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THESIS

**INFORMATION FLOW THROUGH JADC2
AND THE NAVY TACTICAL GRID IN AN AUSTERE
MARITIME ENVIRONMENT**

by

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June 2023

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**INFORMATION FLOW THROUGH JADC2 AND THE NAVY TACTICAL GRID
IN AN AUSTERE MARITIME ENVIRONMENT**

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ABSTRACT

As articulated by the National Defense Strategy (NDS) and National Security Strategies (NSS), potential adversaries have been developing sophisticated technological capabilities. Capabilities such as anti-area/area denial (A2/AD) pose a risk in the Department of Defense's (DOD) ability to win quick, decisive engagements. Senior DOD leadership has identified that ready access to data and information is critical in order to conduct multi-domain operations in future operating environments. Additionally, the current DOD C2 programs in service are not optimized to meet the speed and complexity of future conflict. With this identified capability gap and potential vulnerability, the DOD has initiated the Joint All Domain Command and Control (JADC2) program as an initiative across all services. As part of its role in the JADC2 concept, the United States Navy has initiated the Navy Tactical Grid project. The research described in this thesis examines how communication paths in the U.S. Navy carry knowledge and how the JADC2 concept can improve knowledge flow as well as address the expected discontinuous, delayed, or intermittent communications across naval and joint assets.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	Anti-Area/Area Denial
ADCON	Administrative Control
AOR	Area of Responsibility
BLOS	Beyond Line of Sight
C2	Command and Control
CCDR	Component Commander
CCMD	Combatant Command
CEC	Cooperative Engagement Capability
CG	Guided Missile Cruiser
CIC	Combat Information Center
CIEA	Classification, Identification, Engagement, Area
COP	Common Operational Picture
CSG	Carrier Strike Group
CTN	Composite Tracking Network
CVN	Aircraft Carrier
CWC	Composite Warfare Commander
DCA	Defense Counterair
DDG	Guided Missile Destroyer
DDIL	delayed, disconnected, intermittent, low bandwidth
DESRON	Destroyer Squadron
DoD	Department of Defense
EABO	Expeditionary Advance Base Operation
EHF	Extremely High Frequency
Ei	Information Effect
Ek	Knowledge Efficiency
EMCON	Emission Control
ESG	Expeditionary Strike Group
FDNF	Forward Deployed Naval Forces
FT	Flow Time
GCC	Geographic Combatant Command

HF	High Frequency
HQ	Headquarters
ID	Identification
INDOPACOM	Indo-Pacific Command
int	Intercept
ISAR	Inverse Synthetic-Aperture Radar
JADC2	Joint All Domain Command and Control
JFACC	Joint Force Air Component Commander
JFC	Joint Force Commander
JFLCC	Joint Force Land Component Commander
JFMCC	Joint Force Maritime Component Commander
JTF	Joint Task Force
KE	Knowledge Energy
KF	Knowledge Force
KFT	Knowledge Flow Theory
KP	Knowledge Power
KPi	Knowledge Power Input
KPo	Knowledge Power Output
KW	Knowledge Work
LOS	Line of Sight
MEU	Marine Expeditionary Unit
MOC	Maritime Operation Center
MT&E	Man, Train, & Equip
NDS	National Defense Strategy
nl	Nonlinearity
NSS	National Security Strategy
of	Organizational Factors
OPCON	Operational Control
OTC	Officer in Tactical Command
PACFLT	Pacific Fleet
pf	Personal Factors
PHIBRON	Amphibious Squadrons

PID	Positive Identification
PLAAF	People's Liberation Army Air Force
PLAN	People's Liberation Army Navy
RF	Radio Frequency
ROE	Rules of Engagement
SAG	Surface Action Group
SAGC	SAG Commander
SATCOM	Satellite Communications
SHF	Super High Frequency
sl	Slope
SUBRON	Submarine Squadron
SUWC	Surface Warfare Commander
TACON	Tactical Control
UHF	Ultra High Frequency
USMC	United States Marine Corp
USN	United States Navy
VHF	Very High Frequency

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I. INTRODUCTION

As articulated by the National Defense Strategy (NDS) and National Security Strategies (NSS), potential adversaries have been developing sophisticated technological capabilities. Capabilities such as anti-area/area denial (A2/AD) pose a risk in the Department of Defense's (DoD) ability to win quick, decisive engagements. Senior DoD leadership has identified that ready access to data and information is critical in order to conduct multi-domain operations in future operating environments. Additionally, the DoD command and control (C2) programs in-service are not optimized to meet the speed and complexity of future conflict. With this identified capability gap and potential vulnerability, the DoD has initiated the Joint All Domain Command and Control (JADC2) program as an initiative across all services. As part of its role in the JADC2 concept the United States Navy has initiated the Navy Tactical Grid project. The research described in this thesis examines how communication paths in the U.S. Navy carry knowledge and how the JADC2 concept can improve knowledge flow as well as address the expected discontinuous, delayed, or intermittent communications across naval and Joint assets.

A. PROBLEM STATEMENT

A Commander's ability to understand knowledge and information as it flows through the battlespace is crucial for effective Command and Control. One purpose of JADC2 is to ensure efficient channels are available for communication and data. However, there has been little research to evaluate the efficiency of explicit and tacit information flow in a maritime domain. Research is still needed to analyze this knowledge flow through varying levels of communication availability.

B. PURPOSE STATEMENT

The purpose of this research will be to conduct a comparative analysis of the current state of C2 knowledge flow in a maritime environment with the stated goals, objectives, and requirements of JADC2 using gap and knowledge flow analysis and observing synchronization conflicts. This research seeks to address the information and knowledge flow through existing C2 structures and compare those with expected JADC2 capabilities

in place to gain insight into C2 challenges faced by a future force and inform efforts in JADC2 development and further C2 research.

II. BACKGROUND AND LITERATURE REVIEW

A. U.S. MILITARY

The US Military comprises six services: Army, Navy, Marine Corps, Air Force, Space Force and Coast Guard. The armed services, except for the Coast Guard, fall within the Department of Defense under the direction and supervision of the Secretary of Defense. The military heads of each service compose the Joint Chief of Staffs with the Chairman of the Joint Chief of Staffs working directly with the Secretary of Defense and as a direct military advisor to the President. Furthermore, operational command (OPCON) of military forces falls under the joint Unified Combatant Commands (Joint Chiefs of Staff [JCS], 2020). While the Combatant Commands maintain OPCON of military forces allocated to them, the individual services still maintain administrative control (ADCON) of their forces (JCS, 2020). An important part of this ADCON is the mission of Man, Train, and Equip (MT&E), where each service has the mission to ensure their personnel and platforms are trained and equipped to meet their operational requirements (JCS, 2020).

1. Combatant Commands

Led by a 4-star General or Admiral, Combatant Commands (CCMD) serve as the primary operational commands for military forces reporting directly to the President and Secretary of Defense (JCS, 2020). Combatant Commands are separated into two types: Geographic Commands (GCCs) and Functional Commands (JCS, 2020). GCCs serve as the highest military command in a respective geographic region of the world. These areas of responsibility (AORs) are quite large and are composed of whole continents and oceans. These commands are primarily involved in the strategic and operational level of warfare and are a critical part of the DoD's C2 organization for major military operations (JCS, 2020). Functional Commands serve as the major operational commands for critical DoD-wide functions. Each Combatant Command is composed of Service components where each military service provides the combatant with the forces necessary for their operations (JCS, 2020).

Indo-Pacific Command (INDOPACOM): The primary GCC for this thesis. Responsible for operations spanning from the Indian subcontinent to the Western Pacific. Major areas of maritime interest in the region are China and Taiwan, the Korean Peninsula, and Russia's Pacific forces (Headquarters, United States Indo-Pacific Command [INDOPACOM], (n.d.).

2. U.S. Navy (USN)

The U.S. Navy is the United States maritime military service. As part of the DoD, the Navy operates with the other services to provide the forces and capabilities to the Combatant Commands. As this thesis focuses on maritime operations, analysis of the C2 organizations and operations will primarily involve naval forces. The Navy's operational C2 organization revolves around its Combatant Command Service components and major fleets. Furthermore, maritime tactical C2 organization revolves around the Strike Group and Surface Action Group (SAG) concepts.

a. Pacific Fleet (PACFLT)

INDOPACOM's Navy service component responsible for all operating naval forces in the Pacific and Indian Oceans. PACFLT consists of two major numbered fleets. 7th Fleet for the Western Pacific and 3rd Fleet for the Eastern Pacific. It is led by a 4-star Admiral.

b. Numbered Fleets (7th and 3rd)

Major operational-level commands for Pacific Naval Forces led by 3-star Vice Admirals. A numbered fleet is composed of a combination of Strike Groups and Surface Action Groups. 7th Fleet is responsible for the Indian Ocean and Western Pacific. This includes major areas of activity like the Taiwan Strait and South China Sea. Naval forces stationed here are known as Forward Deployed Naval Forces (FDNF). The 3rd fleet is responsible for the Eastern Pacific and West Coast-based forces.

c. Strike Groups

The Strike Group is the core tactical unit for afloat naval forces and lead by a 1-star Rear Admiral who reports to a numbered fleet commander. There are two types of Strike Groups, Carrier, and Expedition. Carrier Strike Groups (CSGs) are standing commands based around an aircraft carrier. Each CSG will typically be composed of one carrier and attached air wing, several surface combatants, and possibly fast attack submarines. An Expeditionary Strike Group (ESG) is similar but based around an amphibious assault ship and Marine Expeditionary Unit (MEU) to support amphibious operations. A Strike Group's C2 can be further broken down into Squadrons and Air Wings (Office of the Chief of Naval Operations [CNO], 2017).

d. Surface Action Group

A SAG is a tactical level element which provides the Component Commander (CCDR) a level of flexibility and responsiveness to execute tailorable missions independently or as an extension of the CSG. SAGs operate as an extension of naval mission sets and can cover any equipped warfare area. The SAG is organized under a SAG commander (SAGC) and is comprised of a minimum of two surface combatant ships (CNO, 2017).

e. Squadron/Air Wing

The lowest Navy C2 organization before going to individual ships, subs, and aircraft led by an O-6 rank of Captain. Squadrons are typically organized around the same type of platforms and report to the Strike Group commander. Destroyer Squadrons (DESRONs) for surface combatants, Amphibious Squadrons (PHIBRONs) for amphibious support ships. Submarine Squadrons (SUBRONs) for submarines. An air wing is the C2 organization of aircraft attached to a carrier as part of an CSG consisting of the different squadrons of aircraft platforms.

3. Joint Task Force

The core operational level C2 organization in current DoD doctrine for a Joint Force is the Joint Task Force (JTF). A JTF is a large mission oriented C2 organization with deeply

connected efforts, but it does not require logistics to be in the same region (JCS, 2020). Additionally, per current doctrine (JCS, 2020), a JTF is finite, and dissolves once assigned mission objectives are met. Normally, A JTF will consist of two or more Service and Functional components with their respective operational responsibilities. Figure 1 depicts the possible components of a JTF under current doctrine.

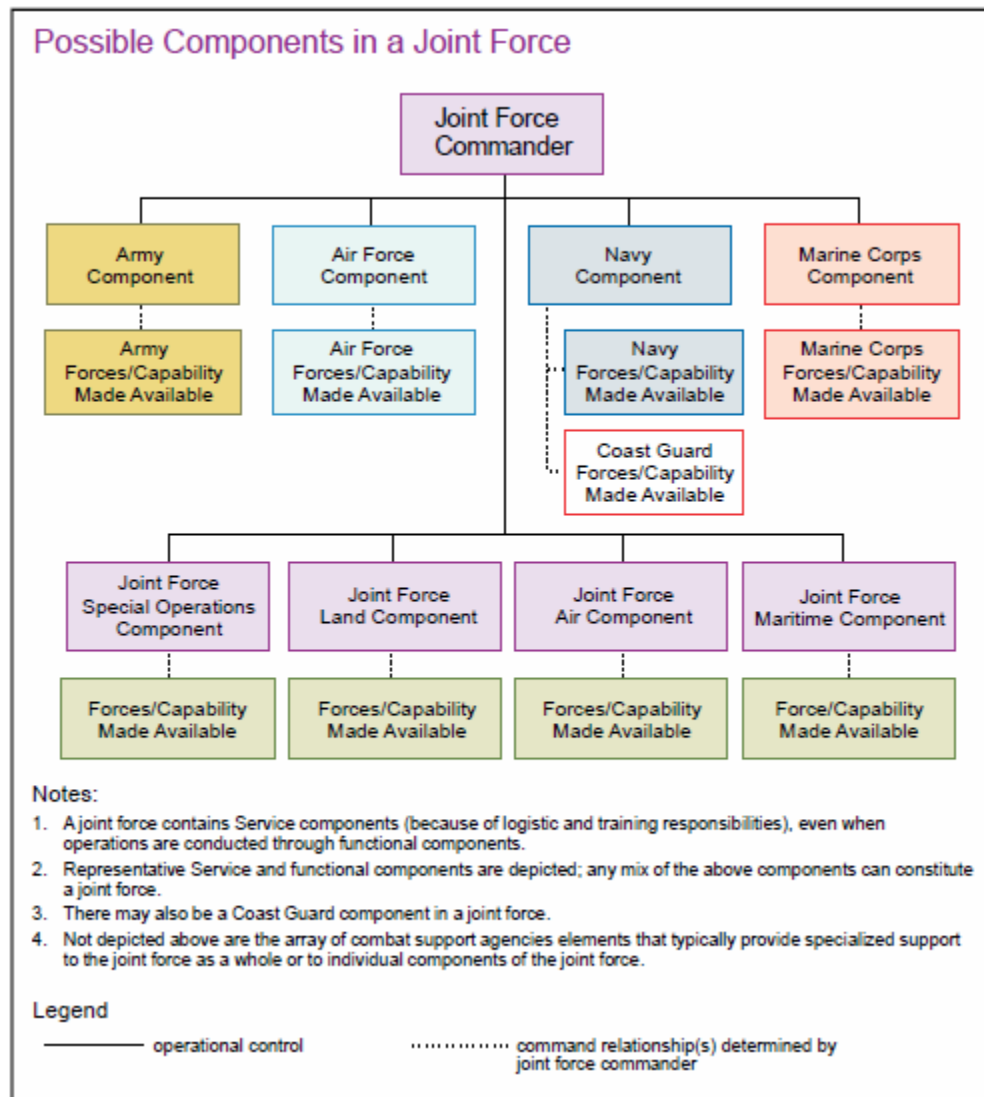


Figure 1. Joint Force Components. Source: JCS (2020).

a. Service Components

Normally, the primary purpose of Service Components commanders in a JTF is to maintain administrative control of their respective forces. ADCON includes administrative and support responsibility such as training, logistics, and manning (JCS, 2020).

b. Functional Components

Functional Components are established in a JTF to conduct operations where joint forces are operating in the same operational area or as distinct aspect of the JTF's mission (JCS, 2020). Normally, these components are Joint Force Land, Air, Maritime, and Special Operations commands. These commanders "have authority over forces or military capability made available to them as delegated by the establishing JFC [Joint Force Commander]" (JCS, 2020, p. III-20). Per doctrine (JCS, 2020), the JFC normally designates a Service component commander of the respective functional domain as a functional component commander to exercise tactical control over the joint forces assigned to them for task execution. For example, Commander, Seventh Fleet, assigned as Joint Force Maritime Commander (JFMCC). Joint doctrine also specifies an important responsibility of subordinate functional commanders relating to the flow of information. It states that "all subordinate commanders possess the general responsibilities to provide ... timely information to the superior JFC relating the subordinate commander's situation and progress" (JCS, 2020, p. III-15).

c. Joint Task Force Commander

The two primary duties of the JTF commander are to exercise Operational or Tactical Control (TACON) over attached forces and develop a supporting relationship among other forces. These duties directly relate to the JTF commander's responsibility to accomplish assigned missions (JCS, 2020). Additionally, Joint doctrine, also specifies several important responsibilities of a JFC relating to C2 Information Flow analyzed in this research:

- Provide a clear commander's intent and timely communication of specified tasks, together with any required coordinating and reporting requirements.

