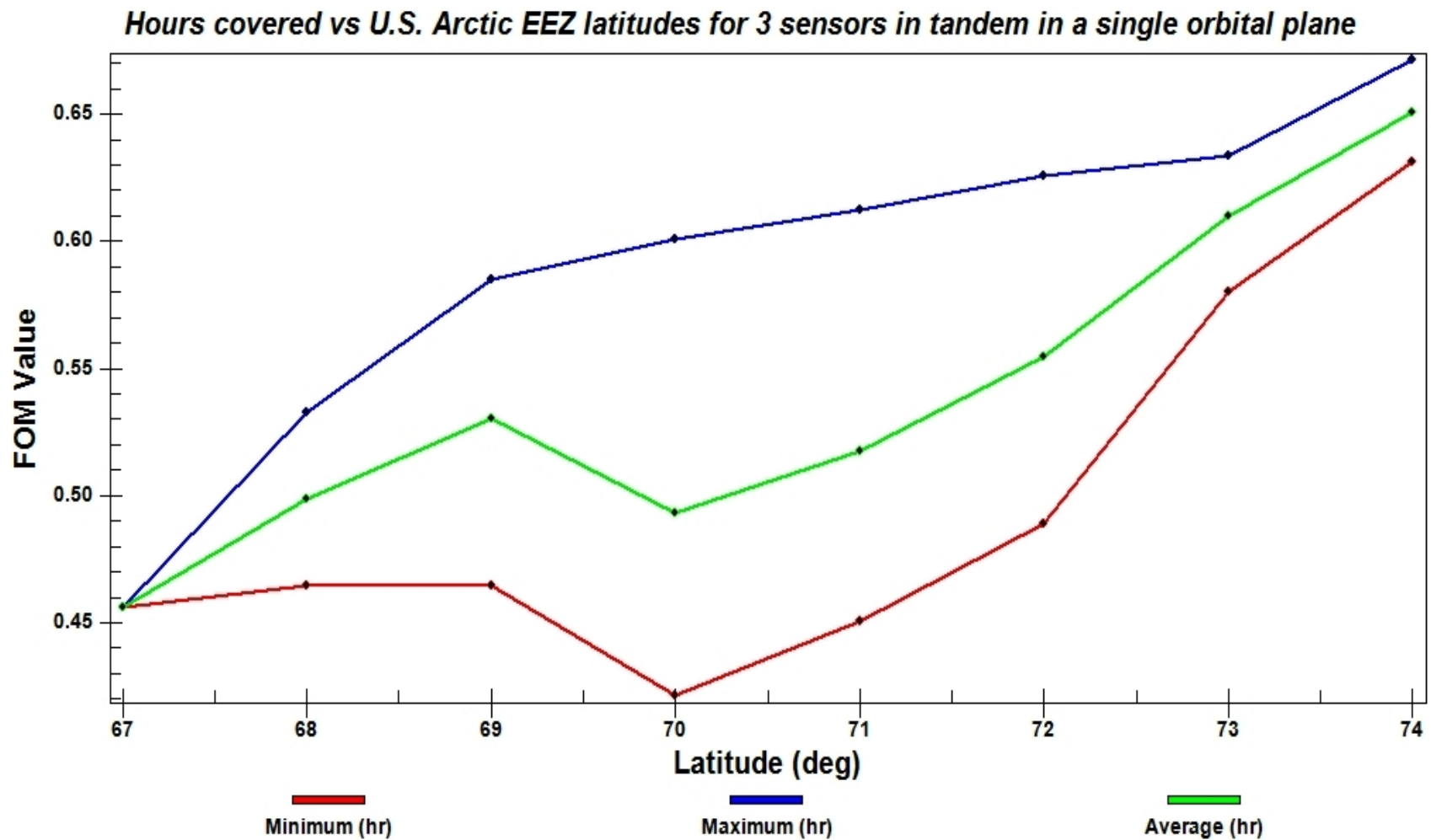


Figure 26. The cumulative hours covered in a 24-hour period by Arctic EEZ latitude for 3 sensors in a single orbital plane with all sensors in tandem.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a one degree separation of RAAN

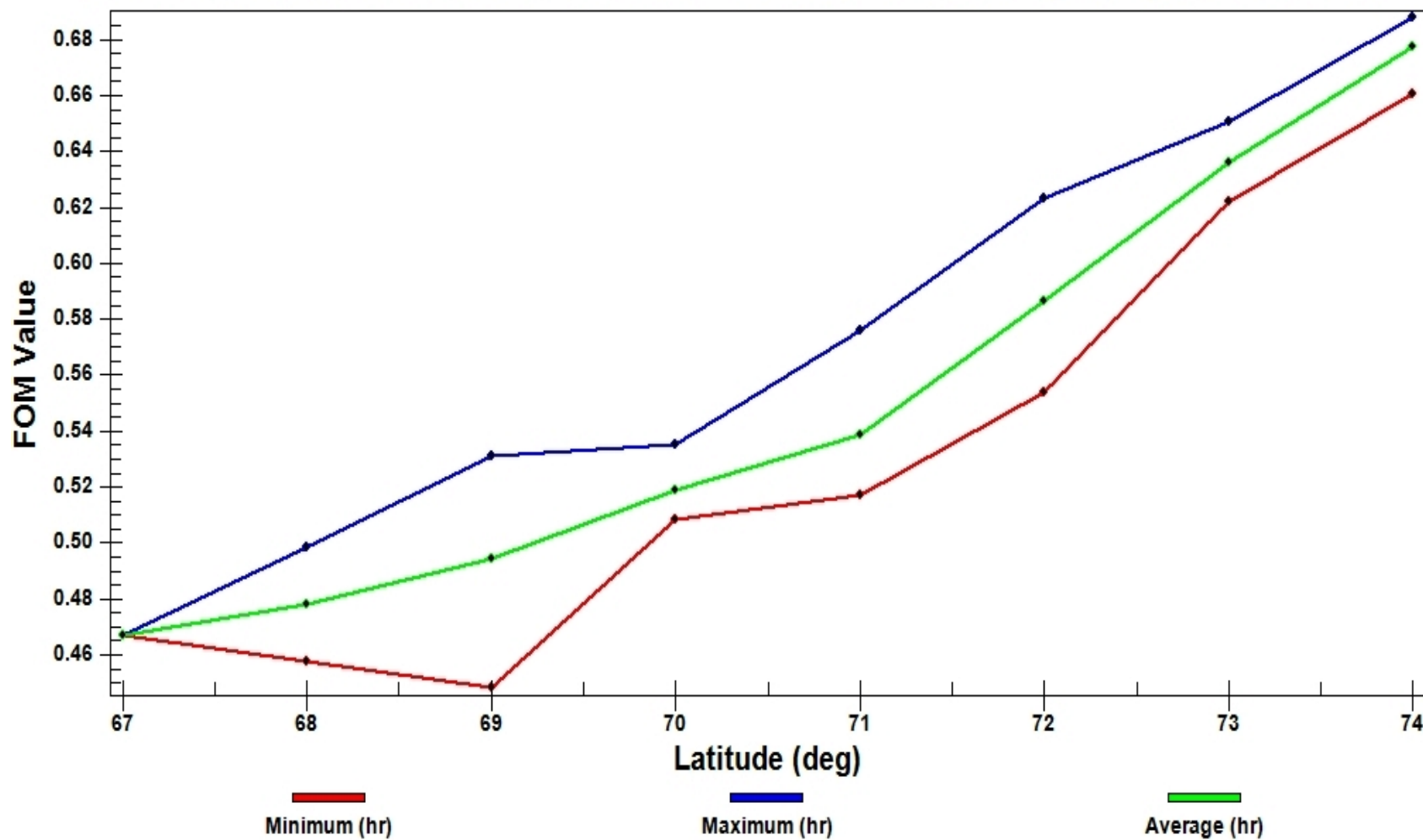


Figure 27. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with one degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a five degree separation of RAAN

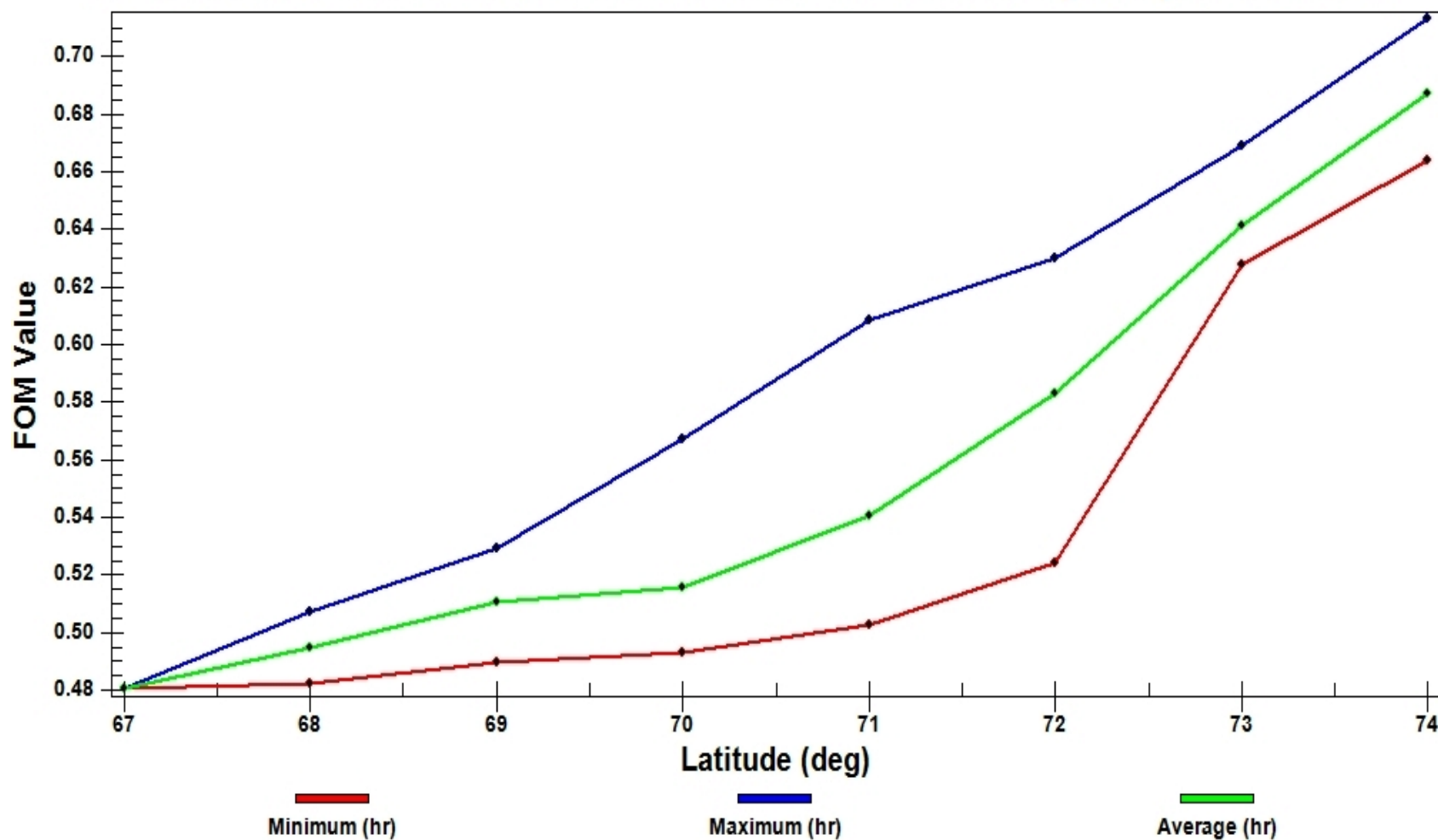


Figure 28. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with five degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a ten degree separation of RAAN

