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All-Domain Sensor Network Orchestration from Seabed-to-Space

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All-Domain Sensor Network Orchestration from Seabed-to-Space

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Executive Summary

All-Domain Sensor Network Orchestration from Seabed-to-Space

Project Summary

The DOD seeks to conduct all-domain operations, requiring intelligence, surveillance, reconnaissance and targeting (ISRT) across all domains of conflict. For the Navy, this includes the deep seabed, undersea, sea surface, air, space, and cyberspace operations. All domain ISRT encompasses and integrates information from sensors across all domains of the maritime environment—sensors and sources from "Seabed-to-Space"—to provide commanders with the most complete picture of adversary activities. This capability supports the Navy approach to Distributed Maritime Operations (DMO), an operational concept that enables widely dispersed naval units to perform sensing, command and control, and weapon activities such that the distributed platforms act as a coherent whole. All-domain ISRT requires a network to enable widely dispersed sensors to exchange, correlate, and combine sensor data (the fusion of data) to provide a complete understanding of the operational picture and to provide targeting information for long-range engagement required by DMO.

The study modeled and evaluated the role of space constellations for sensing and network relay to enable over-the-horizon ISRT. Our findings show that conceptual coordination of Seabed-to-Space sensors via the planned DOD low-earth orbit space constellation relay is feasible and enables DMO over-the-horizon operations for the stressful surface warfare scenario. We have also shown that although the orchestration of the diverse sensors from seabed tip-off to space sensing to perform coordinated fires is complex, it is feasible when space relay constellations demonstrate high availability. For example, our study has shown that a constellation like the planned DOD Space Development Agency constellation as modelled, or larger, will provide coverage to enable distributed search, detection, and tracking but may require local unmanned air and surface vehicles' support for terminal engagement. We recommend the next step in analysis is a simulation of a wider range of cases with dynamic maritime scenarios and a range of constellation parameters and sensors.

Keywords: *maritime domain awareness; MDA; distributed maritime operations; DMO; Seabed-to-Space; AI; artificial intelligence; CIR; Commander's Intelligence Requirements; C5ISRT; command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting; DoD; Department of Defense; ISR; intelligence, surveillance, and reconnaissance; ISRT; intelligence, surveillance, reconnaissance and targeting; IP; internet protocol; JADC2; joint all-domain command and control; LEO, low-Earth orbit, ML; Machine Learning; TCP; transmission control protocol*

Background

The study of networked sensing and distributed collection of ISR information has been addressed at a theoretical level for over 25 years to measure the performance gains from distributed detection, correlation of features from distributed sensors and sources (MultiINT) and inferential reasoning from diverse networked sources. This theoretical foundation provides a basis for understanding the performance (detection rate, recognition accuracy, timeliness, etc.) and effectiveness (targeting accuracy, update rates, etc.) of distributed sensing, but does not address the achievable capability for such extreme cases of the all-domain problem.

An all-domain sensor orchestrator must consider all feasible collection combinations over some time horizon against all targets and then optimize the assignment of sensors-to-targets over time. Optimization requires an objective function—the expected value of each feasible set of collections at each set of collection times. The definition of this expected value must be developed, and the practical optimization approach (algorithms) must be chosen for such a wide range of options. The expected value must be based on a quantitative representation of the Commander's Intelligence Requirements (CIRs).

This research defines the practical MultiINT collection options against maritime targets and identifies the feasible methods to quantify an objective value function and orchestrate such a wide range of sensing systems against dynamic and fleeting maritime targets. The Naval Information Warfare Center (NIWC) Pacific's (N66001-20-R-3412) solicitation for the Development, Technical, Management, and Engineering Services for ISR Systems & Information Operations from the Seabed-to-Space project highlights the importance of this research. NIWC is leading the development of ISR and information operations systems that operate with manned and unmanned platforms, including tactical data communications platforms, satellite terminals, autonomous systems or nonautonomous platforms for air, land, sea, and space missions. This research will support the NIWC efforts.

The research directly supports the focus of the Chief of Naval Operations (CNO) Navigation Plan issued January 2021 which focuses on the following elements:

"Emerging technologies have expanded the modern fight at sea into all domains and made contested spaces more lethal," which is enabled by the resilient command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISRT) capabilities, all-domain coordinated efforts, and project synchronized lethal and non-lethal effects across all domains.

"Ubiquitous and persistent sensors, advanced battle networks, and weapons of increasing range and speed have driven us to a more dispersed type of fight" because of the persistent sensors and information Naval Operational Architecture (NOA) that integrates with Joint All-Domain Command and Control (JADC2), resilient web of persistent sensors, command and control nodes, platforms, and weapons

"Advances in artificial intelligence and machine learning (AI/ML) have increased the importance of achieving decision superiority in combat", enabled by the ability to close the kill chain faster than our rivals, project synchronized lethal and non-lethal effects across all domains. (CNO, 2021, p. 4-5)

This research developed DMO scenario concepts and implemented computer models of one stressful surface warfare scenario to evaluate the feasibility of utilizing planned DOD low-Earth orbit (LEO) satellite constellations for sensing and network relay.

Findings and Conclusions

This evaluation focused on the most critical requirements for the satellite network use to accomplish the most stressful long-range cooperative engagement case. We established a set of critical "Admiral's Questions" that will be posed to any briefer presenting the consideration of this complex operation:

- Can the Satellite Constellation provide required performance in three areas: 1) Relay latency to deliver sensor data in time? 2) Availability at critical times of engagement? and 3) Sensing revisit rates to support persistent detection, identification, tracking, and engagement?
- What would a realistic, stressful scenario look like? The surface warfare scenario looks very complex! Is it feasible? What is the next research step to assure feasibility?
- Can the dynamic network sustain ISRT start-to-finish? What are the operating parameters? What are the marginal areas? How do we increase the margins?

The results of this study have shown, at the depth of analysis performed:

- Conceptual coordination of Seabed-to-Space sensors via the planned DOD low-earth orbit space constellation relay is feasible and will enable DMO over-the-horizon operations for the stressful surface warfare scenario.
- Orchestration of the diverse sensors from seabed tip-off to space sensing and UAS-UAV support to perform coordinated fires is complex but feasible when space relay constellations demonstrate high availability.
- A constellation like the planned DOD Space Development Agency constellation as modelled, or larger, will provide coverage to enable distributed search, detection, and tracking capabilities but may require local UAV and USV support for terminal engagement.
- The network transaction process is complex but feasible; redundancy exists in sensors and in the network.
- We can address the Admiral’s questions with supporting first-order data.
- The next required step is the simulation of scenarios like the scenario in this study over a range of conditions to measure statistical performance.

We found that the complexity of space-based sensing and relay is high, but feasible as demonstrated by our study– and the payoff for the Navy is high. During this study Rear Adm. James Aiken supported this very concept when describing a recent Navy experiment: “We teamed manned and unmanned vessels together. We also used the fusing capability … It was totally passive where we didn’t have active sensors on target… We also look for space as well to actually identify the target and then once we found the target, we were able to track it because of the [electromagnetic signal] that was coming off the target, develop lines of bearing, then launched the missile” (Lagrone, 2021).

Recommendations for Future Research

While this study has used modeling tools to evaluate the concept of space-based sensing and relay to support distributed maritime operations, the next level of research will require quantitative modeling over a wide range of scenarios and network parameters (esp. latency, availability) to assess the statistical performance. The network transactions in the scenario studied exceeded 200 over a 24-hour period and even more complex scenarios must be evaluated. An example next-step study with greater fidelity could include, for example:

- Utilize the Naval Surface Warfare Center Mast Simulation tool (or similar) to create stressful Distributed Maritime Operations (DMO) scenarios that include multiple dynamic maritime targets with radio frequency, electro-optical and radar signatures

- Use the Mast scenarios to drive a sensor and network model with transmission control protocol/internet protocol level fidelity to simulate the detection of maritime targets, relay of detection data, and control of sensors on the net.
- Include a fusion model to simulate the fusion and battle management functions to enable long-range engagement.

The next step will move forward the demonstration of the mechanisms necessary to achieve Adm. Aiken's vision

References

Chief of Naval Operations (2021) *Chief of Naval Operations Navigation Plan 2021.* https://media.defense.gov/2021/Jan/11/2002562551/-1/-1/1/CNO%20NAVPLAN%202021%20-%20FINAL.PDF

LaGrone, S. (2021, April 26). Unmanned systems, passive sensors help USS John Finn Bullseye target with SM-6. *U.S. Naval Institute*. https://news.usni.org/2021/04/26/unmanned-systems-passive-sensors-help-uss-john-finn-bullseye-target-with-sm-6

Acronyms

AI	artificial intelligence
CIR	Commander's Intelligence Requirements
C5ISRT	command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting
DMO	Distributed Maritime Operations
ISR	intelligence, surveillance and reconnaissance
ISRT	intelligence, surveillance, reconnaissance and targeting
IP	internet protocol
JADC2	joint all-domain command and control
LEO	low-Earth orbit
ML	machine learning
NOA	Naval Surface Warfare Center Dahlgren
TCP	transmission control protocol
UAV	unmanned air vehicle
USV	unmanned surface vehicle

All-Domain Sensor Network Orchestration from Seabed-to-Space

1. ABSTRACT

The DoD seeks to conduct all-domain operations, requiring Intelligence, Surveillance, Reconnaissance and Targeting (ISRT) across all domains of conflict. For the Navy, this includes the deep seabed, undersea, sea surface, air, space, and cyberspace operations. All-Domain ISR encompasses and integrates information from all domains of the maritime environment – sensors and sources from "seabed-to-space" – to provide commanders with the most complete picture of adversary activities. This capability supports the Navy approach to Distributed Maritime Operations (DMO), an operational concept that enables widely dispersed naval units to perform sensing, command and control and weapon activities such that the distributed platforms act as a coherent whole.

All-domain ISR requires a network to enable widely dispersed sensors to exchange and combine sensor data (the fusion of data) to provide a complete understanding of the operational picture, and to provide targeting information for long range engagement required by DMO. This research studies the diverse sensor access time horizons, sensor mode options, observation feasibilities, and relative contribution of all-domain sensors (seabed-to-space) pose a significant mathematical and computational challenge to achieve all-domain ISR. Furthermore, the delays from sensing to fusion across such a wide range of sensors can diminish the contribution of some combinations of sensing modes. The study also evaluates the distribution of fusion nodes across an all-domain network to improve the delivery of information across the network.

2. BACKGROUND

The study of networked sensing and distributed collection of ISR information has been addressed at a theoretical level for over 25 years to measure the performance gains from distributed detection, correlation of features from distributed sensors and sources (multi-INT) and inferential reasoning from diverse networked sources. This theoretical foundation provides a basis for understanding the performance (detection rate, recognition accuracy, timeliness, etc.) and effectiveness (targeting accuracy, update rates, etc.) of distributed sensing, but does not address the achievable capability for such extreme cases of the all-domain problem.

An all-domain sensor orchestrator must consider all feasible collection combinations over some time horizon against all targets and then optimize the assignment of sensors-to-targets over time. Optimization requires an objective function – the expected value of each feasible set of collections at each set of collection times. The definition of this expected value must be developed, and the practical optimization approach (algorithms) must be chosen for such a wide range of options. The expected value must be based on a quantitative representation of the Commander's Intelligence Requirements (CIRs).

This research defines the practical MultiINT collection options against maritime targets and identify the feasible methods to quantify an objective value function and orchestrate such a wide range of sensing systems against dynamic and fleeting maritime targets.

The importance of this research is highlighted by the recent solicitation by the Naval Information Warfare Center (NIWC) Pacific (N66001-20-R-3412) for the Development, Technical, Management, and Engineering Services for ISR Systems & Information Operations from Seabed to Space project. NIWC is leading the development of ISR and information operations systems that operate along with manned and unmanned platforms, including tactical data communications platforms, satellite terminals, autonomous systems or nonautonomous platforms for air, land, sea and space missions. This research will support the NIWC efforts.

The research directly supports the focus of the CNO NAVPLAN issued January 2021, as summarized in the table below:

NAVPLAN 2021 Page 4	• **Specific Elements Cited in the Plan**
"Emerging technologies have expanded the modern fight at sea into all domains and made contested spaces more lethal…	• Resilient command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISRT) • All domains coordinated. • Project synchronized lethal and non-lethal effects across all domains
Ubiquitous and persistent sensors, advanced battle networks, and weapons of increasing range and speed have driven us to a more dispersed type of fight.	• Persistent sensors and information • Naval Operational Architecture (NOA) that integrates with Joint All-Domain Command and Control (JADC2) • Resilient web of persistent sensors, command and control nodes, platforms, and weapons
Advances in artificial intelligence and machine learning (AI/ML) have increased the importance of achieving decision superiority in combat."	• Ability to close the kill chain faster than our rivals. • Project synchronized lethal and non-lethal effects across all domains (e.g., coordination of physical, electromagnetic, cyber, Military Deception, and Military Information Support to Operations.

3. RESEARCH/ STUDY AND ANALYSIS OBJECTIVES

This research objective is to quantitatively analyze the potential effectiveness of all-domain maritime ISRT. The research addresses the following key ISR questions regarding the ability to create and deliver a complete all-domain understanding for surveillance, planning, and targeting:

- What is the range of seabed-to-space observations against static, cruise (stationary process) and fleeting (non-stationary process) targets?
- What are the feasible modes in which all-domain sensing can provide unique intelligence or targeting value?
- How can relative values for each target be assigned based on context, feasibility, expected collection merit and static values?

- What methods of constrained optimization (to achieve highest feasible intelligence value) are best suited to the extremely wide range of sensor collection options from subsurface, maritime surface, airborne, and space collection systems?

The study determines the potential effectiveness of maritime all-domain sensing and fusion over a set of DMO scenarios cases.

4. RESEARCH APPROACH

This effort collected data to characterize current and planned Navy networks before performing network modeling and analysis.

Data Collection was conducted by evaluating Navy network document and standards, and interviews with appropriate NIWC technical personnel and review of current standards for Naval tactical, satellite, undersea, and related links.

Analysis was performed by development of network topology model for future All-Domain networks using parametric performance values for links (latency, bit rates, etc.) and fusion nodes (latency, information gain, etc.). Statistical analysis of the ability to deliver actionable surveillance and targeting information was performed in spreadsheet models with statistical simulation.

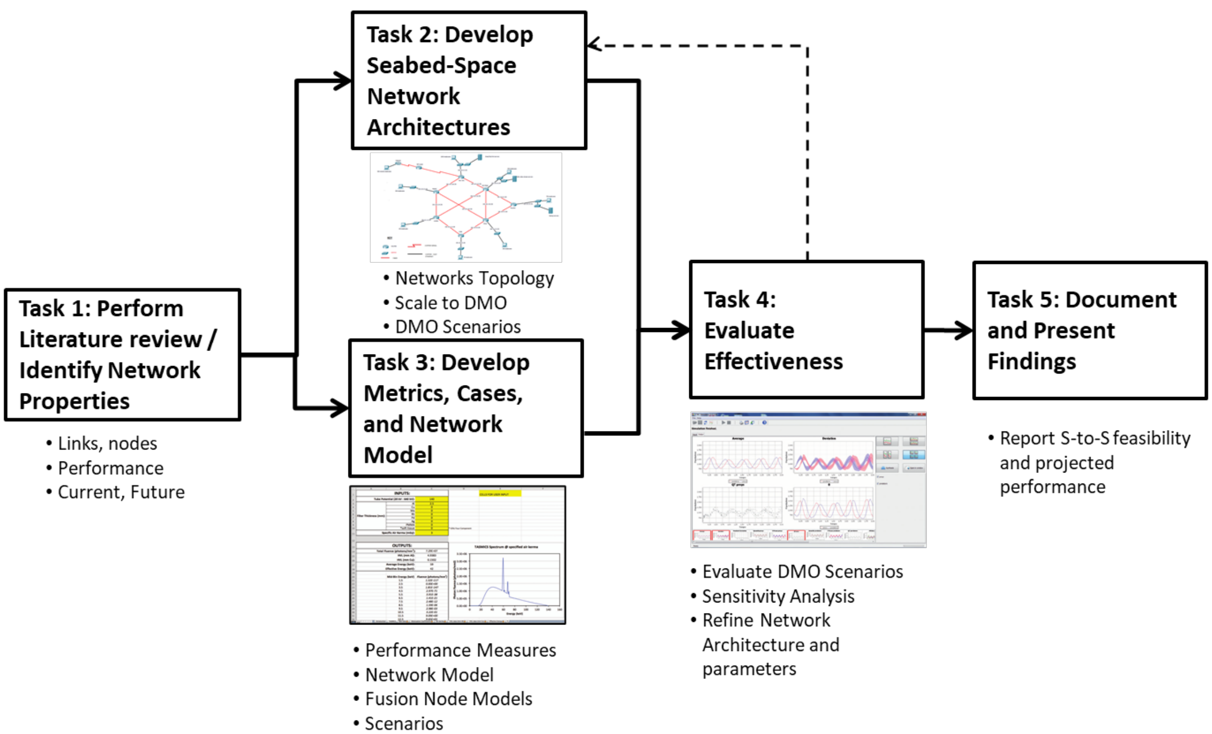


Figure 4-1 Research Task Methodology and Task Flow

5. TASKS

This research is performed in five tasks:

Task 1: Perform Literature review /Identify Network Properties

Conduct a review of the literature on state-of-art distributed detection, recognition, and reasoning processes, as well as tactical, space, undersea (acoustic) communication links. Conduct a review of current and future (e.g., Space Development Agency and DARPA space efforts are strong examples of DoD investments in future capabilities that will transition to operations in the 2025-2030 period) networks to track and report on hypersonic threats. Organize data on network performance ranges to be used in modeling.

Task 2: Develop Seabed-Space Network Architectures

Define and describe the network architecture for a future seabed-to-space DMO ISR capability that is suitable for modeling the transport and fusion of information to provide a distributed operating picture suitable for surveillance and targeting. Identify approaches to that are suitable to assign values to the information provided by each network sensor, to enable a means of constrained optimization to be applied to orchestrate the all-domain sensors.

Task 3: Develop Metrics, Cases, and Network Model

Define and describe the metrics to measure performance in network simulations. Define and describe the DMO all-domain use cases that perform ISR surveillance and targeting across a small but representative set of maritime use cases. Define and develop a network model to enable the evaluation of effectiveness of sensors, networks, fusion models, and targeting methods across the use cases.

Task 4: Evaluate Effectiveness

Conduct model analyses to measure effectiveness of the seabed-to-space DMO capabilities identified in use cases. Identify an approach to apply optimization to orchestrate the sensors to provide the timeliest information to distributed maritime assets.

TASK 5: Prepare and Deliver Research Report

The practical questions that were addressed across the tasks to enable the research to be conducted (Implementation questions) are summarized in Table 5-1.

Table 5-1 Research Questions by Task

Task	Key Questions we addressed	Our Key actions
1	• What are the key parameters: Capacity, Latency, Nodes? • What are current links? Future Links 2025-2030? • What is a feasible S-to-S network? Where are Fusion Nodes? • What new technology links-nets are on the horizon?	• Identify baseline model and verify with NIWC • Build a table of collected data • Make a database in Box
2	• What is the sensor and C2 Architecture in DMO? • What is Sensing-C2-weapon flow? • What are the DMO Over-horizon sense-target needs? • What are reasonable parametric requirements? Constraints?	• List most likely DMO Scenarios • Make timeline for Over-the-horizon counter ship • Make timeline for maritime area surveillance
3	• What are key metrics? (report rate, revisit rate, latency, capacity, range…) • What is the appropriate level of Network model? • What representative DMO scenarios must we model? • What will modeling results look like to meaningful and not trivial?	• Make initial Table of Metrics • Validate metrics • Create scenarios and Use Cases; validate with operational users (NPS and NIWC)

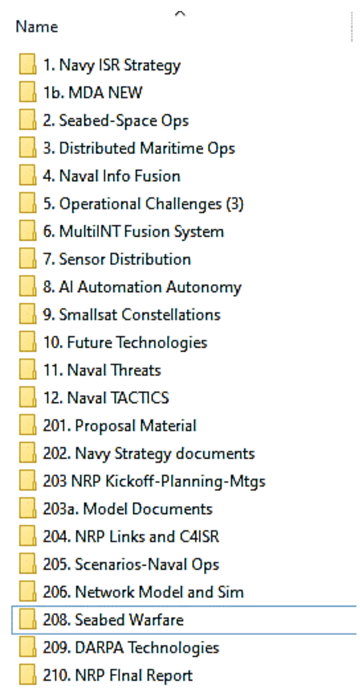
4	• What is the level of model fidelity required? • How do we select DMO scenarios to evaluate in the model? • What are key parameters for variation? • What weapons? Targets?	• Survey tools – discuss with Chris Fitzpatrick at MOVES • Identify model sufficiency

7. Task 1 Literature Review and Network Properties

This task acquired key documents on networked ISR concepts, prior research, and accomplishments in Network Centric Warfare (NCW), Navy ForceNet and CEC (Cooperative Engagement Capability). This formed the baseline for an initial analysis of the implementation of such capabilities in the presence of new technology enablers.