- Provide all available information to subordinate JFCs and component commanders that affect their assigned missions and objectives.
- Delegate authority to subordinate JFCs and component commanders commensurate with their responsibilities. (JCS, 2020, pp. III-14-15)

The information utilized to perform these responsibilities comprise a major part of the communication between JTF Commanders and their subordinates and forms the core of the knowledge analyzed in this research.

B. COMMAND AND CONTROL

1. C2 Concepts and Principles

C2 represents both art and science, dating back to the Stone Age. Van Creveld (1985) observed C2 as command functions and process throughout military history, observing the role and effects of modern technology on C2. He observed modern military technology and weapons have greatly increased the information demand though also decreased the time window to perform important C2 functions, arguing that certain functions can only be performed automatically by computer technology. This dependence on electronic means to communicate information and perform C2 functions also exposes it to the risk of electronic warfare.

Van Creveld (1985) also observed that information is required to perform critical C2 functions and that a C2 system's primary role is to provide such information. As tasks become more complex more information is required, and insufficient information will produce a fall in performance. Thus, C2 system capabilities are required to expand to meet the information requirements of these tasks. Van Creveld suggests several important designs factors of a C2 system to best meet this information demand:

- The need for decision thresholds to be fixed as far down the hierarchy as possible, and for freedom of action at the bottom of the military structure.
- The need for an organization that will make such low-decision thresholds possible by providing self-contained units at a fairly low level.
- The need for a regular reporting and information-transmission system working both from the top down and from the bottom up.

- The need for the active search of information by headquarters to supplement the information routinely sent to it by the units at its command.
- The need to maintain an informal, as well as formal, network of communications inside the organization. (Van Creveld, 1985, *The Essence of Command*, para. 6)

Alberts and Hayes (2003) have made similar observations for C2 systems in their *Power to the Edge* concept of C2. They observed that agility will be a major characteristic of 21st century military forces and that the information enables this agility. In order to meet these dimensions of Agile C2, Alberts and Hayes discuss the concept of *Power to the Edge*. *Power to the Edge* C2 describes empowerment of units at the edge of a command structure. Edge units are defined as those closest to the operational environment while empowerment entails expanding access to information and removing unnecessary constraints. Additionally, Alberts and Hayes identify responsibility, authority, and accountability as essential features of C2 that if not properly distributed or mismatched will result in degraded effectiveness. Furthermore, Agile C2 is defined as having several key dimensions:

1. Robustness: the ability to maintain effectiveness across a range of tasks, situations, and conditions.
2. Resilience: the ability to recover from or adjust to misfortune, damage, or a destabilizing perturbation in the environment.
3. Responsiveness: the ability to react to a change in the environment in a timely manner.
4. Flexibility: the ability to employ multiple ways to succeed and the capacity to move seamlessly between them.
5. Innovation: the ability to do new things and the ability to do old things in new ways.
6. Adaptation: the ability to change work processes and the ability to change the organization. (Alberts & Hayes, 2003, Chapter 8, para. 8)

Alberts and Hayes (2003) describe six types of C2 structures throughout military history. The structures vary from tightly controlled central command authority to edge units with a high amount of autonomy. The following is a breakdown of each structure:

- **Cyclic:** Utilizing a routine schedule, orders are released from a central command authority. Cyclic C2 structures have been used when communication bandwidth is limited compared to the information

requirement; when there must be detailed coordination between separate units, and when subordinates are unable to act in flexible manner (Alberts & Hayes, 2003).

- Interventionist: Similar to Cyclic but effective communication capability allows for directives to be changed at irregular intervals (Alberts & Hayes, 2003).
- Problem Solving: Subordinate Commanders are issued orders based on objectives and constraints. Allowing for greater innovation and flexibility within the stated constraints. Headquarters should issue orders that are clear and contain milestones to stress what should be accomplished (Alberts & Hayes, 2003).
- Problem Bounding: Similar to Problem Solving, but the tasks are issued with much less detail on how to achieve. Allowing for even more innovation and flexibility for subordinates (Alberts & Hayes, 2003).
- Selective Control: Headquarters establish a set of initial conditions and monitor its progress. This requires great trust in the subordinate forces that have the ability to achieve mission goals independent of headquarters. Though headquarters still anticipate situations where intervention on their part is necessary for mission success (Alberts & Hayes, 2003).
- Control Free: The least centralized C2 structure. Here the headquarters only primary role is to set initial conditions to maximize mission success and provide necessary resources and information to subordinates (Alberts & Hayes, 2003).

2. C2 Approach Space

Alberts and Nissen (2009) discuss the concept of a C2 Approach Space. The model incorporates three dimensions of C2 approaches: Allocation of Decision Rights, Patterns of Interaction, and Distribution of Information. Each dimension can be described as a spectrum where different C2 approaches reside on a different point in the spectrum:

- Allocation of Decision rights describes the delegation of decision-making authority within the structure, with the one end being none and the other broad (Alberts & Nissen, 2009).
- Patterns of Interaction describe the interaction capability between entities in the C2 structure with spectrum between tightly constrained and unconstrained (Alberts & Nissen, 2009).
- Distribution of Information describes how broadly information is distributed between entities from none to broad (Alberts & Nissen, 2009).

Different C2 approaches can be placed within the Approach Space according to how they fit the three aspects. Alberts and Nissen (2009) identify five archetypical C2 approaches: Conflicted, De-Conflicted, Coordinated, Collaborative, and Edge. Figure 2 depicts the approaches along the spectrum of each Approach Space dimension. Additionally, the figure depicts that the boundaries between each approach is fuzzy and not sharply delineated (Alberts & Nissen, 2009). Figure 3 represents a three-dimensional view of the C2 Approach Space.

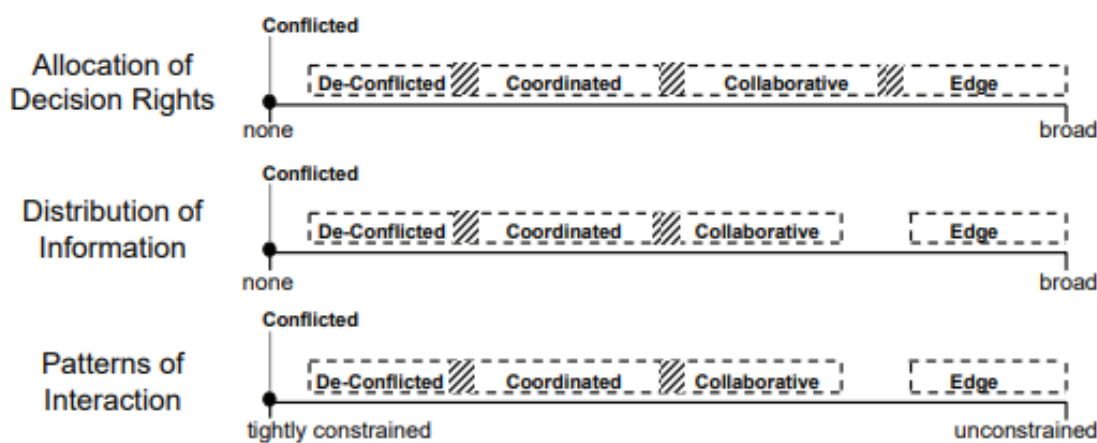


Figure 2. C2 Approach Space Dimensions. Source: Alberts and Nissen (2009).

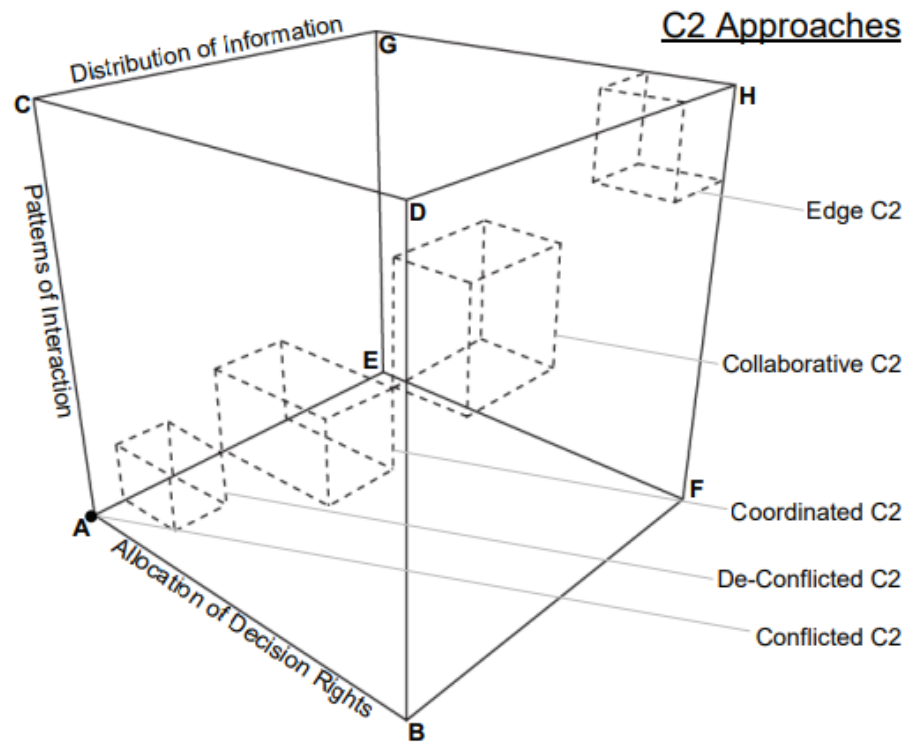


Figure 3. C2 Approach Space. Source: Alberts and Nissen (2009).

Two additional C2 structures of interests, Traditional Military Organizations and Edge Organizations exist on opposite corners of the Approach Space. Traditional Military Organizations with little to no Allocation of Decision Rights and Distribution of Information, and tightly constrained Patterns of Information. While Edge Organizations have broad Decision Rights and Distribution of Information with unconstrained Patterns of Interaction (Alberts & Nissen, 2009). Figure 4 depicts these two structures in the three-dimensional approach space.

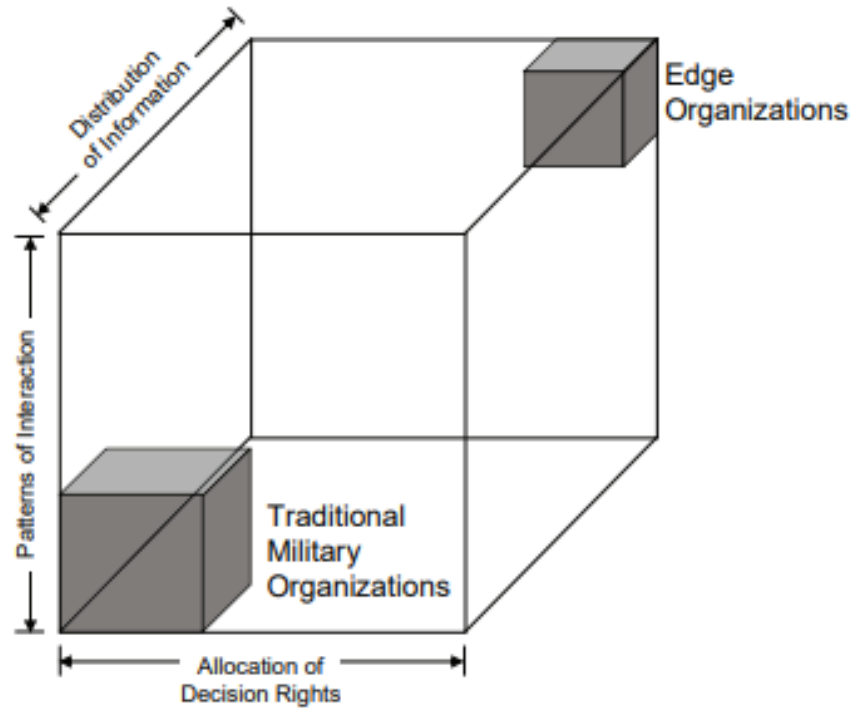


Figure 4. Traditional and Edge Approach Space. Source: Alberts and Nissen (2009).

3. Maritime Command and Control

C2 organization in maritime joint operations revolves around three major aspects. The regional Geographic Combatant Command, the Joint Task Force Commander, and the Joint Component Commanders. Furthermore, a core aspect of U.S Navy C2 organization is the Composite Warfare Commander (CWC).

Mission Command is an important aspect of joint maritime operations and a product of its decentralized environment. Commanders are given mission-type orders where the focus is more “on the purpose of the operation rather than details of how to perform it” (JCS, 2021, p. I-2). Understanding the commander’s intent by the tasked unit is a critical part of the success for Mission Command. Since joint maritime operations tend to be decentralized, mission command is critical for unity of effort (JCS, 2022).

The CWC concept is a USN doctrine that allows a maritime commander as the Officer in Tactical Command (OTC) to assign functions and mission areas of the different

types of maritime warfare to subordinate commanders (JCS, 2021). An important aspect of the CWC is command by negation. Command by negation allows for a CWC to delegate certain warfighting authorities to the different warfare commanders allowing for them to take the required actions without delays caused by the distributed nature of maritime warfare while keeping the CWC informed (JCS, 2021). This allows for the CWC to maintain the initiative while still operating in a dispersed manner (JCS, 2021). Figure 5 depicts the CWC concept in relation to the subordinate commanders.