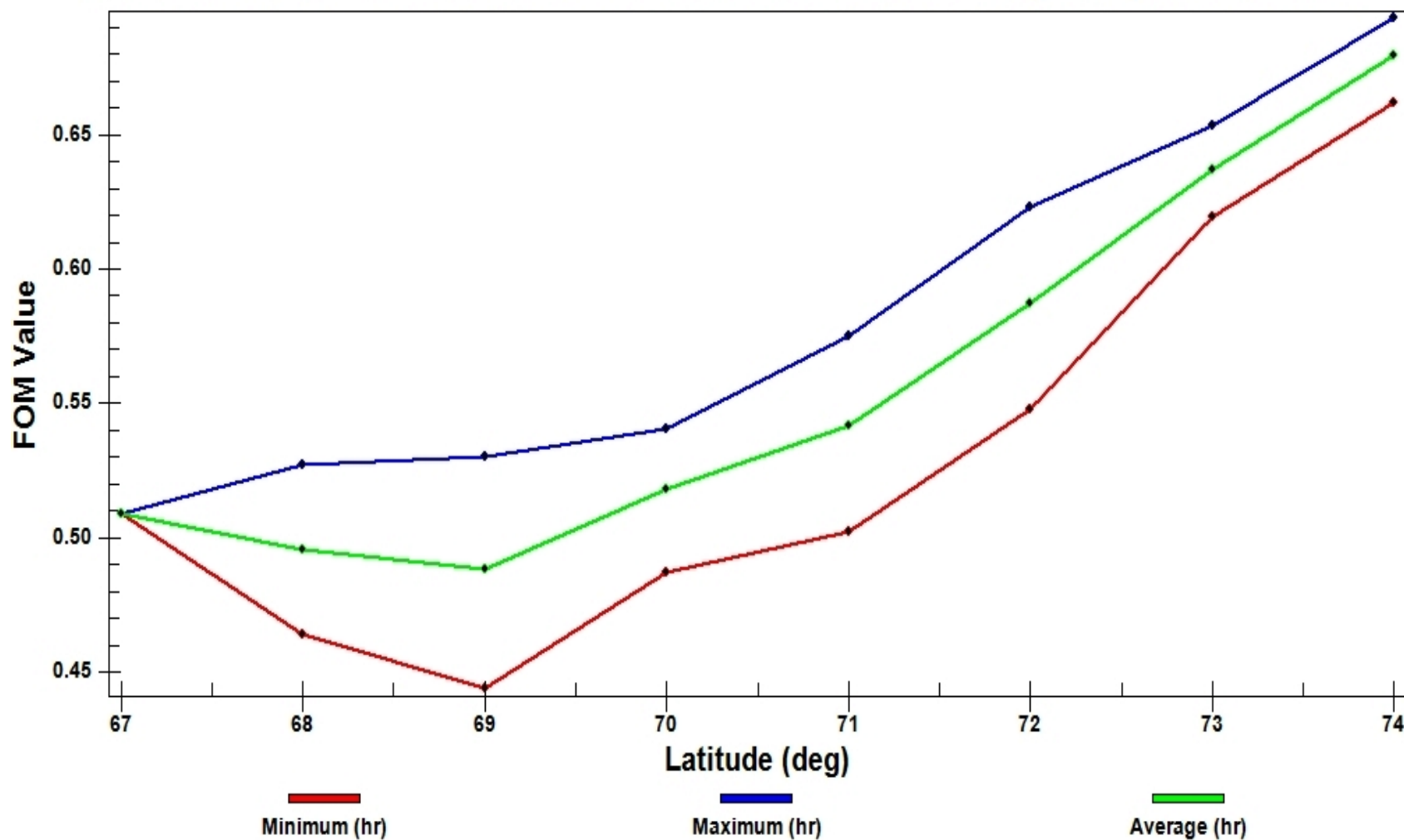


Figure 29. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with ten degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a 30 degree separation of RAAN

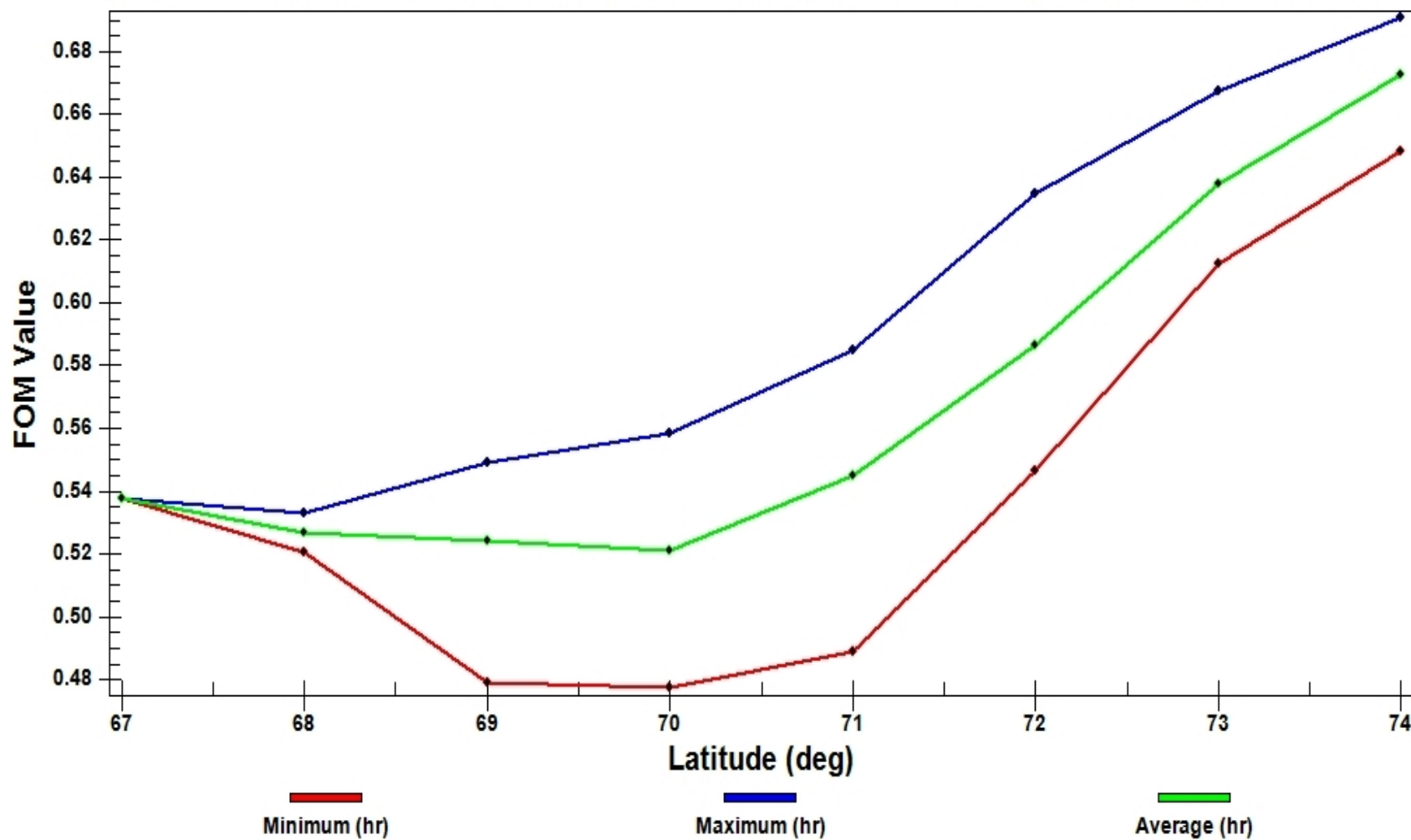


Figure 30. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 30-degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a 40 degree separation of RAAN

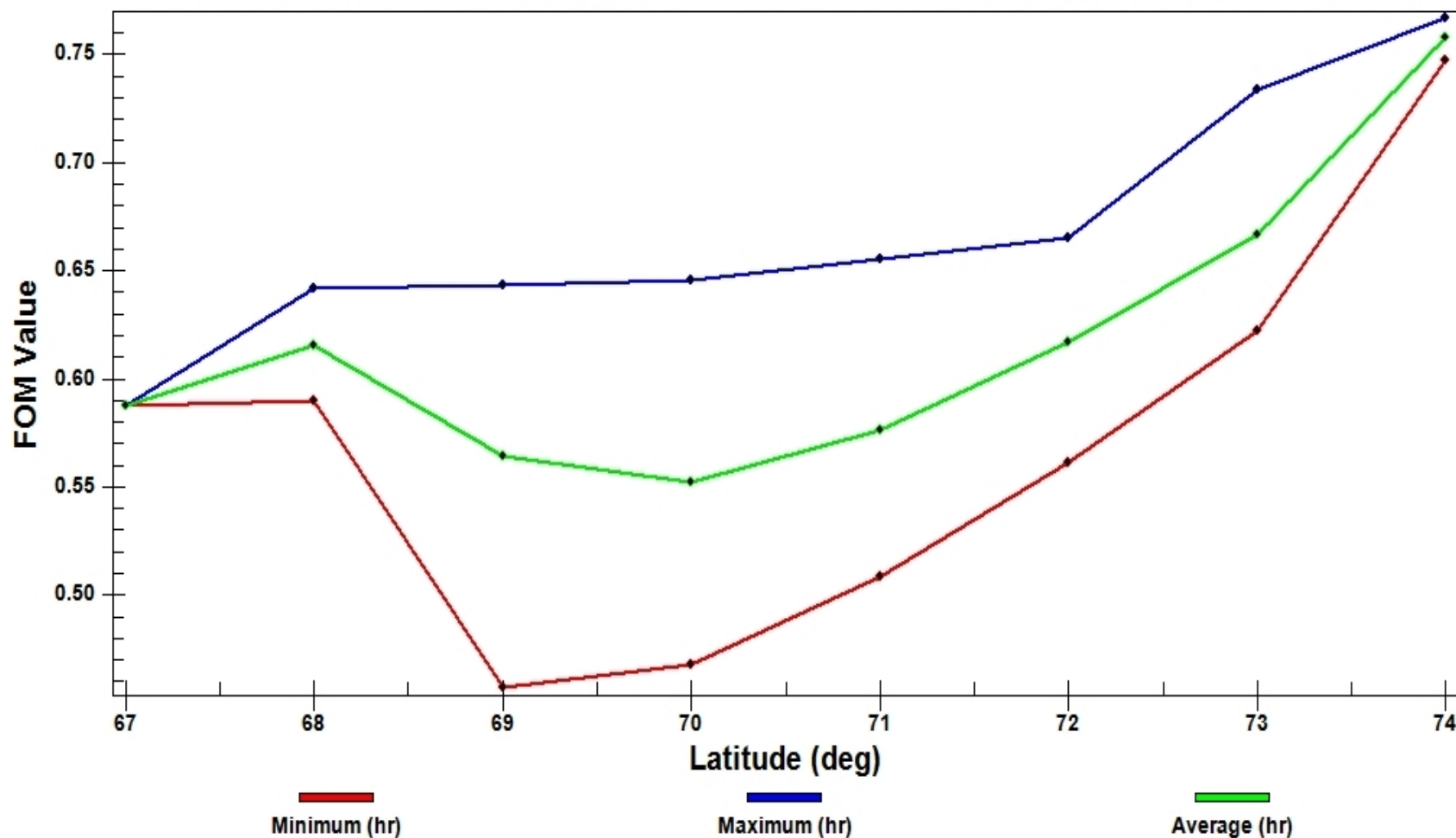


Figure 31. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 40-degree separation of RAAN.