7.1 Literature Review

The literature search is an ongoing activity throughout the project. Initial search located and organized in a the CMIS digital Library a repository of 329 Document Files, in 27 Folders (as of 3-26-2021). We organized a flat taxonomy Right) including a series of 001 documents on Naval ISR Theory, and 200 series that is focused on this NRP topic.



The ongoing academic and Technical Literature Search continued at the NPS Library in more depth and included documents recommended by NIWC SME's and ONR contacts as appropriate.

In addition to the literature, we contacted some of the subject matter experts (SME's) in this field of distributed ISR to provide guidance on the state of the art and the appropriate research to contribute to the knowledge in the field (Table 7.1-1).

Table 7.1-1 Subject Matter Experts

CONTACT	Location	Reference
Mark Owen	mark.owen@navy.mil<mailto:mark.owen@navy.mil Naval Information Warfare Center Pacific (NIWC PAC) US Navy Multi-INT Fusion and Correlation Technology Lead (SSTM)	**NRP Study Sponsor**
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Winfrey Clinton (Simulation)	Winfrey, Clinton M (M32) CIV USN NAVSURFWARCEN DAH VA (USA) clinton.winfrey@navy.mil<mailto:clinton.winfrey@navy.mil	M. Owen

7.2 Baseline Analysis

We begin with an operational level analysis of the key factors that will determine effectiveness of maritime operations that are distributed spatially, wideband networked to share organic sensors, and complemented by a space layer of persistent maritime surface coverage.

The analysis considered:

- **Seabed-to-Space Sensors** – We analyze the value of widely distributed organic sensors on manned and unmanned platforms *and the contribution of each.* Some sensors like autonomous underwater vehicles and stationary seabed sensors, have low bandwidth, and intermittent opportunities to contribute, but their information can be critical.
- **Data Networks** – We analyze the available network from sensor to fusion nodes to weapon systems, particularly the *availability of sensor information; the ability to orchestrate sensing collection at critical times to support fire control.*
- **Fusion Nodes** – We analyze the network structure and placement of nodes *to combine data and orchestrate dynamic collection, enabling sensors toa adapt, track and even target.*
- **Closed-Loop Operation** – We analyze the potential for closed-loop operations from sensor to a fused picture of target dynamics, to prediction of *the necessary ISR dynamics to support DMO targeting.*

We adopt the published Navy rational for DMO that is based on the following operational premises:

1. Distributed forces (Surface, subsurface, distributed seabed, supporting air) is an employment concept that integrates maritime platforms to achieve an objective of increasing overall lethality, while also decreasing susceptibility to attack from an adversary: [[1]]
    a. Distributed forces will amass sea and shore-based fires from distributed platforms [[2]]
    b. Distributed forces will close the kill chain faster than our rivals with a resilient web of persistent sensors, command and control nodes, platforms, and weapons. [[3]]
    c. Distributed forces will apply unmanned platforms will expand our intelligence, surveillance, and reconnaissance advantage, add depth to our missile magazines, and provide additional means to keep our distributed force provisioned. [[4]]
2. Distributed forces provide distributed lethality and Sea Control. [[5]]
    a. Distributed Lethality is the condition gained by increasing the offensive power and defensive hardening of individual warships and then employing them not only in traditional roles, but also in different ways than has been the practice in the past few decades.

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[1] Navy Maritime Domain Awareness Concept, U.S. Navy Chief of Naval Operations, May 2009.
[2] CNO NAVPLAN 2021, p.5
[3] Ibid, p.8
[4] Ibid, p.11.
[5] Director of Surface Warfare RADM Fanta (N96), See VADM Thomas Rowden, RADM Peter Gumataotao, and RADM Peter Fanta. "Distributed Lethality." U.S. Naval Institute. January 2015. Accessed February 13, 2015. http://www.usni.org/magazines/proceedings/2015-01/distributed-lethality.

b. Enable operational commanders' options to control increased ocean areas and hold potential adversaries at risk, at range, whether at sea or ashore.
c. Enables greater scope of surface lethal projection ("if it floats, it fights…,") as all ships are networked.
d. Assigning increased offensive power to individual components of the surface force (cruisers, destroyers, littoral combat ships, amphibious ships, and logistics ships to employ them in dispersed offensive formations ("hunter-killer SAGs").
e. Assigns all surface vessels a role "to Deceive, Target and Destroy."

3. Distributed maritime forces require persistent Intelligence, Surveillance, Reconnaissance and Targeting (ISRT) enabled by a robust wideband and secure.
   a. Fleet and Task Force ISRT must sustain battlespace awareness across the distributed operating environment with all sensors capable of:
      i. Sharing sensor data for fusion (correlation, association, combination) with other sensors.
      ii. Being controlled across the network to orchestrate adaptation to benefit battlespace awareness, command and control, and fire control.
   b. Fleet and Task Force ISRT capabilities must support local battlespace awareness and lethal targeting and fire control.
   c. Networks must sustain operations in a jamming-intensive and even satellite-degraded environment.
   d. ISRT must be supported by persistent space sensor coverage that assures surface and air coverage across gaps between distributed organic sensors.
   e. ISRT must be supported by dynamic and adaptive unmanned sensor platforms (air, surface, subsurface) that operate in at-risk areas to perform surveillance, reconnaissance and targeting.
4. Distributed maritime forces must be protected by stealth and deception in physical maneuver, electronic signatures and operations, and cyber operations.
   a. Countermeasures perform defensive operations to deny, disrupt, deceive or exploit adversary systems.
   b. Counter targeting operations perform pre-emptive actions to prevent anticipated adversary actions.

To perform our analysis, we first baseline a DMO refence case (Table 7.2-1) that defines a blue water scenario defined by the following attributes: [[6]]

- **Sea Area** (or battlespace) encompassed by the Blue DMO force and the Red force.
- **Order of Battle** that defines the Red and Blue forces
- **Blue ISRT** capabilities that may be networked and orchestrated to provide distributed Battlespace Awareness and Lethality.

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[6] We do not consider the more complex brown water/littorals cases. Those cases can be adapted from the results of this study but require the analysis of the additional ground forces and engagement of many small, localized strike forces.

Table 7.2-1 Baseline DMO Case (2025-2030 Scenario and Enabling ISRT)

Category	Parameter	Values
DMO Scenario	Scenario Sea area	500,000 sq. mi. [7]; Surface to-seafloor blue-water depth 5,000 ft. with a littoral (shallow water area) [8]
	Blue DMO Deployed Maritime Force	DMO Force Distribution 62,500 Sq Miles (250 x250 mi area) DMO Force: Maritime 1 carrier strike Group (1 carrier; 8 destroyers, 2 maritime patrol aircraft; 2 air surveillance aircraft; 10 deployed Seabed Sensors, 10 UUVs; 2 attack submarines);
	Red Deployed Land-Maritime Force (Threat targets to surveil-target)	Maritime: 1 carrier; 12 destroyers; 12 frigates; 12 corvettes; 12 landing craft; 12 support and auxiliary ships Land: 10 air defense batteries; 4 Long range Anti-Ship batteries Air: 45 combat aircraft; 2 Air Surveillance; 3 Maritime Patrol UAV;
Blue ISRT	Space Sensors	200 satellite EO/SAR Persistent Low Earth Orbit (P-LEO) Constellation (50/50) with full network transport between satellites (250ms) and to ship net (Latency, L=2 ±2 seconds) Detection from fusion node (L=60 seconds ±30)
	Airborne sensors – aircraft	E-2C, and fighter AC; UAS long-range
	Airborne sensors - surface	Fighter AC and P-8 radar and EO/IR; deployed helicopter LAMPS system; UAS
	Airborne Sensors - subsurface	P8 deployed sonobuoy patterns; drop sensors to subsurface (thermal; hydrophones)
	Ship sensors -Surface	Towed array sonar; radar
	Autonomous sea sensors	Sea-surface autonomous station-keeping and reporting sensors [9]; station-keeping wave rider platforms that use wave-induced energy to maintain station.
	Sub sensors -subsurface	Hull and towed array sonar
	UUV sensors -Subsurface	Unmanned Underwater Vehicles (Large Displacement, Mid- Small-)
	UUV sensors -Seabed	Sonar (Active/passive) with infrequent relay capability when threat activity is detected.
	Seabed Sensors via UUV relay	Seabed network of passive and active unattended and autonomous sensors with infrequent relay capability when threat activity is detected. [10]

The Operational View (OV-1) of the distributed Blue platforms (Figure 7.2-1) shows the location seabed-to-space sensors and illustrates the network challenge to enable all platforms to share sensor data.

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[7] For reference, the South China Sea is a marginal sea that is part of the Pacific Ocean, encompassing an area from the Karimata and Malacca straits to the Strait of Taiwan of around 3,500,000 square kilometers (1,400,000 sq mi).
[8] For reference, the China Sea Basin, has a maximum depth of 5,016 m.
[9] DARPA Ocean of Things (OoT) program seeks to enable persistent maritime situational awareness over large ocean areas by deploying thousands of low-cost, environmentally friendly, intelligent floats that drift as a distributed sensor network. https://oceanofthings.darpa.mil/
[10] See APPENDIX B: Undersea Warfare View of Undersea Distributed Networked Systems

In this study the research also examines the ability to “orchestrate” the sensors for each phase of the ISRT process to adapt and focus sensor observations on the highest value that balances awareness and targeting to support fire control.

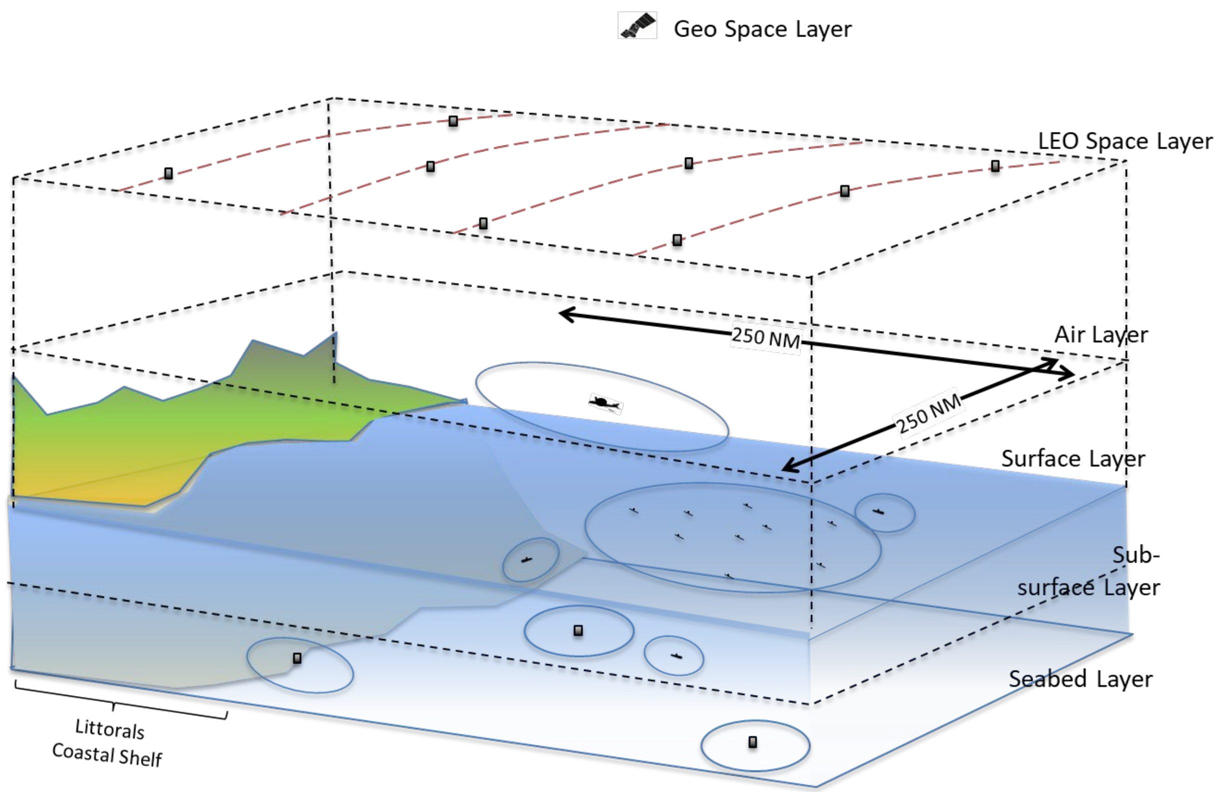


Figure 7.2-1 OV-1 High-level view of the Battlespace or Operating Environment

The Baseline Digital Communication Networks are considered in two cases is summarized in Table 7.2-2.

Case A is the current 2021-2025 capability in which distributed assets are connected by narrowband digital MILSATCOM links. A typical GEO (geostationary orbit spacecraft) provides up to 100 Gbps capacity to distributed users (all services) in a nearly hemispherical coverage and each user has access to a narrowband channel (< 50 Mbps).

Case B considers each distributed user has access to a future P-LEO (Persistent Low Earth Orbit) constellation of DoD satellite relays that enable wideband digital access. The protected P-LEO Transport Constellation (200 satellite) A/J encrypted TCP/IP is assumed to have a Latency < 500 ms Ship-Ship; 200 Mbps downlink; 50 Mbps uplink. This capability is like the existing Commercial Starlink P-LEO constellation, and a future DoD network being implemented by the Space Development Agency. [[11]]

[11] National Defense Space Architecture (NDSA) Systems, Technologies, and Emerging Capabilities (STEC) Broad Agency Announcement (BAA), Space Development Agency (SDA), HQ085020S0001 January 21, 2020; Space Transport Layer Tranche 0 Statement of Work (SOW), Space Development Agency (SDA), HQ085020R0001 Attachment 1 SOW,26 Mar 2020

Table 7.2-2 Baseline Digital Communication Networks

Category	Parameter	Values
DMO Fleet Digital Comms Case A	Surface Comms	Airborne and maritime / fixed station JTRS (AMF JTRS)
	Subsurface Comms	VLF Comm link; UHF and SHF satcom Link 11 and Link 16; Deep Siren tactical paging (DSTP) expendable untethered buoys translate satcom to low-data-rate acoustic signal to submarine Seabed Acoustic short range with relay
	Space Comms	MILSATCOM • Wideband SATCOM - provide worldwide capacity for high-quality voice, imagery, video, and data transport, in the C-, X-, Ku-, and Ka-bands • Protected SATCOM - have the capability to negate or mitigate the purposeful or inadvertent degradation, disruption, denial, unauthorized access, or exploitation attempts of SATCOM. Extremely high frequency (EHF) Ka-, Q-, and V-bands are accessed over Milstar, UFO/EHF (UFO/E), UFO/EHF
DMO Fleet Digital Comms Case B	Surface Comms	Microwave-based wireless wide-area network (WWAN) with nodes on Helos or UAS for 4G LTE; 100 Mbps (20 Nmi. range) Laser optical 1Gbps up to a line-of-sight distance of 50km
	Subsurface Comms	VLF Comm link; UHF and SHF satcom Link 11 and Link 16; Deep Siren tactical paging (DSTP) expendable untethered buoys translate satcom to low-data-rate acoustic signal to submarine. Seabed Acoustic short range with relay
	Space Comms	Protected SATCOM Transport Constellation (200 satellite) A/J encrypted TCP/IP Latency < 500 ms Ship-Ship; 200 Mbps down; 50 Mbps up Antijam; Access ship-to-weapons (over horizon)

7.3 High-Level Analysis of Key Factors

The key ISRT factors to be considered in evaluating the feasibility of DMO operations include the following:

- Communication Network availability is a key factor to enable data sharing, sensor orchestration to adapt and enable distributed battlespace awareness and cooperative targeting. We consider the two cases: Case A current Fleet comm -CAINS with MILSATCOM; Case B advanced fleet comm-CAINS+ with Space Transport.
- Organic sensor coverage is critical for each distributed platform (both for self-protection and weapons employment) but coverage gaps between platforms pose a threat as vessels are distributed over larger ranges. We consider the ability to apply shared sensing to provide over the horizon awareness and targeting.

- Space Surveillance and Reconnaissance provided by new remotes sensing constellations (Contributions for commercial systems such as Radarsat SAR, Capella SAR, Planet EO, Blacksky EO, etc. as well as a similar DoD remote sensing constellation).
- Stealth and Deception are also key factors in the ability of the fleet to operate securely and effectively in A2/AD environments. These activities must be coordinated across the distributed assets in the physical, electromagnetic and cyber domains to mitigate adversary ISRT.

Our analysis considers the effects of three cases of spatial distribution of the Fleet (Figure 7.3-1a):

- Battle Group – Past and current sea control and power projection strategies employ a concentrated (vs. distributed) group depicted in the figure by their overlapping organic sensors. This arrangement is protective, designed to dominate the air-surface-subsurface battlespace. Organic sensors overlap (surface, air, subsurface) allowing tight sensor correlation and handoff. The configuration, however, limits the group to a confined area and places a risk due to the ease of targeting the concentration.

- Mid Distributed – Distributing the air, surface, and subsurface more widely reduces the adversary targeting footprint, while expanding the lethality of the fleet. Organic sensors no longer overlap in all dimensions (surface, air, subsurface) and persistent space sensing or autonomous surface sensing grids (or both) are required to fil the surface gaps. Sensor correlation and handoff requires a robust network to share data, orchestrate sensors and enable cooperative engagement of targets.

- Widely-Distributed – In this case the distribution is very high, enable even larger letal coverage by the fleet, but the platforms have very large gaps between organic sensors, and all require the network to provide situation awareness over the broad coverage area – for awareness, warning, and ISRT functions. The widely distributed target area forces adversary distribution and a change in adversary tactics that increases strategic cost.

Based on this straightforward analysis, the relative effectiveness of each configuration can be estimated (Figure 7.3-1b, aligned below the corresponding spatial arrangement figure). We perform this estimate to think-through what we might find in a more thorough computer-based analysis and to critically think about the key factors in such an analysis.

The curves illustrate our expected findings using a single subjective metric, ISRT effectiveness, Ɛ [overall from Surveil-to-Target and Fire Control]

- ISRT Ɛ should be the highest performing in a tight (and defensive) battle group, where the organic sensors overlap, handoff is efficient, and cooperative engagement can be assured.
- In the Mid- and Widely distributed cases, the effectiveness is reduced across all platforms (relative to the battle group) because the spatial distribution of organic sensors leaves large gaps at all levels. These gaps pose a threat and limit awareness (limiting lethality). The P-LEO space sensing or autonomous surface sensor grids are required to fill the gaps. The "persistence" is limited to SAR and EO sensing plus radio-frequency sensing (e.g., AIS maritime

transponders). [12] Also, autonomous air, surface and subsurface platforms may also be dynamically tasked to provide adaptive gap-filing sensing capabilities.

- The curves show that effectiveness is expected to be improved uniformly across the distribution by the persistent gap-filling sensing capabilities.