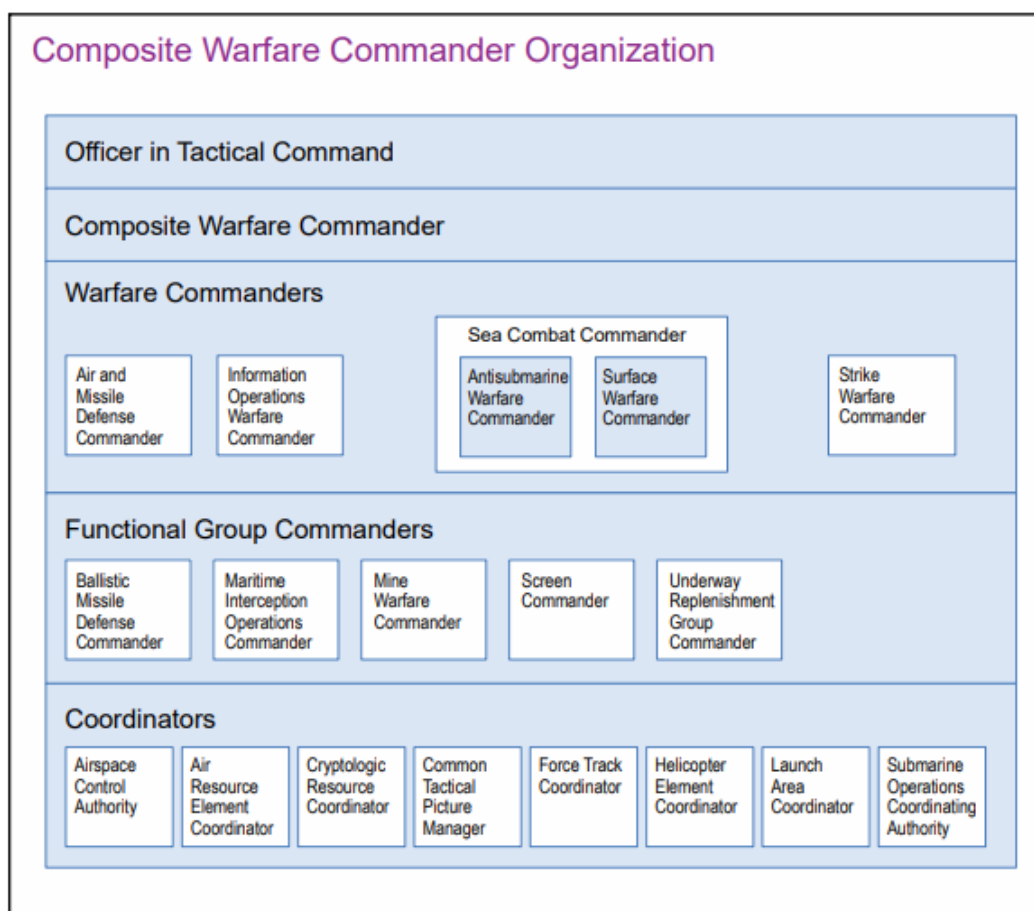


Figure 5. CWC Concept. Source: JCS (2021).

4. JADC2

Joint All Domain Command and Control is a major effort by the DoD to coordinate an effective development of comprehensive joint C2 systems across the services. The result

of this effort is a cohesive C2 system that can connect across all services and platforms between warfare domains and provide Joint Force Commanders with enhanced decision-making capabilities. The JADC2 effort primarily focuses on three C2 challenges joint forces may face in future conflict: Cross service C2 system operability, A2/AD capabilities of adversaries, and rapid decision making (DoD, 2022). With each service department responsible for the development and implementation of both weapon and C2 systems for their forces through their MT&E mission, these systems, more specifically their sensors, are developed independently. This independent development can create situations where a sensor or weapons system of one service is unable to share critical information amongst the systems of other services. These situations are what the efforts of JADC2 seek to resolve.

As the JADC2 Strategy Summary (2022) states, current US adversaries are quickly developing A2/AD capabilities seeking to disrupt traditional C2 capabilities. It is expected that future forces will be operating in a delayed, disconnected, intermittent, low bandwidth (DDIL) environment and JADC2 seeks to be able to address how a joint force can successfully operate in such an environment. Along with A2/AD concerns, future conflict is also expected to require decision-making on a much more rapid scale than before. JADC2 seeks to address this concern in two ways: greater sensor integration across domains and faster operation environment analysis, possibly enhanced by Artificial Intelligence (DoD, 2022).

C. MARITIME COMMUNICATION OVERVIEW

This section provides an overview of the forms and paths of communication that facilitates the flow of C2 related data and information across the various organizations of a Joint Task Force in a maritime environment.

1. Radio Communications

One of the primary mediums that enable a large portion of the communications paths are electromagnetic waves transmitting at various frequencies generally called Radio waves or RF. In regard to military communications the RF spectrum is broken down into

several sets of frequency ranges called bands. There are capabilities and limitations that each band provides to military communications and generally separate communication systems for each as well. Additionally, several RF bands utilize satellites as an important part of the path which brings additional capabilities and limitations. The following is a breakdown of the most common and utilized RF bands that maritime forces would be using in the Pacific region:

a. High Frequency (HF)

HF radios provide both line-of-sight (LOS) and beyond-line-of-sight (BLOS) voice, and data communications. By utilizing how HF interacts with Earth's environment, units are capable of long-distance communications without the use of satellites, though at the cost of significantly smaller data rates (Air Land Sea Application Center [ALSA], 2013).

b. Very High Frequency (VHF)

VHF is primarily promulgated by LOS and is used for short range direct communications of around 25-50 miles (ALSA, 2013).

c. Ultra High Frequency (UHF) LOS

UHF LOS is utilized for short-range (15 to 100 miles) communications. Unlike HF and VHF, UHF "are limited to a short distance beyond the horizon" (ALSA, 2013, p. 43). Though reception is better in terms of static and fading compared to lower frequencies (ALSA, 2013).

d. Satellite Communications (SATCOM): UHF, Super High Frequency (SHF) and Extremely High Frequency (EHF)

SATCOM enables BLOS global communication across the UHF, SHF and EHF spectrum. With higher data rates and bandwidth, SATCOM "often provides data on a COP [Common Operational Picture]. The COP provides situational awareness, supports shared understanding, and supports control of forces by empowering subordinate leaders to gain greater information and independence to facilitate initiative and agility to accomplish the commander's overall intent" (JCS, 2018, p. II-9,10). SATCOM also enables both

commanders and subordinates to “share other operationally relevant information” in a near real time manner (JCS, 2018, p. II-9,10).

2. Non-radio Communications

In addition to Radio Communications, other forms of communication paths enable C2 functions.

a. Submarine Cables

The speed and bandwidth of modern intercontinental telecommunications is mainly enabled using submarine cables throughout the world’s oceans (National Oceanic and Atmospheric Administration [NOAA], 2022). These cables allow for the use of high-speed internet and telecommunications technologies between distant regions of the world, such as the East and West ends of the Pacific. Several of these cables that connect important Pacific land mass such the United States West Coast, Hawaii, Guam, and Japan are utilized both by commercial and government entities, including military (NOAA, 2022). This allows the land based JTF organizations the ability to communicate with high bandwidth capabilities.

b. Visual Signals

An additional communication path available for maritime forces, primarily surface vessels, are visual signals such as semaphores or light signals. The International Code of Signals provides an alternative to verbal communications and allows for communicating intentions critical for navigational safety through coded message (National Geospatial-Intelligence Agency [NGA], 2020). Morse Code can also be used as a means of communicating short messages when language differences are not a factor (NGA, 2020). Though it does not require any use of radio communications this method of communication is very limited by its range restrictions and bandwidth capabilities. Vessels must be in close proximity with short, coded messages for brevity.

c. Direct

In the case of JTF organizations being co-located, direct interpersonal communication can occur between these organizations and should not be overlooked.

D. KNOWLEDGE FLOW THEORY

This section covers the background of Knowledge Flow Theory that will be utilized in the analysis of JTF C2.

1. Knowledge Uniqueness

Gallup et al. (2019) discuss how Knowledge, Information, Data, and Signals can be conceptualized distinctly by the following characteristics: “Knowledge enables effective action” (p. 3), “Information provides meaning and context” (p. 4), “Data answers context-specific questions” (p. 4), and “signals transmit events across physical space” (p. 4). Expanding on these concepts is a hierarchy of data as illustrated in Figure 6.

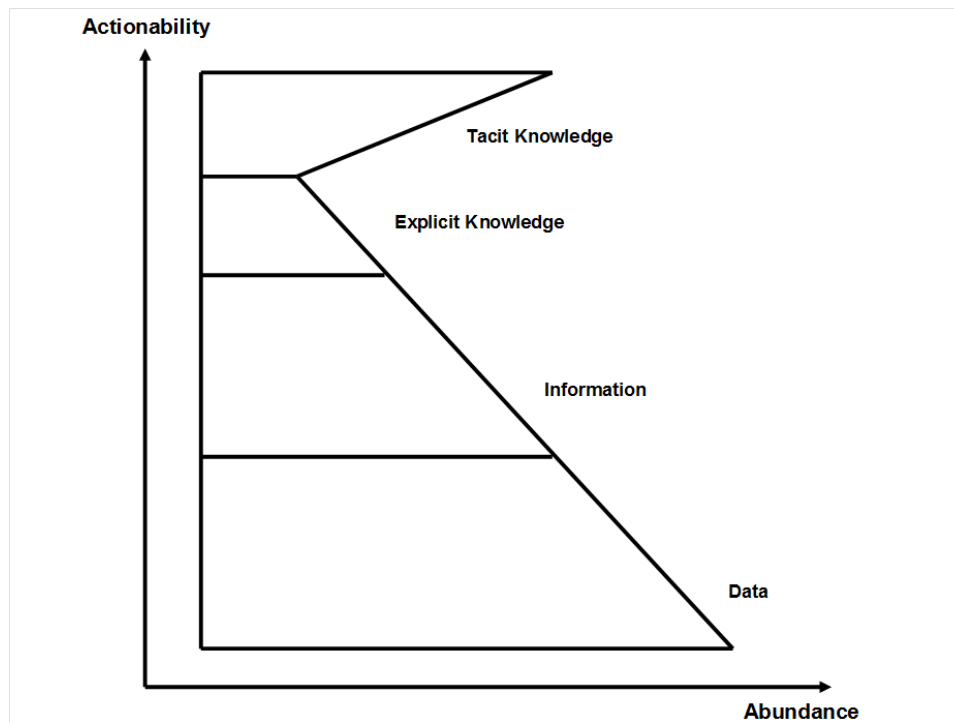


Figure 6. Knowledge Hierarchy. Source: Gallup et al. (2019).

The hierarchy contains two dimensions: abundance and actionability (Nissen, 2014). The triangular shape of the figure illustrates the difference of abundance versus actionability for each level. Where there is more abundance of data it has low actionability, with less abundance of information it is more actionable, knowledge is the least abundant but most actionable (Gallup et al., 2019). Additionally, knowledge is further divided into explicit and tacit knowledge. Explicit knowledge is characterized as being less abundant and actionable than tacit knowledge, since it requires being formalized and made explicit whereas tacit knowledge accumulates naturally (Nissen 2005, Gallup et al., 2019).

2. Knowledge Flows

Figure 7 depicts key concepts of knowledge flows between connected knowledge hierarchies. The arrows represent the directional flow of knowledge between producer and consumer. Gallup et al. (2019) describes the flow process as follows: The producer creates information from their own personal knowledge and through all means available for them to gather knowledge which in turn produces data that is then transmitted over signals. The consumer then receives the signals and interprets the data to build their own knowledge, by developing “information through incorporation of meaning and context” (p. 6). Additionally, an important distinction is made in that the signals flow is in the physical domain, while the flow between data and knowledge is in the socio-cognitive domain (Alberts & Hayes, 2003).

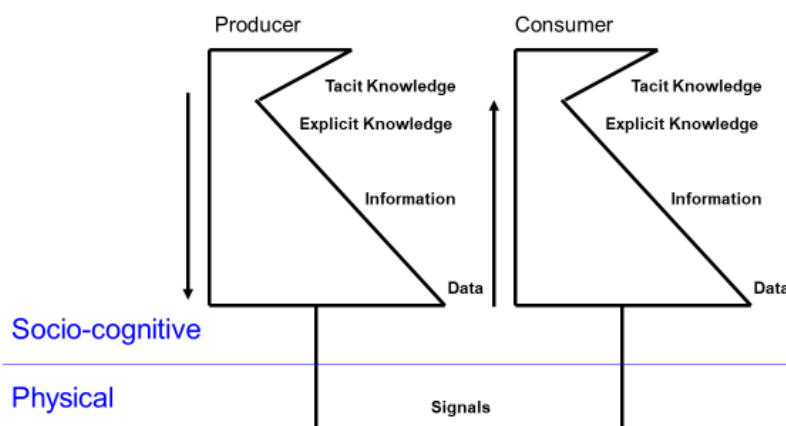


Figure 7. Knowledge Flows Source: Gallup et al. (2019).

3. Knowledge Measurement

Knowledge Flow Theory (KFT) and related equations are utilized in this research to analysis the information and knowledge flow across maritime forces within a JTF. Analogous to classical Newtonian mechanics of a physical systems, these equations allow characterization of “the dynamics of knowledge as it flows through an organization and across organizations” (Gallup et al., 2019, p. 7).

a. Basic Knowledge System

Table 1 outlines the important constructs of the basic analogic knowledge system.

Table 1. Analogic Knowledge System. Source: Gallup et al. (2019).

Construct	Description	Analogy
K-Force (KF)	Effort required to accelerate knowledge	$f(C, E, o)$
K-Work (KW)	K-Force applied through Reach	$KF \times R$
Flow Time (FT)	Time required for knowledge to flow	FT
K-Power (KP)	K-Work done per unit flow time	KW / FT

Knowledge Force (K-Force or KF) will be used to represent the effort necessary for knowledge to move within an organization. Chunks (C) of knowledge of varying Explicitness (E) make up the flow the KF must act upon (Gallup et al., 2019). One chunk of knowledge can facilitate one atomic action or allow for a single distinction from the provided knowledge flow (Gallup et al., 2019). As such, the more chunks in flow, similar to physical mass, the more K-Force necessary to move them (Gallup et al., 2019). Additionally, Gallup et al. (2019) discuss the analogous relationship between physical friction and the explicitness of knowledge. More tacit knowledge will require greater K-Force, just as a surface with great friction will require greater physical force. Gallup et al., further specify tacit knowledge requires ten times the K-Force to flow over explicit

knowledge, thus making $KF = C \times (10 - 9E)$. Figure 8 depicts this representative linear relationship between K-Force and explicitness.

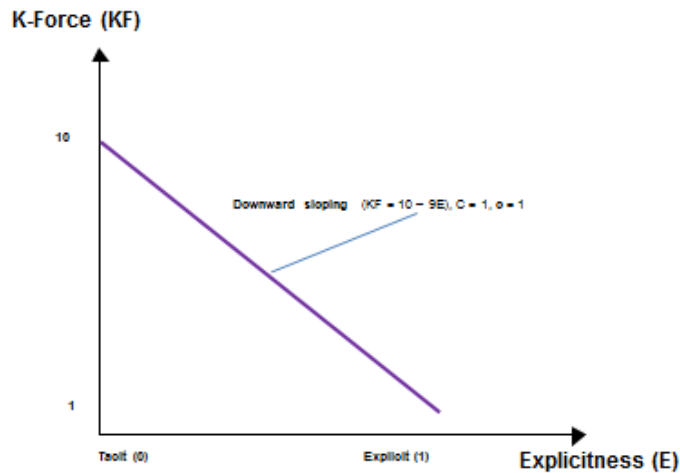


Figure 8. Knowledge Force and Explicitness. Source: Gallup et al. (2019).