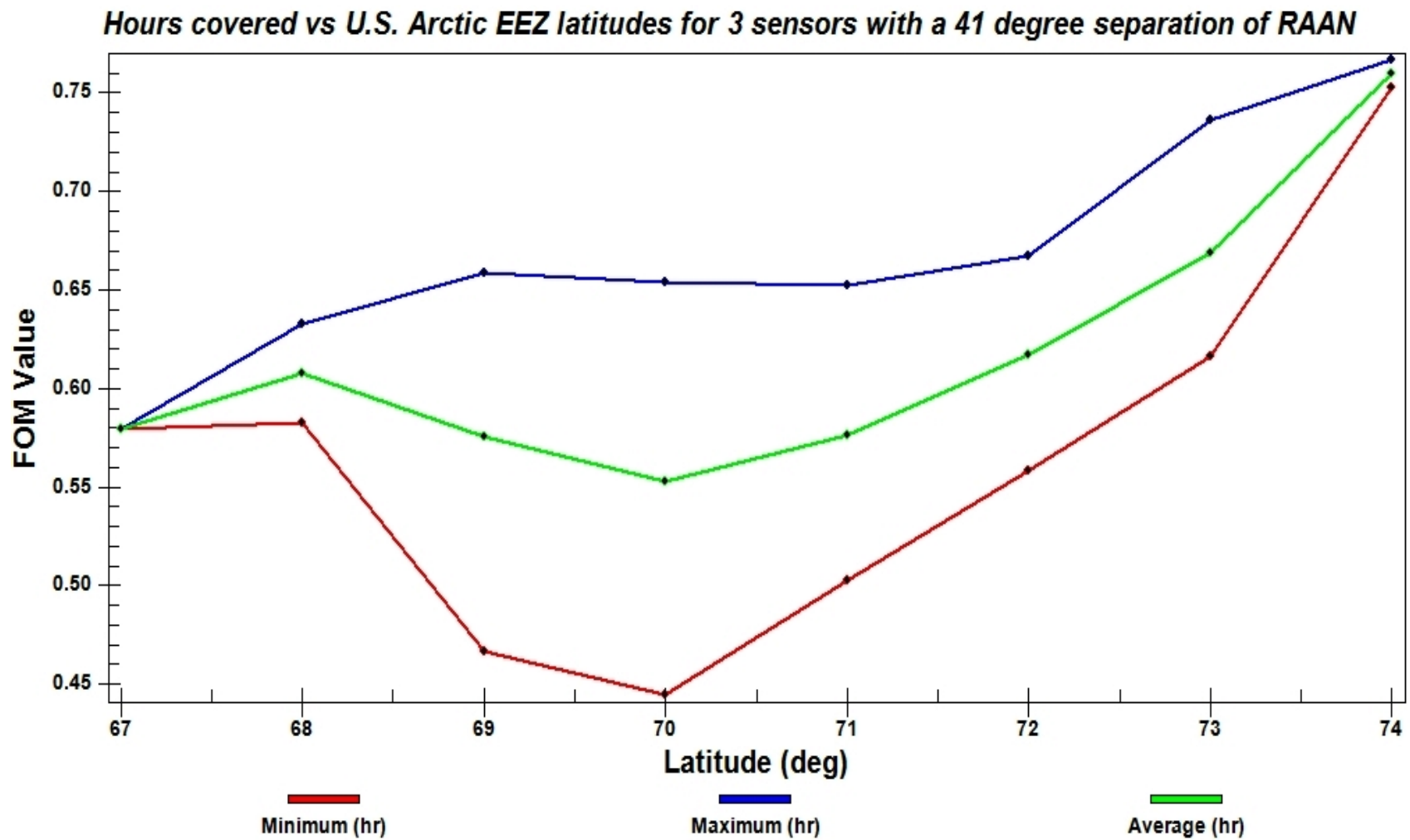


Figure 32. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 41-degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a 42 degree separation of RAAN

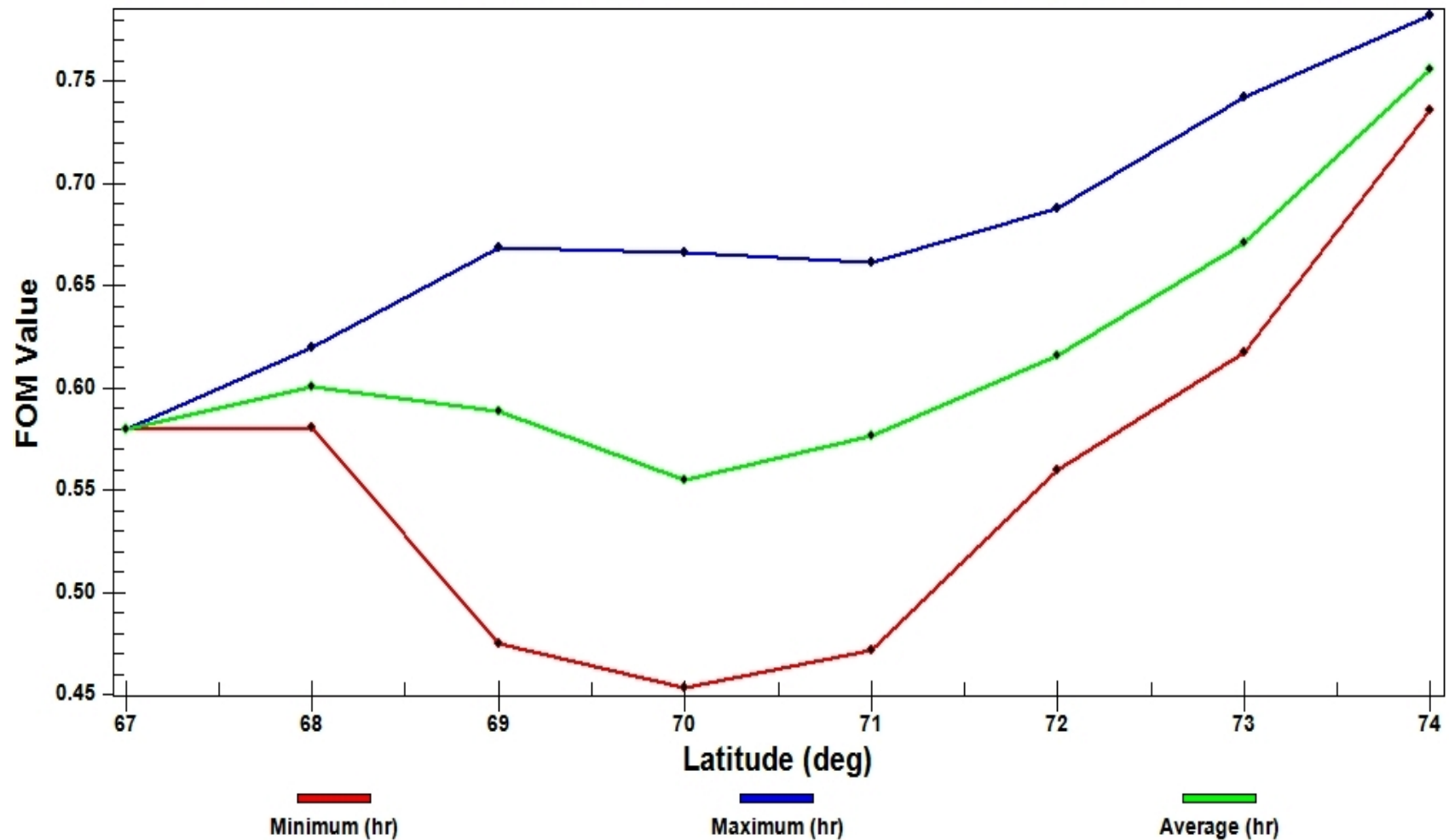


Figure 33. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 42-degree separation of RAAN.

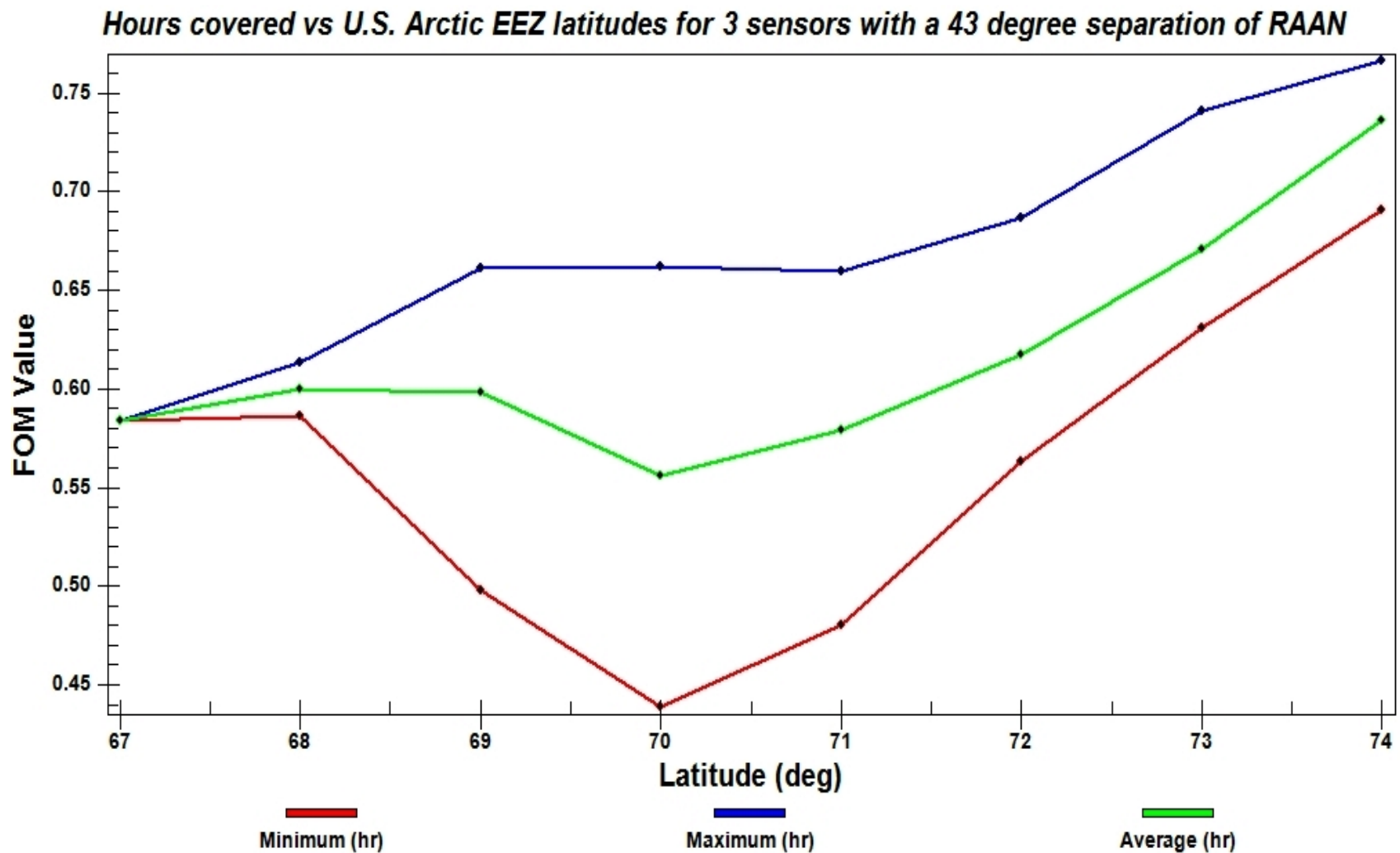


Figure 34. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 43-degree separation of RAAN.

