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Assessing the Value of Information Superiority for Ground Forces – Proof of Concept

Dan Gonzales, Lou Moore, Chris Pernin, David Matonick, Paul Dreyer

National Defense Research Institute

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Prepared for the Joint C4ISR Decision Support Center

National Defense Research Institute

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PREFACE

This report describes a new simulation model designed to assess the value of Information Superiority or Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) capabilities for ground forces. This model includes autonomous decisionmaking on both sides. Opposing force commanders can take advantage of battlefield situation awareness information to alter offensive or defensive maneuver operations. Thus, this model enables quantitative analysis of the value of information in the decisionmaking and command-and-control processes of ground force commanders. Initial results obtained using this proof-of-concept model are also presented in this report.

This research should be of interest to those involved in assessing the military utility and operational value of C4ISR systems for U.S. ground forces, and to those interested in simulation models of military forces containing autonomous adaptive agents and independent decisionmaking capabilities.

This study is sponsored by the joint C4ISR Decision Support Center. It is being conducted in the Acquisition and Technology Policy Center of RAND's National Defense Research Institute (NDRI), a federally funded research and development center (FFRDC) sponsored by the Office of the Secretary of Defense and the Joint Staff. Please direct any comments on this report to the project leader,

Daniel Gonzales

(703) 413-1100 x5281

Daniel_Gonzales@rand.org

or to the director of the Acquisition and Technology Policy Center,

Eugene C. Gritton

(310) 393-0411 x7010

Gene@rand.org

SUMMARY

In this report we examine the importance of Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems for ground force maneuver operations. Advanced C4ISR systems are intended to provide Information Superiority (IS), or the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same.[1] However, a growing number of analysts and military operators view Information Superiority not as an end in itself but as a means of achieving what some term Decision Superiority. Decision Superiority is defined as the ability to make better decisions and to arrive at and implement them faster than an opponent can react. Decision Superiority is viewed as the essential or desired output of having IS,[2] and IS is viewed increasingly as important to the command decisionmaking process. Therefore, to evaluate the true military value of C4ISR systems, one should evaluate and take into account the quality of the information provided by C4ISR systems to the command decisionmaking process. For this type of analysis, new IS metrics and new tools are needed. These are the subjects of this project and proof-of-concept model demonstration.

In this analysis all of the C4ISR systems were linked to autonomous decisionmaking agents that simulated division and brigade commanders. These decisionmaking agents were implemented in a notional operational-level scenario in which the quality of situation awareness data provided to ground force units can be varied as a function of the performance of the C4ISR system architecture, thereby making it possible to determine the impact of C4ISR system performance on combat outcome. For this purpose we employed the System Effectiveness Analysis Simulation (SEAS) and augmented this agent-based model by incorporating command-and-control (C2) agents capable of adaptive command decisionmaking based on dynamic battlefield awareness information.

SEAS was originally developed to assess the military utility of space systems but has been adapted by RAND to assess the value of a wide range of C4ISR systems. The version of SEAS used in this effort enables the modeler to incorporate adaptive decisionmaking behaviors into individual ground force units simulated in the model.

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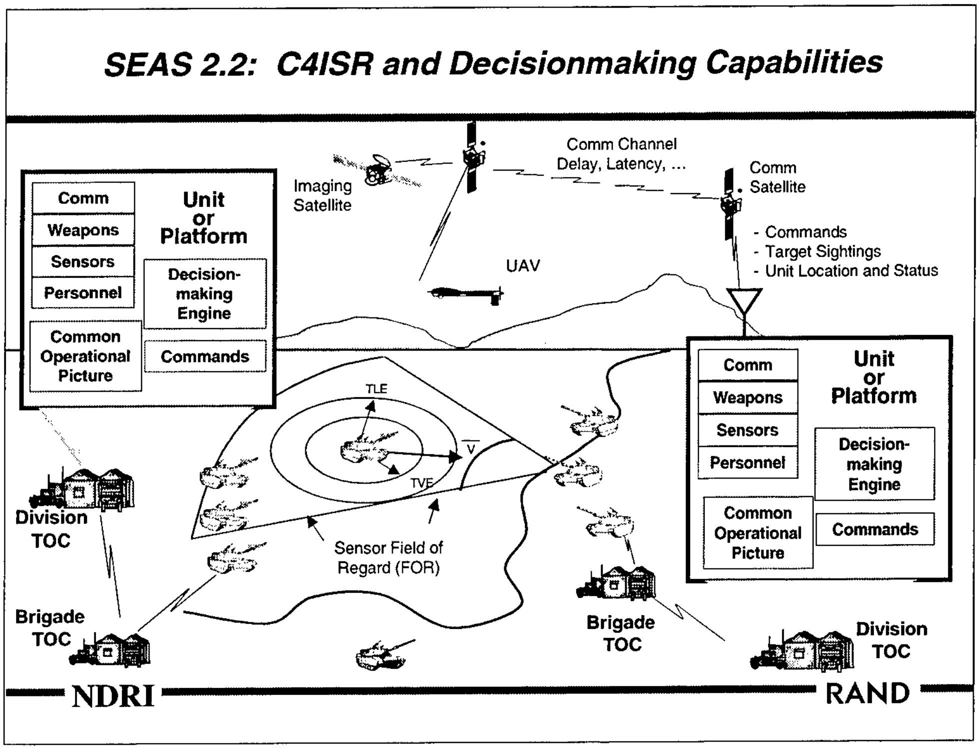
[1] DoD *Dictionary of Military and Associated Terms,* Joint Publication 1-2, Joint Chiefs of Staff, 12 April 2001.

[2] *Joint Vision 2020,* Joint Chiefs of Staff, November 2000.