Knowledge Work (K-Work or KW) is a combination of KF and Reach (**R**). Reach is representative of “the number of people able to access and utilize the knowledge chunks” and is “analogous to physical distance” (Gallup et al., 2019, p. 11). Gallup et al. (2019) explain how Knowledge Work and Knowledge Energy (K-Energy or KE) is used as related to physical work and energy to conceptualize a correspondence between KW and Knowledge Energy (K-Energy or KE). K-Energy is expended to perform K-Work, analogous to physical energy. Flow Time (**FT**) is a measurement of the “time required for knowledge chunks to flow from one person, group, place, or time to another” (Gallup et al., 2019, p. 11). When combined with KW, it represents Knowledge Power (K-Power or KP) which signifies the Knowledge Work accomplished as a unit of time (Gallup et al., 2019).

b. Extended Knowledge System

(i) K-Force

Gallup et al. (2019) extend the basic knowledge system discussed above to incorporate factors not previously integrated into the basic knowledge system. In regard to the K-Force function, Gallup et al. expand on the influence of explicitness as well as the personal factors affecting knowledge. For the influence of explicitness, (10-9E) is expanded to be more general. Gallup et al. add in the variables of slope (sl), intercept (int), and nonlinearity (nl) to the equation to allow for change in the relationship between explicitness and K-Force as depicted in Figure 8. This transforms, (10-9E), to the new form, $(int - [sl \times E^{nl}])$ (Gallup et al., 2019).

For personal factors, Gallup et al. (2019) introduce the variables of **pf** and Knowledge Power Input (**KPi**). The variable **pf** is defined as personal factors affecting the K-Force and includes factors such as communication skill, motivation, and stress (Gallup et al., 2019). Gallup et al. describes **KPi** as a factor of skill and experience where a person with greater skills or experience will have a positive impact on K-Force. This transforms the basic K-Force equation to the extended form of $KF = (C \times pf \times KPi) = (int - [sl \times E^{nl}])$ (Gallup et al., 2019). Gallup et al. observe that substituting 1.0 for **pf** and **KPi** and the basic slope-intercept for explicitness results in the original basic equation.

(ii) K-Work

As Gallup et al. (2019) observe in the basic system K-Work always equaled K-Energy, K-Work was extended to enable separation of knowledge input, as KE, from knowledge output, as KW. K-Work was also extended by the introduction of knowledge efficiency (**Ek**), information effect (**Ei**), and organizational factors (**of**) (Gallup et al., 2019). Gallup et al. further describes **Ek** as a product of **Ei** and **of**, where **Ei** represents the effect quality information would have on knowledge and of being factors such as organizational climate and IT support impacting an organization's ability to convert K-Energy to K-Work. The addition of these variables extends the basic K-Work equation to the new extend form of $KW = KE \times Ei \times of$.

(iii) K-Power

Gallup et al. (2019) expand the basic K-Power equation of $KP = KW/FT$ to incorporate the introduced variables that impacted K-Force and K-Work to produce an extended K-Power output (**KPo**) equation. This extended equation includes all the basic and newly introduced terms into a single equation that can be effectively used for conducting knowledge flow analysis (Gallup et al., 2019). The extended equation is in the form of $KPo = [(C \text{ pf of } Ei^2 KPi^2 R) \times (int - [sl \times E \wedge nl])] / FT$ (Gallup et al., 2019). Gallup et al. empathizes that the factors of information effect (**Ei**) and K-Power input (**KPi**) are squared terms while **pf** and **of** are linear, highlighting the impact each term will have on K-Power output (**KPo**). Table 2 summarizes extended Knowledge system equations and how they compare to the basic system.

Table 2. Extended Knowledge System Equations. Source: Gallup et al. (2019).

Construct	Equation
K-Force basic	(5) $KF = C \times (10 - 9E) \times o$
K-Force	(5c) $KF = (C \times \text{pf} \times KPi) \times (int - [sl \times E \wedge nl])$
K-Work basic	(6) $KW = KF \times R (= KE)$
K-Energy	(6a) $KE = KF \times R$
K-Work	(6d) $KW = KE \times Ei \times of$
Flow Time	Measure
K-Power basic	(7) $KP = KW / FT$
K-Power output	(7b) $KPo = (KW \times Ei \times KPi) / FT$
K-Power out ext	(7c) $KPo = [(C \text{ pf of } Ei^2 KPi^2 R) \times (int - [sl \times E \wedge nl])] / FT$

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III. METHODOLOGY

This research is based upon comparative analysis. Specifically, it compares the current state of C2 with the stated goals, objectives, and requirements of JADC2 using gap and knowledge flow analysis. The core of the comparative analysis will be a case study scenario of U.S. forces operating in the INDOPACOM AOR. **All information presented in this thesis derives from open sources. No aspect of the case study or information derives from classified sources.** The forces are composed of a JTF tasked with providing a show of force as a deterrent and ensure freedom of navigation in response to increased provocation against forward deployed U.S. forces and partner nations.

The JTF consists of Navy, Air Force, Army, and Marine Corps assets. Commander, PACFLT, is assigned as JFC with headquarters located in Hawaii. Commander, Seventh Fleet, is assigned as JFMCC, and is operating out of Japan. TACON of air and land assets fall under a JFACC and a JFLCC, respectively. The JFACC is an Air Force commander out of Guam and the JFLCC is a Marine Corps commander out of Okinawa. Maritime assets allocated to the JFMCC consist of a Carrier Strike Group and Surface Action Group currently operating in theater. The air assets consist of an Air Force Air Wing composed of a bomber and fighter squadron. The land assets will consist primarily of USMC forces deployed in accordance with their Expeditionary Advanced Base Operations (EABO) concept.

The scenario looks at the knowledge flow between the JFMCC to their subordinate forces as well as to supporting CCDRs. To conduct comparative analysis, the scenario forms the structure of three vignettes that have the JTF operating in distinct levels of a DDIL communication environment and enemy hostility. Additionally, each vignette consists of two versions: one with the JTF operating with currently available C2 systems and communications capabilities and the other with the JTF assets outfitted with JADC2 enabling systems. The first vignette consists of JTF forces operating at full communication capacity with no threat of adversary efforts to deny or degrade C2 functions. The second vignette consists of self-imposed Emissions Control (EMCON) by JTF forces as well as an unknown source causing degradation for communication links. Traditional methods for

enabling C2 functions are limited and communication with subordinate units and higher headquarters is intermittent. The third vignette has the JTF facing an environment where the adversary is actively conducting DDIL operations and the JTF is without traditional C2-enabling communication, such as SHF/UHF satellite communications. Units can expect to operate without communication to higher headquarters for an extended time through traditional communication channels.

A. COMMUNICATION PATHS

The communication paths of the JTF form the basis of our analysis. Figure 9 represents an abstracted general view of the different communication paths between units in a traditional C2 environment. The purple connections are SATCOM paths, the black are submarine communications cables, the green are LOS RF, and the blue are visual signals. The width of each line represents the relative C2 information flow capability of each path. The larger the width the more capable the communication path is.

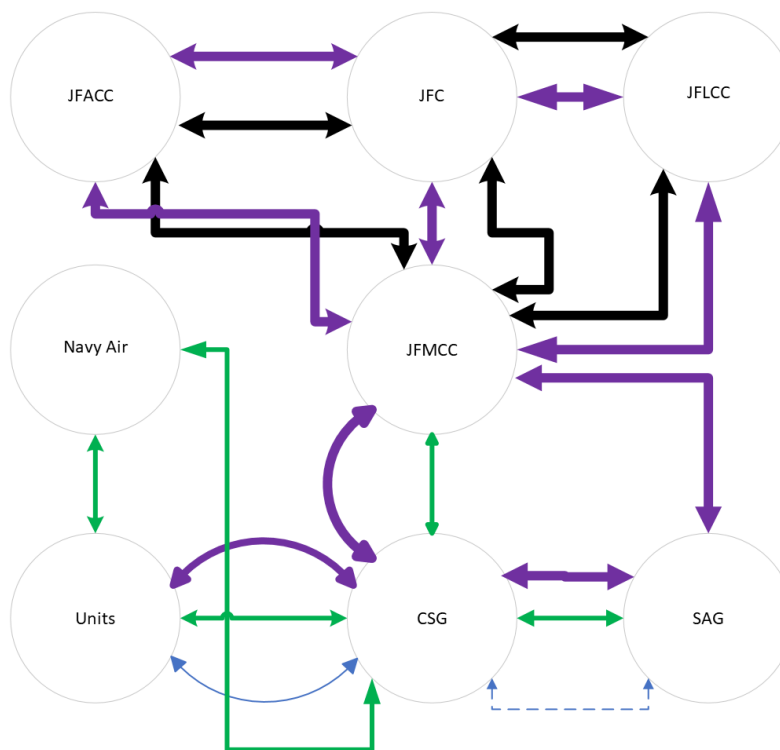


Figure 9. JTF Communication Paths

With a hypothetical JADC2 enabled JTF, C2 communications become “transport agnostic” (Walker, 2022). This will mean that the certain kinds of information tied to specific systems will not be tied to set communications paths as in the current traditional C2 environment and that JADC2 systems allow for any information to travel over available communication paths (Walker, 2022). Figure 10 represents an abstract view of JTF units communicating through JADC2 enabled communication paths. It’s important to note that the communication paths in Figure 9 still exist, they are just abstracted into a cloud like JADC2 environment.

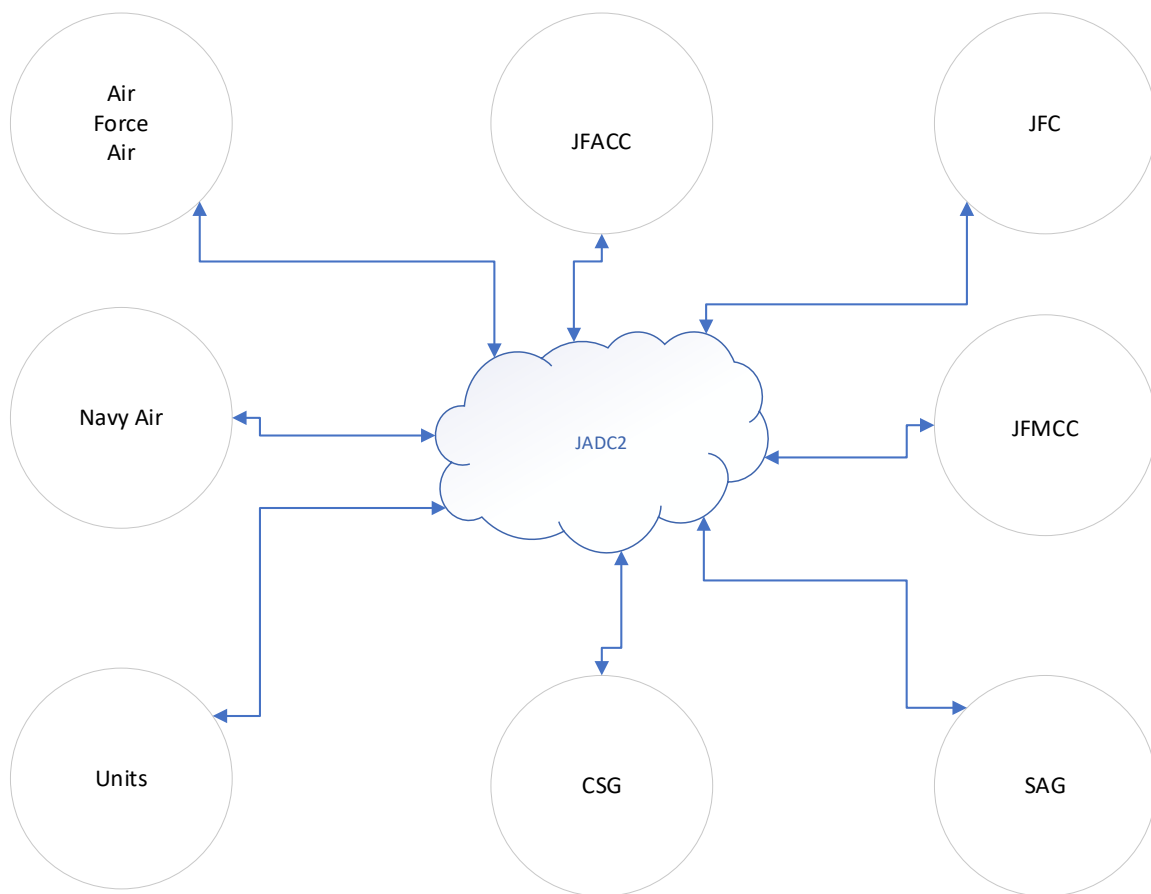


Figure 10. JADC2 Enabled C2 Communication

In the most extreme version of our scenario, it is assumed that the JTF forces be operating in a DDIL environment with restricted access to SATCOM resources. To reflect this Figure 9 is updated in Figure 11 to represent the traditional C2 communication paths

without the use of SATCOM where black represents submarine communications cables, green represent LOS RF, and blue represent visual signaling.