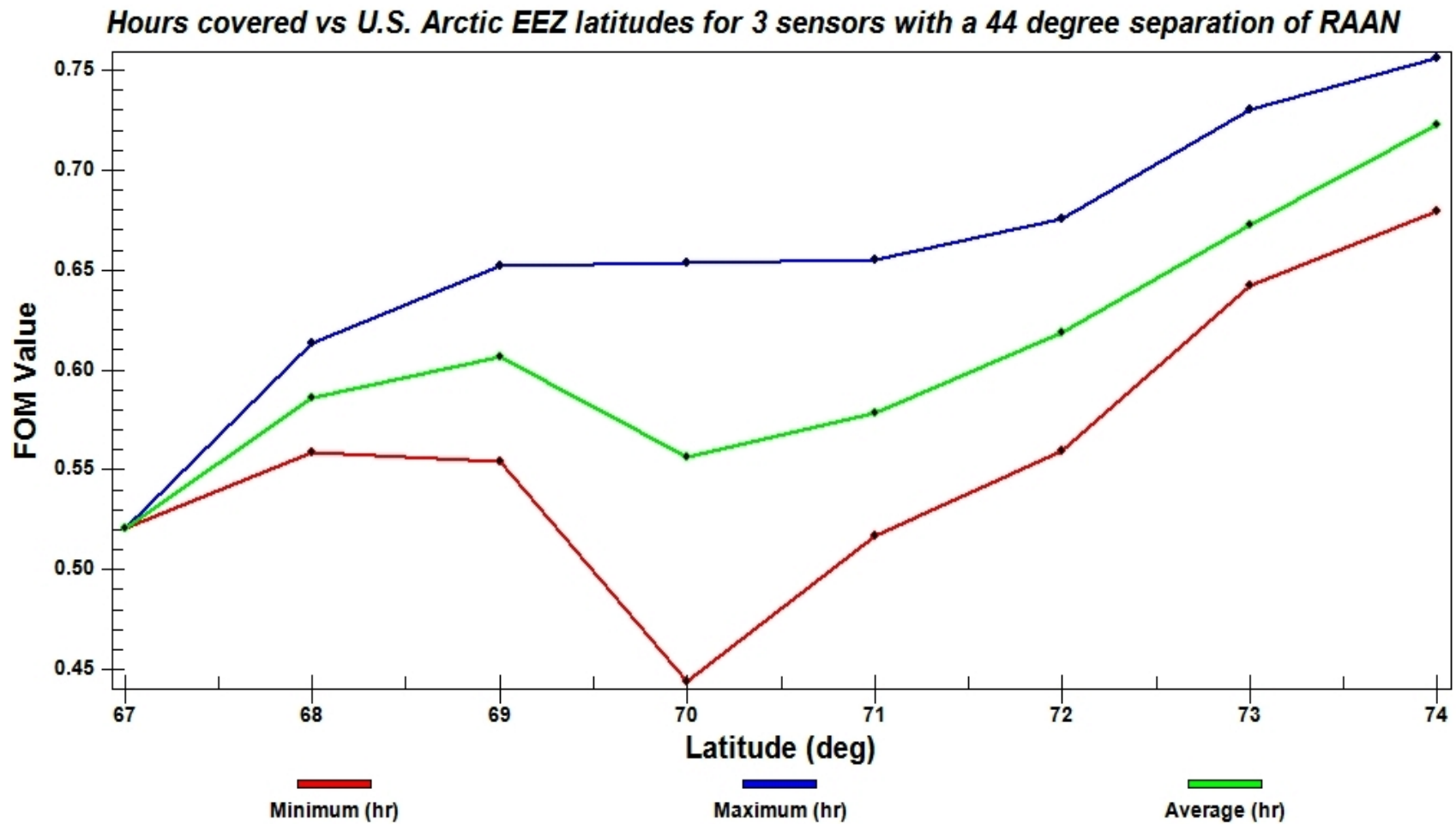


Figure 35. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 44-degree separation of RAAN.

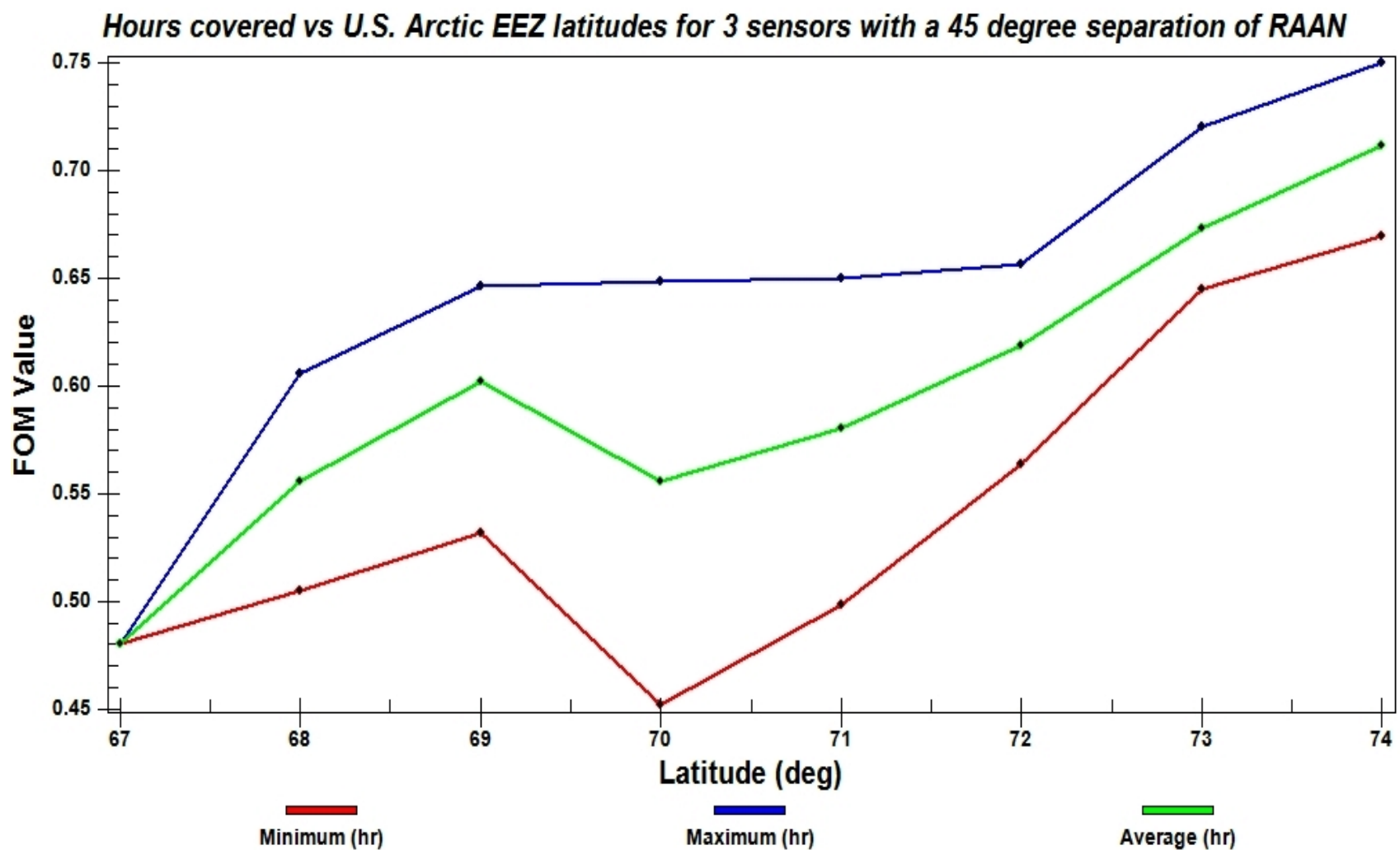


Figure 36. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 45-degree separation of RAAN.

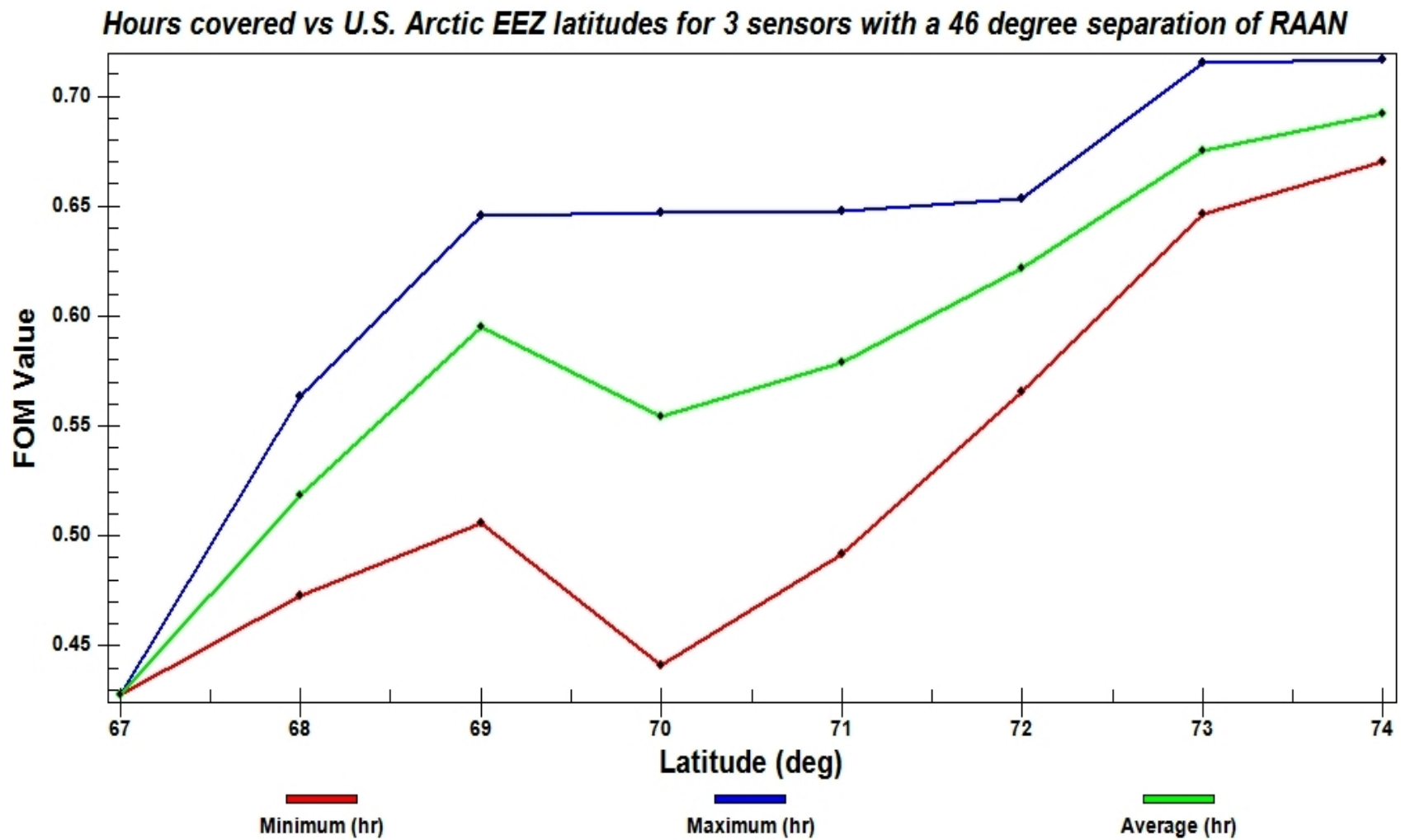


Figure 37. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 46-degree separation of RAAN.