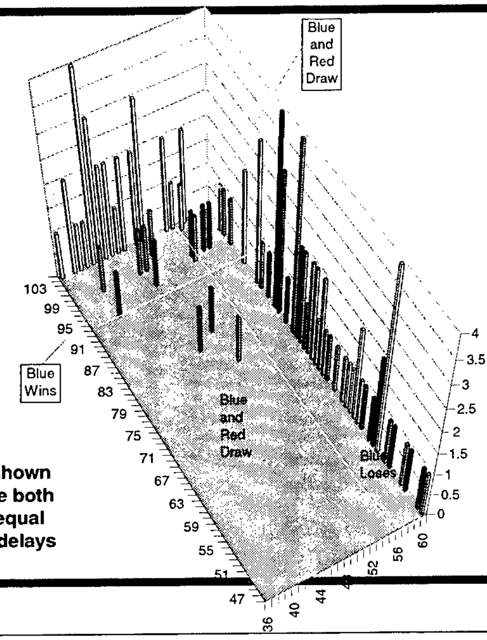
The chart above describes the essential components of this proof-of-concept model. The simulated division commander has access to theater-level Intelligence, Surveillance, and Reconnaissance (ISR) capabilities—long-range unmanned aerial vehicles (UAVs). Brigade commanders have access to close battle area ISR capabilities—short-range UAVs. Division and brigade echelons are connected by communications networks that transmit C2 and situation awareness information. Tanks are equipped with their own organic Forward Looking Infrared (FLIR) sensors and share locally generated and theater-level situation awareness information with other tanks in each unit via a tactical Internet. Message delivery time delays in these communications networks can be adjusted parametrically. It should be emphasized that in the model simulated, Blue and Red commanders make decisions on the basis of only the battlefield awareness information available to them—not ground truth.

The command decisionmaking algorithms used in the model are based on the Correlation of Forces and Means (COFM), a decisionmaking logic system that is described in detail in the body of this report. In COFM estimates of friendly force combat capability for specific areas of the battlefield are made based upon unit status and location reports. Estimates of enemy combat capability are developed for specific areas of the battlefield based on the Common Operational Picture (COP) available to those commanders. The COFM decisionmaking engine combines these estimates of force effectiveness with time, distance, and terrain factors to compute a likelihood of operations success. Using these algorithms, a unit commander can compare his own location and those of his subordinate units to given maneuver goals and subgoals. Unit commanders can modify their maneuver plans, orientation, and weapons readiness state based on analysis of their local COP. Unit commanders can also direct subordinate units to change their maneuver plans and their state.

In the particular notional scenario considered in this proof-of-concept analysis, Red initiates a series of attacks and attempts to invade Blue territory. The Red maneuver plan includes a series of intermediate and ultimate objectives. In the scenario Blue is in a defensive posture and attempts to defend its front line. In those cases where Blue cannot defend its Blue front line, units retreat to defend the main Blue base located deep in Blue territory. At each stage in the battle, Red and Blue unit commanders use the COFM algorithm to monitor the likelihood of success of ongoing operations. The COFM algorithm is used to determine whether attack or defensive operations are likely to be successful and whether objectives can be achieved or maintained. Based on this analysis, Red and Blue commanders can adjust their maneuver plans.

Initial results from this proof-of-concept model indicate that combat outcomes depend critically on C4ISR architecture performance. In the particular scenario we examined, Red has an approximate two-to-one force advantage over Blue, but Blue has a maneuver advantage in terms of the speed of its combat vehicles. We found that C4ISR system performance is critically important to Blue but much less so to Red.

Win and Loss Criteria



Results histogram shown is for the case where both Red and Blue have equal 15-minute decision delays

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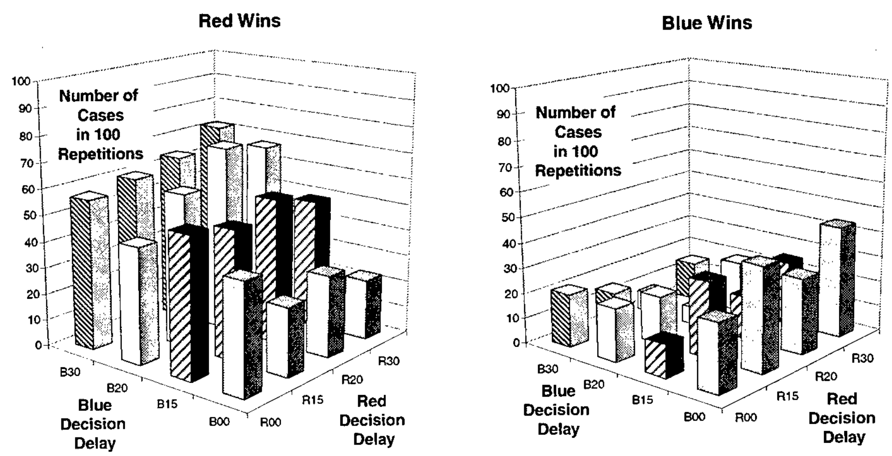
Because of the wide possible variation in results for individual model runs, we developed an aggregation method for capturing the main features of these runs—overall combat outcome. This aggregation approach is based on battle win and loss criteria in which we have divided up the loss-exchange ratio (LER) results space into four quadrants as indicated above. Blue wins if the LER falls into the upper left-hand quadrant. Blue loses if the LER falls into the upper right-hand quadrant. The battle is a draw if the LER falls into the other two quadrants.

The histogram above, which is used to illustrate the win and loss criteria, corresponds to the case in which both Red and Blue have equal 15-minute decision delays and minimal communications delays. The plot shows the number of Red and Blue combat vehicles lost in each simulation run (up to a total of 105 Red and 60 Blue combat vehicles—as indicated by the "walls" of the histogram above). A total of 100 runs were made; in some cases multiple runs resulted in the same combat outcome or LER, as is indicated by the Z or vertical axis of the histogram. As is apparent from the chart, this distribution of results is broad and does not appear to converge to a single LER value. We believe this is the case because of the large set of possible decisions Blue and Red commanders can make (or the large decision space) inherent in this unscripted model of dynamic C2 decisionmaking.