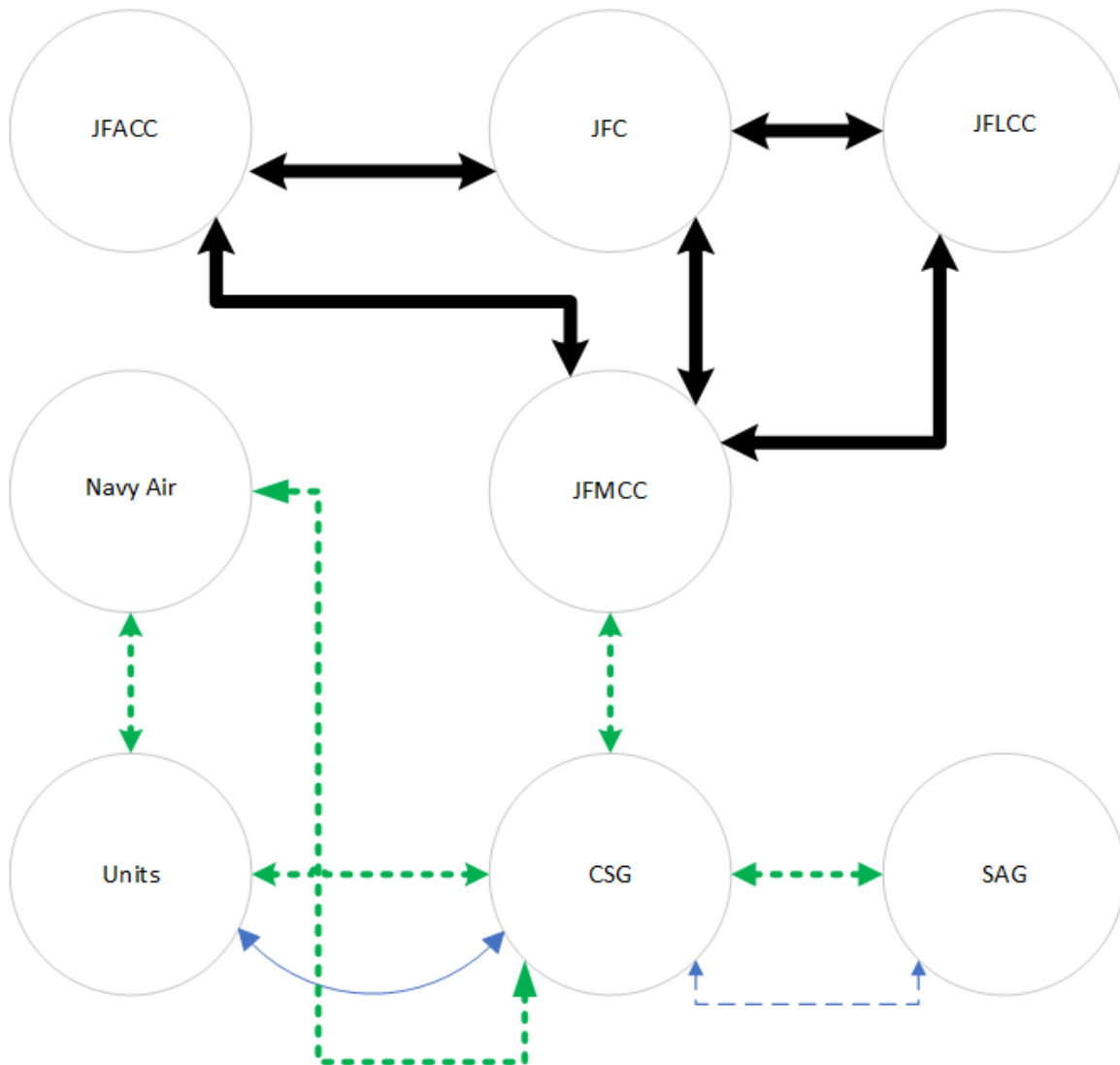


Figure 11. JTF DDIL Communication Paths

B. JOINT TASK FORCE ILLUSTRATION

The following scenarios look at various assets allocated to the JTF during escalating tensions and the knowledge flow that occurs between them in a comparison of traditional C2 structure to the expected JADC2 structure in operation during a degraded and denied

environment. These scenarios will provide the case structure that will be evaluated through the knowledge measurement system.

1. Background

a. Force Make-up

A Carrier Strike Group is operating in the South China Sea, comprised of one nuclear powered aircraft carrier (CVN) with an attached air wing, one guided missile cruiser (CG), and three guided missile destroyers (DDGs). A Surface Action Group is operating in the East China Sea comprised of one CG and two DDGs with the CG as acting SAGC. Both task forces are operating under the tactical control of the JFMCC. Marine Forces are conducting multi-national EABO training on the Senkaku Islands and are under TACON to the JFLCC. Guam Air Force units are placed on high alert by the JFACC for rapid deployment, if needed.

b. All-Up Scenarios

In the All-Up scenarios tensions are at a heightened level due to continued harassing flight profiles flown by the Peoples Liberation Army Air Force (PLAAF) into Taiwanese claimed air space and repeated incursions of Taiwanese territorial waters by Peoples Liberation Army Navy (PLAN) vessels. Due to this and supporting intelligence, the JTF has been stood up by INDOPACOM and the Secretary of Defense. The CSG is operating South-West of Taiwan in international waters with its air wing in standard flight profiles surrounding the strike group as a show of force. The SAG is operating independently of the CSG, reporting directly to the JFMCC, with an airborne MH-60R providing identification of vessels within the designated surveillance area. This scenario sets the initial stage for the subsequent scenarios.

c. Degraded Scenarios

In the degraded scenarios, the Peoples Liberation Army has escalated tensions through suspected denial operations. Current intelligence has not pin-pointed the source to support treating the situation as an act of war, but all U.S. forces have been elevated to a heightened state of readiness in preparation for hostile actions. As a result of the DDIL

environment and EMCON conditions within the force, consistent connection through satellite communications is intermittent or unreliable. The CSG and SAG continue operating as in the All-Up scenario with greater expectations to positively identify unknown aircraft and vessels according to Rules of Engagement (ROE).

d. Denied Scenarios

In the Denied scenarios, all satellite communications have been rendered unreliable through an unidentified means. JFMCC, CSG, and SAG are staged as set up in the All-Up scenario but are forced to continue operations through mission command authorization and current ROE. Table 3 summarizes the above scenarios.

Table 3. Scenario Matrix

	All-Up	Degraded	Denied
CSG	Unknown Air Contacts – All-Up Comms	Unknown Air Contacts – Degraded Comms	Unknown Air Contacts – No Satellite Comms
SAG	Helo ISR on Unknown Warship – All-Up Comms	Helo ISR on Unknown Warship – Degraded Comms	Helo ISR on Unknown Warship – No Satellite Comms

2. Case Scenarios

a. Case 1: Carrier Strike Group (CSG)

CSG 7 is operating in the South China Sea under the operational control of the JFMCC. The airwing is doing standard flight operations as a show of force. An E-2D acting as the airborne early warning detects a suspected Chinese fighter group inbound to the CSG. The E-2D has assessed them as a possible threat due to their flight profile and direct approach to the CSG identification zone.

(1) Case 1.1: CSG – All-Up

Utilizing Cooperative Engagement Capability (CEC), the E-2D transmits the radar data to all CEC capable ships within the range. This data is processed and designated by the Composite Warfare Commander who then transmits the data through a SATCOM voice call to JFMCC Headquarters (HQ), reporting the contacts to higher authority. Utilizing intelligence collected on the area, the JFMCC identifies recent airbases with large military operations and active aircraft and passes the information to the CSG. Satellite images show the aircraft are armed prior to take-off. From the intelligence provided, the JFMCC relays orders to designate inbound aircraft as hostile and orders the CVN to intercept inbound aircraft with DCA to verify intentions and issue warnings in accordance with standard ROE. Coordination also occurs between JFMCC and Joint Force Air Component Commander (JFACC) for a fighter squadron to detach from Guam, refuel enroute and be on standby for support. CSG CEC and link data are updated by the CWC, upon receiving the order, and the entire strike group now sees the incoming aircraft as hostile. The CSG designates F-18s and F-35s for interception and issuing queries and warnings.

(2) Case 1.2: CSG – Degrade

(i) Traditional C2 Structure

At an elevated readiness level, the E-2D collects and transmits track data using CEC to capable ships within range. Track data is updated on the local COP, but UHF SATCOM is intermittent forcing the CSG to inform the JFMCC over HF voice reports once established, rendering the data time late. Meanwhile, the aircraft continue to close the CSG's designated classification, identification, and engagement area (CIEA). Acting under mission command, the CSG CWC designates the inbound aircraft as suspect and sorties airborne fighters to intercept for positive identification (PID). No current information is known on types of aircraft or status of weapons.

(ii) JADC2 Structure

At an elevated readiness level, the E-2D collects and transmits track data using CEC to capable ships within range. Track data is updated on the local COP, but UHF SATCOM

is intermittent forcing the data to be relayed over any available communication path, causing minor delays in reporting. Once informed, the JFMCC relays orders to designate inbound aircraft as hostile through established HF voice channels and orders the CVN to intercept inbound aircraft with DCA to verify intentions and issue warnings in accordance with standard ROE. Coordination also occurs between JFMCC and JFACC for a fighter squadron to detach from Guam, refuel enroute and be on standby for support. CSG CEC and link data are updated by the CWC, upon receiving the order, and the entire strike group now sees the incoming aircraft as hostile. The CSG designates F-18s and F-35s for interception and issuing queries and warnings.

(3) Case 1.3: CSG – Denied

(i) Traditional C2 Structure

Complete loss in reliable satellite communications has shifted the force to mission command. Upon detection of a suspected Chinese fighter group assessed from their flight profile, the airborne E-2D distributes the track data via CEC to assets within range. Continued attempts to update JFMCC through SATCOM and other means are unsuccessful due to degradation and range. With no direct communication to higher authority, the CSG Commander designates the fighter group as suspect and shifts defensive counterair (DCA) stations to a position between the CSG and inbound aircraft as a precaution for unknown intentions. Communications with the JFMCC are established through Iridium satellite phones and the JFC is made aware of the situation after the fact.

(ii) JADC2 Structure

Complete loss in reliable satellite communications has shifted the force to mission command. Upon detection of a suspected Chinese fighter group assessed from their flight profile, the airborne E-2D distributes the track data via CEC to assets within range. Continued attempts to update JFMCC through SATCOM are unsuccessful due to degradation. HF voice communications are established, and a slow data transfer goes through to the JFMCC (Maritime Operation Center) MOC. Once informed, the JFMCC relays orders to designate inbound aircraft as hostile through established HF voice channels and orders the CVN to intercept inbound aircraft with DCA to verify intentions and issue

warnings in accordance with standard ROE. Coordination also occurs between JFMCC and Joint Force Air Component Commander (JFACC) for a fighter squadron to detach from Guam, refuel enroute and be on standby for support. CSG CEC and link data are updated by the CWC, upon receiving the order, and the entire strike group now sees the incoming aircraft as hostile. The CSG designates F-18s and F-35s for interception and issuing queries and warnings.

b. Case 2: Surface Action Group

A SAG is operating on the North-Eastern side of Taiwan, in the East China Sea, steaming in a relaxed screen just outside of visual range. A single MH-60R Helicopter is airborne prosecuting unknown contacts for visual identification (ID). While flying 50 nautical miles West of the SAG, the Helicopter has an inverse synthetic-aperture radar (ISAR) profile of several foreign warships steaming in close formation at 28 knots with a target angle directed towards the SAG.

(1) Case 2.1: SAG – All Up

The helicopter transmits the contact link data to the SAG. The surface warfare commander (SUWC) and supporting combat information center (CIC) begin prosecuting the ships comparing historical data to the provided silhouettes. The SUWC also reports the contacts to the JFMCC, who then provides collected intelligence on Chinese ships operating within the region and those that have recently gotten underway. The JFMCC coordinates with JFLCC for USMC EABO coordination. The SAGC orders the ships to remain in the current formation while communications are established. CEC data from the CG, as the nearest ship to the island, is transmitted to the EABO CEC Composite Tracking Network (CTN) for joint prosecution drills. The JFMCC orders the SAG to maintain posture to determine intent and for the MH-60R to remain at a minimum standoff of 50 nautical miles. Ships are positively identified by comparing ISAR silhouette to known ships in the region.

(2) Case 2.2: SAG – Degraded

(i) Traditional C2 Structure

The helicopter transmits the link data to the SAG, as done previously, but degraded communications prevent the SUWC from reporting the contacts to the JFMCC. SAG combat teams are forced to resort to previously collected data of Chinese ships operating in the region for identification. The SAGC orders the MH-60R to close to within 30 nautical miles for further prosecution and to receive a positive identification and all units to close with 15 nautical miles of one another. Due to degradation in LOS RF from increased distance to land, CEC data transmissions are not being received by the Marine CTN and coordination between JFMCC and JFLCC does not occur until intermittent communications relay the new contact data. Ships are not positively identified with full certainty.

(ii) JADC2 Structure

The helicopter transmits the link data to the SAG, as done previously, but degraded communications prevent a direct SATCOM connection from the SUWC to the JFMCC. SUWC reports shift to HF communication channels and the JFMCC is updated on the new contacts at a slightly increased latency. The JFMCC then provides collected intelligence on Chinese ships operating within the region and those that have recently gotten underway and coordinates with Joint Force Land Component Commander (JFLCC) for USMC EABO coordination. The JFMCC orders the SAG to maintain posture to determine intent and for the MH-60R to remain at a minimum standoff of 50 nautical miles. CEC data from the CG is transmitted to the EABO CEC Composite Tracking Network (CTN) for joint prosecution. Ships are positively identified by comparing ISAR silhouette to known ships in the region.

(3) Case 2.3: SAG – Denied

(i) Traditional C2 Structure

The SAG, now operating in Mission Command, has little non-organic information available on the unknown group of vessels. The SAGC orders immediate maneuvers to

close ships within visual range to increase communication capabilities. Previous briefs are referenced to further classify the unknown group from possibly obsolete intelligence. The SAGC must determine whether to risk further prosecution of the group through the airborne MH-60R in a heightened threat environment or designate the contacts hostile from the provided data. No certain weapons threat can be determined until vessels are positively identified.

(ii) JADC2 Structure

The SAG continues operating under command by negation limited to voice-only communications with the JFMCC. Previous briefs are referenced to further classify the unknown group and compared to new intelligence available to the JFMCC over voice channels. CEC data transmission is intermittent from interference, but the Marine EABO is aware of suspect vessels inbound. The SAGC receives orders to maintain current posture and have a minimum standoff distance of 50 nautical miles for the airborne helicopter. Ships are positively identified by comparing ISAR silhouette to known ships in the region.

C. KNOWLEDGE FLOW ANALYSIS

The KFT portion of this research utilizes the extend Knowledge System equations as described by Gallup et al. in their 2019 Technical Report. Utilizing the scenario and measurements described in the 2019 Technical Report as a baseline, important knowledge flows are identified and measured through the application of the extended Knowledge System equations. These equations will be applied to several knowledge flows across each case scenario and between the Traditional C2 structure and envisioned JADC2 structures. Table 4 is an example of the model used for the analysis.

The description and justification of any assumptions for each parameter value across the different scenarios is discussed in Chapter IV. Factors included in determination of each parameter include scale (SAG vs CSG vs JFMCC), personal training and experience (JMCC Admiral vs SAG Captain), available communication paths (All-up, Degraded, Denied), operational environment (calm, tense, hostile), and form of communication (interpersonal, structured report, system made). As the parameters change for specific knowledge flows between the different scenarios, the impact to Knowledge

Power output (KPo) are noted and any highlights and insights made are discussed in Chapters IV and V.

Table 4. Knowledge Flow Analysis Model Template

Model Params	Knowledge Flow (e.g., JFMCC C2 -> CSG)
C	
E	
pf	
KPi	
KF	
R	
KE	
Ei	
of	
Ek	
KW	
FT	
KPo	

IV. ANALYSIS

A. KNOWLEDGE FLOW ANALYSIS

1. Case 1.1: CSG All-Up

This section is a breakdown of the knowledge flow analysis for Case 1.1: CSG All-up. The values for each Knowledge Equation parameter focusing on the JFMCC are shown in Table 5. The “JFMCC SA” column represents the Situational Awareness of the JFMCC after spending an hour in the Maritime Operation Center ($FT = 3600$). Utilizing the case scenario described by Gallup et al. (2019), we scale up the knowledge chunks (C) from 1,000 for a ship CO to 5,000 for the JFMCC. Representing the JFMCC’s personal tacit understanding and knowledge of the Maritime picture, Explicitness (E) and Reach (R) are assigned values of 0.0 and 1, respectively. As a senior flag level office with over 20 years of service that is highly motivated, Personal Factors (pf) is assessed as 1.5. Knowledge Power input (KPi) is assigned a value of 2.0 for the JFMCC due to their naval experience being applied to presented information. With the JFMCC operating as normal in the current scenario with no excessive stressors or system problems, the other extended variables (Ei , of) are assessed at the baseline of 1.0. Utilizing the Knowledge Flow Equations, this produces a Knowledge Power output (KPo) of 83.33 Bacons (B). The columns of “JFMCC Red I&W” and “JFMCC Blue Ops” represent a further breakdown of the “JFMCC SA”. “JFMCC Red I&W” is the JFMCC SA regarding Indications and Warnings (I&W) for Red Forces, while “JFMCC Blue Ops” represents the operations of all Blue Forces in the maritime picture. Thus, outside of the chunks, most of the variables for these Knowledge Equations mirror the JFMCC SA column.