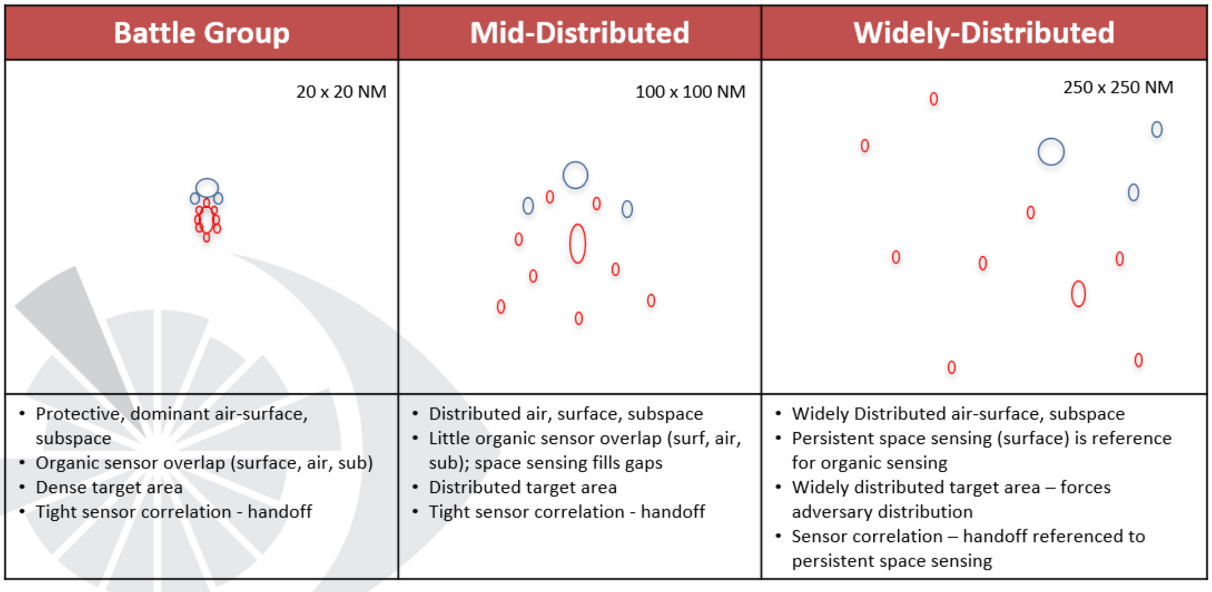


Figure 7.3-1a – DMO Spatial Distribution Top Level Analysis

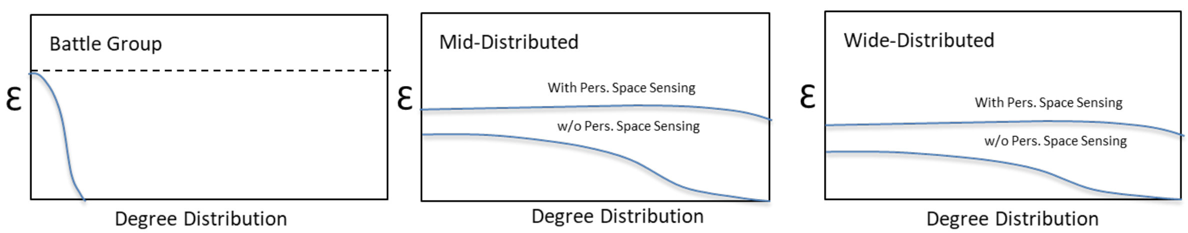


Figure 7.3-1b –High-Level Expected Relative Performance

We must also consider the ISRT needs across the timeline of ISRT activity phases (Figure 7.3-2). The normal maritime domain awareness (or Joint Intelligence Preparation of the Maritime Environment) occurs continuously and builds a threat operating picture over time (days). In periods of tension and crisis, surveillance and recon functions are more carefully (and intensely) focused on threats and targets.; this occurs in hourly updates and search for gaps, lost or dark adversary platforms, behavioral changes, etc. Targeting and fire control activities require the most demanding update rates for focused sensors that are orchestrated to supply target state updates, state predictions and assessments.

[12] AIS is the maritime automatic identification system that provides automatic tracking by placing transceivers on ships to provide regular reporting on the ship identity, route, and current GPS-based location. It is used by vessel traffic services (VTS) to monitor ships worldwide. Satellite receivers on INMARST spacecraft as well as smallsat constellations such as Hawkeye 360 can provide vessel reporting services.

ISRT Phase	JIPOE Intelligence	Situation Awareness	Surveil Recon	Targeting	Fire Control
Cyber	Cyber monitoring and initiate target access			Coordinated Cyber Node Attack	
Space	Orchestrate for aggregate coverage per NIPF maritime priorities		Focus Orchestration on combatants	Focus on target priorities	Support coordinated fires
Air	Normal fleet coordination of manned and unmanned sensor assets Adapt deployed sensors, relay comms, to predicted threats; threat axis			Coordinated air-surface target tracking nomination.	Coordinated air-surface fires
Surface					
Sub-surface	Coordinate manned, unmanned and relay comms for sensing, maneuver			ASW and surface warfare operations	
Seabed	Monitor-report early precursor adversary activities		Focus seabed sensors; Move Deep UUV's to position	Issue and relay commands to enable and target mines, torpedoes	
DAYS			*HOURS*	*MINUTES*	

Figure 7.3-2 Considerations for DMO Fusion

The most demanding capability of the network is to enable distributed over-horizon targeting. For analysis, we adopt the basic three modes of cooperative engagement between sensing platforms and firing (weapons) platforms.

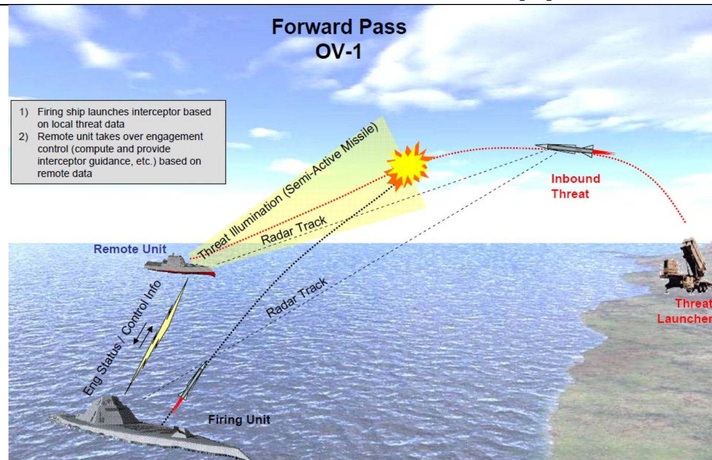
We illustrate three modes of long-range cooperative engagement in Figure 7.3-3 that can be considered for distributed operations using surface platforms (manned or unmanned).

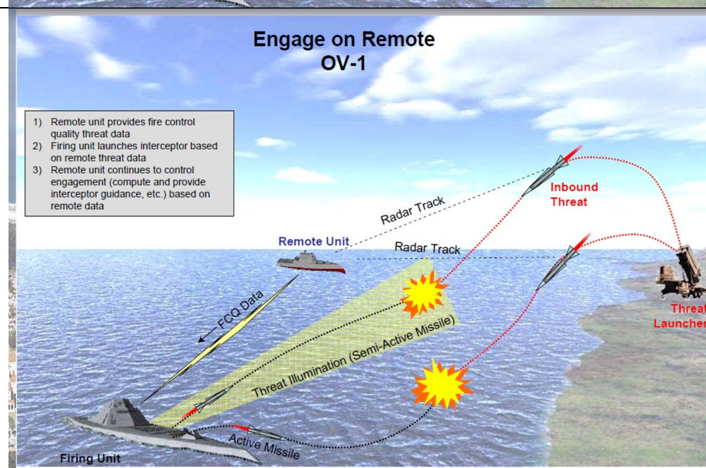
- **Forward Pass**, where in-flight missile control is transitioned or forward passed from one weapons sensor system to another unit to complete the engagement.

- **Engage on Remote** where a remote sensor provides pre- and post- launch Fire Control quality sensor data up to and including terminal illumination. The firing unit provides the weapon and guidance which based on the remote sensors (a combination of distributed sensors may provide this information, if fire control quality)

- **Remote Fire** where the remote unit initiates the launch from a local unit and retains control of the target engagement; the local unit only provides the weapon.

<table>
<tr><th>Mode of Fire Control</th><th>Illustration [13]</th></tr>
<tr><td>Forward Pass

In-flight missile control is transitioned or forward passed from one weapons sensor system to another unit to complete the engagement</td><td>
</td></tr>
<tr><td>Engage on Remote

Remote sensor provides pre- and post- launch Fire Control quality sensor data up to and including terminal illumination</td><td>
</td></tr>
<tr><td>Remote Fire

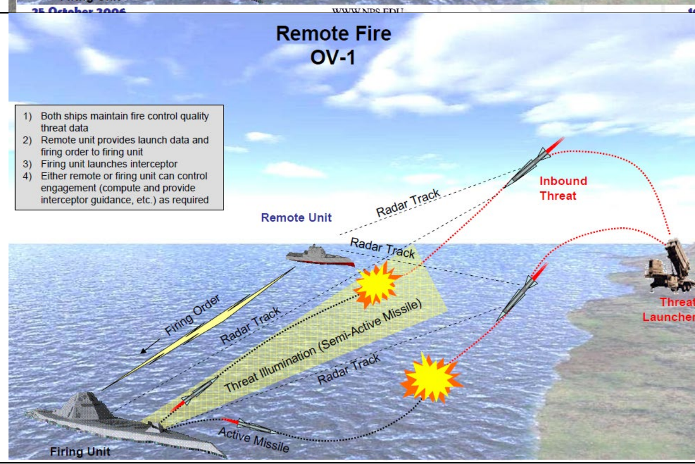
Remote unit initiates the launch from a local unit and retains control of the target engagement: local unit only provides the weapon.</td><td>
</td></tr>
</table>

Figure 7.3-3 Conceptual Modes of Cooperative Engagement

Indeed, during the conduct of this study, both the U.S. and Russian Navies demonstrated and publicly announced the test of long-range surface to Surface missiles (SSMs). In April 2021 the U.S. Navy used

[13] Source: Tom Hedge, Source: Open Architecture as an Enabler for FORCEnet, NSWC PHD San Diego; NPS, 25 October 2006.

unmanned platforms and passive sensors to enable the guided-missile destroyer USS John Finn to engage an over the horizon target with a standard missile SM-6. The fleet experiment used a blend of information from unmanned and manned ships and aircraft to launch and guide the SM-6 to the target more than 250 miles away. Active sensors (radar) were not used. The test was a part of the Unmanned Integrated Battle Problem 21 [Experiment]. Rear Adm. James Aiken: "We teamed manned and unmanned vessels together. We also used the fusing capability … It was totally passive where we didn't have active sensors on target," Aiken said. "We also look for space as well to actually identify the target and then once we found the target, we were able to track it because of the [electromagnetic signal] that was coming off the target, develop lines of bearing, then launched the missile." [[14]]

In July 2021 the Russian Navy conducted a long-range missile test, launching a hypersonic missile (figure 7.3-4) from the Admiral Gorshkov FFG in White Sea to a static target on the coastline of the Barents Sea. The missile, a Zircon (Russia 3M22; NATO SS-N-33) that can fly at Mach 7 (5,370 mph) Russia claimed that the test demonstrated a range of 350 km (217 miles). The Russian Navy claims a design range of 1000 km, or 621 miles for the missile. [[15]]

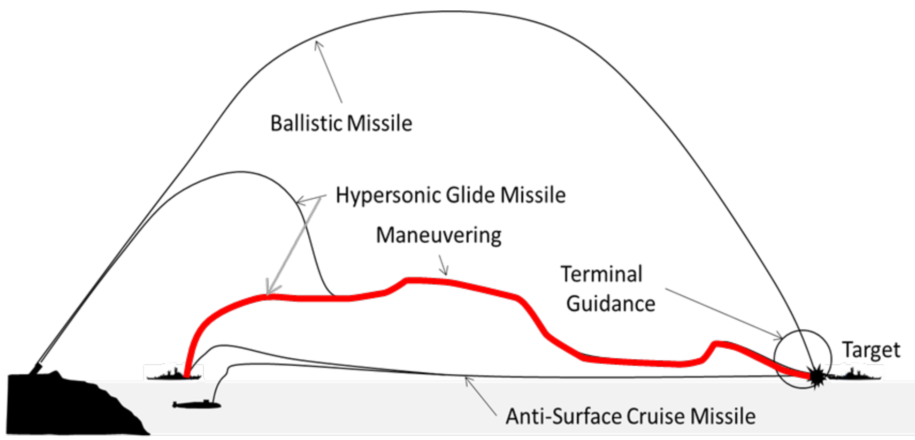


Figure 7.3-4 Typical Missile trajectories, highlighting the Hypersonic threat

While it appears, the Russian test focused only on the advanced hypersonic missile against a static target, the U.S. test focused on the ability to guide the missile to target cooperatively (using networked sensors) and passively (using non-radar sensors).

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[14] Sam LaGrone, Unmanned Systems, Passive Sensors Help USS John Finn Bullseye Target With SM-6, U.S. Naval Institute, April 26, 2021, 7:22 PM, https://news.usni.org/2021/04/26/unmanned-systems-passive-sensors-help-uss-john-finn-bullseye-target-with-sm-6

[15] Source: Russia says it successfully tested hypersonic missile praised by Putin, Reuters,19, July 2021, https://www.reuters.com/world/europe/russia-conducts-ship-based-hypersonic-missile-test-ifax-cites-defence-ministry-2021-07-19. See RU Defense Ministry video at: https://youtu.be/JMw7DJovyyM. Russian SSM Missiles capable of Long-Range attack include the BrahMos: Supersonic Cruise Missile SSM, and Tsirkon (Zircon): Hypersonic SSM.

This study considers the use of space sensing constellation(s) and a relay constellation like that being developed for DoD use by the Space Development Agency (SDA). Cooperative engagement in this case (Figure 7.3-5) relies on two "layers" of space platforms to enable long-range engagement by the fleet operating in DMO:

- Sensing layer(s) – Low Earth orbit (LEO) sensing spacecraft operating at 400-500km provide sensing (EO, radar and RF signals detection and locating) capabilities to detect, ID and track maritime traffic.
- Transport Layer – Relay spacecraft provide a network to route messages between all platforms in the network, including:
    - Space sensor-to-Transport layer
    - UAV sensor-to-Transport Layer
    - UAS sensor-to-Transport Layer
    - Transport layer relay spacecraft-to- Transport layer relay spacecraft (Network Routing)
    - Transport layer relay spacecraft-to-surface ships
    - Transport Layer-to-surface ships
    - Surface ship command guidance-to- missile (via transport layer or UAV, UAS within range of target)

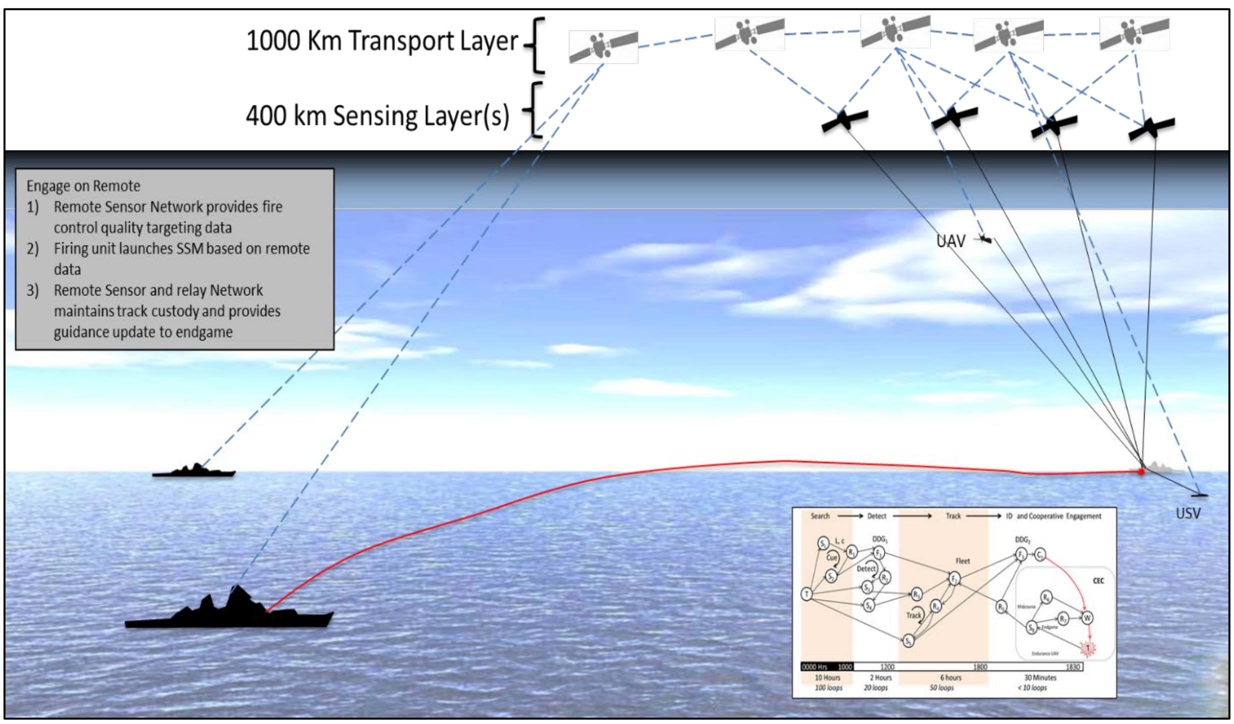

Figure 7.3-5 Conceptual Engagement with Space-Based or unmanned vehicle sensing and relay

The engagement factors that must be considered to implement a space-based coordination network include the following factors:

- Most critical support need from Sensor Net is 30-minute missile salvo period
    - Sustained Tracking (Update Rate for maneuvering surface target is estimated to be 0.1 observations/sec)

    - Sustained data link throughout cruise to missile endgame
- Long Range missile engagement factors to consider when estimating the TOTAL ability to detect, ID, track and engage an over-the-horizon target.
    - Detection, ID, and Track
        - Range-to-target; ID accuracy, ROE, adversary warning-surprise
        - Likelihood of sustained track to impact
        - Likelihood of sustained data link to missile through flight
    - Engagement
        - Missile Single shot Kill Probability (SSPK)
        - Target decoy effectiveness
        - Target SSPK of defensive weapons and servicing rate (rate-of-fire)
        - No. of Missiles in Salvo

7.4 Preliminary Analysis Observations

This preliminary analysis sets the stage for more detailed quantitative modeling and analysis by identifying the critical factors of analysis:

- DMO Key Operational Factors
    - Spatial Distribution of fleet, spatial configuration, and allocation of assets.
    - Effect on fleet tactics: ISRT performance-gaps, maneuver, coverage gap risks, self-protect risks, forcing distribution of enemy targeting.
    - Coordinated Engagement: Engage on Remote; Forward Pass; Remote Fire
- DMO Digital Comm Network Availability Factors
    - Fleet Organic JTRS, UAS Relay 4G
    - Space comm assurance, coverage, and capacity (MILSATCOM, Persistent Space Transport Layer with persistent-secure- AJ >150 Mbps network sensors (Update 5 sec – 5 min)
- DMO Assured Maritime Sensing (MDA) Factors
    - Organic Surface and Air sensor coverage (Horizon, Over-the-horizon)
    - Organic subsurface and seabed (current; future autonomous surface-to-seabed sensing and reporting via satcom links)
    - Space (Current; persistent commercial P-LEO EO-SAR and P-LEO Maritime RF for AIS monitoring)

The importance of distributed and networked sensing has, of course, long been recognized to accomplish any form of integrated fires, as required by DMO. [[16]]

[16] For an old, but still relevant study of land battle integrated fires, see Report of the Defense Science Board Task Force on Integrated Fire Support in the Battlespace, October 2004, Office of the Under Secretary of Defense, https://dsb.cto.mil/reports/2000s/ADA428791.pdf

8. Task 2: Develop Seabed-Space Network Architectures

Task 2 defines and describes the network architecture for a future seabed-to-space DMO ISR capability and identify what is suitable for modeling the transport and fusion of information to provide a distributed operating picture appropriate for ISRT.

The network architecture Operational View-1 (OV-1) (Figure 8-1) illustrates the distinct links required to establish and orchestrate the network of sensors.

Figure 8-2 provides the 7-layer OSI structure of the major layers of the network, distinguishing on the right-hand side, two major elements (labelled 1 and 2). The figure also compares the layers in the standard Link-22 data link.