Summary of Results for the Decision Delay Cases



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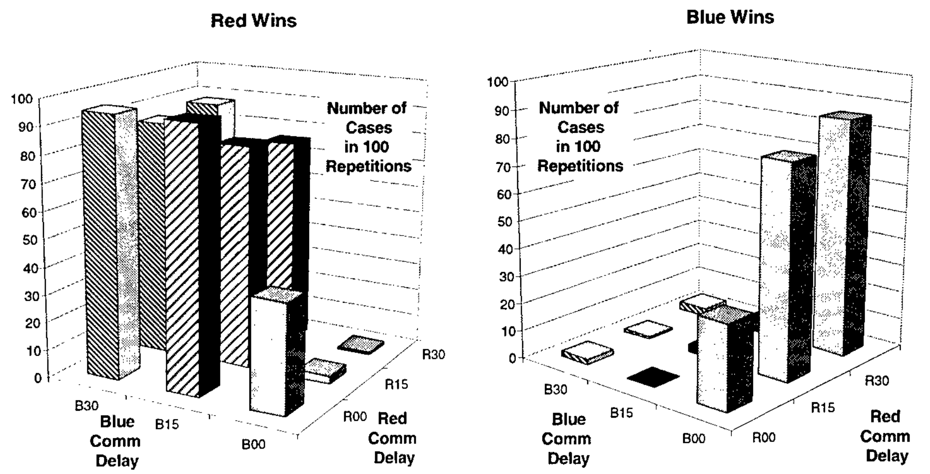
These charts summarize results for all of the decision delay cases considered where communications delays were held to a minimum. Battle results were grouped into four bins: Blue wins, Red wins, Blue and Red both win, and draws. If a side loses 90 percent or more of its vehicles, that side loses. Otherwise, the side wins or draws. If neither side loses, the battle is declared a draw. Not shown is the number of times that Blue and Red draw. Draws occurred 20 to 30 percent of the time.

From the charts it is evident that if Blue has a decision delay of 15 minutes or more, it loses most of the time. On the other hand, if Blue has a short decision delay (the B00 case, which corresponds to approximately a 1-minute decision delay), then Blue has a much better chance of winning, especially if Red suffers from a substantial decision delay.

It is interesting to note that Red has less dependence on decision delay than does Blue if Blue suffers from a decision delay of 15 minutes or more. In many such cases Red has a greater chance of winning with a longer decision delay. In these cases it would appear that if Red simply sticks to its plan and does not try to outmaneuver Blue it can take better advantage of its numerical force advantage. Note that Blue wins four times as often in the B00R30 case as in the B30R00 case.

Summary of Comm Delay Results for Minimum Red and Blue Decision Delays



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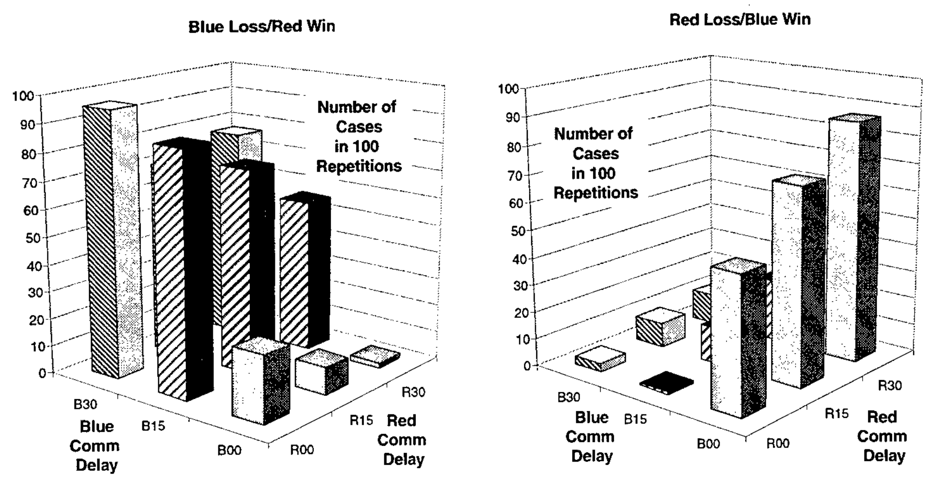
Shown here is the summary of communications delay results for the case where both Red and Blue have minimum decisionmaking delay. In this case Blue has very little chance of winning if there is any sizable time delay in its communications networks. On the other hand, Blue wins in most cases if it has minimum communications net delays and if Red communications networks have a message delivery time delay of 15 minutes or more. What is striking about these results is the major change in outcome as a function of relative communication delay. There is a sharp "knee in the curve" somewhere between Blue time delays of 0 and 15 minutes, indicating a strong nonlinear dependence of combat outcome on communications time delay. More sensitivity analysis is needed to determine exactly where this knee in the curve is.

Summary of Comm Delay Results for the Red 30 and Blue 1 Decision Delay Case



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Shown here are results for the communications net time delay cases in which Blue also has a 30-minute advantage in decision delay. As is evident from the chart, the same strong dependence on relative communication delay is evident as is seen in the prior results. Blue's chance of winning, however, is even greater with greater relative advantage in decision delay if Blue's communication delay is set to a minimum.

Summary

- We have developed a sophisticated model of dynamic C2 decisionmaking
  - Command structures and decision engines have general applicability
  - C2 decisions causally linked to comm and ISR system performance
- Results indicate strong nonlinear dependence of combat outcomes on C3ISR architecture performance
  - Decision or comm delay advantage is critically important to Blue, much less important to Red
  - Blue wins most of the time if it has significant decision delay advantage
  - Blue wins or draws most of the time if it has zero comm delays in its networks
- Deep battle surveillance valuable for more than deep targeting
  - Model can assess the operational level advantages provided by situation awareness of the deep battle area

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We have developed a two-sided model of ground warfare that includes adaptive agents that can simulate dynamic C2 and decisionmaking processes. The decisionmaking logic implemented is based upon the COFM. Because of the flexibility inherent in COFM, this model has general applicability beyond the notional scenario used in this proof-of-principle analysis. Further, command decisionmaking processes are causally linked to C4ISR system performance in this model because the decisions made by simulated commanders are based on the situation awareness information delivered to those commanders by onboard sensors and by communications links to off-board sensors—not ground truth.