The next column, “JFMCC -> JFACC”, represents the interaction taking place between the Joint Commanders. 100 chunks ($C = 100$) represent orders from the JFMCC for coordinating efforts. The Informational Effect (Ei) is assessed as 0.75 due to it being verbal communication occurring over the timespan of one minute ($FT = 60s$). Personal Factors ($pf = 1.5$), Knowledge Power input ($KPi = 2.0$), and Organizational Factors ($of = 1.0$) remain the same, but Reach is extended by one for a total of 2 ($R = 2$), representing

the collaboration between both commanders. The following interaction results in a **KPo** of 11.25 B for the exchange.

Going further along the table, the “JFMCC C2 -> CSG” column is the JFMCC communicating their C2 knowledge and direction (i.e., Commander’s Intent) to the CSG commander. As this entails a direct conversation between the two commanders, the knowledge is explicit (**E** = 1.0) and has a Reach (**R**) of 2. It is also a one-minute verbal conversation (i.e., **Ei** = 0.75, **FT** = 60). The overall interaction results in a **KPo** of 11.25 B. Both the “JFMCC Red I&W -> CSG” and “JFMCC Blue Ops -> CSG” columns represent the JFMCC passing their knowledge regarding Red I&W and Blue Force operations and orders, respectively, to the CSG commander. Chunks (**C**) between the JFMCC and the CSG values of 1,000 and 500 are assigned respectively to represent I&W covering double the amount of data Blue Force operation represents. **E**, **pf** and **KPi** are valued at 1.0 due to standardized message formats and data sharing. With a Reach of 2 and **Ei** and **of** baselined at 1.0, the equations result in a **KPo** of 1.11 B and 0.56 B respectively for information provided over a span of 30 minutes (**FT** = 1800s).

Table 5. Case 1.1 JFMCC Flow Analysis

Model Params	JFMCC SA	JFMCC Red I&W	JFMCC Blue Ops	JFMCC -> JFACC	JFMCC C2 -> CSG	JFMCC Red I&W -> CSG	JFMCC Blue Ops - > CSG
C	5000	3000	2000	100	100	1000	500
E	0.00	0.00	0.00	1.00	1.00	1.00	1.00
pf	1.50	1.50	1.50	1.50	1.50	1.00	1.00
KPi	2.00	2.00	2.00	2.00	2.00	1.00	1.00
KF	150000	90000	60000	300	300	1000	500
R	1	1	1	2	2	2	2
KE	150000	90000	60000	600	600	2000	1000
Ei	1.00	1.00	1.00	0.75	0.75	1.00	1.00
of	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ek	1.00	1.00	1.00	0.75	0.75	1.00	1.00
KW	150000	90000	60000	450	450	2000	1000
FT	3600	3600	3600	60	60	1800	1800
KPo	83.33	50.00	33.33	11.25	11.25	1.11	0.56

Table 6 is a breakdown of the Knowledge Flow analysis values focusing on the CSG. The “CSG SA” column represents the CSG commander’s personal SA (**R** = 1) after having been inside the Carrier’s Combat Information Center (CIC) for ten minutes (**FT** = 600s). The chunks of 2,500 and explicitness of 0.0 denotes the local tacit knowledge of all CSG related knowledge available to the commander (i.e., **C** = 2500, **E** = 0). The CSG commander is as highly motivated as the JFMCC (**pf** = 1.5), but still a few years junior in terms of experience (**KPi** = 1.5). As with the JFMCC, the CSG is operating as normal with no excessive stressors or system issues (**Ei** = 1, **of** = 1). This produces a **KPo** of 140.63 B. The “CSG COP -> JFMCC” denotes the communication of the CSG’s Common Operation Picture (COP) knowledge from the CSG to the JFMCC over a one-minute period (**R** = 2, **FT** = 60s). This is to represent the JFMCC receiving near real-time updates from the CSG. As this is information that is explicit and either system produced or highly standardized, Personal Factors and Information Effect are assessed as 1.0 (**E** = 1.0, **pf** = 1.0, **Ei** = 1.0). Additionally, the systems are operating as normal (**of** = 1.0). This produces a **KPo** of 33.33 B. The “Local Sensors” column represents the communication of all the sensor information between the five separate CSG ships over a one-minute period (**R** = 5, **FT** = 60s). Similarly, the information is explicit, and system produced from sensors operating as normal (**E**, **pf**, **Ei**, **of** = 1.0). This produces a **KPo** of 83.33 B.

Table 6. Case 1.1 CSG Flow Analysis

Model Params	CSG SA	CSG COP -> JFMCC	Local Sensors
C	2500	1000	1000
E	0.00	1.00	1.00
pf	1.50	1.00	1.00
KPi	1.50	1.00	1.00
KF	56250	1000	1000
R	1	2	5
KE	56250	2000	5000
Ei	1.00	1.00	1.00
of	1.00	1.00	1.00
Ek	1.00	1.00	1.00
KW	56250	2000	5000
FT	600	60	60
KPo	140.63	33.33	83.33

2. Case 1.2i: CSG Degraded

The following breaks down the analysis of knowledge from the CSG Degraded scenario. As the knowledge flows analyzed are the same across scenarios, the focus is now on the impact that the degraded communications have on each knowledge flow. Table 7 shows the values for each knowledge flow focusing on the JFMCC. Changed values are highlighted yellow. For the “JFMCC SA” through “JFMCC Blue Ops” columns the impacts are to **pf**, **Ei**, and **of**. For **pf**, this is the added stress experienced by the JFMCC caused by the devolving scenario and communication issues. This is represented by a change in value from 1.5 to 1.2. For **Ei**, this is the impact that the degraded communication has on the quality of information received by the JFMCC, which is represented by a change in value from 1.0 to 0.85. For **of**, this is the stress both on the JFMCC’s organizational staff and IT support that affects his knowledge efficiency and is represented by a change in value from 1.0 to 0.75. This produces a reduction of 57% in **KPo** across each of the three columns.

In the Case 1.2i scenario the JFMCC does not communicate with JFACC nor the CSG. This results in no knowledge flow and thus a chunk value of 0 and resulting **KPo** of 0.0 B. For the remaining JFMCC columns, “JFMCC Red I&W -> CSG” and “JFMCC Blue Ops -> CSG”, only **Ei** and **of** are impacted. For **Ei**, this is the impact on the quality of the information flowing from the JFMCC to the CSG caused by the degradation described in the scenario. This represents a change of value from 1.0 to 0.5. For **of**, this is the added stress and impact to IT support suffered by the JFMCC staff affecting their efficiency in transmitting knowledge over the available communication path and is represented by the change in value from 1.0 to 0.75. This produces a reduction of 81% in **KPo** for both columns.

Table 7. Case 1.2i Traditional C2 Structure: JFMCC Flow Analysis

Model Params	JFMCC SA	JFMCC Red I&W	JFMCC Blue Ops	JFMCC -> JFACC	JFMCC C2 -> CSG	JFMCC Red I&W -> CSG	JFMCC Blue Ops -> CSG
C	5000	3000	2000	0	0	1000	500
E	0.00	0.00	0.00	1.00	0.00	1.00	1.00
pf	1.20	1.20	1.20	1.20	1.20	1.00	1.00
KPi	2.00	2.00	2.00	2.00	2.00	1.00	1.00
KF	120000	72000	48000	0.00	0.00	1000	500
R	1	1	1	2	2	2	2
KEF	120000	72000	48000	0.00	0.00	2000	1000
Ei	0.85	0.85	0.85	0.75	0.50	0.50	0.50
of	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Ek	0.64	0.64	0.64	0.56	0.38	0.38	0.38
KW	76500	45900	30600	0.00	0.00	750	375
FT	3600	3600	3600	60	60	1800	1800
KPo	36.13	21.68	14.45	0.00	0.00	0.21	0.10

Table 8 shows the values for knowledge flows focusing on the CSG in a degraded state, again, with changes highlighted in yellow. Like the JFMCC, **Ei** and **of** are impacted from the degradation to communications with **Ei** being reduced from 1.0 to 0.70 and **of** being reduced from 1.0 to 0.75. Just as with the JFMCC, the CSG commander is also experiencing stress from communication issues. This is represented by a change in **pf** from 1.5 to 1.2. This along with the negative changes in **Ei** and **of** causes a reduction of 71% in the “CSG SA” column **KPo**. For the “CSG COP -> JFMCC” column the **FT** is increased by a factor of 10 due to having to utilize a slower form of communication (60 to 600). This produces a reduction of 98% in **KPo** for “CSG COP -> JFMCC”. For “Local Sensors” the communication degradation has less of an effect on the CSG’s locally collected sensor data, so **Ei** is only reduced from 1.0 to 0.75. This produces a reduction in **KPo** of 58%.

Table 8. Case 1.2i Traditional C2 Structure: CSG Flow Analysis

Model Params	CSG SA	CSG COP -> JFMCC	Local Sensors
C	2500	1000	1000
E	0.00	1.00	1.00
pf	1.20	1.00	1.00
KPi	1.50	1.00	1.00
KF	45000	1000	1000
R	1	2	5
KE	45000	2000	5000
Ei	0.70	0.50	0.75
of	0.75	0.75	0.75
Ek	0.53	0.38	0.56
KW	23625	750	2812.5
FT	600	600	60
KPo	41.34	0.63	35.16

3. Case 1.3i: CSG Denied

The following is a breakdown of the knowledge flow analysis from the Case 1.3i CSG Denied scenario. This analysis only focuses on the impact represented by the two commanders' (JFMCC, CSG) SA, as this sufficiently displays the most impactful knowledge loss across the Joint maritime force. Table 9 shows the values for the commanders' SA with the impacted values highlighted in yellow. Just as in the Case 1.2i degraded scenario, the **pf** for both commanders are impacted by the communication issues with a changed value of 1.0. With the major communication loss, **Ei** and **of** are greatly impacted. The loss of near real-time voice reports that are now after the fact results in the JFMCC's **Ei** reduced to a value of 0.50. For **of**, the loss of consistent communication and information to and from the CSG, an extremely valuable asset, has a strong impact on the JFMCC staff's focus and their IT efforts to reestablish communications, resulting in a reduced value of 0.50. The CSG experiences the same issue with lesser impact. While the CSG's IT support is degraded from the communication loss (i.e., **Ei** = 0.50), the CSG is operating within the Mission Command concept, thus mitigating the impact on **of** and resulting in a value reduced to 0.75. These impacts to **pf**, **Ei**, and **of** produce a heavy

reduction of 92% in **KPo** for the JFMCC and 87% for the CSG commander compared to All-Up communications.

Table 9. Case 1.3i Traditional C2 Structure: Denied Flow Analysis

Model Params	JFMCC CSG Loss	CSG SA
C	5000	2500
E	0.00	0.00
pf	1.00	1.00
KPi	2.00	1.50
KF	100000	37500
R	1	1
KE	100000	37500
Ei	0.50	0.50
of	0.50	0.75
Ek	0.25	0.38
KW	25000	14062.5
FT	3600	600
KPo	6.94	17.58

4. Case 1.2ii: CSG Degraded with JADC2

The following is a breakdown of the knowledge flow analysis of the Case 1.2ii CSG Degraded scenario with JADC2 enabled. Table 10 shows the values of the JFMCC flows with the changes brought by having JADC2. The affected variables remain **pf**, **Ei** and **of**, but to a lesser extent due to data and communication paths being established through other means available. This results in a 1.30 for all JFMCC **pf** values to denote less stress experienced as credited to JADC2. Additionally, **Ei** increases to 0.90 from the 0.85 experienced in the traditional C2 structure as some written messages find alternative paths and do not need to be communicated over voice links. As a result of the lifted stress to communication networks, Staff and IT support experience an increase in **of** from 0.75, seen in the traditional C2 scenario, to 0.90. When compared to the traditional C2 structure degraded scenario, these improvements result in the “JFMCC SA” **KPo** increasing 46% from 36.13 B to 52.65 B. “JFMCC Red I&W” and “JFMCC Blue Force Ops” **KPo** also

increase 46%, 21.68 B to 31.59 B and 14.45 B to 21.06 B, respectively. With JADC2 enabling better communication, coordination between the JFMCC and the JFACC, as well as direction from the JFMCC to the CSG commander, now occurs. This allows for a knowledge flow analysis for the columns “JFMCC -> JFACC” and “JFMCC C2 -> CSG”. The knowledge flow chunks equal to those in the Case 1.1 All-up scenario ($C = 100$). Additionally, since the JFMCC to the JFACC communication line is a voice call through submarine cables unaffected by degradation the **Ei** remains 0.75 but with the same personal and organizational factors affecting JFMCC (i.e., **pf** = 1.3, **of** = 0.90). Ultimately, degradation is still occurring even with JADC2, and the communication between the JFMCC and the CSG is slower as a result. Thus, an increase in **FT** to 180 seconds. This produces a **KPo** of 8.78 B for “JFMCC -> JFACC” and 2.93 B for “JFMCC C2 -> CSG”. An obvious improvement over the nulled values experienced in the Case 1.2i traditional C2 structured scenario, but still a respective reduction of 22% and 74% from All-Up. For the Red I&W and Blue Force Ops, communication paths enable the CSG to receive reports from the JFMCC, though with slight delays. These are represented using increased **FT** from 1800 to 2400 seconds. The “JFMCC Red I&W -> CSG” and “JFMCC Blue Ops -> CSG” columns both now experience an increase of 190% in **KPo**, from 0.21 B to 0.61 B for Red I&W and 0.1 B to 0.3 B for Blue Ops.