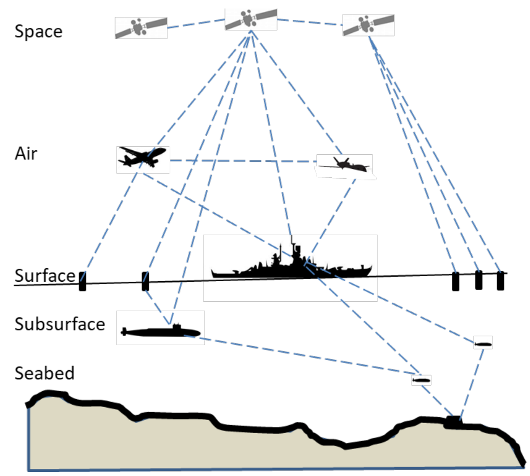

Figure 8-1 OV-1 of Seabed to Space Network Links

This effort focuses on analyzing the feasibility of the dynamic network (Green) and the Fusion, Orchestration Process (Blue):

1. Communication Networks (green) include the physical links and supporting protocols to enable point-to-point data communication (e.g., sensors-to-relay, sensors-to-fusion).
2. Fusion and network orchestration process (blue)

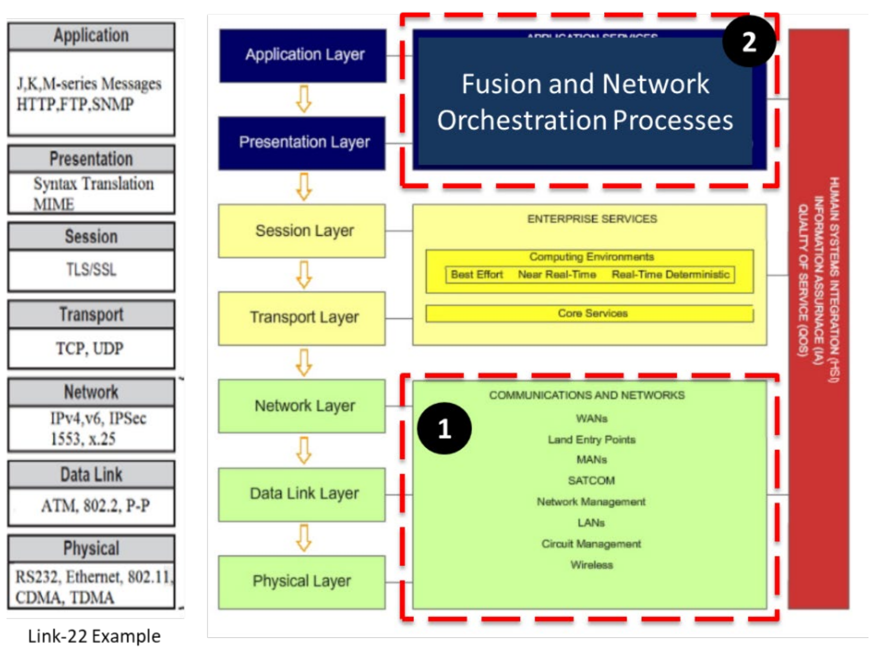

Figure 8-2 Architecture layers [[17]]

[17] Figure adapted from Fred M. (Mike) Stewart, The State of the Art, and the State of the Practice FORCEnet Net Centric Architecture – A Standards View, 2006 CCRTS, Space and Naval Warfare System Center.

The links (current and future Wideband (WB) links on space layers) are matched to the OV-1 diagram in Figure 8-3 to illustrate the large number of links that must be coordinated over time to control and receive data from disparate sensors to search, acquire and maintain custody on targets to enable the long-range targeting required for DMO.

Seabed-to-Space Network Links		
Layer	Elements	Comments
Space Relay	P-LEO WB Comm Constellation Intersatellite and relay	Advanced full coverage WB comm Space Development Agency AFRL
	P-LEO Link 16	
	Wideband Global Satcom (WGS) Defense Satellite Communications System (DSCS)	Legacy, limited WB capacity and coverage
	Mobile User Objective System (MUOS) Ultra High Frequency Follow-On (UFO) FLTSATCOM UHF satellites	Legacy Navy NB will not support network; may be useful for infrequent autonomous sensor reporting
Air Surface	Link-16 -22; HF/UHF Spread; TDMA/DTDMA Link-22 HF BLOS (Beyond Line of Sight) 300 nm. Access to all Space laser comms for relay Sonobuoy VHF short-term links	Airborne UAV relay platforms provide surface-surface relay
Sub-surface Seabed	Acoustic signaling (telesonar) lbi-directional inks. Radio/acoustic communications (Racom) buoys link submarines, UUV's and submerged sensor grids to maritime patrol aircraft and satellite relays	Used for ASW sensor grids such as the Deployable Autonomous Distributed System (DADS) and SeaWeb. Local area networks (Sealan) cover an undersea region up to 5 km².

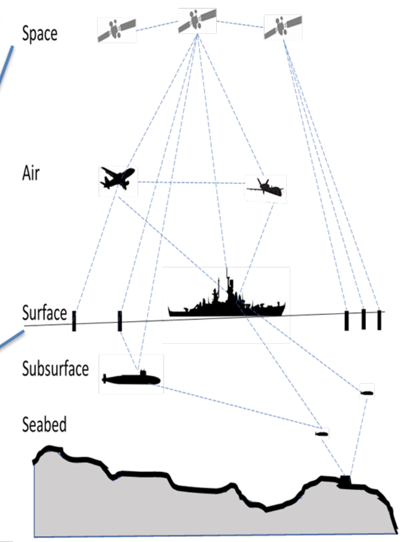

Figure 8-3 Network Link Elements

We consider two categories of required coordination-control to maintain custody of many maritime targets over the dispersed DMO fleet (Table 8-1)

- ***Sensor or Collection Orchestration***– The structure of applications required to manage the sensor collection and network paths over time to proceed from search, detection, track-ID, and fire control. This fusion Level 4 process requires the automation of the distributed network of multi-INT collection and processing elements to focus dynamic collection on emergent events as well as pre-planned (standing) collection needs in an optimal way.
- ***Network orchestration*** – The network must adapt to vary coverage, focus and priority as the system changes the importance of different missions (ocean search, ship-track, reacquire, engagement), areas, and targets. The network must allocate bandwidth as phases of the mission change over time. Of course, engagement operations must have priority during fire control activities that require sensors to provide updates throughout missile flight.

The table illustrates the specific functions in each orchestration and task; both tests must be coordinated to operate the network and sensors to optimize an objective function. Then objective function must consider the balance several alternatives:

1. Objective 1- Maintain custody of the *maximum number of targets* identified by the fleet as important and within DMO operating areas.
2. Objective 2 – Maintain custody to achieve the *highest aggregate target value*, where each target has a defined "value" (e.g., an aircraft carrier has a higher value than a frigate).
3. Objective 3 – Search an area to locate and acquire a threat vessel by maximizing *the greatest coverage area in the shortest time*.

ISRT Orchestration				
Sensor Orchestration			**Network Orchestration**	
Multi-INT sensor planning based on target value			Route Planning based on message priority	
Target valuation	Sensor Collection Feasibility Prediction	Aggregate Value Optimization	Network routing prediction	Message Priority based on ISRT state
• Coordination of multiple sensors to sustain continuity of target custody • Prediction and valuation of each feasible sensor collection • Assignment of values for priority targets-in-track			• Network instantaneous performance management (e.g., CAINS) • Priority message stream assurance (e.g., weapon in-flight; target in-track)	

Table 8-1 Orchestration Architecture elements

When optimizing for a "value" there are two contributors to the value of a candidate target (or area) for collection. Figure 8-4 illustrates the role of the two contributions (Figure 8-4):

- **Target value** is the importance of a target, object, or activity (or an area when searching) that requires collection. High importance targets have a higher value. This is related to the *intrinsic intelligence value* of the knowledge about that that target.
- **Opportunity Value** is the expected value of the collection on the target under predicted collection conditions (Range, SNR, etc.). Poorly observed collections (due to weather, obscuration, long range, etc.) have lower values.

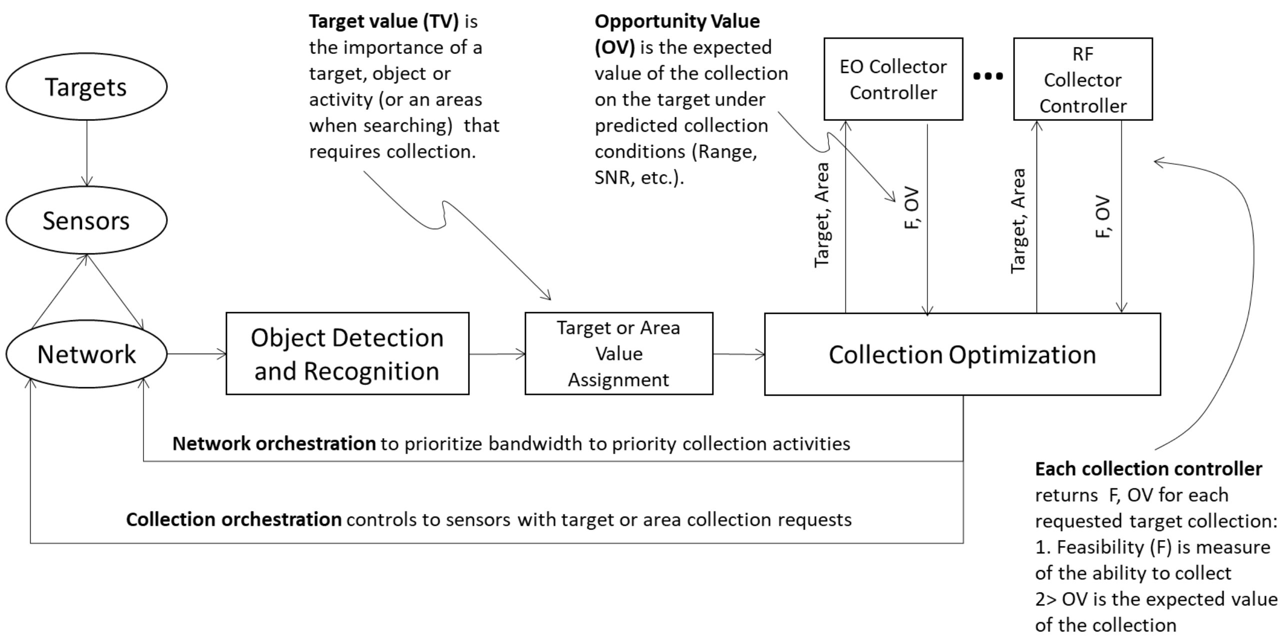

Figure 7-1 Example Value Assignment Process

The orchestration process then applies an algorithm to assign an overall value (the collection value) to each collection request item (e.g. maritime target, or ocean search area) based on the combination of its target and opportunity values.

The overall values of all targets (at a point or window of time) can be rank-ordered and optimized to achieve the highest overall value. Several approaches to optimization may be applied to perform the optimization, including:

- Linear programming maximizes (or minimizes) a linear objective function subject to one or more constraints.
- Mixed integer programming adds one additional condition that at least one of the variables can only take on integer values.
- Simulated annealing is a probabilistic technique for approximating the global optimum of a non-linear objective function.
- Genetic search methods apply heuristics to search large spaces (objective functions) either constrained or unconstrained, by expanding a search, choosing the best results, pruning unpromising results, and repeating the search for a global optimum.

The purpose of the optimization is to use the collection resources available most efficiently and to dynamically focus attention on the most critical maritime targets. The effect is a dynamic control of the network and collection resources.

9. Task 3 Develop Metrics

Task 3 developed metrics to measure the performance and effectiveness of the seabed-to-space orchestration process. These measures (Table 9-1) provide values to quantify the network and the overall system capability to orchestrate ISR and to enable engagement of adversary targets. We distinguish:

- Performance measures – Quantify the objective evidence of the degree to which a system achieves a metric value of a required measure of performance (MOP) metric. For example, latency is a performance measure of delay; it measures the time it takes for data to get to its destination across the network.

- Effectiveness Measures –Measures of Effectiveness (MOEs) assess changes in system behavior, capability, or operational environment that is tied to measuring the attainment of an end state, achievement of a mission objective, or creation of an effect. In the ISRT case, effectiveness measures quantify the ability to apply the ISRT capability to perform DMO detect-ID-track to achieve mission objectives (e.g., Defensive evasion, Offensive attack).

Metric	Type	Description	Use
Latency	Performance	1. Transmission latency -The time it takes for a data message (e.g., Target Detection) to travel from one designated node in a network to another node. 2. Node Latency - The time it takes to process a single multiple data message to produce a result to be sent forward on a network	Measure the delay from sense-to-fusion node
Capacity		Network capacity is the amount of traffic that a network can handle at any given time.	Ability to get data to user nodes
Sensor Detection Performance		Performance-level measures (e.g., Probability Detection, Probability False Alarm) of individual sensors	Individual Sensor performance
Fusion Performance		Performance-level measures (e.g., Probability Detection, Probability False Alarm) of fused data reporting sensors	ISR performance
Detection Rate	Effectiveness	Percent targets detected and correctly identified (Type).	Ability to warn and Situation Awareness,
Update rate		The rate at which updates are produced on a target state or a dynamic target track	Ability to track and target
Targeting Rate		(Percent ISRT Chain Completion) Percent Targets acquired (sensed, located, Identified, and reported to ISR) and targeted to enable engagement	Targeting Ability
Network Availability (Uptime)		The percentage of uptime in a network system over a specific time interval. Uptime refers to the amount of time a network is fully operational.	This determines effectiveness of all other net-dependent measures

Table 9-1 Performance Metrics to evaluate Network Architecture

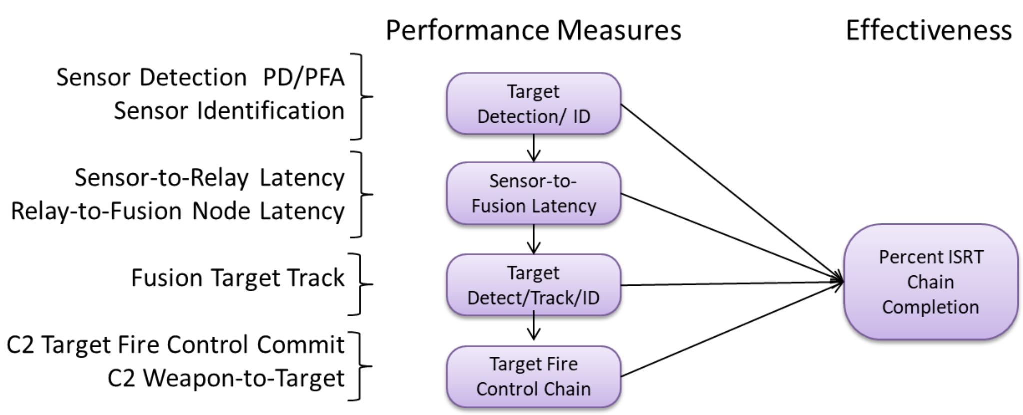

Figure 9-1 The relation between system performance and operational effectiveness

The performance measures can be used by plotting the events, network use and latency (delays) throughout each detect-to-engage scenario. In addition, the metrics can be used to measure network demand, evaluate sensitivity to net parameters such as: Sensor detection, latency (delays), availability, sample rate, Network relay link latencies, and target ID and custody performance.

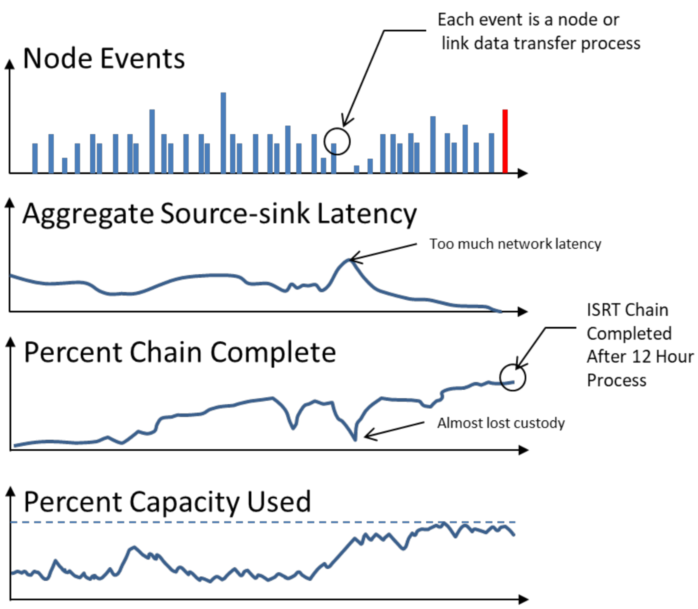

Figure 9-2 Example plot of performance measures over a notional ISRT chain of events

Effectiveness measures are a function of performance of component performance measures (Figure 9-1) plotted over time. Because the entire ISRT chain requires a complex, sustained network exchange, network availability and latency are critical parameters to sustain the successful operation of the ISRT chain of events; effectiveness measures over a range of scenarios enable evaluation of operational utility.

10. Tasks 4 and 5 Evaluate Effectiveness and Report Results

In this task, we defined and described the network architecture for a future seabed-to-space DMO ISR capability that is suitable for modeling the transport and fusion of information to provide a distributed operating picture suitable for DMO surveillance and targeting.

We Identified approaches to that are suitable to assign values to the information provided by each network sensor, to enable a means of constrained optimization to be applied to orchestrate the all-domain sensors.

The analytic flow (Figure 10-1) included the following steps:

- Identify DMO-enabling scenarios (use cases) that utilize networked seabed-to-space sensors and fusion operations to provide revolutionary new capabilities
- Evaluate the feasibility of using the Space Development Agency (SDA) satellite constellations for relay, and commercial EO, Radar and RF Sensing constellations for collection (Quantitative model Q1).
- Explicitly define the network dynamics and timeline required to conduct the S-to-S scenario and all sensors and links required in narrative and graphical form (Quantitative structure model Q2).
- Translate the scenario to a detailed event (Sensing and comm transactions) spreadsheet

- Analyze and measure performance using Analyst Notebook and Simio modeling tools (Quantitative models Q3).

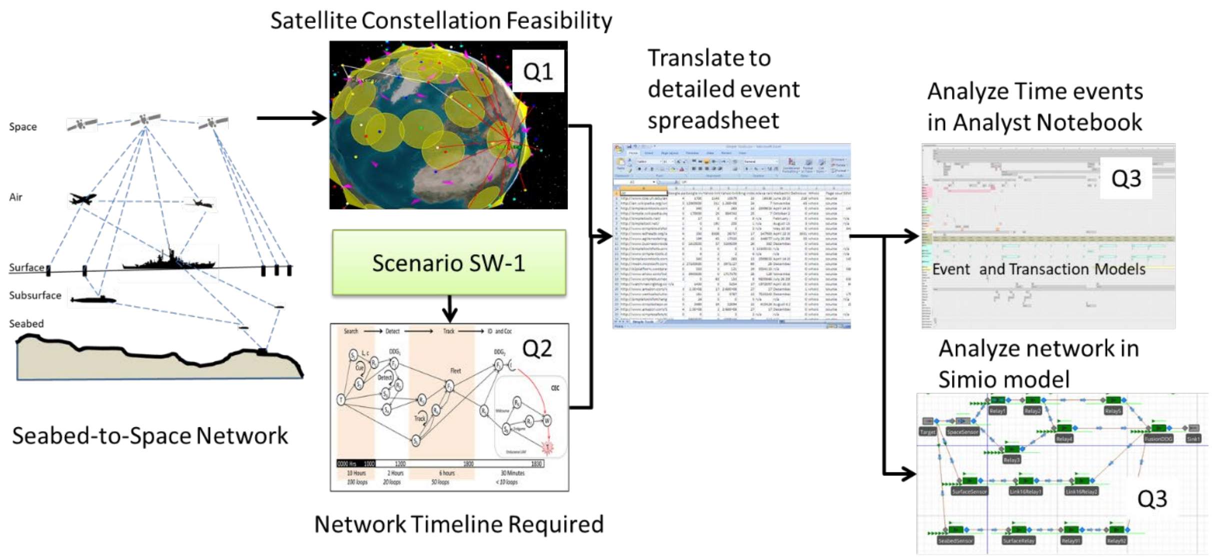

Figure 10-1 Analytic Flow

The analytic flow resulted from a study of the appropriate ways to represent (model) the DMO scenario for this and any future research efforts; the analysis is provided in APPENDIX A.

The following sections describe the elements of the process used to select and model the DMO Scenario, and model sensing and network operations.

10.1 Scenarios Considered

The performance of the sensing and relay network is dependent on many factors, including the number of targets and their dynamic behaviors, the number, structure, and performance of the sensors available, the dynamics of the scenario (both red and blue forces), the performance of the network that interconnects sensors and forces, and environmental conditions.