The results indicate a strong nonlinear dependence of combat outcome on decision and communications time delays. As indicated in the chart above, Blue is more dependent on superior C4ISR system performance and decisionmaking advantage than is Red because of Blue's numerical force disadvantage. Despite this disadvantage, Blue wins 80 percent of the time if it has an advantage in both decisionmaking and communications network performance. These results hold when both Red and Blue have very good ISR coverage of the close battle area and neither side has any ISR coverage of the opposing side's rear area.

CONTENTS

ACKNOWLEDGMENTS

The authors thank Greg McNeill and his SEAS development team at Computer Sciences Corporation for their help and support, especially for their quick response in fixing bugs and adding needed features in SEAS during the course of this project. Robert Weber and Farhad Zaerpoor of Aerospace Corporation also shared their insights and expertise on some of the modeling challenges we encountered during this research. We thank them for their assistance. We express our appreciation to project sponsor Chuck Taylor, deputy director of the Decision Support Center, and his special assistant, Hans Keithley, for the insightful guidance and review of our work. Finally, we thank Leland Joe of RAND for his careful and thoughtful review of this work, and Myron Hura for sharing his insights and for his astute guidance.

ACRONYMS

AGL	Above Ground Level
ATCAL	Attrition Calibration
BDA	Battle Damage Assessment
CAS	Complex Adaptive System
C2	Command and Control
C4ISR	Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance
CEP	Circular Error Probability
CEUR	Central Europe
COA	Course of Action
COFM	Correlation of Forces and Means
CONOPS	Concepts of Operation
CONUS	Continental United States
COP	Common Operational Picture
CSC	Computer Sciences Corporation
FCS	Future Combat System
FIFO	First In, First Out
FLIR	Forward Looking Infrared
FOR	Field of Regard
IPB	Intelligence Preparation of the Battlefield
IS	Information Superiority
ISR	Intelligence, Surveillance, and Reconnaissance
IBCT	Interim Brigade Combat Teams
JV	Joint Vision
LER	Loss-exchange ratio
LOS	Line of sight

MDMP	Military Decisionmaking Process
METT-T	Mission, Enemy, Tactics & Terrain, Troops and Time
MOE	Measure of Effectiveness
MOO	Measure of Outcome
MOP	Measure of Performance
MTI	Moving Target Indicator
Pd	Probability of Detection
PDF	Probability Density Function
Pk	Probability of Kill
QRA	Quick Reaction Analysis
RSS	Route sum of squares
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SBL	Space-Based Laser
SEAS	System Effectiveness Analysis Simulation
SOAP	Satellite Operations Analysis Program
SUA	Standardized Unit Armament
TAO	Tactical Area of Operation
TBM	Tactical Ballistic Missile
TEL	Transporter Erector Launcher
TLE	Target Location Error
TVE	Target Velocity Error
UAV	Unmanned aerial vehicle
WEI	Weapons Effectiveness Index
WUV	Weapons Unit Value

Assessing the Value of Information Superiority for Ground Forces

- Phase I Results -

Dan Gonzales, Lou Moore, Chris Pernin, David Matonick, Paul Dreyer

March 25, 2001

NDRI RAND 1

The subject of this briefing is a new proof-of-concept simulation model designed to assess the value of Information Superiority (IS) or Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) capabilities for U.S. ground forces. We describe the model and present initial results obtained using it in a notional scenario. The results obtained relate combat outcome to command decisionmaking processes and to C4ISR system capabilities.

Outline

- ➡ ❑ Introduction
  - Background
  - Objectives
- ❑ SEAS
- ❑ Autonomous C2 Decisionmaking and the Correlation of Forces and Means
- ❑ Scenarios, C4ISR Capabilities, and Decision Spaces
- ❑ Results

NDRI RAND 2

Shown here is the report outline. In the introduction we briefly discuss the importance of IS for future U.S. ground forces, the relationship of IS to command decisionmaking, and why it is important to understand the relationship of IS and command decisionmaking to ground force combat effectiveness. Next we discuss the objectives and the analytical approach for Phase 1 of this project.

In the next section, we describe the simulation system—the System Effectiveness Analysis Simulation (SEAS)—that was adapted and enhanced to address the objectives of this research.

In the third section, we describe the decisionmaking algorithms or expert systems that were incorporated into SEAS that enabled simulated opposing ground forces to make autonomous decisions based upon information provided to individual commanders.

In the fourth section, we describe the notional scenario, its characteristics from a Command and Control (C2) standpoint, and the C4ISR capabilities assumed in this initial proof-of-concept model.

Finally, we describe the results obtained in this analysis and end with some observations on IS concepts for future Army ground forces.

Information Superiority and Decisionmaking

Information Superiority (IS)
The capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same.
Joint Pub 1-2

Information Superiority
...not an end in itself.... Joint force must ...achieve "decision superiority" – better decisions arrived and implemented faster than an opponent can react...
Joint Vision 2020

- **Information superiority identified as important to command decisionmaking process**
- **Information quality (accuracy, completeness, timeliness, and relevance) important for achieving operational advantage and Decision Superiority**

NDRI RAND 3

IS has been identified as a key element of U.S. doctrine. Shown in the box on the left is the joint definition of IS. This definition emphasizes generating and protecting the flow of information within U.S. C4ISR systems, and disrupting or preventing the flow of information within enemy C4ISR systems.

In Joint Vision (JV) 2020, IS has been tied to the commander's decisionmaking process. IS is an important foundation element in JV 2020 and is seen as an enabler for improved, rapid, and "smart" command decisionmaking—or so-called Decision Superiority. This implies that the contributions of C4ISR systems should be evaluated not just at the technical level (e.g., how quickly and accurately systems collect and transmit information) but also at a higher level that can be related to emerging joint doctrine and operational-level command decisionmaking processes. In other words it is important to determine how the information supplied by C4ISR systems helps to achieve operational advantages that in turn result from dynamic command decisionmaking.