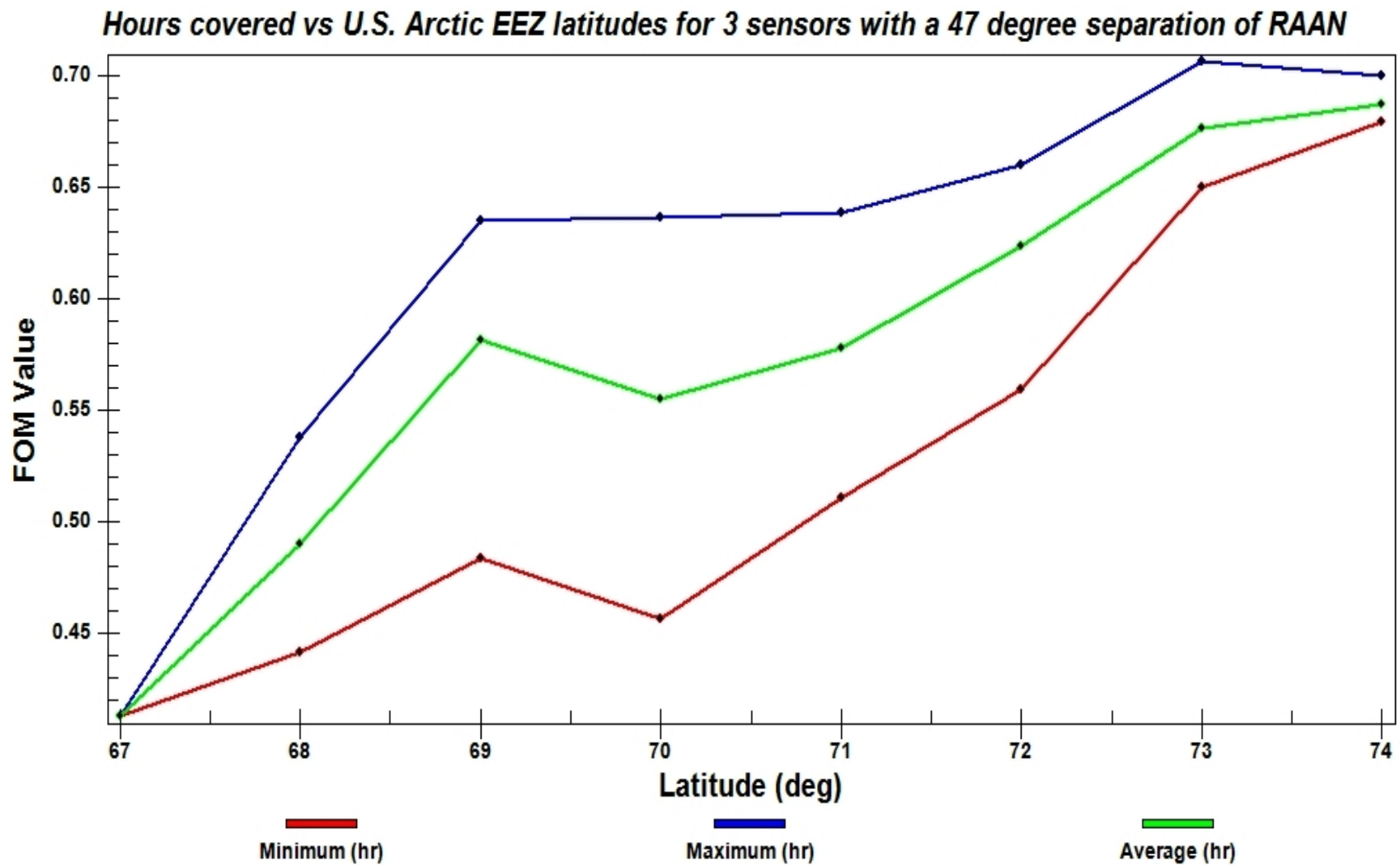


Figure 38. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 47-degree separation of RAAN.

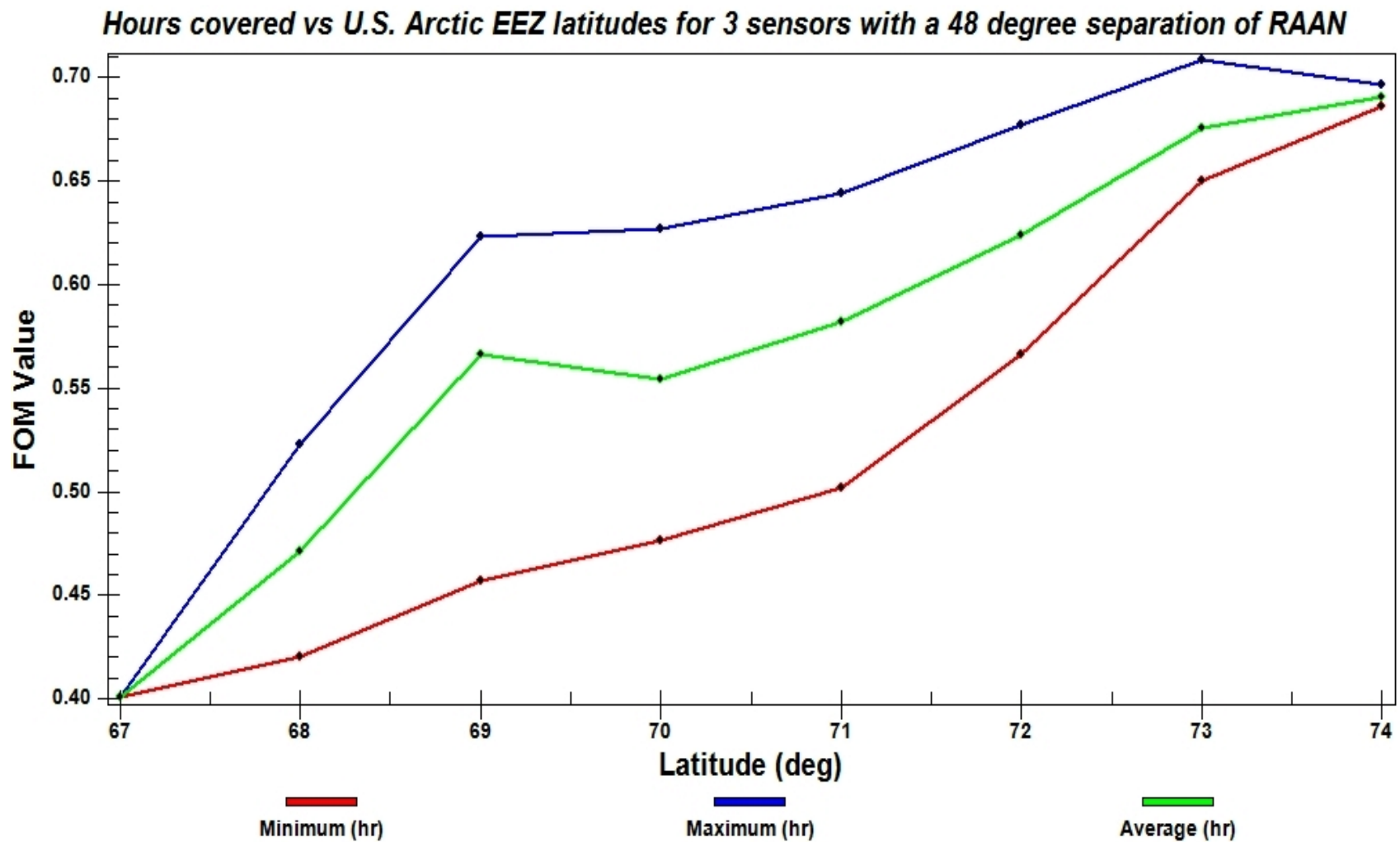


Figure 39. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 48-degree separation of RAAN.

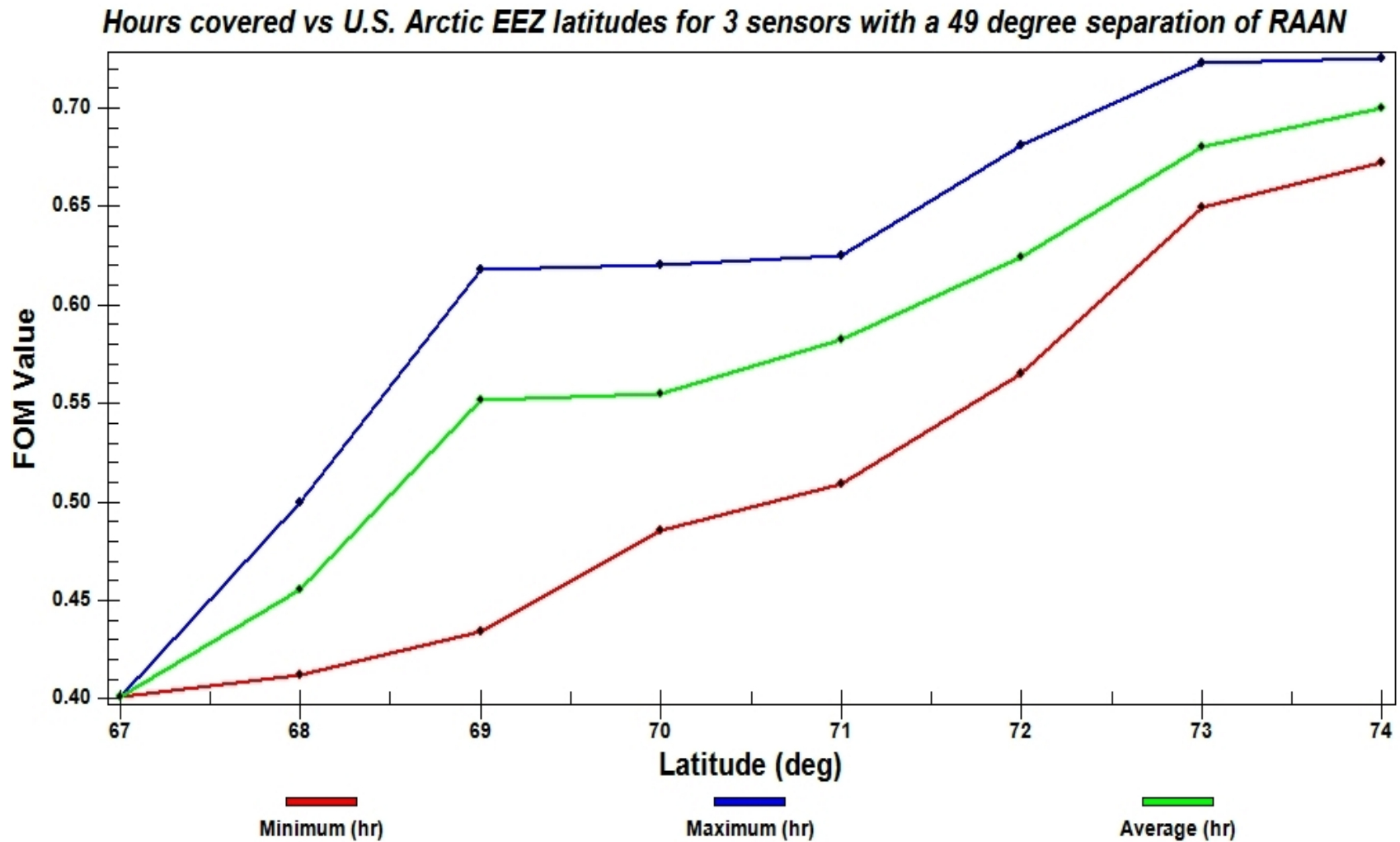


Figure 40. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 49-degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a 50 degree separation of RAAN