We considered seven fundamental DMO scenarios (Table 10.1-1) for evaluation. The scenarios were chosen based on:

- Use of all sensor and link categories.
- Focus on surface warfare because long-range air warfare is not new, but is very reliant on radar sensors, and is not unique to DMO.
- Demonstrates fleet combat with distributed lethality that is over-the-horizon because it is a necessary capability for DMO (and a current U.S. Navy priority)

Use Case	Category	
SW-1	SW Surface Warfare Targeting	Seabed Alert; Space search-custody; UAV and USV relay; coop. engage
SW-2	SW Surveillance	Seabed Alert; UAV and USV search-custody
SW-3	SW Surveillance	Surface Alert; Space search-custody → UAV and USV custody
SW-4	SW Search	Dark Vessel Alert→Space search → UAV -custody
SW-5	SW Drone Defense	Long-range detection of drone threat to enable Counter UAV
ASW-1	ASW Anti-Sub Warfare	Seabed Alert; UUV and attack sub search to custody
AAW-1	AAW Anti-Air Warfare	Gap Fill air search by Airborne Early Warning and UAV, space sensors

We focused on modeling SW-1 (long range surface warfare 1) for the following reasons:

1. It is the most complex and stressful case that will reveal the most critical performance needs.
2. It is representative of the demanding use of the complete seabed-to-space network
3. If it can be accomplished, most of the other cases will also be feasible; some are subsets of the SW-1 case.

The specific scenario details for SW-1 are provided in Section 10.3.

10.2 Constellation Study

We evaluated the feasibility of a persistent global surveillance and transport capability provided by a pair of satellite constellations to provide persistent coverage for seabed-space sensing and relay by adopting the results from a separate study of the Space Development Agency (SDA) sensing system.

We adopted a notional satellite coverage model implemented in the System toolkit (STK) tool to assess the feasibility of the SDA-like communication relay constellation to provide a responsive network between space sensors, unmanned vehicle sensors (UAV, UAS) and surface vessels. [[18]]

The SDA Transport Constellation Layers (Tranche 1) and sensing layers were derived from first principles

- Low earth orbit (LEO) constellation layer of 50-200 small EO and SAR imaging satellites to provide persistent, steerable sensing
- Higher constellation layer of 50-200 small relay satellites that enable fast internet-like routing of cueing and detected target information between the sensing satellites

[18] The STK model was previously developed, and analyses were completed for the U. S. Government under a separate unclassified effort. In this study we leveraged selected results to demonstrate feasibility of the relay for the DMO application.

We addressed the question: Can this capability provide performance (e.g., latency, availability) to enable seabed-to-space remote engagement?   This required the analysis of target revisit rates for tracking and communication relay potential for sensor network (space, air, surface, subsurface).

The basic concept is derived from the ambitious Space Development Agency ongoing layered constellation concept to detect, track, and manage engagement of hypersonic threats (Figure 10.2-1).

The SDA architecture includes: [[19], [20]]

- A space transport layer: A global mesh network providing 24/7 data and communications.
- A tracking layer: Provides tracking, targeting and advanced warning of missile threats.
- A custody layer: Provides "all-weather custody of all identified time-critical targets."
- A deterrence layer: Provides space situational awareness—detecting and tracking objects in space to help satellites avoid collisions.
- A navigation layer: Provides alternative positioning, navigation and timing services in case GPS is blocked or unavailable.
- A battle management layer: A command, control and communications network augmented by artificial intelligence that provides self-tasking, self-prioritization, on-board processing, and dissemination.
- A support layer: Ground command and control facilities and user terminals, as well as rapid-response launch services.

In this study, we presume only a sensing constellation and a relay (transport) constellation and further we presume:

- Sensing spacecraft can be controlled by issuing collection requests on specific areas , and spacecraft-to-spacecraft cueing requests may be passed through the relay network.
- Maritime target detection screening and identification (e.g., ship class) is performed onboard the spacecraft and target data only is passed through the relay network (not full ocean images).

Both of these assumptions are consistent with capabilities being projected for the 2025-2028 timeframe for commercial experimental spacecraft and on the DARPA Blackjack project.

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[19] National Defense Space Architecture (NDSA) Systems, Technologies, and Emerging Capabilities (STEC) Broad Agency Announcement (BAA), Space Development Agency (SDA), HQ085020S0001 January 21, 2020.
[20] Space Transport Layer Tranche 0 Statement of Work (SOW), Space Development Agency (SDA), HQ085020R0001 Attachment 1 SOW,26 Mar 2020

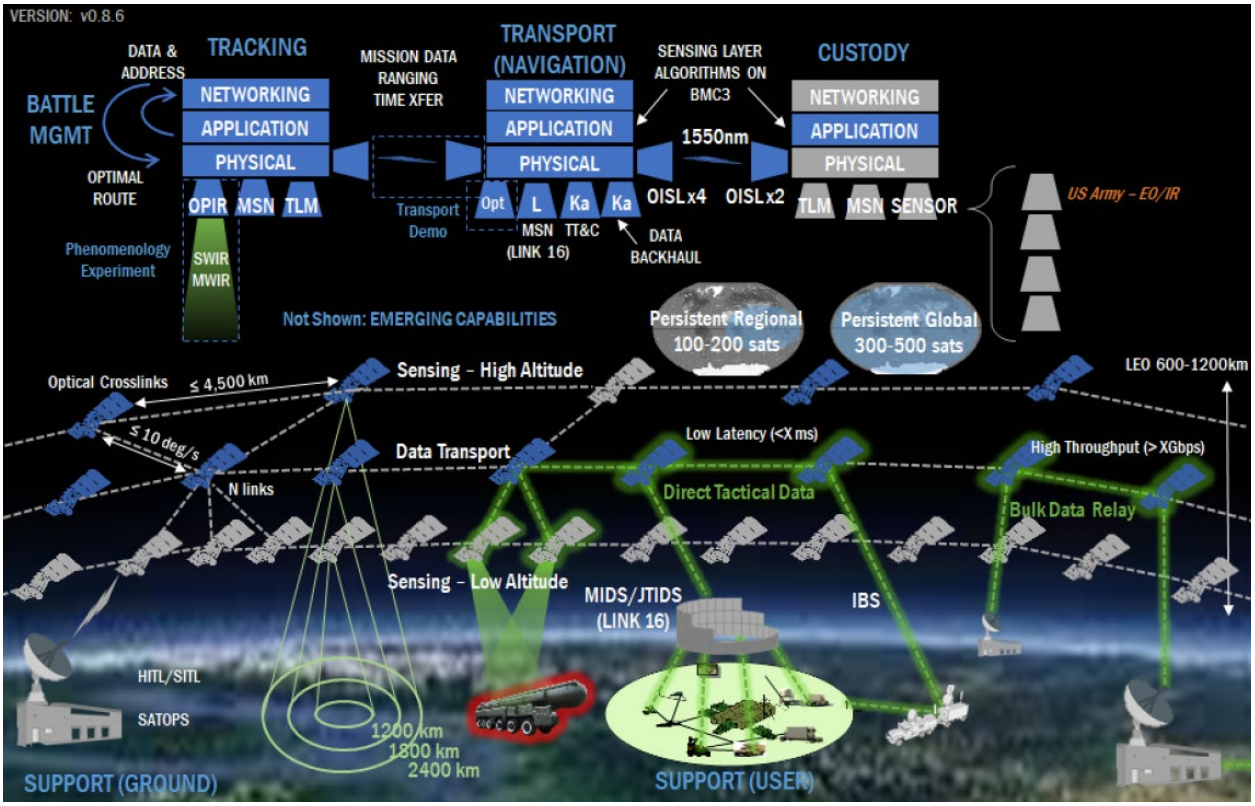


Figure 10.2-1 Space Development Agency National Defense Space Architecture (NDSA)

The analysis built in STK the two-constellation model with the ability to change the number of satellites in each constellation in the range of 50-200 satellites with models of a nominal EO Sensor and SAR sensor on the sensing satellites. The objective was to develop constellations to provide approximately 20–50 minute (average) maritime revisit on each constellation (independently) and to enable relay from satellite to ground, as well as to a neighboring satellite (the next-pass-over-target satellite).

Nominal Parameters for the constellations are:

Sensing Constellation	Altitude	200-300 km
	Inclination	75 to 100 degrees
	Sensors	100 EO and 100 SAR (0.5 GSD)
Communication Constellation	Altitude	1000-1500 km
	Inclination	75 to 100 degrees
	Satellites	150-200
	Communications (not Modeled)	Relay satellites perform routing/packet switching protocol to relay from sensing satellites across multiple relays to next sensing satellite

The notional constellations (*minimum* required to achieve coverage) used in the study were:

- Imaging Constellation: 9 planes / 6 satellites per plane / 87° inclination
- SAR Constellation: 9 planes / 6 satellites per plane / 92.5° inclination
- COMM Relay Constellation: 9 planes / 10 satellites per plane / 75° inclination

– Ground station minimum 10° elevation constraint
– Line-of-sight access with Imaging/SAR constellation satellites
– Line-of-sight access to other COMM relay satellites

To achieve the desire global maritime coverage the sensing attributes of the minimum sized constellations are summarized in Table 10.2-1.

EO Constellation 54 satellites

- Goal: Persistent Global Coverage
- 475 km circular x 87° inclination
- Number of satellites: 54
- 9 planes
- 6 satellites per plane
- Delta Walker constellation

Revisit Times

Minimum (min)	Maximum (min)	Average (min)
0.000 [a]	37.188	18.988 [b]

SAR Constellation 54 satellites

- Sensor IFOV smaller than conical IFOV
- Non-steerable sensor modeled – 'push broom' type
- Coverage analysis for 475 km circular x 92.5° inclination
- Walker Delta constellation: 9 planes / 6 satellites per plane
- Coverage area omits south pole (-85° to +90° latitude)

Revisit Times:

Minimum (min)	Maximum (min)	Average (min)
0.159	74.588	56.375 [c]

Note: [a] Zero indicates simultaneous coverage with no time between visits
[b] This constellation meets the 20-minute revisit objective
[c] This constellation exceeds the 50-minute revisit objective by 12% will require ~ 10 more spacecraft

Table 10.2-1 Sensor Constellation Performance

Note that these update rates, though very frequent compared to traditional standards before large smallsat constellations, is appropriate for non-maneuvering maritime targets. Of course, the *combined* revisit rate provides greater the individual constellations.

Note the following factors for consideration:

- This analysis derived the minimum number of satellites, and much larger constellations will, of course, reduce the revisit rate.
- The design on both a SAR and EO constellation is predicated by the need to provide all-weather, day-night coverage with the complement of the two sensing modes.
- The 20–50-minute requirement can maintain custody of a fast 30 kt (35 mph) vessel that can travel only 10-15 miles between samples (requiring a 20 x 20 km area collect to assure custody.)
- Highly maneuvering and evasive vessels remain at risk of custody even with these revisit rates and must then invoke more sophisticated denial and deception measures.
- During missile terminal engagement phases, where the target location is critical to assure the missile seeker will acquire the (correct) target, the 20-minute sample rate is unsatisfactory, and this may require coordinated UAS or UAV collection to assure terminal capture.

The constellation analysis simulated notional image relay scenario to demonstrate feasibility and produce performance values for the following case:

1. Collect data using the EO and SAR imagers passing over the Suez Canal to collect an image of the merchant ship (IMO 9811000) *Ever Given (*at the site where the vessel blocked the canal In March 2021) at 30.455° Lat, 32.350° Lon

2. Relay the detected ship image chip to a ground station located at the Naval Postgraduate School in Monterey, CA 36.6002° Lat, -121.895° Lon. (Of course, in the Surface Warfare scenario the relay would be much shorter because the relay endpoint would be to a vessel operating in the same area as the target (within 500 miles, typically).

The simulated relay configuration for both EO and SAR constellations are provided in Figure 10.2-1

Imager Complete Chain and COMM constellation Accesses

SAR Complete Chain and COMM constellation Accesses

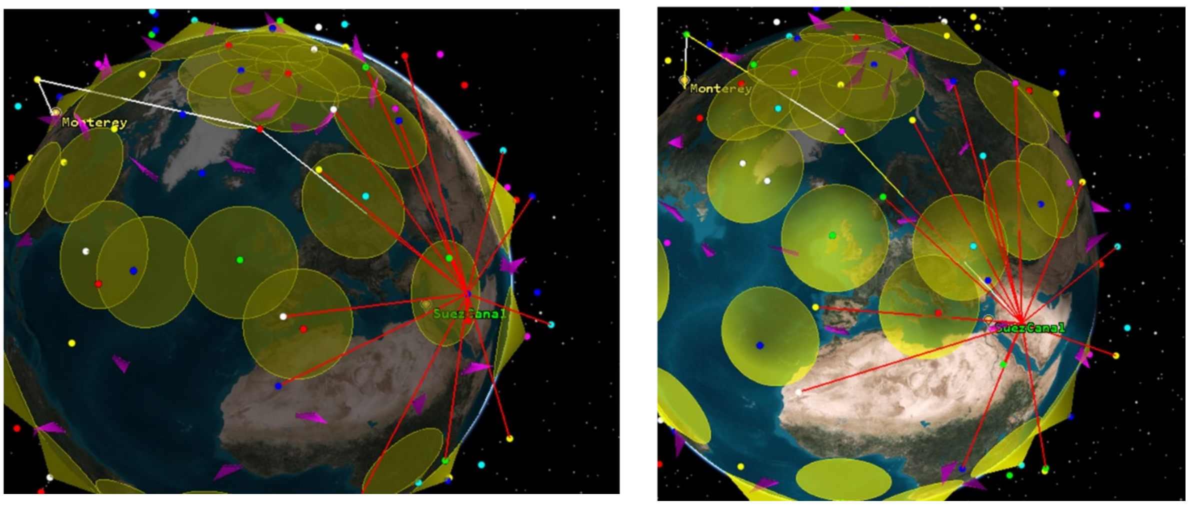


Figure 10.2-1 EO Imager and SAR to COMM Constellation Relays to Monterey Ground station

For each chain from orbiting sensor to ground station, relay distances are provided in Table 10.2-2. The access time to the target is provided (duration of satellite line-of-sight access to the Suez target) as well as the line-of-sight ranges between target, sensor and relays, and ground station. Notice that

Based on comparable relays on the similar LEO Starlink wideband internet system (Space-X) the latency over these paths should be <100ms and the latency within an ocean region < 20ms. Intersatellite laser links will provide the low latency for longer relay sequences. The Starlink constellation, with over 1700 satellites provide wideband internet at reported speeds up to 200 Mbps and latencies between 20 and 88 msec. The Starlink satellites operated at 550 nmi. orbit (half of the altitude modelled here) and are designed to accommodate a very large user base.

The Space and Missile Systems Center (SMC), the procurement arm of the U.S. Space Force, has a Commercial Satellite Communications Office (CSCO) that procures broadband from operators of geostationary satellites and narrowband communications from mobile satellite services provider Iridium Communications. CSCO is planning to add LEO broadband providers such as SpaceX, OneWeb, Telesat and others to provide some DoD services.

Example SAR Complete Chain Access for Day 1

- SAR Access #4: 14 sec duration
- Access Details (1 Jan 2024 13:31:34 to 1 Jan 2024 13:31:48)

From	To	Min. Range (km)	Max. Range (km)
Target	SAR_Sat_B55	746.9	751.7
SAR_Sat_B55	COMM_Sat706	5843.0	5902.0
COMM_Sat706	COMM_Sat505	7228.7	7295.9
COMM_Sat505	Ground Site	1370.5	1395.4
Sum Total:		15,189.1	15,345.0

Example EO Imager Complete Chain Access for Day 1

- Imaging Access No. 7: 85 sec duration
- Access Details (1 Jan 2024 02:28:41.481 to 1 Jan 2024 02:30:07.149)

From	To	Min. Range (km)	Max. Range (km)
Target	ImagingSat_A16	991.5	1149.7
ImagingSat_A16	COMM_Sat309	5766.8	6185.7
COMM_Sat309	COMM_Sat108	7068.6	7479.3
COMM_Sat108	Ground Site	1103.8	1376.2
Sum Total:		14,930.7	16,190.9

Table 10.2-2 Chain Access parameters for SAR and EO imaging systems

The implications and our assessment of the satellite constellation analysis are:

1. The persistent minimum LEO imaging satellite constellation:
   1.1. Provides sufficient revisit to detect, ID, and track maritime targets (SAR+EO)
   1.2. Is insufficient, alone, to provide terminal guidance remote engagement against maneuvering vessel targets
   1.3. Can enable remote engagement when supplemented by endurance UAV or USV to support terminal guidance for maneuvering and evasive targets.
2. The minimum Transport Relay Constellation that is like the DoD SDA plan:
   2.1. Can provide available and low-latency (< 200 msec.) relay between the following platforms:
      2.1.1. Sensing satellite-to-sensing satellite (tip relay)
      2.1.2. Relay satellite-to-relay satellite
      2.1.3. Relay Satellite-to-surface User (Command vessel, DDG, UAV, UAS, autonomous surface sensors)
   2.2. Supports long range over-the-horizon engagements where ships in 500 nm radius have common access to transport satellites, and sensor constellations (Government and commercial) that exchange sensor data via the relay network. [[21]]
3. DoD security and assurance must be met by these systems (Compared to commercial systems).
4. These LEO layers are a major enabler for DMO long-range ISRT.

[21] Sandra Erwin, DoD space agency to create marketplace for commercial satellite data, *Space News*, June 22, 2021. "The Space Development Agency is looking to work with commercial operators of imaging satellites so they can send data directly to U.S. government satellites in orbit, the agency's director Derek Tournear." Optical crosslink on a commercial satellite can transmit data directly to the DoD Transport Layer so that it can be fused with other data. https://spacenews.com/dod-space-agency-to-create-marketplace-for-commercial-satellite-data/

10.3 Network and Transaction Flow Analysis

A network flow was developed for the SW-1 scenario to describe the necessary sensor, network and fusion activities that would be required to search, detect, track, and engage an over the horizon surface target using seabed-to-space sensors and sources. The Anti-Surface Warfare Scenario that stresses the dynamic network between many sensors over time (Satellite sensors must handoff targets on approximately 10–20-minute intervals) to maintain custody of many targets over long periods of time.

The following narrative sequence of network events (and the associated network flow in Figure 10.3-1) illustrates the required sensor, network, relay, fusion, and fire control events to complete the ISRT chain.