Information Superiority in Ground Warfare

- ❑ **U.S. Army investing heavily in C4ISR capabilities**
  - **Army may trade mass and firepower for lighter, more mobile digitized forces**
- ❑ **Information Superiority is the key underlying assumption of Army investment strategy**
- ❑ **Value and role of Information Superiority in ground warfare needs to be better understood**

NDRI RAND 4

The U.S. Army is investing heavily in C4ISR systems. Army plans call for Army units to be converted or "digitized" according to an aggressive force modernization schedule. Army transformation plans also call for the creation of Interim Brigade Combat Teams (IBCTs). These units will be equipped with lighter and more mobile medium-weight armored vehicles. IBCTs will be more deployable and able to serve as early entry forces in many types of contingencies. However, IBCT armored vehicles may be more vulnerable to large-caliber direct-fire weapons. To enhance IBCT combat effectiveness and survivability, they will be equipped with advanced C4ISR systems capable of providing timely and accurate off-board situation awareness and threat warning information well before adversary forces can employ their direct fire weapons. Thus, the timely delivery of accurate and complete situation awareness information, provided by Army and supporting joint C4ISR architectures, will be as critically important to Army transformation forces as it is to current forces, if not more so.

The Army is also designing systems for next-generation ground forces, the Objective Force, which will be equipped with technologically advanced lighter, more-mobile combat vehicles—the Future Combat System (FCS). If current conceptual designs are adopted, the Objective Force will depend, to a much greater degree than do current forces, on indirect fires and on robotic systems. Robotic FCS reconnaissance vehicles will collect situation awareness and targeting information for other elements of the force, including robotic indirect-fire systems that will be commanded remotely or that may even operate autonomously. Tight C2 linkages will be required between elements of the force, and it will depend on robotic systems to collect timely and accurate situation awareness information on threats that are beyond line of sight. These force characteristics imply that advanced C4ISR systems and the IS concepts they will support may be critically important to the Objective Force. This suggests that the role of IS and the operational value of C4ISR systems in ground warfare should be better understood in order to help ensure that adequate investments are made in supporting C4ISR systems. At the request of the sponsor, we have limited our analysis to forces on the ground and have not considered the effect of C4ISR on air forces, although a similar analysis can certainly be performed.

Project Objectives

- ❑ **Verify existing autonomous dynamic C2 capabilities of ground force units in SEAS 2.2**
- ❑ **Improve SEAS to enable adaptive ground force command decisionmaking based on dynamic battlefield awareness information**
- ❑ **Develop a notional operational/tactical-level scenario and compare situation awareness data of appropriate ground units**

NDRI RAND 6

Shown in this chart are the three objectives of this initial proof-of-concept research project. The first was to verify the autonomous dynamic C2 capabilities of the latest version of SEAS, version 2.2. This version of the model enables the user to create adaptive agents capable of autonomous behavior and decisionmaking.

The second objective was to enable adaptive ground force command decisionmaking based on dynamic battlefield information. In this particular research, autonomous agents were created to emulate the decisionmaking processes of ground force commanders. As explained in more detail later in this report, the decisions made by simulated commanders were dependent on the information supplied to them by the C4ISR architecture.

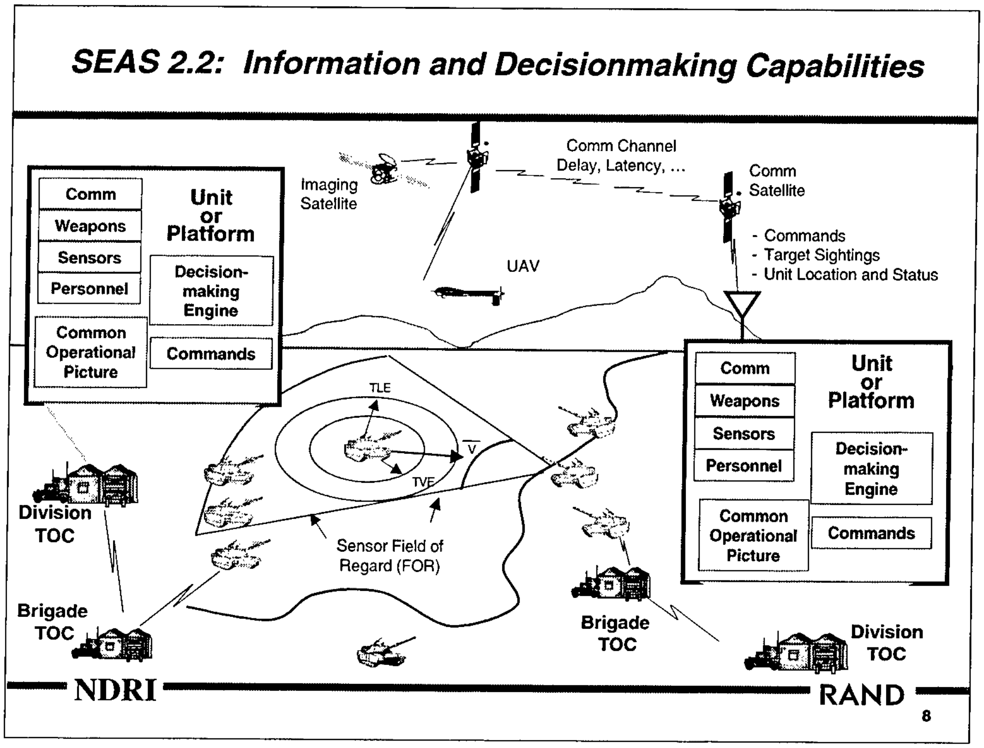
The third objective was to develop a notional division-level scenario in which decisionmaking and dynamic situation awareness information were implemented and available at both the operational and tactical level.

Outline

- ❑ Introduction
- ➡ ❑ SEAS
- ❑ Autonomous C2 Decisionmaking and the Correlation of Forces and Means
- ❑ Scenarios, C4ISR Capabilities, and Decision Spaces
- ❑ Results

NDRI RAND 7

Next we provide a brief overview of SEAS, which we enhanced and adapted to assess the operational value of IS for U.S. ground forces. A more detailed description of SEAS can be found in Appendix A.