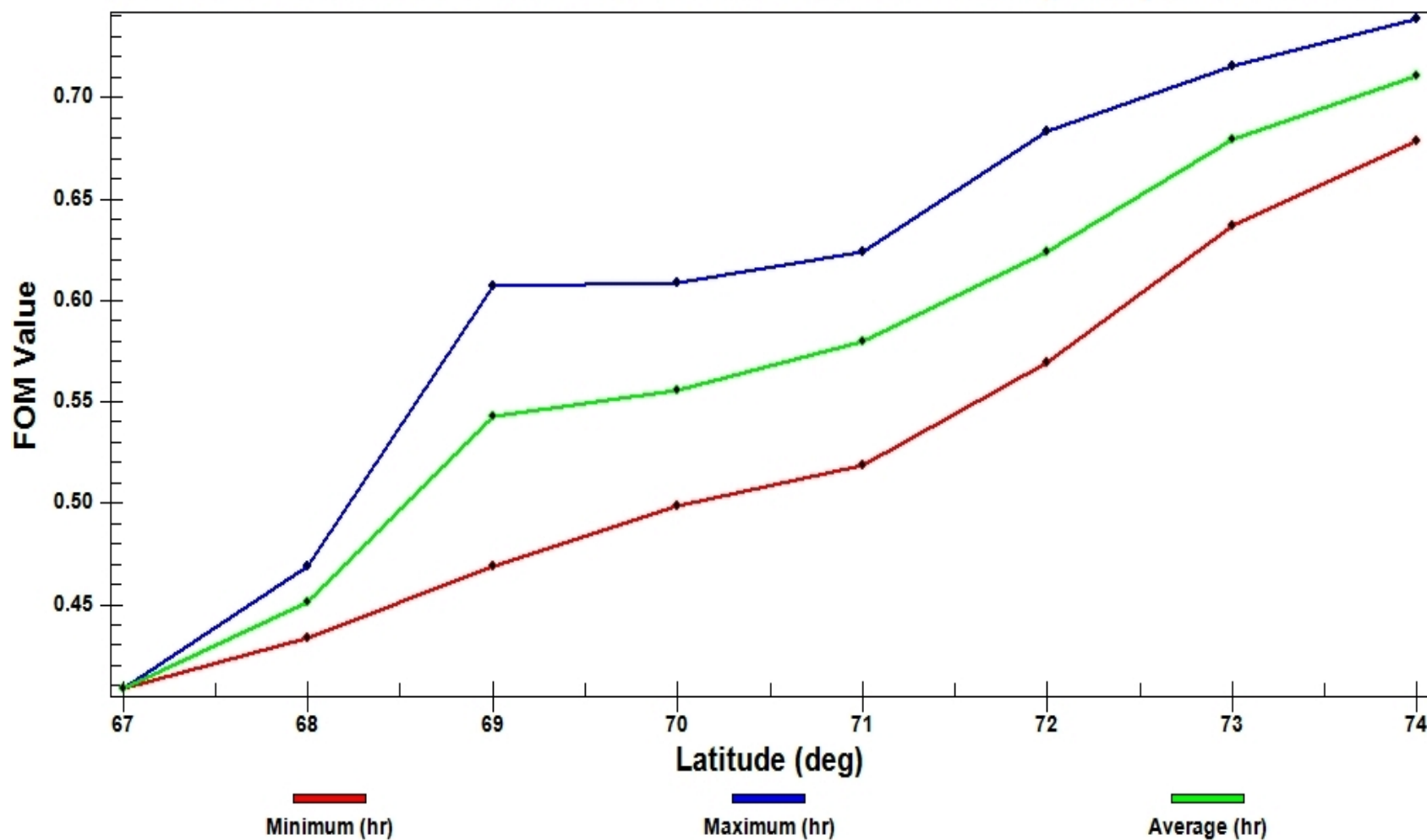


Figure 41. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 50-degree separation of RAAN.

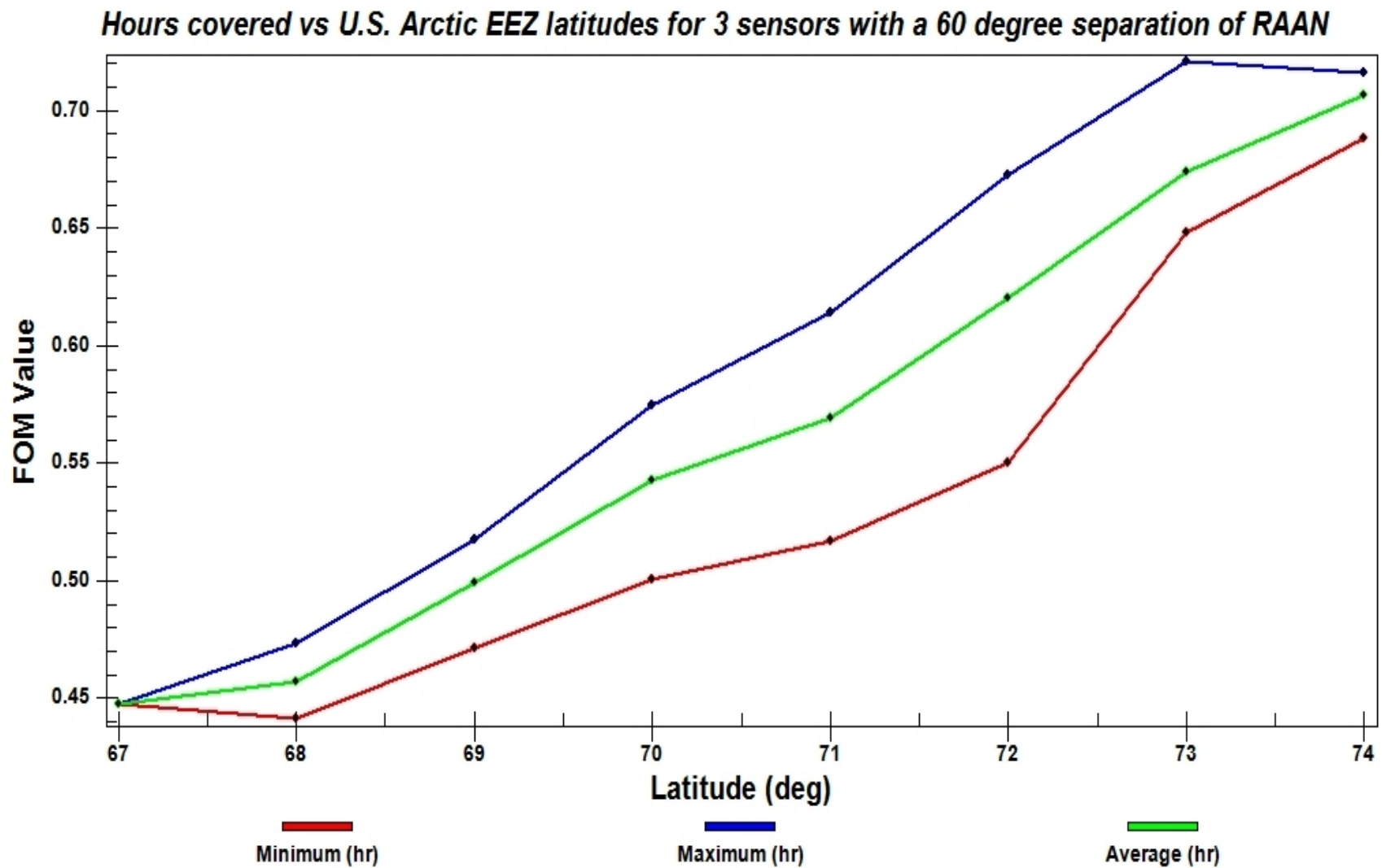


Figure 42. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 60-degree separation of RAAN.

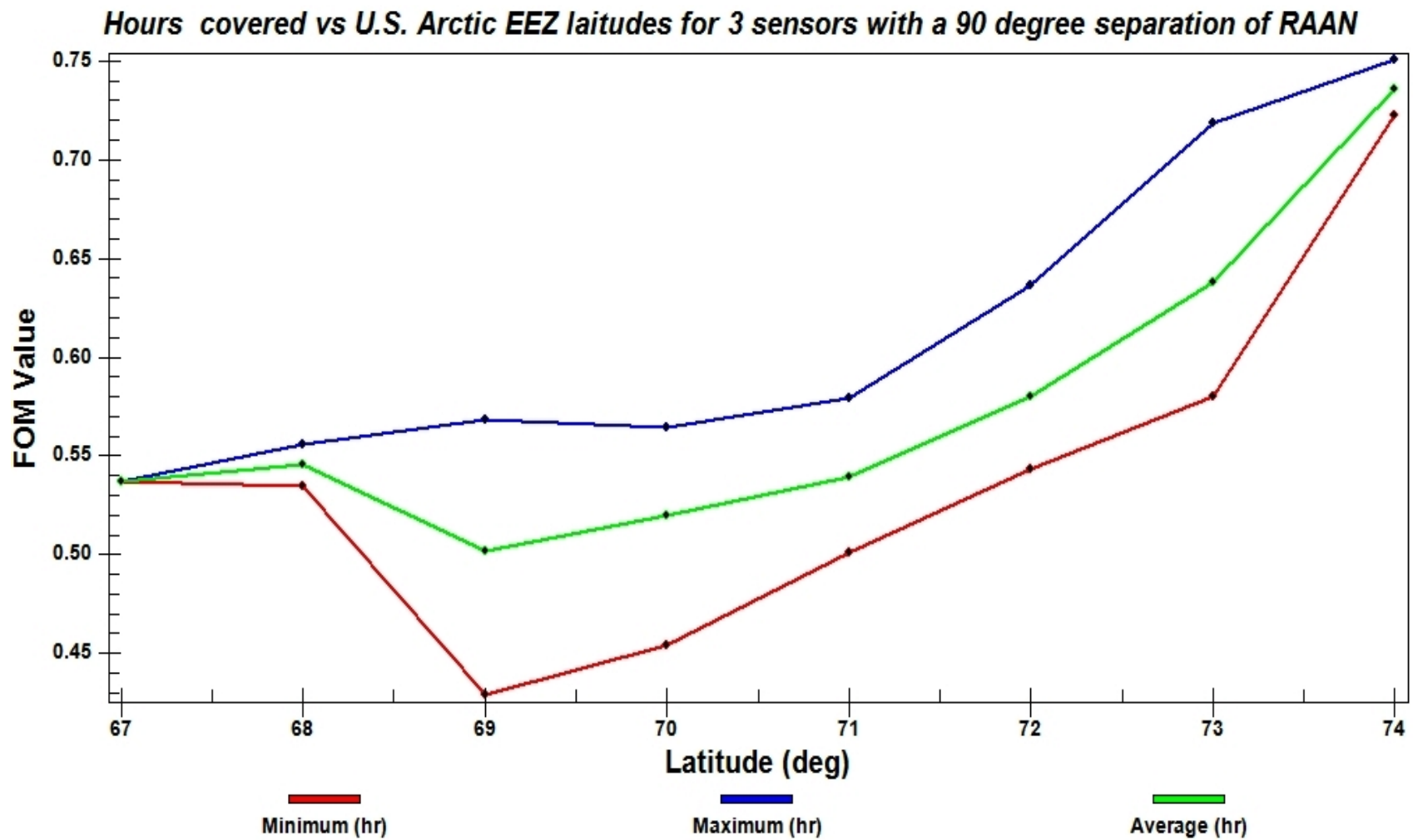


Figure 43. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 90-degree separation of RAAN.