- Search (Nightime)
  - Adversary ship target departs foreign port and is detected by **seabed sensor net** (S1) that relays the detection to surface **buoy (**R1) that relays to a satellite comm constellation (R1) This is the highest latency warning and tip to initiate collection.
  - Message is relayed across the **comm constellation** (R1) to a DDG1 **fusion node** (F1)
  - DDG1 fusion node (F1) cues sensor (S2) **smallsat radar constellation** to search for target vessel in a 75 x75 km target area based on the latency from the seabed detection.
- Detect (Morning)
  - Multiple S2 detections locate the ship and focus subsequent persistent revisits to track the target that heading toward U.S vessels
  - Organic sensor platforms S3 (**local USV**) and S4 (**UAV**) are tasked to move 150 km toward the target track to provide local sensing (and relay for cooperative engagement)
  - Multiple S2 persistent revisits (multiple satellites in the S2 constellation) to track the target that heading toward U.S vessels
- Track and ID (Daylight)
  - DDG1 fusion node relays the track to **Fleet fusion node** (F2)
  - As daylight dawns, F2 tasks **smallsat EO constellation** (S5) to acquire and ID the target ship in daylight hours, and to maintain track custody as it move toward the U.S. vessels
  - F2 assigns **cooperative engagement to fusion node** (F3) on DDG2
  - F3 designates **UAV Sensor** S8 as the cooperative engagement sensor; S8 relays target data via relay R5 to Fleet F2 and DDG2 F3
  - F3 Designates R6 (**LEO Sat comm**) as midcourse relay to weapon and R7 (**Endurance UAV**) as relay to terminal guidance and endgame updates, then fires weapon.
- Engage (Nightfall)

- Weapon (W) is fired by **Command and Control (C2)** node (C1)
- Weapon receives updates from Endurance UAV Sensor S8 via relays from sensor –to-weapon links R6 and R7
- S8 performs battle damage assessment (BDA), and relays results to Fleet (F2) and DDG2 (F3) fusion nodes to determine if reattack is required

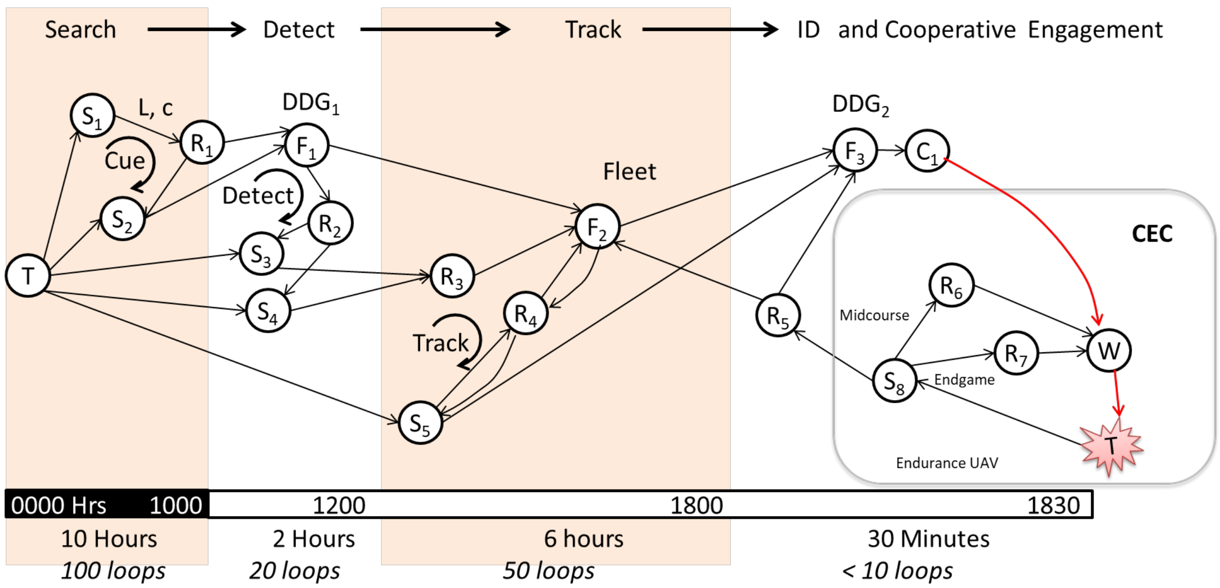


Figure 10.3-1 High-level graphic of the Network flow in SW-1 ISRT Scenario

The example scenario includes the following assumptions:

1. Assumes seabed sensor net with < 1 hour latency to report target traffic
2. Assumes smallsat sensor constellations with approximately 20-minute (or less) target revisit
3. Assumes smallsat comm relay constellation (SDA Transport layer) with < 100 ms latency between spacecraft and < 500 ms latency from any sensor to any fusion node
4. Assumes UUV and USV sensor platform vehicles, and endurance UAV with sensors (RF intercept, EO and LPI maritime radar) and relay capability
5. Assumes SM-6 long range SSM (>200nm)
6. Applies "Remote Fire" method for Cooperative Engagement

The assessment of this basic narrative of the SW-I scenario and sensing-relay process was translated from a conceptual sequence to an explicit model in Excel (Figure 10.3-2) to detail the events and timing of such a process to examine the number of required network transactions, required target revisits, etc. The spreadsheet provided a model that can be quantitatively analyzed in IBM analyst notebook (ANB) by transaction analysis.

The spreadsheet could also be used to drive a network model such as the Simio model previously discussed (though this was beyond the scope of this study). The following paragraphs describe the two models developed in this study.

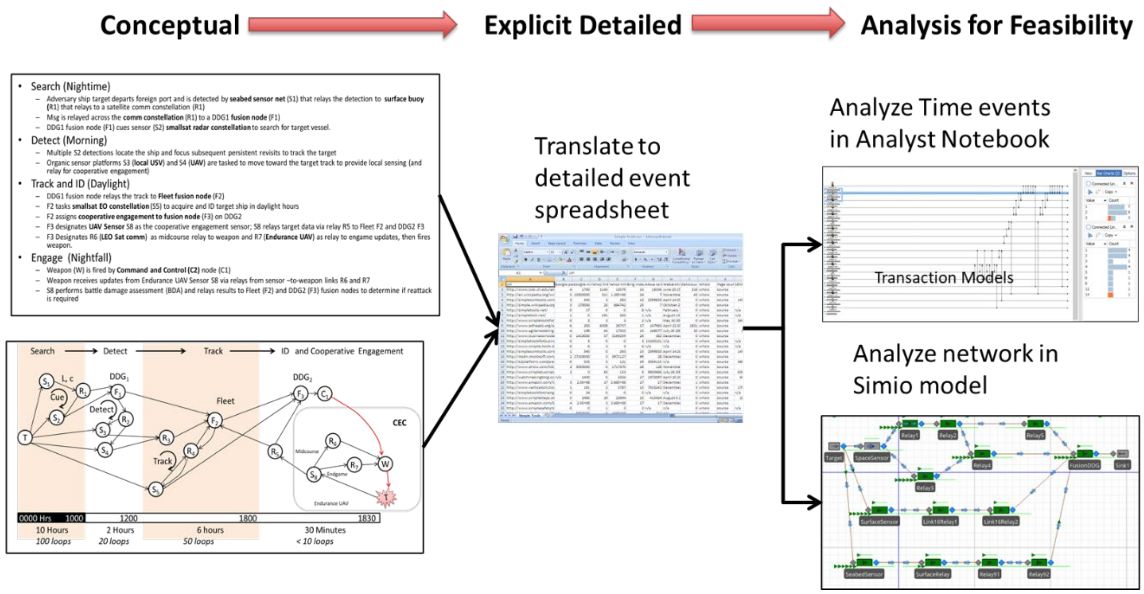


Figure 10.3-2 Example SW1 Analytic Process Flow

Model A: Network Simulation

We evaluated approaches to modeling the network of paths from seabed, surface (USV), aIr (UAV), and space sensors to fusion nodes that:

- Maintain a sequence of POSITs (Positions in Time) to generate a target history track
- Create and maintain a dynamic model of target behavior (track) over time
- Correlate and combine data from two or more sensors to derive higher level information (e.g., target classification, improved location accuracy, target track update, etc.)
- Cue or handoff a target to other sensors

The objective is to model the dynamic behavior of the network at the fundamental transaction level; we considered a range of tools (Table 10.3-1) to locate a tool appropriate for this project.

Based on our assessment, we chose the SIMIO discrete event simulation (DES) package to develop a basic model of the network operations for seabed (high latency), surface, and space sensors. The modeling approach (Figure 10.3-2) built the movement of targets in an Excel Spreadsheet to model a two-ship convergence to provide dynamics to the targets

Alternative	Description	Comment on applicability for this analysis
Excel	Most basic ability to create data files and perform basic computations; can perform basic Monte Carlo runs	Useful to create most basic illustrative timelines, ship movements and events; not suitable for parameterized simulation
SimPy	Python-based Discrete Event Simulation	DES capability, but code-level creation
Matlab Simulink	Graphical Discrete event simulation	Graphical build – most sophisticated
ExtendSim	Graphical Discrete event simulation	Graphical build – continuous DES; Monte Carlo Able to represent network and ISTR process
Simio	Graphical Discrete event simulation	Graphical Build; Excellent for network flows; high end tool with complex extensions
AnyLogic	Graphical Discrete event, System Dynamics, Agent-based simulation	Like ExtendSim with agent-building capability
OPNET; NS-3	Simulate TCP/IP network traffic in a DES	Network sim only – high fidelity TCP/IP model may be too detailed for message passing relays
MAST 2.0 (NSWC Dahlgren)	Naval combat scenario generator with agent-based behavior capability	Capable of moving naval assets but mot model the IRSRT Process; useful in advanced simulation with more complex maneuvers

Table 10.3-1 Modeling tool options considered

Note that we also downloaded and evaluated the MAST 2.0 simulation provided by NAVSURWEPCEN Dahlgren as a candidate for more complex scenario generation, but its use was considered beyond the scope of this project.

The functional flow of the modeling approach (Figure 10.3-3) moved from target to sensor (the observation event) through a series of link nodes (Relay events) to the fusion process, the command and control (C2) events and then to the engagement event (Cooperative Engagement Capability). Each discrete event was represented by a statistical latency distribution and the flow of events across the network could be observed.

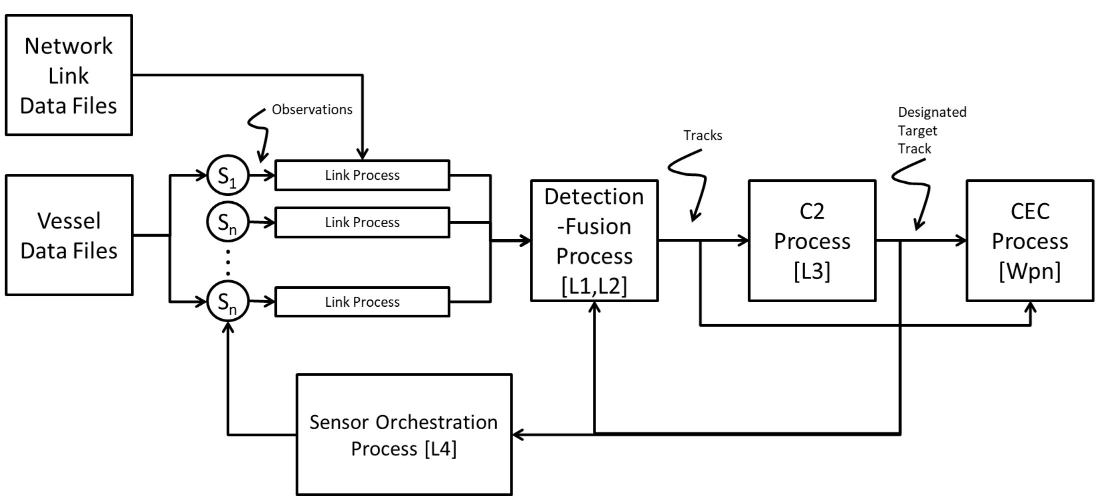


Figure 10.3-2 The functional concept to be modeled

The translation of objects to DES model elements is provided in Figure 10.3-3 to complement the function flow in figure 10.3-2.

Model Objects	Model Element Description	NRP Simulation
Entity objects	Entities are smart objects that behave based on user-specified characteristics or state assignments. Entities are generated by sources, routed along paths, serviced by servers, and destroyed by sinks throughout the network model.	Messages (signals, pixels, acoustics, sensor-detects, fusion-tracks, C2-fires)
Source Object	Source objects create model entities and insert them into the network. A designated inter-arrival time distribution controls the rate at which the entities are produced.	Targets (emit entities-signals, pixels, acoustics)
Path objects	objects that are primarily used to transport entities between locations when the standard flow between nodes is not appropriate. They retain information and adhere to user-inputted process logic.	Links
Server Objects	Entities enter a server to undergo a process with a designated service time distribution. Servers may have limited or infinite capacity to process entities simultaneously. After receiving service, entities wait in an output queue to be routed to the next destination	Sensor Satellite nodes Relay satellite nodes
Transfer Nodes, Splits	Denoted by the blue diamonds, the transfer nodes are implemented in the network for design simplification purposes. These nodes contain user-inputted processing capabilities to route the flow of entities across the network. Rather than linking every node together and filling the network with superfluous arcs, transfer nodes help reduce the complexity of the network.	Transfer links
Sink Objects	Sinks destroy entities and record statistics about them as they exit the system. When an entity enters a sink object, it is exiting the network.	Weapon to target and target exits the simulation

Table 10.3-2 Translation of the Seabed-to-Space network to model elements

The SIMIO model was implemented for a basic network (Figures 10.3-3 and 10.3-4) and elements of scenario SW-1 were modeled with statistical latencies from the target, though sensors, to the fusion nodes.

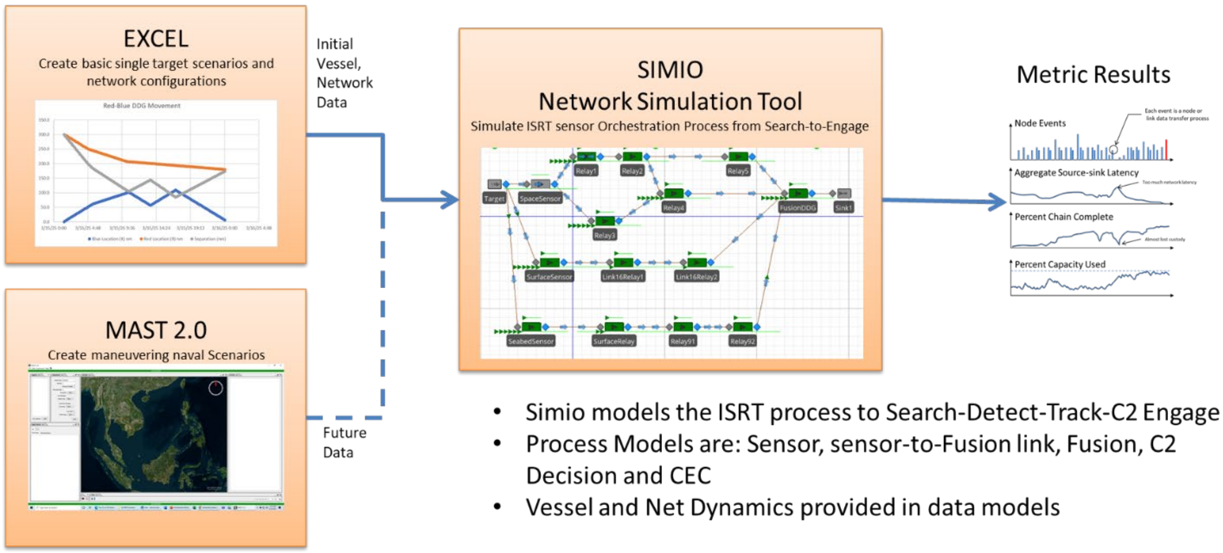


Figure 10.3-3 Simio Modeling concept from scenario data to Metric results

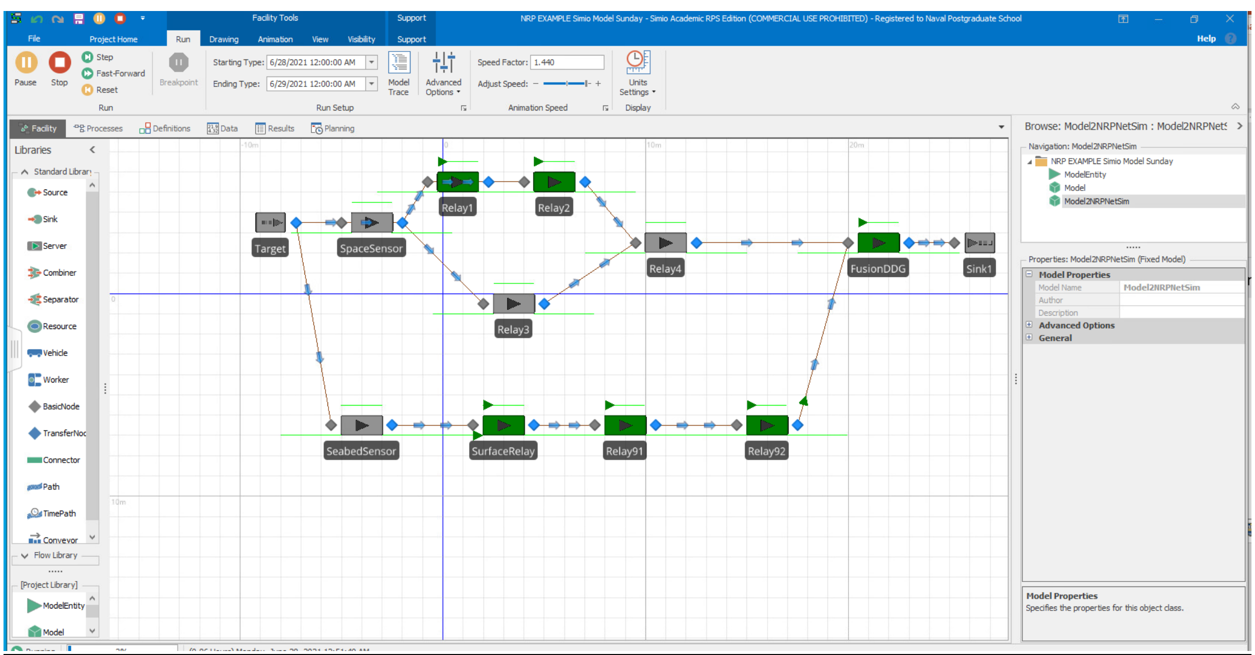


Figure 10.3-4 Simio basic model from target (left) through relays (center) to Fusion (right)

The model successfully represented the different latencies across the network, and collected metrics, such as the Instantaneous messages at any time across the network (a measure of demand for capacity) as shown in Figure 10.3-5. Several runs were conducted to evaluate both the usefulness of the modeling approach and the value of the metrics available in the tool.

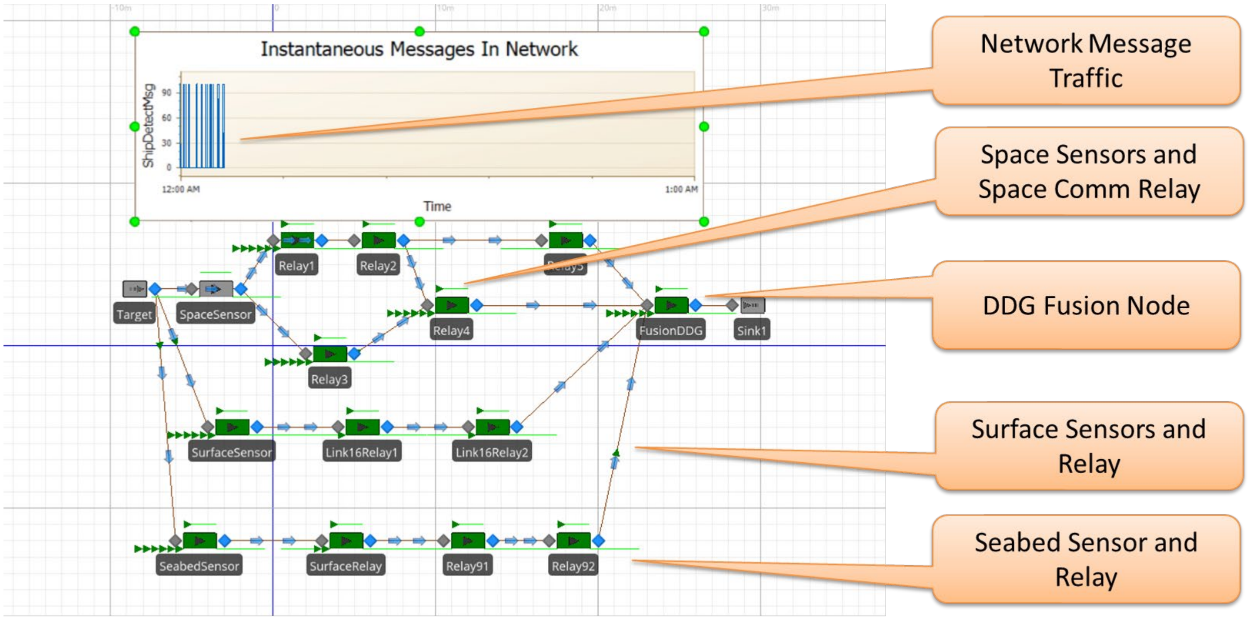


Figure 10.3-5 Example Simio run evaluating net instantaneous traffic

There were, however, several limitations to this modeling approach that resulting in proceeding to a more direct model. Table 10.3-3 summarizes the benefits and limitations of this DES approach.

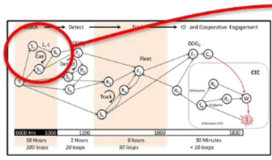
Benefits	Limitations
• Allows statistical distributions of latency to be represented • Allows rapid model construction and testing	• Does not easily allow dynamic scenario input to represent moving sensors (satellite platforms) and moving targets (ships) • Standard measures in the tool do not represent the metrics desired for network modeling

The limitations of this DES approach caused us to move to the next more direct modeling approach described in the next section.