The System Effectiveness Analysis Simulation (SEAS) 2.2 (called SEAS II, SEAS, or SEAS 2.2) is an entity-based, time-stepped, stochastic, multimission-level model specifically designed to help evaluate the military utility of C4ISR systems. It can contain representations of ground-based, airborne, and space-based intelligence, surveillance, and reconnaissance (ISR) systems, a variety of communications networks, and various hierarchical or nonhierarchical C2 structures. SEAS is a government-owned simulation model that was developed by Computer Sciences Corporation (CSC) and Aerospace Corporation, with assistance from RAND.

SEAS 2.2 entities are *units or platforms* that are governed by settings, commands received from higher-level units, or by programmed behaviors. Platforms are typically grouped hierarchically into *units*. Units are collected into superior units and, ultimately, *forces*. Platforms and devices on them interact stochastically with other entities. They may be sensors or weapons that detect or kill objects with probabilities given in probability of detection (Pd) or probability of kill (Pk) tables, respectively. Communications channels are devices that send and receive messages. Platforms may be vehicles that move in the battle space such as aircraft, unmanned aerial vehicles (UAVs), tanks, and satellites. They may be C2 entities (headquarters) that control units. Movement scripts, force descriptions, Pd and Pk tables, and satellite traces are some examples of *settings* that govern the behavior of SEAS entities.

Representations of C4ISR architectures, sensor-to-shooter chains, and sensor-to-decisionmaker-to-shooter links can be incorporated into SEAS. A number of important sensor measures of performance are included in the SEAS sensor model, such as target probability of detection, target location error, target velocity, minimum and maximum target detection range, and target velocity error. Target detections by any sensor on a platform are reported on the platform's communication channel. Other platforms having access to that channel (directly or via their command hierarchy) will place target sightings in their local situation awareness database or common operational picture as indicated in the earlier chart. The platform or unit will shoot mounted weapons at the reported target if it is within weapon range and satisfies other constraints such as the number of rounds on hand, firing interval, shot coordination, weapon-target priority rules, and authorizing commands from higher headquarters (if needed).

The latest version of SEAS, version 2.2, has incorporated into it a programming interface that can be used to program specific SEAS entities with sophisticated behaviors and autonomous decisionmaking capabilities. This new modeling and simulation capability has made it possible to develop autonomous C2 units capable of making decisions based on information delivered by the C4ISR architecture in which the units are embedded. This new capability makes SEAS well suited for this research project. Using this new capability autonomous SEAS agent-based models of ground force commanders were developed by RAND as a part of this research project. These autonomous C2 decisionmaking agents and the theory they are based on will be described later in this report.

Why SEAS?

- ❑ **Legacy combat-level models are based on decades-old approximation techniques**
  - **Aggregation of military units**
  - **Assumed, indirect unit enhancement factors to "approximate" C3ISR system effects**
    - e.g., constant sortie effectiveness factors remain unchanged throughout the war
- ❑ **Individual C3ISR systems not modeled so causal connections to weapons effectiveness not possible**
  - **Cannot capture essential insights, output from higher resolution models**
- ❑ **SEAS is a next-generation theater-level model with causal information connections between C3ISR and weapons systems built in**

Key Aspects of Sensing and Communications Processes	*Sensor-Decisionmaker-Shooter Chain Modeled Explicitly*	*Hierarchies of Interacting Adaptive Agents Capture Warfare Nonlinearities*

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Why use SEAS for analysis of IS issues and not existing, more well-known campaign models? In older legacy combat models, individual battlefield entities were subsumed or aggregated into larger units, such as brigades or battalions. These models were developed when computers had much more limited capabilities, making it necessary to reduce the number of simulation entities and to use aggregation techniques. As a consequence these campaign-level simulations were based on approximation techniques that describe the combat effectiveness and interactions of aggregated military units. Furthermore, these approximation techniques were developed to describe the combat effectiveness of traditional military units and not those equipped with advanced C4ISR systems or new transformed Army forces.

Various approximations or parameter adjustments have been developed for these legacy models to help assess the military utility of C4ISR systems, but these approximations are not based on the causal behavior of individual battlefield entities or on the value of the information supplied by C4ISR systems. Instead, they approximate the value of information supplied to aggregated units parametrically. In fact, in legacy models individual C4ISR systems are not represented. Therefore, it is not possible to represent the causal connections between C4ISR system performance and overall military force combat effectiveness. In addition, the insights and results from high-resolution C4ISR system models such as JANUS cannot be used directly in such models.

Because of the parametric approaches employed in legacy models and because these models are largely scripted, they also cannot take into account how information is used to support command decisionmaking processes. Thus, it is not possible to assess many IS concepts, such as force synchronization, that may be enhanced or enabled by advanced C4ISR systems in traditional legacy models.

SEAS differs in many fundamental ways from traditional legacy models. SEAS has a number of appealing features that are useful for assessing IS concepts: the ability to model overhead ISR systems at moderate levels of resolution and any battlefield entity at the soldier, platform, or vehicle level; inclusion of theaterwide geography; simultaneous representation of multiple missions in a theater context; a good sensor-to-shooter chain representation; inclusion of semi-independent autonomous agents; relatively fast execution speed; and the ability to run on less-expensive computer hardware (PCs using Windows 98 or NT).

A variety of sensors can be put on ground-based, airborne, and space-based platforms. Sensor coverage patterns or footprints are modeled for each sensor-platform combination. In each one-minute time step, enemy assets in the footprint of a friendly sensor are stochastically detected with location and velocity errors and put on the platform's local common operational picture and its communication channels. Despite the limitations of this relatively simple representation, the SEAS sensor model is useful because it can capture the complex coverage dynamics of sensors over extended geographic areas and periods of time.

Another important dimension to SEAS is multimission-level analysis. SEAS models multiple, sequential, several-on-several missions over time in a campaign context and over an entire theater of operations. Because it does not include detailed design specifications of assets, it can simulate the interactions of hundreds of entities in reasonable run times, which is vital for quick reaction and exploratory analysis.

Finally, SEAS contains hierarchies of interacting agents that can adapt their behavior based on commands received from higher-level headquarters and from sensor systems. In the latest version of SEAS, individual agents can execute complex military strategies and pursue operational-level as well as tactical-level goals. As described later in this report, agents can modify their behavior substantially, making it possible to assess the operational value of IS systems and concepts using largely unscripted scenarios where the decisions of simulated commanders depend strongly on the quality of the information provided by C4ISR systems.