Hours covered vs U.S. Arctic EEZ latitudes for 3 sensors with a 119 degree separation of RAAN

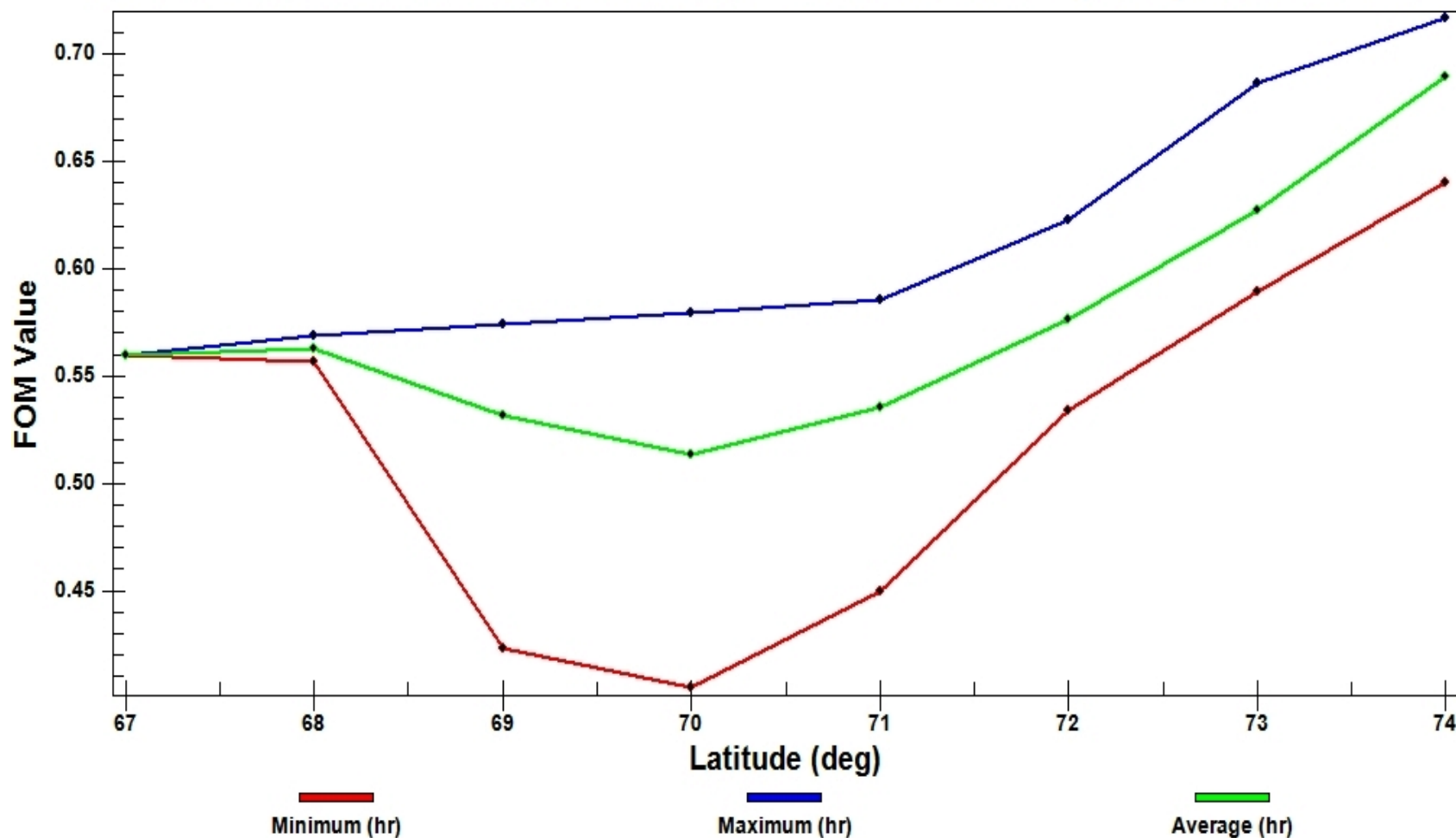


Figure 44. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors with 119-degree separation of RAAN.

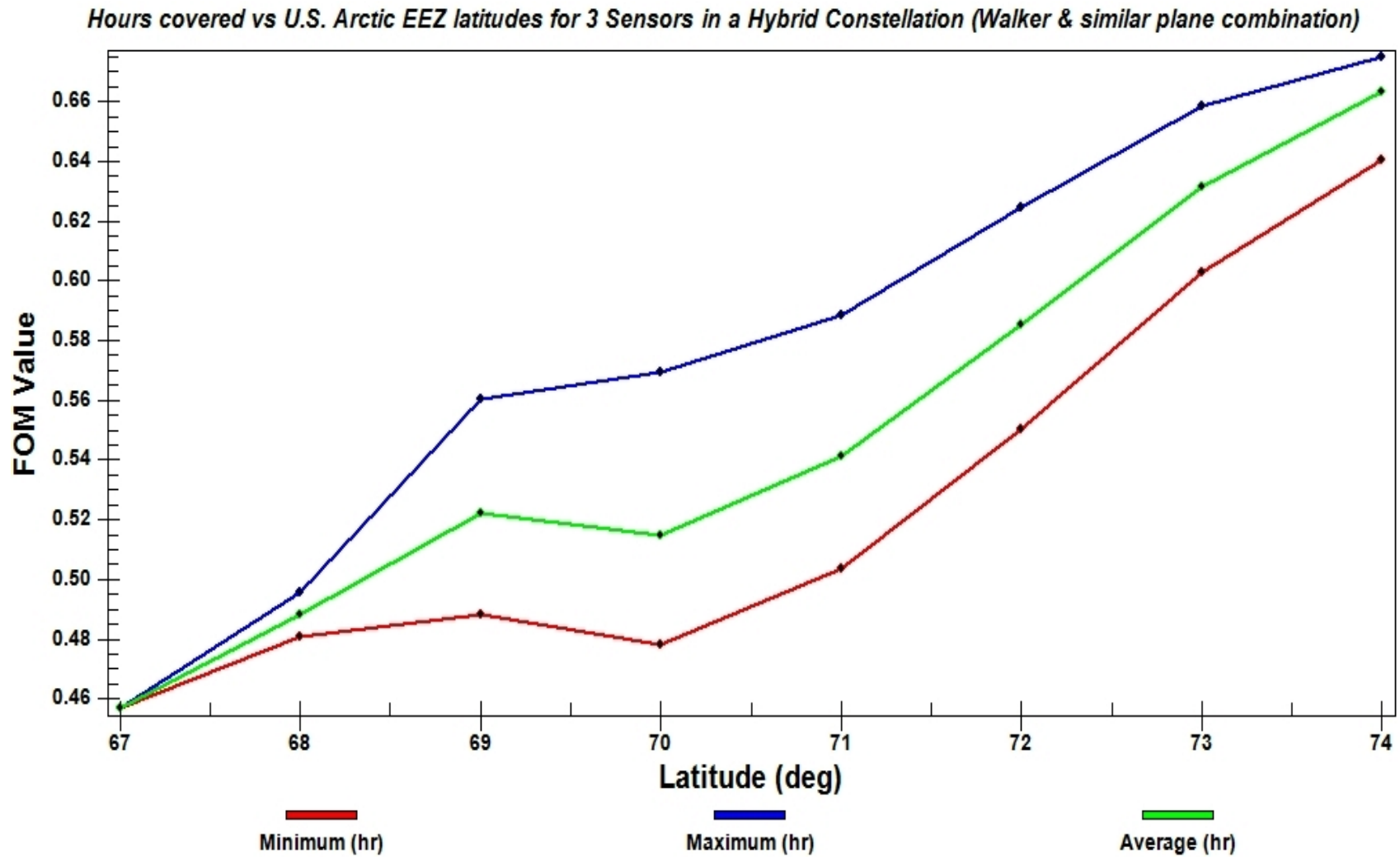


Figure 45. The cumulative hours covered in a 24-hour period of Arctic EEZ latitudes for 3 sensors in a hybrid Walker and similar plane combination.

Finding 10: Spacing three sensors in similar orbital planes but one degree apart in RAAN was able to match the temporal coverage efficiency of the 3/3/1 Walker Constellation. It was also determined that varying the orbital planes by any degree of RAAN from anything in between the same RAAN to a Walker Constellation (120-degree spacing) resulted in the same coverage efficiency for the totality of the Arctic Circle.

Finding 11: For the Arctic Circle writ large, there was no temporal performance coverage enhancement from ad-hoc constellation designs when compared to Walker Constellation designs.

Finding 12: While the Arctic Circle latitudinal coverage and coverage efficiency varied slightly, if at all, for all of the Arctic Circle, the efficiency of EEZ coverage is where ad-hoc constellation designs made a noticeable difference. Efficiency of EEZ monitoring was optimized with RAAN spacing between three orbital planes each with 42 to 45 degrees with one sensor in each plane. 43-degree spacing appears to offer the best sensor efficiency of the U.S. EEZ in the Arctic (Table 12). However, the consistency with which these RAAN spacing monitors the EEZ is sub-optimal (Figures 33-36).

Finding 13: The steadiest and lowest variation in latitude coverage for the EEZ appears to be three sensors in three separate orbital planes separated by 50 degrees. This constellation design offers very good coverage efficiency and the most consistent temporal coverage performance throughout the EEZ (Table 12 and Figure 41).

E. MODELING AND SIMULATION RESULTS AND EXPECTATIONS

It was unknown whether the results of the M&S would likely show that a different constellation design would supplant what exists today (single orbital plane) or a Walker Constellation in temporal surveillance performance coverage of the Arctic. If consistency of coverage by latitude and coverage offered per sensor are used as measures of performance, the M&S suggests that there is an alternate constellation design other than a single orbital plane or Walker Constellation design that is more cost-effective in monitoring the lower latitudes of the Arctic Circle.