Model B: Network Transaction Model

This approach implemented an Excel spreadsheet model of the explicit transactions required to conduct the SW-I scenario, allowing calculations directly in Excel and in Analysts Notebook (ANB) to measure the network transactions. The activities over the 24-hour period were manually translated into the spreadsheet (Figure 10.3-3 illustrates the first 3 hours of the 24-hour scenario) where events (target detects, relay messages, fusion actions) are recorded in actual event times.

Explicitly represent the Network Transactions



- Represent Key Orchestration Parameters:
  - Sensor detections (Cues)
  - Response to Next Sensor Actions
    - Task: Search, ID, Track
  - Latency from A to B

The first 3 hours

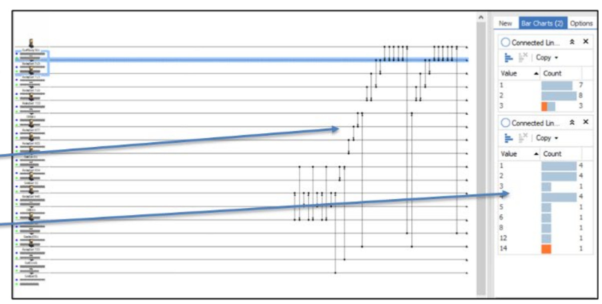
	A	B	C	D
1	Time	FROM	TO	Event
2	0:55	Seabed 301	SurfBuoy 301	Detect 1 High-Priority
3	1:00	SurfBuoy 301	RelaySat 712	
4	1:01	SurfBuoy 301	RelaySat 712	
5	1:02	SurfBuoy 301	RelaySat 712	
6	1:03	SurfBuoy 301	RelaySat 712	
7	1:04	SurfBuoy 301	RelaySat 712	
8	1:05	RelaySat 712	RelaySat 713	
9	1:05	RelaySat 712	RelaySat 710	
10	1:05	RelaySat 713	RelaySat 722	
11	1:05	RelaySat 710	RelaySat 722	
12	1:06	RelaySat 722	DDG01	
13	1:15	Seabed 301	SurfBuoy 301	Detect 2 High Priority
14	1:19	SurfBuoy 301	RelaySat 712	
15	1:20	SurfBuoy 301	RelaySat 712	
16	1:21	SurfBuoy 301	RelaySat 712	
17	1:22	SurfBuoy 301	RelaySat 712	
18	1:23	SurfBuoy 301	RelaySat 712	
19	1:24	RelaySat 712	RelaySat 713	
20	1:25	RelaySat 712	RelaySat 710	
21	1:26	RelaySat 713	RelaySat 722	
22	1:27	RelaySat 710	RelaySat 722	
23	1:28	RelaySat 722	DDG01	
24	1:40	DDG01	RelaySat 977	DDG Request Search
25	1:41	RelaySat 977	RelaySat 955	
26	1:51	RelaySat 955	SatCon 01	
27	1:52	SatCon01	RelaySat 954	Begin Search
28	2:02	RelaySat 954	SARSat 55	SARSAT 55 Search Pass
29	2:12	SARSat55	RelaySat 946	SARSAT 55 Relay Detects
30	2:22	RelaySat 946	DDG 01	SARSAT 55 Report Detects
31	2:32	RelaySat 954	SARSat 66	SARSAT 66 Search Pass
32	2:42	SARSat 66	RelaySat 946	SARSAT 66 Relay Detects
33	2:52	RelaySat 946	DDG 01	SARSAT 66 Report Detects

Seabed Tip (rows 2–23); Track Cue (rows 24–26); Sat Search (rows 28–33)

Figure 10.3-3 Example translation of Scenario to Spreadsheet for Analysis

The next step in the analysis was to import the spreadsheet into IBM ANB to perform a transaction analysis (Figure 10.3-4) and measure the number, rates and types of transactions and compare the load of sensor, network, and fusion events.

- Enables analysis of required network and transactions:
  - Entities
    - Sensors, Relays, Fusion Nodes, Weapons
  - Transactions
  - Overall transaction Analysis
  - We can also display the effective network represented across all transactions for the detect-to-engage lifecycle



The first 3 hours

Figure 10.3-4 -Analysis in the Analyst Notebook Transaction Model

The data from a set of SW-1 is provided in Appendix C. The model included 54 unique entities and the modest 64 links (and many more transactions). We observed:

1. A more complex model with one-minute increments would improve the model fidelity and allow for more realistic simultaneous relays from all three satellite sensors through the relay net.
2. Most relays were only 1-hop due the relatively close nature of the vessels and the ground station (on the DDG).
3. Even this example that shows the benefits of rapid revisits by sensors to establish target track in non-dense maritime environment presumed.
4. The transaction complexity is not at all infeasible compared to the complexity of transactions maintained by the existing Starlink Systems.

11. Research Findings

This evaluation focused on the most critical requirements for the satellite network use to accomplish the most stressful long-range cooperative engagement case. We established a set of critical “Admiral’s Questions” that will be posed to any briefer presenting the consideration of this complex operation:

- Q1 - Can the Satellite Constellation provide required performance in three areas: 1)–Relay latency to deliver sensor data in time? 2) Availability at critical times of engagement? and 3) Sensing revisit to support persistent detect, ID, track, engage?
- Q2 – What would a realistic, stressful scenario look like? SW-1 looks very complex! Is it feasible? What is the next research step to assure feasibility?
- Q3 - Can the dynamic network sustain ISRT start-to-finish? What are the operating parameters? What are the marginal areas? How do we increase the margins?

The results of this study have shown, at the depth of analysis performed:

- Conceptual coordination of Seabed-to-Space sensors via the planned DoD Low Earth Orbit space constellation relay is feasible and will enable DMO over-the-horizon operations for the stressful surface warfare scenario.
- Orchestration of the diverse sensors from seabed tip-off to space sensing and UAS-UAV support to perform coordinated fires is complex but feasible when space relay constellations demonstrate high availability.
- A constellation like the planned DoD SDA constellation as modelled, or larger, will provide coverage to enable distributed search, detect, and track but may require local UAV and USV support for terminal engagement.
- The network transaction process is complex but feasible; redundancy exists in sensors and in the network
- We can address the Admiral’s questions with supporting first-order data
- The next required step is the simulation of scenarios like SW-1 over a range of conditions to measure statistical performance.

We found that the complexity of space-based sensing and relay is high, but feasible as demonstrated by our model– *and the payoff for the Navy is high*. During this study Rear Adm. James Aiken supported this very concept when describing a recent Navy experiment: “We teamed manned and unmanned vessels together. We also used the fusing capability … It was totally passive where we didn’t have active sensors on target… *We also look for space as well to actually identify the target* and then once we found the target, we were able to track it because of the [electromagnetic signal] that was coming off the target, develop lines of bearing, then launched the missile.” [[22]]

[22] SOURCE: Sam LaGrone, Unmanned Systems, Passive Sensors Help USS John Finn Bullseye Target With SM-6, U.S. Naval Institute, April 26, 2021, 7:22 PM, https://news.usni.org/2021/04/26/unmanned-systems-passive-sensors-help-uss-john-finn-bullseye-target-with-sm-6

APPENDICES

APPENDIX A: Seabed-to-Space Analysis and Network Model Description

Version 1 - 20210319

The Seabed-to-Space (S-to-S) Network Model (SSNM) supports the FY 21 Naval Research Project that has the following Goal, Objectives, and Research Challenges.

1. NRP PPROJECT "All-Domain Sensor Network Orchestration from Seabed-to-Space"

Project Goal: 1) Determine the feasibility, and 2). measure the performance of a wide-area distributed and networked sensing system to support Distributed Maritime Operations (DMO) by orchestrating ISRT assets that range from seabed-to-space (S-to-S).

Project Objective: This research will define the wide range of practical MultiINT collection options against maritime targets and identify the feasible methods to quantify an objective value function and orchestrate such a wide range of sensing systems against dynamic and fleeting maritime targets.

Research Challenges

1. Understand 2025-2030 Naval Digital Networks - Describe the full range of U.S. Navy digital communication networks (current and planned) and their properties, applications, and technical characteristics. These links connect sensors and command control (C2) between platforms with sensors on the seabed, on subsurface submarines, on unmanned undersea vehicles (UUV's), on the surface, in the air (manned and unmanned), and satellite constellations in space.
2. Model a Future S-to-S Network – Model and quantify the performance of an S-to-S network that senses, routes data, applies data fusion, and distributes information to support DMO in stressful scenarios. In particular, the model should include the ability to actively and dynamically orchestrate S-to-S sensors to optimize collection to support ISRT (Intelligence Preparation of the Maritime Environment, Surveillance, Reconnaissance, Targeting) as threats change. The Model elements should include:
    a. S-to-S Sensors – and the contribution of each sensor and sensing modality
    b. Data Networks – the availability of sensor information across a network and the ability to orchestrate sensing collection against a threat
    c. Fusion Nodes – the network structure to combine data, to identify information needs, and orchestrate dynamic collection (to point sensors and guide collection priority, focus, cueing, and intensity) as conditions change.
    d. Closed-Loop Operation – the necessary ISRT dynamics to support DMO
3. Describe the Operation and Performance of S-to-S ISR – Using the model to represent the performance of such a network in relevant DMO scenarios, describe the feasibility and identify any fundamental limits of S-to-S ISRT to support DMO.

2. Analytic Considerations

2.1. Levels of Analysis

Consider three levels of analysis that may be applied to the S-to-S network and the questions they may answer.

<table>
<tr><th>Level</th><th>Questions</th><th>Analysis</th></tr>
<tr><td>Level 1 – Manual analysis (mental simulations and back of envelope)</td><td>How far apart can nodes be spatially distributed before the ensemble loses surveillance and fire control effectiveness?
How dependent is the spatial distribution dependent on range of sensor nodes?
How dependent is the distribution on link connectivity? On satellite transport layer connectivity?</td><td>TOOL: Spreadsheet
Compute basic range equations for sensor ranges, link ranges, and fire control effectiveness.</td></tr>
<tr><td>Level 2 – Static Computer Network Model</td><td>Map conceptual DMO scenario to a static network model of sensing, linking, fusion, and action (fire control, maneuver) nodes:
How do data flows influence capacity and performance?
How do path dependencies influence performance?
How do real-network delays and path properties (capacity) affect performance?</td><td>TOOL: Basic Graph model (e.g. NS2/ NS3, OPNET. NetSim; simple target models)
Build and measure latency, capacity in network topology model with node, link properties</td></tr>
<tr><td>Level 3 – Dynamic computer Model (Simulation)</td><td>Map network in a full 3D plus time dynamic simulation with:
Moving DMO over 24 hours
Able to vary DMO Fleet spatial distribution.
Full network (Sensing, nodes, weapons)
Able to simulate different scenarios, repeat mover a wide range of parameters and find fundamental limits
All questions in Level 1 and 2 plus the effect of SDA transport layer and its limitations.
BUT FIRST, must do Level 1 to understand what the simulation will produce.</td><td>TOOL: AFSIM

Parameterize AFSIM for a DMO Scenario to measure network performance and its effectiveness to provide ISRT as a function of spatial dispersion, threat speed, Network connectivity (with-without transport layer) and sensing.</td></tr>
</table>

2.2. The Role of any Computer Modeling (Level 2 and 3)

The role of computation models in this effort are twofold:

1. To support quantitative analysis of complicated (or complex) network operations that involve many nodes, or links, or both.
2. To enable example scenarios or use cases to be conducted to emulate and demonstrate how the network would operate. This can be useful to explain the normal operation, special cases, or fundamental limits of the networking concept.

Seabed-to-Space (S-to-S) Network Model (SSNM) Requirements

2.3. Model Level – SSNM is a high-level model to assess feasibility (yes-no); operational-level performance (operational metrics), and fundamental limits (or envelope) of operations.

2.4. Model Scope – The model must represent the DMO and ISRT characteristics in the following table.

	Parameter	Values
DMO Scenario	Scenario Sea area	500,000 sq. mi. [23]; Surface to-seafloor blue-water depth 5,000 ft. with a littoral (shallow water area) [24]
	Blue DMO Deployed Maritime Force	DMO Force Distribution 62,500 Sq Miles (250 x250 mi area) DMO Force: Maritime 1 carrier strike Group (1 carrier; 8 destroyers, 2 maritime patrol aircraft; 2 air surveillance aircraft; 10 deployed Seabed Sensors, 10 UUVs; 2 attack submarines;
	Red Deployed Land-Maritime Force (Threat targets to surveil-target)	Maritime: 1 carrier; 12 destroyers; 12 frigates; 12 corvettes; 12 landing craft ; 12 support and auxiliary ships Land: 10 air defense batteries; 4 Long range Anti-Ship batteries Air: 45 combat aircraft; 2 Air Surveillance; 3 Maritime Patrol UAV;

2.4.1. ISRT Sensor Nodes must be modelled to represent detectability of a target as a function of range only and representation of the target measurable properties (e.g., Identity as adversary target) also as a function of range.

2.4.2. Network Nodes and links must encompass the following S-to-S areas (Figure 1 and Table 1). Network and link nodes are modelled as delays and switches to provide latency and capacity limits.

2.4.3. Data fusion nodes are modeled to represent and report multiple sensor detection, ID and tracking when fusion criteria are met. This the most complex node to be modeled, and should provide lookup tables to represent:

2.4.3.1. Correlation-Association model to assign cross-detection associations.

2.4.3.2. Combination model to provide assured identification by lookup table for multiple identities across sensors.

2.4.3.3. Tracking model to provide track quality when sufficient sample update rate is provided by sensors

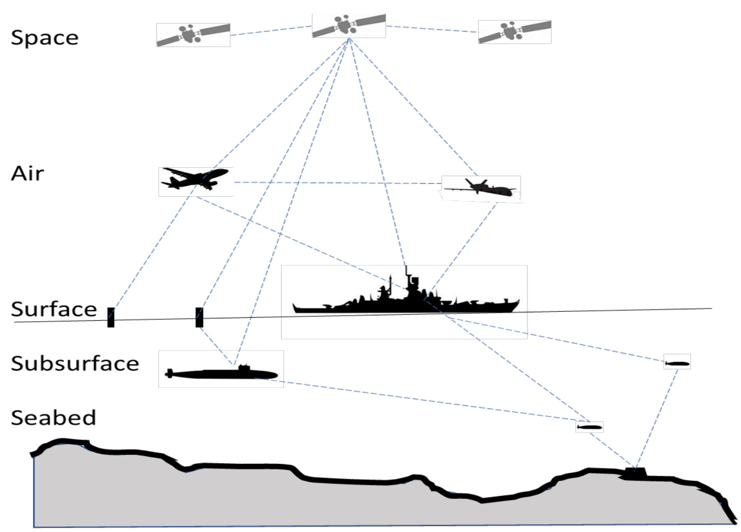


Figure 1 – S-to-S sensor platforms and Data Links for Sensor Data and Sensor Commands

[23] For reference, the South China Sea is a marginal sea that is part of the Pacific Ocean, encompassing an area from the Karimata and Malacca straits to the Strait of Taiwan of around 3,500,000 square kilometers (1,400,000 sq mi).

[24] For reference, the China Sea Basin, has a maximum depth of 5,016 m.

Platform	Sensors (Detect and ID in-range)	Targets	Comments
Seabed	Acoustic active passive	Ships, Subs, UUV	
Surface Autonomous	Acoustic, environmental, EO, RF signals	Ships, Subs, UUV, ASV, UAV	Ocean of things, Wave Gliders
UUV	Acoustic active-passive, IR	Subs, seabed activity	
Submarine	Subsurface Acoustic array	Subs, seabed activity	
Surface Ship	Towed and hull-mount Subsurface Acoustic array	Subs, UUV, seabed activity	
	Air track (Radar, IR)	Air (Manned, UAV)	
Air Patrol	Air track (Radar, IR)	Air (Manned, UAV)	P-8
	Surface track (Radar, ISAR)	Surface ships	P-8
	Sonobuoy acoustic arrays	Submarines	P-8
Space Constellation	EO imagery	Ports, ships-at-sea	Future 2025 constellation
	SAR imagery	Ports, ships-at-sea	

Table 1 – 2025-2030 Sensors and Sensor Platforms

2.4.4. The model may map the three-dimensional DMO scenario to a two-dimensional graph (network) model

2.4.5. The model does not require a time-dynamic simulation but may be performed as a sequence of static cases (ISRT Detection, ISRT Tracking, ISRT Fire Control).

2.5. Model Metrics -The primary metrics required to measure feasibility and performance of the network are provided in the Table below.

Metric	Description	Use
Latency	1. Transmission latency -The time it takes for a data message (e.g., Target Detection) to travel from one designated node in a network to another node. 2. Node Latency - The time it takes to process a single multiple data messages to produce a result to be sent forward on a network	Ability to sense, locate, report to ISR and Targeting
Capacity	Network capacity is the amount of traffic that a network can handle at any given time.	Ability to get data to user nodes
Update rate	The rate at which updates are produced on a target state or a dynamic target track	Ability to warn, ability to target
Detection Rate	Percent targets detected	Situation Awareness
Targeting Rate	Percent Targets targeted	Effectiveness

Table 2 Model Metrics (Preliminary)

2.6. Key Results– To meet the objectives and experimental questions, the model must produce the following categories of results in an appropriate graphical, quantitative forms:

2.6.1. Latency to get sensor data to fusion nodes

2.6.2. Latency for fusion nodes to derive and report target or swarm information for awareness and for targeting

2.6.3. Capacity required over the network

2.6.4. Update rate for individual target to allow tracking, targeting

2.6.5. Percent targets detected; percent targets targeted

3. Seabed-to-Space (S-to-S) Experiment Plan

The SSNM will used to perform model (or simulation) experiments to evaluate feasibility of a network of sensors and fusion nodes to achieve sufficient situation awareness (Intelligence Preparation), Surveillance and Targeting to achieve effective DMO. The experiment Plan will include the following elements:

3.1. Experiment Objective – Feasibility and Performance; and fundamental limits of operation
3.2. Research Hypothesis – That a sensor network, within fundamental limits, can provide sufficient ISRT to effectively perform DMO.
3.3. Metrics – Network Latency, Capacity, Update Rate at weapon nodes.
3.4. Scenarios
3.4.1. Adversaries flood the maritime area [air-surface-submarine-seabed mining]
3.4.1.1. Subset: air-surface
3.4.1.2. Subset: Submarine- seabed mining
3.4.2. Adversary Undersea Attack
3.4.3. Adversary Land Anti-Ship Surface Missile attack [Not included]

4. References

1. *Navy Maritime Domain Awareness Concept*, U.S. Navy Chief of Naval Operations, May 2009.
2. *A Design for Maintaining Maritime Superiority*, Version 2.0, U.S. Navy, December 2018, p.6.
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14. Frans Osinga, *Science, Strategy and War: The Strategic Theory of John Boyd*, Netherlands: Eburon Academic Publishers, 2005.

APPENDIX B: Undersea Warfare View of Undersea Distributed Networked Systems

The concept of undersea systems (Submarines, unmanned undersea vehicles (UUV's), and seabed sensor and weapons (mines) being networked has been examined by NAVSEA. The impact is significant if this capability were available. Plausible tactical and system paradigm shifts enabled by undersea distributed networked systems (DNS) relative to the traditional undersea Warfare (USW) capability of 2017 is described in the table below. The key to understanding Undersea Distributed Network Systems (UDNS) is the notion that system functions (for example, sensing, transporting, and networking) that must be performed in the battlespace can be decoupled from the large platform functions of today. While platforms are an important part of the overall system, the focus turns to marshaling functional effects from several subsystems that have sufficient spatial separation integral to the functionality.

Table B-1 Distributed networked systems (DNS) Paradigm Shift

DNS Function	From	To
Sensing	• Surveillance dominated by uncertainty • Target search • Intermittent observations	• Surveillance based on information conditions • Focus on target actions • More continuous observations
Transport	• Single transport mechanism w/coupled speed, endurance, payload tradeoff • Deliver cargo perspective • Organic cargo delivery	• Distributed transport mechanism w/decoupled speed, endurance, payload • Cargo that is auto-locomotive • Parasitic transport mechanisms/means
Networking	• Few major nodes • Discrete path communications and direct connections • Only active-element communicator	• Distributed server and agent nodes • Multiple router alternatives and indirect connections • Include passive-element responder
Information Fusing & Pattern Recognition	• Episodic and inferred information • Discrete source composed information • Display of data	• More continuous "actual" information • Contextually derived information • Display of information
Interpretation, Cognition & Decision	• Isolated decision making • Few centralized decision making teams • Detailed Command directed decision and actions	• Collaborative, multi-level decision making • Large numbers of distributed decision making • Self-synchronization
Influence	• Attrition/destruction based influence • Small numbers of major offensive options	• Effects/deterrence/disruption based warfare and asymmetric means • Greater number of distributed offensive options

Source: Raymond J. Christian [Office of the Director of Undersea Warfare], *Next-Generation Undersea Warfare and Undersea Distributed Networked Systems,* NASVEA Naval Undersea Warfare Center, NUWC-NPT Technical Report 11,790, 31 January 2007.