Outline

- Introduction
- SEAS
- ➡ Autonomous C2 Decisionmaking and the Correlation of Forces and Means
  - Origin of COFM
  - COFM algorithm
  - SEAS implementation
  - Additional decisionmaking logic
- Scenarios, C4ISR Capabilities, and Decision Spaces
- Results

NDRI RAND

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Next we describe the autonomous C2 decisionmaking agents and algorithms we implemented in SEAS and the theory these are based on: the Correlation of Forces and Means (COFM). We first discuss the origin of COFM, and then we discuss the COFM algorithm in detail and how we implemented COFM within SEAS.

Origin of COFM

- COFM is a simply implemented, quantitative process for estimating the likelihood of attack success, assessing projected resource allocations, and monitoring current operations
  - Applicable to the operational level of war and above
  - Based on METT-T (Mission, Enemy, Tactics & Terrain, Troops and Time)
    - Mission: Objectives, distance, attrition
    - Enemy: Strength of opposing forces, resources allocated
    - Tactics & Terrain: Attack strike sectors and frontages, movement rates
    - Troops: Strength of friendly forces, resources allocated
    - Time: Phase completion times
  - Well suited for computational (expert system) applications
- Robust applicability
  - Taught by Soviets to own and client states' armies
  - Used in qualitative methods developed by the U.S. Army
    - Military Decision Making Process (MDMP)
    - Battle Damage Assessment Process
    - Course of Action (COA) Analysis
    - War games

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The COFM methodology has a long history. (Unpublished 1989 research by John G. Hines and Philip A. Petersen, "Operational Calculations for Equal Security Under Arms Control.") See John G. Hines, "The Soviet Correlation of Forces Method," in R. K. Huber, H. J. Linnenkamp, I. Scholch, eds., *Military Stability—Prerequisites and Analysis Requirements for Conventional Stability in Europe*, Baden-Baden, FRG: NOMOS Verlag, pp. 185–199, for a good summary of the background and origins of COFM.

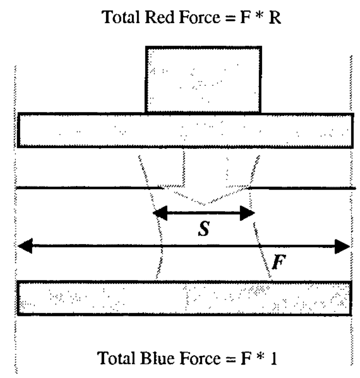
The chart above describes some of the key elements of COFM and how it has been applied within the U.S. Army and by the armed forces of other countries, most notably the Army of the former Soviet Union.

COFM Measures Attacking Force Superiority

COFM itself is a quantitative measure for determining and monitoring the likelihood of attack success based on attack frontages and force ratios

$$\delta = r + (R - r)F / S$$

δ = COFM = Force ratio in strike sector
R = Force ratio for entire attack
r = Force ratio outside strike sector (1)
S = Width of the strike sector
F = Width of the entire attack front



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The COFM for an attack is the ratio of attacking to defending forces in the attack strike sector. The formula for COFM is $\delta = r + (R - r)F/S$, where the symbol R is the attacker-to-defender force ratio, the symbol F is the entire width of the frontage for the attack, and the symbol S is the width of the strike sector. The strike sector is the subregion of the frontage upon which the attacker has massed his forces for the attack. On the other regions of the frontage, the attacker is assumed to maintain a force equivalent to some proportion, r, of the defender's force.

Soviet-style COFM relies on force strength calculated using Standardized Unit Armament (SUA) scores for each weapon system. One might also use the comparable U.S. Army Weapons Effectiveness Index Weapons Unit Value (WEI/WUV) scores. The scores for each weapon system could also be taken from user input, or they could be based upon the "importance" score for each weapon as derived using an attrition methodology, such as ATCAL (Attrition Calibration) from a standard battle for the attack. The sum of the scores for all the attacker's weapon systems that are allocated to the attack becomes the attacker's force strength. This strength includes allocated reserves, indirect fire support, and interdiction assets. The defender's force strength is computed from the weapons systems allocated by the defender. COFM values are dynamic and can change due to losses in attacking or defending forces, or if unallocated reserves are assigned to a unit.

The COFM Algorithm (1)

- **Likelihood of attack success**

$$L_{succ}(\delta) = 1 - e^{-\frac{\lambda T}{D}\left[\frac{\delta^2}{\alpha^2+\delta^2}\right]}$$

D = distance to goal
λ = terrain movement factor
α = correlation planning factor
T = time allocated to reach goal

- **COFM explicitly takes into account key variables that influence the outcome of battles**
  - Time allocated to achieve objectives
  - Spatial relation between unit locations and goals
  - Estimates of combat power of opposing forces
  - Terrain

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The likelihood of success of an attack is given by $L_{succ}(\delta)$ as shown above, where δ is the value of COFM, T is the time remaining to accomplish the attacker's objective, D is the distance remaining to the objective, and λ is the maximum unopposed rate of advance over the terrain of the attack. These factors are usually calibrated to a 95 percent likelihood of breakthrough for a COFM denoted α, usually 5. Stated another way, 95 percent of attacks with a COFM of 5 should advance at a rate of at least 0.16λ. Only 50 percent of such attacks would achieve a rate of at least 0.72λ. If L_{succ} is the minimum likelihood of success (which is one minus the risk level) that one is willing to tolerate for an attack to be substantiated, the minimum COFM allowed is δ_{min}, which is shown in the next chart.