While it was expected that coverage performance for the Arctic Circle and U.S. EEZ in the Arctic may differ - even with the same constellation - the U.S. EEZ, probably due to its lower latitude within the Arctic, offered the best insight into the differences in coverage performance among the constellations tested. While it was expected that the lower latitudes would have the least coverage given the physics of polar orbiting satellites and the spherical shape of the Earth, optimizing surveillance at the lower latitudes (best coverage with fewest number of sensor assets) appears to require a more customized constellation design.

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V. CONCLUSIONS AND FURTHER RESEARCH

A. RESEARCH SUMMARY

From the evidence provided in Chapter I, it should be clear the United States must be aware of the increasing levels of maritime activity in the Arctic Circle. It is strategically imperative for the long term security of North America to understand what maritime activities that are occurring there in order to use U.S. diplomatic, informational, military, and economic power to greatest effect. Moreover, tactical responses to emergent issues such as vessels in distress, hydrocarbon spills, and enforcement of laws and treaties depend on the United States having a sustained information advantage in the Arctic and in particular the U.S. Exclusive Economic Zone (EEZ) contained within the Arctic Circle.

Chapter II made evident that space-based surveillance is likely the best way and perhaps the only practical way to achieve the level of surveillance required of the Arctic Circle. Given the level of maritime surface area within the Arctic Circle and the applicability of SAR sensors to detecting and characterizing maritime activities, it is sensible that SAR sensors are the answer to the nation's Arctic surveillance needs. Moreover, a space-based SAR mission supporting U.S. and allied government agencies is consistent with the National Security Space Strategy (NSSS) of 2011 which seeks to strengthen safety, stability, and security; enhance advantages from space; and energize the space industrial base (Department of Defense, 2011). The compelling case for using SARs to meet the long-term surveillance needs of the U.S. government in the Arctic begged a significant technical question: what constellation design of SAR sensors would offer the best return on investment for the United States?

Chapter III described the methodology and rationale for determining the performance of different constellation designs of SAR sensors with respect to monitoring the Arctic Circle and sub-regions within it. While some variables were controlled in the analysis such as satellite/sensor inclination and altitude above the Earth that are critical for successful remote sensing with SARs, variables in the number of sensors, number of

orbital planes, location of sensors within orbital planes, and right ascension of ascending nodes (RAANs) were tested and evaluated in isolation and in combination for their coverage performance of the Arctic. Given the complex variables that were required to remain constant and controlled and the number of simulations/calculations required to assess performance of dozens of various constellation designs, modeling and simulation (M&S) was employed utilizing state-of-the-art M&S software (Systems Tool Kit) to efficiently test constellations for their coverage performance in the Arctic for both the totality of the Arctic Circle (approximately 66-90 degrees latitude) and a smaller sub-region of the Arctic Circle that is of significant interest to the United States—the EEZ (approximately 66-74 degrees latitude). Since consistency in coverage, particularly at lower Arctic latitudes, is important from one period to the next, coverage consistency across the Arctic EEZ latitudes within repeated time intervals was established as a key evaluation criterion for temporal coverage performance. Likewise, return on investment is very important which drove the second key evaluation criterion for coverage performance: the time the Arctic area of interest could be remotely sensed per sensor deployed.

In Chapter IV, it was evident that when observing the totality of the Arctic Circle, single orbital plane, Walker, and custom constellation designs did not result in wide variations in coverage time by latitude from interval to interval. A more focused and lower latitude area of the Arctic Circle such as the U.S. EEZ (66 to 74 degrees) encompassing much of Alaska’s North slope was subject to a much wider variation in day-to-day coverage by latitude. Coverage was *consistent* across the totality of the Arctic Circle latitudes from nearly all constellation designs. At times, coverage by latitude was *inconsistent* in the U.S. Arctic EEZ depending on the constellation design.

Ultimately, the temporal coverage efficiency (time area of interest could be remotely sensed per sensor deployed) of the entire Arctic Circle was best served by either a 3/3/1 Walker Constellation or custom designed three-sensor constellation. Both of these constellation designs improved upon single orbital plane temporal coverage efficiency designs by a clear margin. In contrast, single orbital plane and Walker Constellation designs *did not* improve temporal coverage efficiency of the U.S. EEZ. The U.S. EEZ in

the Arctic was better served in temporal coverage efficiency by a *customized* tri-sensor constellation.

B. CONCLUSIONS AND JUDGMENTS

The intent of this research was to determine if a constellation of SAR sensors with a dedicated mission to monitor the Arctic could be optimized for monitoring the Arctic beyond traditional or typical constellation designs. It became apparent during the research and analysis that the Arctic maritime activity with which we are most interested is very likely to occur where there is perennially the *least* ice. It also became apparent that attempting to monitor irregular areas of the lower latitudes of the Arctic caused the most variation in coverage performance from the variety of constellation designed tested. By holding the most important satellite orbit variables such as inclination and altitude constant and by testing combinations of other variables such as number of sensors, number of orbits, and RAANs in a reasonable way, a custom constellation design for monitoring the Arctic that outperformed single orbital plane and Walker Constellation designs was determined.

If monitoring the Arctic Circle in a consistent way and most efficiently is the objective, a Walker Constellation will be more effective than a single orbital plane constellation design. Efficiency is diminished for sub-regions of the Arctic Circle such as an area the size of the U.S. EEZ in the Arctic. The best temporal coverage performance (consistency and efficiency) is achieved for *both* the totality of the Arctic Circle (equal to what a Walker Constellation would provide) *and* the EEZ by a custom three-sensor constellation design with ascending node spacing of 50 degrees.

For lower latitude regions of the Arctic Circle, minor adjustments in ascending node can make a large difference in the temporal coverage consistency (maximum and minimum coverage over a given interval). While it may be necessary to give up some efficiency to achieve better consistency in coverage, the cost-benefit analysis favors trading a small margin of efficiency for consistency across the range of latitudes of interest from time interval to time interval.

C. LIMITATIONS

Analysis was not conducted to determine the sensors necessary for continuous coverage of the Arctic Circle or the EEZ that resides in the Arctic. Based on the modest availability of three sensors (and even eight sensors) for remote sensing of the Arctic and sub-region such as the EEZ within it, it is likely the number of Polar Low Earth Orbiting sensors required to achieve continuous coverage would be impractical if not impossible.

Inclinations other than 98 degrees were not varied in testing the constellation designs. While it might be possible that inclinations other than 98 degrees could provide better coverage of the U.S. EEZ in the Arctic (such as using inclinations from 66 to 74 degrees where the U.S. EEZ in the Arctic is located), the constellations tested were required to balance monitoring both the totality of the Arctic Circle and the U.S. EEZ in the Arctic. Inclinations of 66 to 74 degrees may offer diminished coverage of the entire Arctic Circle if not preclude coverage of some areas of the Arctic altogether.

In addition, analysis did not take into account the duty cycle limitations of SAR sensors in every orbit. With a nominal duty cycle limitation of 28 minutes per orbit, any competing missions or duty time for the sensor beyond the Arctic could reduce the remote sensing time available for high latitudes. More than six hours of duty cycle time per 24 hour interval appeared viable for each model sensor (greater than 18 hours of duty cycle time per day for the entire constellation). Notwithstanding competing remote sensing requirements throughout the globe, this predicted aggregate duty cycle time portends sufficient operational availability for monitoring the Arctic.

D. RECOMMENDATIONS

Since the lower latitudes of the Arctic are of the most concern, it is sensible that the recommended constellation design that modeling and simulation demonstrated could perform the best over a lower latitude area of the Arctic such as the U.S. EEZ is likely the best constellation option. Furthermore, the best constellation design will strike a balance between efficiency in coverage per sensor deployed and consistency across the latitudes that are of most concern. While the data in Table 12 show that the most efficient RAAN spacing between SAR sensors is 42 to 44 degrees, the latitudinal analysis in Figures 33-

35 shows that the temporal coverage is very inconsistent from period to period. Table 12 data shows that temporal coverage efficiency and consistency in latitudinal coverage from interval to interval can be achieved by trading a few hundredths of an hour of average temporal coverage for increased RAAN spacing. This meager trade in coverage *efficiency* provides much improved coverage *consistency* (Figure 41). For this reason, the recommended design for an ideal SAR sensor constellation for U.S. government information needs in the Arctic is as follows:

- A total of three SAR sensors (findings two, four, six, and eight)
- Starting with the RAAN of RADARSAT-2 of 91.0729, each additional sensor should be placed 50 degrees apart at RAANs of 141.0729 and 191.0729 respectively (findings 10, 13, and Table 12)
- The sensors should be staggered maximally at 120 degrees within their respective orbital planes (as in a Walker Constellation, Table 12)

Given a typical duty-cycle range over which to remotely sense the Arctic, the optimized constellation should provide weather agnostic detection capabilities for vessels of interest, oil slicks, and/or scientific (including meteorological) data collection for an average of 52 minutes daily within the Arctic Circle and an average of 36 minutes daily for the U.S. EEZ. The revisit frequency, efficiency, and consistency of remote sensing with which the constellation provides may provide better sustained data collection in the Arctic which is the basis for improved intelligence about Arctic activities, threats, and hazards. It has yet to be proven and often debated that better intelligence always leads to better outcomes. On the contrary, history has shown that it is often true, if not always a certainty, that little or no intelligence often leads to poor outcomes. As the Arctic becomes a more contested and disputed region yet more navigable and habitable, the information advantage provided by improved Arctic intelligence is critical at all levels of national policy for the security interests of United States in the Arctic to be protected and preserved.

E. FUTURE RESEARCH

An Electro-optical Geospatial Information Constellation for the U.S. EEZ

While space-based remote sensing with SARs may provide the all-weather capabilities and broad area surveillance requirements desired by geospatial information customers, there is also demand for electro-optical imagery. While the results of this study indicate that a constellation of SAR payloads may provide adequate coverage for an Arctic area of interest, the primary function of the constellation of SARs would be continuous or near-continuous detection (not necessarily identification due to the limitations of SAR) of vessels or anomalies on the ocean surface in the Arctic region of interest. A study using similar methodology for modeling an EO constellation requirement that could potentially provide better identification performance should also be considered.

Myriad Arctic Equities and Stakeholders Demands a Division of Responsibilities within a Security Consortium

There are an abundance of nation-state interests in the Arctic. Many disagreements, conflicts, or disputes are arbitrated within multilateral international bodies such as NATO, IMO, and/or the Arctic Council. Perhaps equally important to dispute resolution within these forums is a division of security responsibilities for the Arctic in the context that no nation, Arctic or otherwise, can go it alone with respect to providing security activities and the attendant resources required. A study on which nations within already existing multilateral forums should agree to take the lead for necessary security activities (surveillance and environmental response among others) would be appropriate to advance the cause and benefit of the multiple international forums established to enhance Arctic cooperation.

SAR constellation Architecture Features Critical to Effective Surveillance

Beyond a constellation configuration that is suited to provide maximum coverage, or access to target or region of interest on the Earth, myriad other components of space system architecture are necessary for an effective mission. Based on the recommended configuration of SARs in this research, determining where the best locations for satellite

access to ground stations or relay stations to minimize data latency is a critical component to an effective surveillance mission. Additionally, determining the components of those ground stations to ensure a successful communication link along with sufficient throughput are essential requirements to understand for beginning the acquisitions process and developing a successful SAR mission.

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