APPENDIX C – Scenario SW-1 Data Set Example

The SW-1 surface Warfare model was developed in an Excel spreadsheet model (Table C-1) that represented events in 10-minute increments over a 24-hour period. The overhead access times for the SAR and EO satellites in our earlier baseline STK simulations were used (Red SAR and Blue EO) and the Hawkeyes 360 commercial RF intercept systems (Green; the full 7-cluster constellation revisit rate is modelled) was also included to observe periodic emissions. Relays to the Transport layer are recorded with the transactions between sensing satellites and two DDG vessels.

The model includes a hostile vessel that closes on DDG 02 and is engaged by that vessel over the horizon at approximately 185 nm.

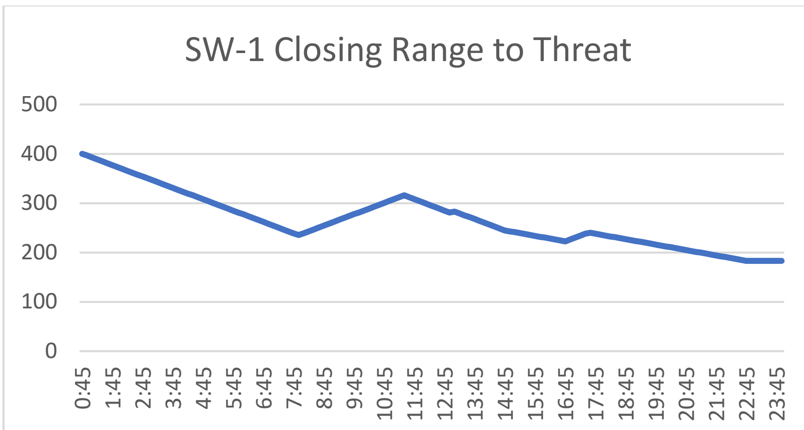

Figure C-1 Closing range between threat vessel and DDG 01 Thant engages over the Horizon

The network relays were analyzed in Analyst Notebook (IBM ANB) to view and measure the complexity of transactions as a network of communicators (Figure C-2) and as a chronology of transactions (Figure C-3) where each horizontal line is a unique entity (sensing satellite, relay satellite, seabed sensor, relay, UAV, DDG). These charts enabled an analysis of the 54 unique entities and the modest 64 links (and many more transactions) in this model. We observed:

1. A more complex model with one-minute increments would improve the model fidelity and allow for more realistic simultaneous relays from all three satellite sensors through the relay net.
2. Most relays were only 1-hop due the relatively close nature of the vessels and the ground station (on the DDG).
3. Even this example that shows the benefits of rapid revisits by sensors to establish target track in non-dense maritime environment presumed.
4. The transaction complexity is not at all infeasible compared to the complexity of transactions maintained by the existing Starlink Systems.

Table C-1 SW-1 Spreadsheet

This is a 24 hour model of the SW-1 scenario in 10-minute increments. The red, blue, green bars represent SAR, EO, and H360 Accesses the target areas.

Time	FROM	TO	Day/Nt	SAR	EO	RF	Range	Phase	Event
0:45	Target Ship 1	Seabed 301					400		Detect 1 High-Priority at Sea
0:55	Seabed 301	SurfBuoy 301					396.2		
1:05	SurfBuoy 301	RelaySat 712		11			392.3	Det	
1:15	SurfBuoy 301	RelaySat 712					388.5	Relay	
1:25	RelaySat 712	DDG01					384.7		DDG01 Receive Detect
1:35	SurfBuoy 301	RelaySat 712					380.8		
1:45	SurfBuoy 301	RelaySat 712					377.0		
1:55	RelaySat 712	RelaySat 713		22			373.2		
2:05	RelaySat 722	DDG01					369.3		DDG01 Receive Detect
2:15	Target Ship 2	Seabed 301					365.5		Detect 2 High Priority
2:25	Seabed 301	SurfBuoy 301					361.7		
2:35	SurfBuoy 301	RelaySat 712					357.8		
2:45	SurfBuoy 301	RelaySat 712					354.0		
2:55	SurfBuoy 301	RelaySat 712		33			350.2		
3:05	SurfBuoy 301	RelaySat 712					346.3		
3:15	RelaySat 722	DDG01					342.5		
3:25	DDG01	RelaySat 977					338.7		DDG Request Search
3:35	RelaySat 977	SARSat 44					334.8		Begin SA earch
3:45	RelaySat 977	RelaySat 899					331.0		
3:55	RelaySat 899	RelaySat 855		44			327.2		
4:05	SARSat 44	RelaySat 988					323.3		SARSAT 44 Search Pass 1
4:15	RelaySat 988	DDG 01					319.5		SARSAT 44 Relay Detects
4:25	RelaySat 977	RelaySat 899					315.7		
4:35	RelaySat 899	RelaySat 855					311.8	SEARCH	
4:45	SARSat 55	RelaySat 988		55			308.0	Resolve	SARSAT 55 Search Pass 2
4:55	RelaySat 988	DDG 01					304.2	ID	SARSAT 55 Report Detects
5:05	RelaySat 988	RelaySat 899					300.3		
5:15	RelaySat 899	RelaySat 855					296.5		
5:25	RelaySat 899	RelaySat 845					292.7		
5:35	SARSat66	RelaySat 988		66			288.8		SARSAT 66 Search Track
5:45	RelaySat 988	DDG 01					285.0		SARSAT 66 Report Track
5:55	RelaySat 988	RelaySat 899					281.2		
6:05	RelaySat 899	RelaySat 855					277.3		DDG 02 Track
6:15	RelaySat 899	RelaySat 845					273.5		
6:25	SARSat 77	RelaySat 988		77			269.7		SARSAT 77 Track Update
6:35	RelaySat 988	DDG 01					265.8		SARSAT 77 Report Track
6:45	RelaySat 899	RelaySat 855					262.0		
6:55	DDG 01	RelaySat 855					258.2		DG Request EO CUE- handoff
7:05	RelaySat 855	EOSat 111			111		254.3		EO search in CUE area
7:15	RelaySat 899	RelaySat 855		88			250.5		
7:25	H360 Cluster 2	RelySat 900				C4	246.7	EO	
7:35	RelaySat 900	DDG 01			110		242.8	Reacq	EO search in CUE area - DETECT; ID
7:45	EOSat 110	RelaySat 900					239.0		
7:55	RelaySat 900	DDG 01					235.2		Report Detect
8:05	RelaySat 900	RelaySat 899			120		239.0		EO search ReDETECT start track
8:15	RelaySat 899	RelaySat 855		99			242.8		
8:25	RelaySat 899	RelaySat 845					246.7		
8:35	EOSat 130	RelaySat 900			130		250.5		EO Track
8:45	RelaySat 900	DDG 01					254.3		EO Report Track
8:55	RelaySat 900	RelaySat 855					258.2		
9:05	DDG 01	RelaySat 855		12	140		262.0		
9:15	RelaySat 855	EOSat 111					265.8		
9:25	RelaySat 899	RelaySat 855					269.7		
9:35	EOSat 150	RelaySat 900			150		273.5		EO Track
9:45	RelaySat 900	DDG 01					277.3		EO Report Track
9:55	RelaySat 900	RelaySat 899					281.2		
10:05	RelaySat 899	RelaySat 855		13	210		285.0	Track	
10:15	RelaySat 899	RelaySat 845					288.8		
10:25	RelaySat 899	RelaySat 855					292.7		
10:35	EOSat 220	RelaySat 900			220		296.5		EO Track
10:45	RelaySat 900	DDG 01					300.3		EO Report Track
10:55	RelaySat 900	RelaySat 855					304.2		
11:05	SARSat 14	RelaySat 944		14	230		308.0		
11:15	RelaySat 944	DDG 01					311.8		
11:25	RelaySat 900	RelaySat 899					315.7		
11:35	RelaySat 899	RelaySat 855			240		311.8		
11:45	RelaySat 899	RelaySat 845					308.0		
11:55	RelaySat 899	RelaySat 855		15			304.2		
12:05	EOSat 250	RelaySat 900			250		300.3		EO Track
12:15	RelaySat 900	DDG 01					296.5		EO Report Track
12:25	RelaySat 899	RelaySat 855					292.7		
12:35	RelaySat 899	RelaySat 845			260		288.8		
12:45	SARSat 15	RelaySat 944		15			285.0		
12:55	RelaySat 944	DDG 01					281.2		
13:05	EOSat 265	RelaySat 900			265		283.0		EO Track
13:15	RelaySat 900	DDG 01					279.2		EO Report Track
13:25	RelaySat 944	RelaySat 899					275.3		
13:35	SARSat 17	RelaySat 944		17	270		271.5		
13:45	RelaySat 944	DDG 01					267.7		
13:55	RelaySat 944	RelaySat 899					263.8		
14:05	RelaySat 899	RelaySat 855			280		260.0		
14:15	RelaySat 899	RelaySat 845					256.2		
14:25	RelaySat 899	RelaySat 855		18			252.3		
14:35	EOSat 290	RelaySat 900			290		248.5		EO Track
14:45	RelaySat 900	DDG 01					244.7		EO Report Track
14:55	RelaySat 899	RelaySat 855					242.8		
15:05	RelaySat 899	RelaySat 845			300		241.0		
15:15	RelaySat 900	RelaySat 855					239.2		
15:25	RelaySat 855	RelaySat 835		19			237.3		
15:35	EOSat 310	RelaySat 900			310		235.5		EO Track
15:45	RelaySat 900	DDG 01					233.7		EO Report Track
15:55	RelaySat 899	RelaySat 855					231.8		
16:05	RelaySat 899	RelaySat 835			320		230.0		
16:15	SARSat 20	RelaySat 944		20			228.2		
16:25	RelaySat 944	DDG 01					226.3		
16:35	EOSat 330	RelaySat 900			330		224.5		EO Track
16:45	RelaySat 900	DDG 01					222.7		EO Report Track
16:55	RelaySat 900	RelaySat 855					226.5		
17:05	RelaySat 855	RelaySat 835			340		230.3		Handoff DDG 01 to DDG02 For Fire Contro
17:15	SARsat 11	RelaySat 688		11			234.2		Handoff Track to SARSat 11
17:25	RelaySat 688	DDG02				C2	238.0		
17:35	H360 Cluster 4	RelaySat 688			350		239.8		
17:45	RelaySat 888	DDDG 02					238.0		Correlat RF andSARr Track
17:55	RelaySat 899	RelaySat 855					236.2		
18:05	RelaySat 899	RelaySat 845			360		234.3		
18:15	SARsat 22	RelaySat 788		22			232.5		SAR Custody
18:25	RelaySat	DDG02					230.7		
18:35	RelaySat788	RelaySat 855					228.8		
18:45	RelaySat 855	RelaySat 845					227.0		
18:55	RelaySat 900	RelaySat 855					225.2		
19:05	SARsat 33	RelaySat 788		33	370		223.3		SAR Custody
19:15	RelaySat	DDG02					221.5		
19:25	RelaySat788	RelaySat 855					219.7		
19:35	RelaySat 855	RelaySat 845			380		217.8		
19:45	RelaySat 900	RelaySat 855					216.0		
19:55	SARsat 44	RelaySat 788		44			214.2		SAR Custody
20:05	RelaySat	DDG02			390		212.3		
20:15	RelaySat788	RelaySat 855					210.5		UAV launched to provide wpn relay
20:25	RelaySat 855	RelaySat 845					208.7		
20:35	RelaySat 900	RelaySat 855			400		206.8		Target Range 206 Nm and Closing
20:45	H360 Cluster 4	RelaySat 788				C1	205.0		RF intercept correlated to SAR target
20:55	RelaySat 788	RelaySat 801					203.2		
21:05	RelaySat 801	DDG02			410		201.3		
21:15	RelaySat 801	FleetHQ					199.5		DDG assign UAV to relay at 50 miles
21:25	RelaySat 801	UAV					197.7		Establish Link with Relay UAV
21:35	SARSat 55	RelaySat 788		55	420		195.8		
21:45	RelaySat 788	DDG 02					194.0		Update Track;Confirm ID
21:55	FleetHQ	RelaySat 788					192.2		
22:05	RelaySat	DDG02			430		190.3		Engagement Approval
22:15	RelaySat 855	RelaySat 845					188.5		
22:25	SARSat 55	RelaySat 788		66			186.7		Final Location Fix
22:35	RelaySat 788	DDG 02			450		184.8	Flight	Weapon Release
22:45	RelaySat788	RelaySat 855					183.0	Time	Weapon Flight = 18.5 minutes (185mi)
22:55	RelaySat 855	RelaySat 845					183		
23:05	RelaySat 900	RelaySat 855			460		183		
23:15	RelaySat 855	RelaySat 835		77		C6	183		BDA Nor emissions
23:25	H360 Cluster 6	RelaySat 788					183		
23:35	RelaySat 788	DDG 02			470		183		
23:45	SARSat 77	RelaySat 788					183		BDA Imagery; Confirm Kill
23:55	RelaySat 788	DDG 02					183		

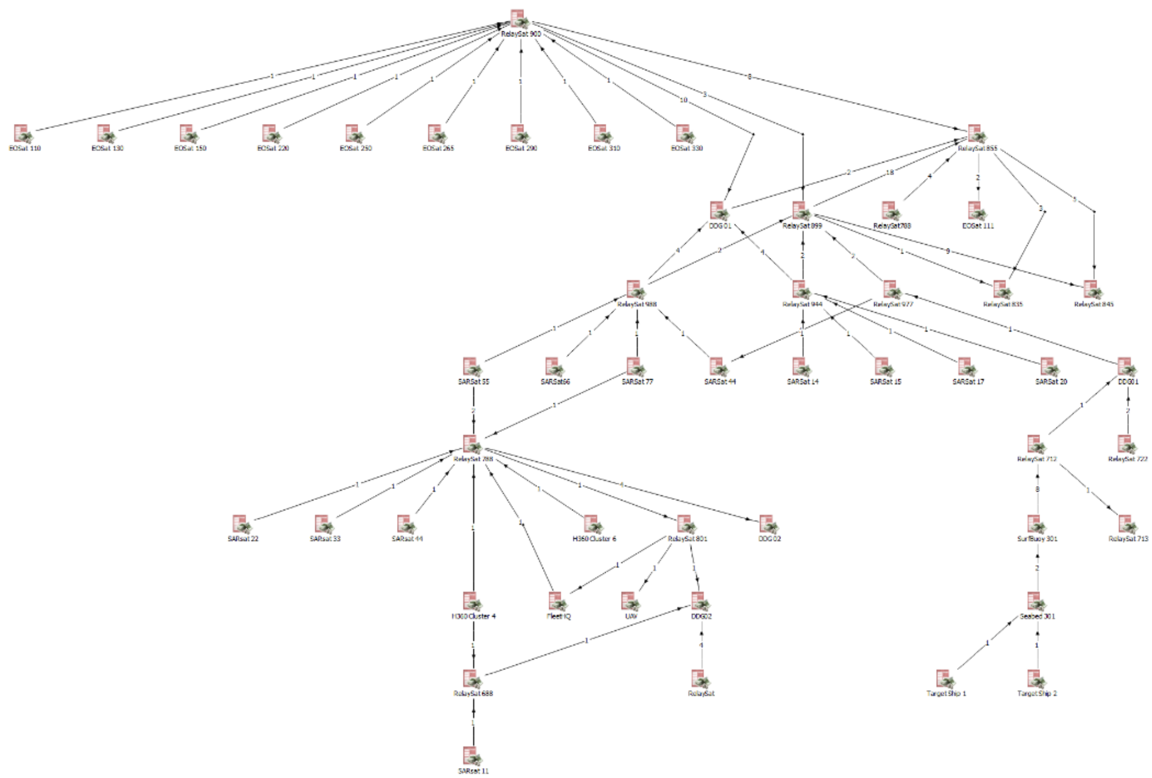

Figure C-2 Network Transaction View of the 24-hour scenario

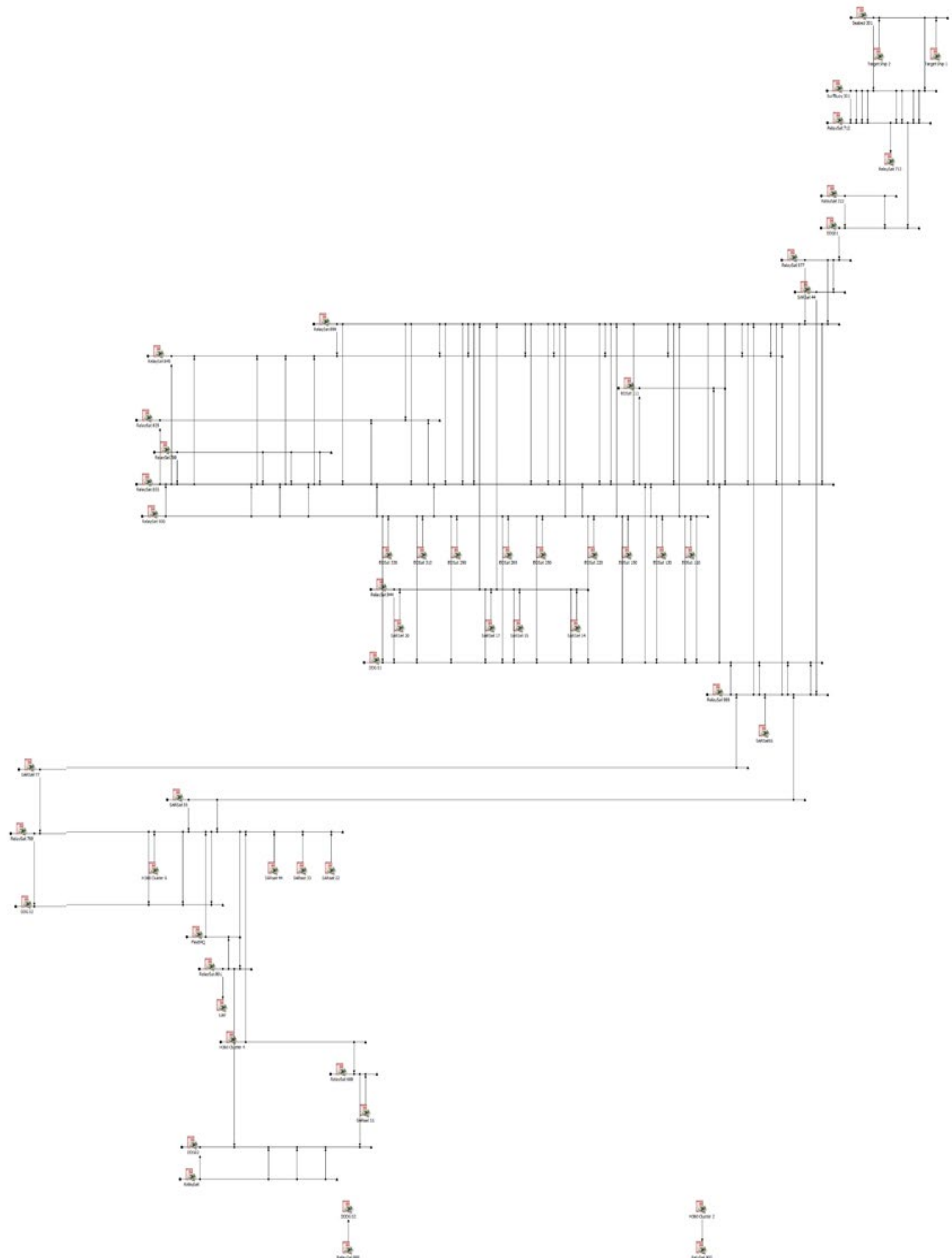

Figure C-2 Transaction Sequence view of the 24-hour scenario