Table 10. Case 1.2ii JADC2 Enabled: JFMCC Flow Analysis

Model Params	JFMCC SA	JFMCC Red I&W	JFMCC Blue Ops	JFMCC -> JFACC	JFMCC C2 -> CSG	JFMCC Red I&W -> CSG	JFMCC Blue Ops - > CSG
C	5000	3000	2000	100	100	1000	500
E	0.00	0.00	0.00	1.00	1.00	1.00	1.00
pf	1.30	1.30	1.30	1.30	1.30	1.00	1.00
KPi	2.00	2.00	2.00	2.00	2.00	1.00	1.00
KF	130000	78000	52000	260	260.00	1000	500
R	1	1	1	2	2	2	2
KE	130000	78000	52000	520	520.00	2000	1000
Ei	0.90	0.90	0.90	0.75	0.75	0.90	0.90
of	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Ek	0.81	0.81	0.81	0.68	0.68	0.81	0.81
KW	105300	63180	42120	351	351.00	1620	810
FT	3600	3600	3600	60	180	2400	2400
KPo	52.65	31.59	21.06	8.78	2.93	0.61	0.30

Table 11 shows the impact JADC2 has on the values for the CSG. The incorporation of JADC2 reduces personal stress on the CSG commander, increasing **pf** to 1.3 for the “CSG SA” column. JADC2 also mitigates the communications issues and information degradation for the CSG raising the **Ei** to a value of 0.85 for the “CSG SA” column. These mitigations also similarly relieve organizational and IT stress experienced by the CSG raising **of** to a value of 0.85 in each of the columns. For the “CSG COP -> JFMCC” column, JADC2 enabled communication paths improve reporting times reducing **FT** to 300, compared to the degraded flow time of 600 but this information still suffers from some information degradation (**Ei** = 0.75). Additionally, the CSG’s local sensors suffer less information degradation (**Ei** = 0.80). In comparison to degradation without JADC2, these mitigations result in an 81% improvement in **KPo** for “CSG SA” (41.34 B to 74.85 B), 406% for “CSG COP -> JFMCC” (0.63 B to 3.19 B), and 29% for “Local Sensors” (35.16 B to 45.33 B).

Table 11. Case 1.2ii JADC2 Enabled: CSG Flow Analysis

Model Params	CSG SA	CSG COP -> JFMCC	Local Sensors
C	2500	1000	1000
E	0.00	1.00	1.00
pf	1.30	1.00	1.00
KPi	1.50	1.00	1.00
KF	48750	1000	1000
R	1	2	5
KE	48750	2000	5000
Ei	0.85	0.75	0.80
of	0.85	0.85	0.85
Ek	0.72	0.64	0.68
KW	35221.88	1275	3400
FT	600	300	60
KPo	74.85	3.19	45.33

5. Case 1.3ii: CSG Denied with JADC2

The following is a breakdown of the knowledge flow analysis from the Case 1.3ii CSG Denied scenario with JADC2 applied, again only relating the impact to the two commanders' (JFMCC, CSG) SA to simplify the analysis and highlight the most critical loss of knowledge flow. Table 12 shows the values for the commanders' SA with the impacted values highlighted in yellow. Just as in the degraded scenario, **pf** for both commanders are impacted but experience a vast improvement of 0.3, a new total value of 1.3 compared to 1.0 in the traditional C2 structure. As opposed to the denied environment with traditional C2 structure, both commanders see their **Ei** and **of** closer to that experienced in the All-Up and Degraded scenarios. With JFMCC experiencing less denial activity the values increase to 0.85 and 0.90 for **Ei** and **of**, respectively. While the CSG values both increase to 0.8 This results in an increase of the JFMCC's **KPo** by 577% (6.94 B to 46.96 B) and 255% for the CSG (17.58 B to 62.40 B).

Table 12. Case 1.3ii JADC2 Enabled Flow Analysis

Model Params	JFMCC SA	CSG SA
C	5000	2500
E	0.00	0.00
pf	1.30	1.30
KPi	2.00	1.50
KF	130000	48750
R	1	1
KE	130000	48750
Ei	0.85	0.80
of	0.90	0.80
Ek	0.77	0.64
KW	99450	31200
FT	3600	600
KPo	46.96	62.40

6. Case 2.1: SAG All-Up

The analysis for Case 2.1: SAG All-Up is similar to Case 1.1: CSG All-Up, though with important variations. Table 13 displays the flow analysis values focusing on the JFMCC. The “JFMCC SA”, “JFMCC Red I&W”, and JFMCC Blue Ops” columns remain unchanged as the information and experience remain constant. The equations produce a **KPo** of 83.33 B for situation awareness, 50.0 B for Red I&W, and 33.33 B for Operations. The next column, “JFMCC -> JFLCC”, represents the new interaction taking place between the Joint Commanders. The method for request of forces between the JFMCC and JFLCC is like that of the JFMCC and JFACC in the CSG scenarios, therefore result in the same values for **KPo** (11.25 B).

The remaining columns are where differences begin to emerge. The SAGC, an O-6, processes 75% of the same knowledge from the CSG scenario as it now applies to the SAG. The “JFMCC C2 -> SAGC” column still represents the JFMCC communicating their C2 knowledge and direction, but now to the SAG commander (**C** = 75 vice 100). The knowledge remains explicit (**E** = 1.0), and Reach remains 2 (**R** = 2). It is still verbal communication occurring over the timespan of one-minute (**Ei** = 0.75, **FT** = 60). The new interaction results in a **KPo** of 8.44 B. Both the “JFMCC Red I&W -> SAGC” and

“JFMCC Blue Ops -> SAGC” represent the JFMCC passing the same knowledge regarding Red I&W and Blue Force operations and orders, respectively, to the SAGC. Chunk values shift from 1,000 to 750 and from 500 to 375 respectively as there is less data to process. **FT** also decreases from 1800 to 1500. **E**, **pf** and **KPi** remain unchanged due to standardized message formats and data sharing. A Reach of 2 and **Ei** and **of** baselined at 1.0, the equations result in the same **KPo** of 1.0 B and 0.5 B, respectively, representing an equal value received from the provided information for both the CSG and the SAGC.

Table 13. Case 2.1 JFMCC Flow Analysis

Model Params	JFMCC SA	JFMCC Red I&W	JFMCC Blue Ops	JFMCC -> JFLCC	JFMCC C2 -> SAGC	JFMCC Red I&W -> SAGC	JFMCC Blue Ops -> CSG
C	5000	3000	2000	100	75	750	375
E	0.00	0.00	0.00	1.00	1.00	1.00	1.00
pf	1.50	1.50	1.50	1.50	1.50	1.00	1.00
KPi	2.00	2.00	2.00	2.00	2.00	1.00	1.00
KF	150000	90000	60000	300	225.00	750	375
R	1	1	1	2	2	2	2
KE	150000	90000	60000	600	450.00	1500	750
Ei	1.00	1.00	1.00	0.75	0.75	1.00	1.00
of	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ek	1.00	1.00	1.00	0.75	0.75	1.00	1.00
KW	150000	90000	60000	450	337.50	1500	750
FT	3600	3600	3600	60	60	1500	1500
KPo	83.33	50.00	33.33	11.25	8.44	1.00	0.50

Table 14 displays the Knowledge Flow analysis values focusing on the SAG. The “SAGC SA” column represents the SAG commander’s personal SA (**R** = 1) after having been inside the Cruiser Combat Information Center (CIC) for 10 minutes (**FT** = 600 s). The chunks of 1,500 and explicitness of 0.0 denotes the local tacit knowledge of all SAG related knowledge available to the commander (i.e., **C**=1,500, **E** = 0.0). The SAG commander is as highly motivated as the JFMCC and CSG Commander (**pf** = 1.5), but even more junior in terms of experience (**KPi** = 1.25). As with the JFMCC, the SAG is operating as normal with no excessive stressors or system issues (**Ei** = 1.0, **of** = 1.0). This

produces a **KPo** of 58.59 B. The “SAGC COP -> JFMCC” denotes the communication of the SAG’s COP knowledge from the SAGC to the JFMCC over a one-minute period (**R** = 2, **FT** = 60s). This again represents the JFMCC receiving near real-time updates but now from the SAG. The information is explicit and either system produced, or highly standardized and Personal Factors and Information Effect are assessed as 1.0 (**E**= 1.0, **pf** = 1.0, **Ei** = 1.0). Additionally, the systems are operating as normal (**of** = 1.0). This produces a **KPo** of 20.0 B. The “Local Sensors” column represents the communication of all the sensor information between the three ships within the SAG over a one-minute period (**R** = 3, **FT** = 60s). Similarly, the information is explicit, and system produced from sensors operating as normal (**E**, **pf**, **Ei**, **of** = 1.0). This produces a **KPo** of 30.0 B.

Table 14. Case 2.1 SAGC Flow Analysis

Model Params	SAGC SA	SAGC COP -> JFMCC	SAG Local Sensors
C	1500	600	600
E	0.00	1.00	1.00
pf	1.50	1.00	1.00
KPi	1.25	1.00	1.00
KF	28125	600	600
R	1	2	3
KE	28125	1200	1800
Ei	1.00	1.00	1.00
of	1.00	1.00	1.00
Ek	1.00	1.00	1.00
KW	28125	1200	1800
FT	600	60	60
KPo	58.59	20.00	30.00

7. Case 2.2i: SAG Degraded

This section describes the Knowledge Flow analysis for Case 2.2i: SAG Degraded and the impact of degraded communications. Table 15 shows the values for each knowledge flow focusing on the JFMCC. Changed values are highlighted yellow. For the “JFMCC SA” through “JFMCC Blue Ops” columns, the impacted rows are **pf**, **Ei**, and **of**.

Again, **pf** represents the added stress experienced by the JFMCC as the devolving scenario continues, changing in value from 1.5 to 1.25. Similar concerns experienced in the Case 1.2i CSG scenario result in **Ei** changing in value from 1.0 to 0.90 due to lower quality information received and **of** also decreasing from 1.0 to 0.75 due to added stress on the JFMCC's organizational staff and IT support affecting their knowledge efficiency. This produces a reduction of 49% in **KPo** across each of the three columns, 83.33 B to 42.19 B for "JFMCC SA", 50.0 B to 25.31 B for "JFMCC Red I&W", and 33.33 B to 16.88 B for "JFMCC Blue Ops".

Interaction between the JFMCC and JFLCC never occurs (**C** = 0) due to the SAG's inability to establish communications resulting in a **KPo** of 0 B. The remaining JFMCC columns, "JFMCC Red I&W -> SAGC" and "JFMCC Blue Ops -> SAGC", only have **Ei** and **of** impacted. Information Effect (**Ei** = 0.90) again due to the quality of the information flowing from JFMCC to SAG and Organizational Factors (**of** = 0.75) from the added stress and impact to IT support to staff. This produces a reduction of 39% in **KPo** for both columns, 1.0 B to 0.61 B for Red I&W and 0.50 B to 0.30 B for Blue Ops.

Table 15. Case 2.2i Traditional C2 Structure: JFMCC Flow Analysis

Model Params	JFMCC SA	JFMCC Red I&W	JFMCC Blue Ops	JFMCC -> JFLCC	JFMCC C2 -> SAGC	JFMCC Red I&W -> SAGC	JFMCC Blue Ops -> SAGC
C	5000	3000	2000	0	0	750	375
E	0.00	0.00	0.00	1.00	1.00	1.00	1.00
pf	1.25	1.25	1.25	1.25	1.25	1.00	1.00
KPi	2.00	2.00	2.00	2.00	2.00	1.00	1.00
KF	125000	75000	50000	0.00	0.00	750	375
R	1	1	1	2	2	2	2
KEF	125000	75000	50000	0.00	0.00	1500	750
Ei	0.90	0.90	0.90	0.75	0.60	0.90	0.90
of	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Ek	0.68	0.68	0.68	0.56	0.45	0.68	0.68
KW	84375	50625	33750	0.00	0.00	1012.5	506.25
FT	3600	3600	3600	60	60	1500	1500
KPo	42.19	25.31	16.88	0.00	0.00	0.61	0.30

Table 16 shows the values for knowledge flows focusing on the SAG in a degraded environment again with changes highlighted in yellow. Similar to the JFMCC, **Ei** and **of** are impacted from the degradation to communications. The SAG commander is also experiencing stress from the communication issues, resulting in a change of **pf** from 1.5 to 1.0. This along with the negative changes in **Ei** (1.0 to 0.8) and **of** (1.0 to .75) result in a reduction of 68% in the “CSG SA” column, from 58.59 B to 18.75 B. The “SAGC COP -> JFMCC” column experiences the greater loss in **Ei** (1.0 to 0.5), representing the limited real-time information flow from the SAG to the JFMCC. “SAG Local Sensors” **Ei** reduces to 0.75 (previously 1.0) because of degraded equipment. The value **of** for each column is reduced from 1.0 to 0.75 for the added stress of the degraded communications. Additionally, **FT** increased by a factor of 10 (60 to 600) for the “SAGC COP -> JFMCC” column because of a delayed form of communication. This produces a reduction of 98% in **KPo** for “SAGC COP -> JFMCC” and a reduction of 58% for “SAG Local Sensors”, 20.0 B to 0.38 B for COP and 30.0 B to 12.66 B for Local Sensors.

Table 16. Case 2.2i Traditional C2 Structure: SAGC Flow Analysis

Model Params	SAGC SA	SAGC COP -> JFMCC	SAG Local Sensors
C	1500	600	600
E	0.00	1.00	1.00
pf	1.00	1.00	1.00
KPi	1.25	1.00	1.00
KF	18750	600	600
R	1	2	3
KE	18750	1200	1800
Ei	0.80	0.50	0.75
of	0.75	0.75	0.75
Ek	0.60	0.38	0.56
KW	11250	450	1012.5
FT	600	600	60
KPo	18.75	0.38	12.66

8. Case 2.3i: SAG Denied

The section is a breakdown of the knowledge flow analysis for Case 2.3i: SAG Denied. This analysis, similar to Case 1.3i: CSG Denied, again only focuses on the impact on the two commanders' (JFMCC, SAGC) SA to denote the most critical knowledge loss across the maritime forces. Table 17 shows the values for the commanders' SA highlighting impacted values in yellow. Like previous scenarios discussed, the **pf** for both commanders are impacted by communication issues, resulting in a value of 1.15. **Ei** and **of** are greatly impacted by the major communication loss. JFMCC's **Ei** reduced to a value of 0.60 due to the loss of timely voice reports and a delayed briefing when able. The loss of communication and subsequent guidance from JFMCC has an even greater effect on the SAGC's SA with a reduction in value to 0.55 but shows the SAG operates more efficiently as compared to the CSG (**Ei** = 0.5). JFMCC staff experiences similar loss to **of** as that in the Case 1.3i CSG scenario but at a slightly lesser value, reducing to 0.60. On the other hand, the SAG **of** has a reduction to 0.75 matching the value of the Case 1.3i CSG scenario, as they are also operating in the Mission Command concept. These impacts to **pf**, **Ei**, and **of** produced a heavy **KPo** reduction for both commanders. For the JFMCC, it is a reduction of 83% compared to the All-Up scenario in Case 2.1 (83.33 B to 13.80 B) and 67% compared to the Degraded scenario in Case 2.2i (60.92 B to 13.80 B). For the SAG commander, it is a reduction of 83% compared to Case 2.1 (58.59 B to 10.19 B) and 46% compared to Case 2.2i (18.75 B to 10.19 B).

Table 17. Case 2.3i Traditional C2 Structure: Denied Flow Analysis

Model Params	JFMCC SAGC Loss	SAGC JFMCC Loss
C	5000	1500
E	0.00	0.00
pf	1.15	1.15
KPi	2.00	1.25
KF	115000	21562.5
R	1	1
KE	115000	21562.5
Ei	0.60	0.55
of	0.60	0.75
Ek	0.36	0.41
KW	41400	8894.53
FT	3600	600
KPo	13.80	10.19

9. Case 2.2ii: SAG Degraded with JADC2

The following is a breakdown of the knowledge flow analysis of Case 2.2ii SAG Degraded with JADC2. Table 18 shows the values of the flow analysis with the impact JADC2 enables. The affected variables remain **pf**, **Ei** and **of**, but to a lesser extent due to data and communication paths being established through other means available. This results in a 1.35 for all JFMCC **pf** to denote less stress experienced credited to alternative communication paths. Additionally, **Ei** increases to 0.95 from 0.90, as experienced in the Case 2.2i traditional C2 structure, since some written messages find alternatives paths and do not need to be communicated over voice links. As a result of the lifted stress to communication networks, staff and IT support experience an increase in **of** from 0.75, seen with traditional C2 structures, to 0.90. When compared to the Case 2.2i degraded scenario with the traditional C2 structure, these improvements see the JFMCC's SA increase 44% to a **KPo** value of 60.92 B. JFMCC Red I&W and Blue Force Ops also both increased 44% (**KPo** = 36.55 B and **KPo** = 24.37 B), respectively. The alternative communication paths enable the SAG to receive reports and orders from the JFMCC, though with slight delays. These delays are presented into the equation using increased **FT**. As in Case 1.2ii CSG

scenario with the Joint Commanders, communication now occurs between JFMCC and JFLCC. This is still a one-minute verbal conversation over submarine cable (**Ei** = 0.75, **of** = 1, **FT** = 60) and produces a **KPo** of 9.11 B for “JFMCC -> JFLCC” and 3.04 B for “JFMCC C2 -> SAG”. An obvious improvement over the 0.0 in the degraded without JADC2 scenario, but still a respective reduction of 19% and 64% from the All-Up scenario. The “JFMCC Red I&W -> SAG” and “JFMCC Blue Ops -> SAG” columns experience a respective increase of 11% and 13%. An increase in **KPo** from 0.61 B to 0.68 B for Red I&W and 0.30 B to 0.34 B for Blue Ops.

Table 18. Case 2.2ii JADC2 Enabled: JFMCC Flow Analysis

Model Params	JFMCC SA	JFMCC Red I&W	JFMCC Blue Ops	JFMCC -> JFLCC	JFMCC C2 -> SAGC	JFMCC Red I&W -> SAGC	JFMCC Blue Ops - > SAGC
C	5000	3000	2000	100	100	750	375
E	0.00	0.00	0.00	1.00	1.00	1.00	1.00
pf	1.35	1.35	1.35	1.35	1.35	1.00	1.00
KPi	2.00	2.00	2.00	2.00	2.00	1.00	1.00
KF	135000	81000	54000	270	270.00	750	375
R	1	1	1	2	2	2	2
KE	135000	81000	54000	540	540.00	1500	750
Ei	0.95	0.95	0.95	0.75	0.75	0.95	0.95
of	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Ek	0.86	0.86	0.86	0.68	0.68	0.86	0.86
KW	115425	69255	46170	364.5	364.50	1282.5	641.25
FT	3600	3600	3600	60	180	1800	1800
KPo	60.92	36.55	24.37	9.11	3.04	0.68	0.34

Table 19 represents JADC2’s influence on the SAG and SAGC. “SAGC SA” **pf** increases to 1.25, a lesser increase than that seen of the JFMCC due to higher stress levels within theater. This also contributes to the slight increase in **Ei** (0.90) and **of** (0.85), but results in a 79% increase in SAGC **KPo** (33.62 B vice 18.75 B). The “SAGC COP -> JFMCC” column displays similar value increases as those experienced by the JFMCC, an **Ei** and **of** equal to 0.85 (0.5 and 0.75 in traditional C2, respectively). Flow Time changes slightly due to the alternative pathways with limited transmission resulting in a **KPo** equal

to 2.46 B, a 547% increase. “SAG Local Sensors” are not affected by transmission times and see no change to **FT**, however with the new **Ei** and **of** values for the SAG (**Ei** = 0.80, **of** = 0.85), the **KPo** increases by 29% (**KPo** = 16.32 B) from relief of communication errors and poor link qualities.

Table 19. Case 2.2ii JADC2 Enabled: SAGC Flow Analysis

Model Params	SAGC SA	SAGC COP -> JFMCC	SAG Local Sensors
C	1500	600	600
E	0.00	1.00	1.00
pf	1.25	1.00	1.00
KPi	1.25	1.00	1.00
KF	23437.50	600.00	600.00
R	1	2	3
KE	23437.50	1200.00	1800.00
Ei	0.90	0.85	0.80
of	0.85	0.85	0.85
Ek	0.77	0.72	0.68
KW	17929.69	867.00	1224.00
FT	600	300	60
KPo	33.62	2.46	16.32

10. Case 2.3ii: SAG Denied with JADC2

The following is a breakdown of the knowledge flow analysis from the Case 2.3ii SAG Denied scenario with JADC2 applied. This analysis again only relates the impact on the two commanders’ (JFMCC, SAGC) SA, again, for ease of reading and highlighting the most impactful loss of knowledge flow. Table 20 shows the values for the commanders’ SA with the impacted values highlighted in yellow. Just as in the Case 2.2ii Degraded scenario the **pf** for both commanders’ is impacted but JFMCC experiences a vast improvement of 0.2, a new total value of 1.35 (previously 1.15), whereas the SAGC sees a slight increase to 1.25 (previously 1.15) again due to added stresses of in theater operations. As opposed to the denied environment with traditional C2 structure, both commanders see their **Ei** and **of** close to a similar difference of that experienced in the All-Up and Degraded

cases, JFMCC **Ei** and **of** now 0.9 (previously 0.6) and SAGC **Ei** equal to 0.85 (previously 0.55) and **of** equal to 0.8 (previously 0.75). This results in an increase of the JFMCC's **KPo** by 296% (**KPo** = 54.68 B, previously 13.8 B) and 299% for the SAGC (**KPo** = 40.64 B, previously 10.19 B).

Table 20. Case 2.3ii JADC2 Enabled Flow Analysis

Model Params	JFMCC SAGC Loss	SAGC JFMCC Loss
C	5000	1500
E	0.00	0.00
pf	1.35	1.25
KPi	2.00	1.50
KF	135000.00	28125.00
R	1	1
KE	135000.00	28125.00
Ei	0.90	0.85
of	0.90	0.80
Ek	0.81	0.68
KW	109350.00	19125.00
FT	3600	600
KPo	54.68	40.64

B. RESULTS

Knowledge Flow Theory and the results stemming from these scenarios create insights as to the value of knowledge within an organization. Using theoretical values, this model highlights devastating effects a maritime force can experience due to degraded or denied environments. With limited resources available to describe the role JADC2 will play within these environments, the values selected demonstrate a best-case scenario in C2 critical communications. Tables 21 and 22 display the **KPo** values compared across the different scenario cases. To represent total Knowledge Power output for each commander, the following values are added: For JFMCC, **KPo** values for JFMCC SA, CSG/SAG COP -> JFMCC, and JFMCC <-> JFACC/JFLCC; For the CSG/SAGC, **KPo** values for CSG/

SAGC SA, CSG/SAG Local Sensors, JFMCC Red I&W -> CSG/SAG, JFMCC Blue Ops -> CSG/SAG, and finally JFMCC C2 -> CSG/SAGC. The **KPo** values for the JFMCC Red I&W and the JFMCC Blue Ops are not included in the summation as they simply represent a further breakdown of the JFMCC's SA column.

Table 21. Knowledge Power Output: All-Up and Degraded Cases

	All-Up	Degraded	JADC2 Degraded
JFMCC Cumulative SA - CSG Scenario	127.92	36.75	64.61
CSG Cumulative SA	236.88	76.81	124.02
JFMCC Cumulative SA - SAG Scenario	114.58	42.56	72.49
SAG Cumulative SA	98.53	32.32	53.99

Table 22. Knowledge Power Output: Denied Cases

	Denied	JADC2 Denied
JFMCC CSG Loss	6.94	46.96
CSG JFMCC Loss	17.58	62.40
JFMCC SAG Loss	13.80	54.68
SAGC JFMCC Loss	10.19	40.64

The cumulative situation awareness **KPo** values result in a 71% loss in Knowledge Power output for JFMCC in the CSG Degraded scenario and a 63% loss in the SAG Degraded scenario. Similarly, the CSG experiences a 68% loss and the SAG experiences a 67% loss. The denied cases offer a critical look in the extensive loss in Knowledge Power that can be expected with a complete loss of satellite communications in the traditional C2 environment. The JFMCC sees a decrease of 95% for the CSG scenario and that of 88% loss for the SAG scenario. The CSG experiences a 93% loss, while the SAGC only sees a 90% decrease.

JADC2 demonstrates a significant improvement in retaining Knowledge Power output. The Degraded scenario results show a lesser impact of 49% loss for JFMCC SA in the CSG case and a 37% loss for the SAG case. Correspondingly, the CSG SA drops 48%

and the SAG, 45%. The Denied scenario demonstrates a limited loss of similar proportion to that of the Degraded values, with the JFMCC experiencing a 63% loss for the CSG case and a 52% loss for the SAG case and the CSG commander seeing a 74%, and the SAGC seeing a 59% loss. Comparing the **KPo** values in the traditional C2 and theoretic JADC2 environments shows a vast improvement but does not represent an error free situation. With JADC2 enabled, the JFMCC experiences an increase of 76% in Knowledge Power output when compared to traditional C2 structures in a degraded environment for the CSG case and a 70% for the SAG case. Similarly, the CSG increases efficiency by 61% and 67% for the SAG. In a denied environment, JADC2 provides an increase of 576% for the JFMCC for the CSG case and a 296% increase for the SAG case, a 254% improvement for the CSG's **KPo**, and 298% for the SAG's. This can be correlated to the substantial amount of information a CSG can provide for the C2 operational picture.

An aspect that allows for this improvement is how JADC2 affects the values of Personal Factors (**pf**), Organizational Factors (**of**), and Information Effect (**Ei**). Recalling the fully extended **KPo** equation, $KPo = [(C \text{ pf of } Ei^2 KPi^2 R) \times (int - [sl \times E \wedge nl])] / FT$, any decrease in **pf**, **of**, or **Ei** result in a decreased **KPo**, while a decrease in **FT** increases **KPo**. As JADC2 is envisioned, the systems capabilities would alleviate stressors on both the personal commander and organization, especially their IT support and how information is processed and transmitted (i.e., increasing **pf**, **of**, and **Ei**). Additionally, envisioned future JADC2 capabilities should enable faster Flow Time in certain situations and thus leads to an even greater increase in Knowledge Power output.

V. CONCLUSIONS AND FUTURE STUDY

The Knowledge Flow Theory methodology provides a unique ability to display the impact associated with a loss of knowledge within an operation. As represented in the scenario, both the CSG and SAG experienced a large impact to total Knowledge Power output and information flow caused by degraded and denied environments. For JADC2 to have an impact, it must bridge the gaps in communication paths to allow the knowledge and experience of higher echelon commanders to flow directly to the in-theater forces. However, also demonstrated in the scenarios, Mission Command operations allow for a freedom of operations unique to the United States Military, but the mission must be understood at all levels. The continued development of sophisticated technologies by near peer adversaries presents a great risk to a traditional C2 approach. A2/AD environments have the capacity to greatly limit information and knowledge flow within theater. JADC2 can play a critical role in limiting the impact in an A2/AD environment but cannot be expected to relieve all issues. The Navy's role in JADC2 and its Navy Tactical Grid project has the potential to offer knowledge flow in scenarios it would otherwise be denied.

A. POTENTIAL BENEFITS

The knowledge flow model proposed and analyzed in this thesis offers several areas of potential benefits. The model itself is a quantitative way to measure information flow and its resulting Knowledge Power and can be utilized and further refined to provide beneficial insights into JADC2 development requirements and efforts. Additionally, the use of this model can highlight critical areas of interest which should be prioritized in the JADC2 design. The results of the analysis give insight into the impacts that different levels of communication degradation would have on knowledge flows across a Joint Force. This model can be replicated throughout other C2 structures to expose bottlenecks limiting knowledge flow within other organizations. The model and its results can be paired with other areas of C2 research to measure the effects that result from changes to C2 structures and practices have on Knowledge Power, and thus the efficiency of decision making across C2 approach spaces.

B. LIMITATIONS

There are several limitations to address in this thesis. As this thesis primarily utilized a hypothetical scenario and equally hypothetical implementation of JADC2, the values used in the knowledge flow analysis were theoretic in nature. Each value can easily change once measured and studied in future research. Additionally, the model was developed from the current state of research in Knowledge Flow Theory. As research in that field progresses the model and analysis of this thesis will become more obsolete. Future study utilizing advances in Knowledge Flow Theory will then need to be conducted to update the model and highlight any significant changes. The model itself is also limited in that only a select few knowledge flows were analyzed. As the amount of knowledge flows at the scale of a JTF are numerous, the authors of this thesis only selected ones believed to provide the most significant insight. Future study may find other knowledge flows that are of equal or greater significance to this area of research.

C. FUTURE STUDY

The model this thesis proposes presents a multitude of avenues for future research. Again, as the values included in this thesis are theoretical in nature, a prime area of future study is in developing and conducting empirical studies on the values and factors of each knowledge flow. This includes studies for ways to accurately measure the values of chunks (**C**) and Flow Time (**FT**) at both the tactical unit levels and maritime operations center. Additionally, the extended factors of Personal Factors (**pf**), Organization Factors (**of**), and Informational Effect (**Ei**) can be refined by future study to identify specific factors of limitation or enhancements related to each organization and develop more accurate values. Example studies include research on the stress experienced by the personal commanders, as well as the total organization or unit, when communication is impacted to gain insight into more accurate values of **pf** and **of**. Future study can also include research on how, and at what scale, information degrades due to communication issues and delays. This will allow for better refinement and accuracy for the values of **Ei**. For each of these values empirical studies will lead to a more refined and accurate model that better reflects what a Joint Force would experience.

Another avenue of research is on the side of JADC2. As the DoD and services develop and field JADC2 technologies, future studies can refine the model of this thesis to better reflect the impact of JADC2 on each knowledge flow. Future study expanding this model can add further insight into knowledge requirements of a Joint Force and provide more beneficial inputs into the development efforts of JADC2.

Since the model of this thesis is based on current research in Knowledge Flow Theory, future research in KFT and the associated equations can lead to a better refined model. With progression in the KFT equations the model can be updated to include this progress and provide further insight than as proposed in this thesis. As this thesis primarily analyzes a Joint force operating in a traditional military organization that utilizes a problem solving C2 structure (Mission Command), future study can further apply this model to a force operating with different C2 structures and approach spaces. Such as those Alberts and Nissen (2009) discuss.

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