COFM Algorithm (2): Minimum COFM Needed to Substantiate an Attack

$$\delta_{\min} = \alpha \frac{\sqrt{-D_{obj} \ln(1-L_{succ})}}{\sqrt{\left(\lambda T_{obj} + D_{obj} \ln(1-L_{succ})\right)}}$$

Guidelines exist for level of confidence, L_{succ}, Distance, D, Time, T, and terrain, λ, in many areas of the globe

- ❑ **L_{succ} is commonly set to 75%, 95%, or 99% for aggressive, moderate, or timid commanders**
- ❑ **Movement Rate (*D/T*), Frontage (*F*), Strike Sector (*S*), depend on type of attack, i.e., in Central Europe (CEUR)**
  - **Main - *D/T* = 30 km/day, *F* = 30 km, *S* = 10 km**
  - **Supporting - *D/T* = 10-20 km/day, *F* = 10 km, *S* = 4 km**
  - **Holding - *D/T* = 0-5 km/day, *F* = 5 km, *S* = 1-2 km**

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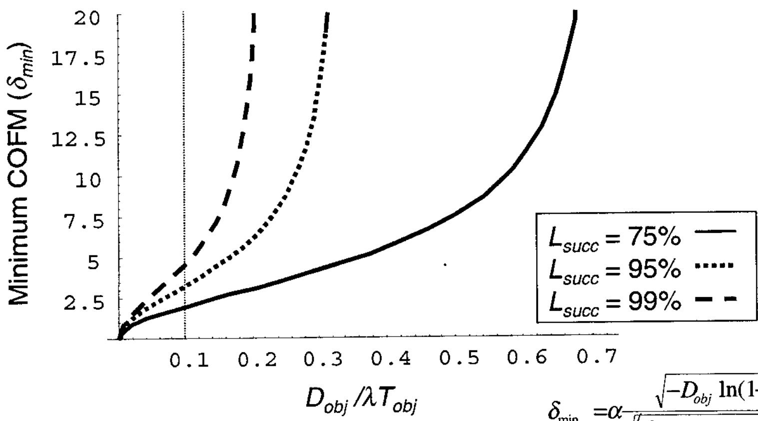
The quantity δ_{min} quantitatively relates forces (R), massing (F/S), time (T), distance (D), terrain (λ), and risk level ($1-L_{succ}$) that a commander is willing to accept. Since the quantity of supplies allocated to the attack directly affects the allowed time, T, logistics constraints are reflected in δ_{min} as well. COFM can be a valuable metric with which to monitor and adjust the allocation of aggregate forces in a simulation. For example, the amount of required close support and interdiction sorties may be computed from this equation. Close support sorties are computed as an increase in friendly forces. Interdiction sorties are usually included as a decrease in opposing forces.

Rules and formulae have been published in the classified literature for the appropriate values for α, λ, F, S, and COFM for each level of command and type of attack (Main, Secondary, or Holding) for most terrain types and areas of the world. For example, in one type of terrain, a division-level attack might require a strike sector width, S, of at least 10 kilometers for a Main attack, 5 kilometers for a Secondary attack, and 1 kilometer for a Holding attack. In addition, an attack is said to be substantiated, that is, likely to succeed, if the COFM is at least 5 for a Main attack, at least 3 for a Secondary attack, and at least 1 for a Holding attack.

Values of δ_{min} for Multiple Confidence Levels



$$\delta_{min} = \alpha \frac{\sqrt{-D_{obj} \ln(1-L_{succ})}}{\sqrt{\left(\lambda T_{obj} + D_{obj} \ln(1-L_{succ})\right)}}$$

λ = 1 km/hr, T_{obj} = 1 hr, α = 5

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This chart shows values of δ_{min} for a variety of confidence levels. We fix α to be 5, λ to be 1 kilometer per hour, and T_{obj} to be one hour. For example, if a unit was 100 meters from its objective ($D_{obj} / \lambda T_{obj} = 0.1$), then an aggressive commander would consider the attack substantiated if the COFM was about 2, while a conservative or risk averse commander would consider the attack substantiated if the COFM was about 4.62.

Incorporation of Red and Blue Long-Range Fires

$\text{Red}_{\text{after deep fires}}$ = Red – Sum[Expected deep fire kills]*

$\text{Blue}_{\text{after close support}}$ = Blue + Sum[Expected CAS kills]*

***Sum over time for specific operation (engagement)**

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Long-range fires and air support can be incorporated into the COFM decisionmaking process in the ways indicated on this chart. The effects of long-range fires and air support on COFM depend on how the artillery and air support are used. For example, if Blue artillery and air support are used to attack rear positions of the opposing Red force, then the force strength of the Red force is decreased based on estimates of the effectiveness of these Blue weapon systems. Alternatively, if Blue artillery or air forces are used in close support to attack Red forces near the front, then the combat effects of the weapons are added to Blue's total force strength. Reducing Red forces and increasing Blue forces have different effects on the force ratio. For example, if the Blue to Red force ratio was 2:1 at one point, a close-support weapon that increased the Blue force strength by 20 percent would increase the force ratio to 2.4:1, while an artillery unit that decreased the Red force strength by 20 percent would increase the force ratio to 2:0.8 or 2.5:1.

COFM Algorithm (3): Use of COFM by Operational-Level Commanders

- ❑ **Commander initiates a series of attacks as specified in a plan**
  - **Designed to achieve specific intermediate and ultimate objectives**
- ❑ **At each stage in plan sequence Commander uses COFM to monitor likelihood of success**
  - **COFM used to determine whether attack is on plan, i.e., objectives can be achieved**
- ❑ **Commander adjusts plan for failing attacks**
  - **Reinforce success, starve failure**

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The substantiation of an attack is hierarchical. First, the commander of an attack substantiates his own overall attack. Then the commander of an attack is expected to allocate enough of his reserve forces, both air and ground, to subordinate attacks for them to reach the required COFM for those attacks. Unneeded reserves are maintained at the highest level of attack. Defenses are handled similarly to attacks except that the goal is to prevent the enemy from reaching its COFM requirement.

The superior evaluates his subordinate attacks sequentially in order of priority depending, the overall plan of the campaign, which specifies the initial type, objectives, and risk levels of each attack. If the minimum COFM for the attack is achieved, the attack is said to be substantiated. If the minimum COFM is not achieved, the superior must allocate forces from reserves to substantiate the attack. If enough forces are not available, the attack may be downgraded.

An attack is downgraded by reducing its type and thus its strike sector width; or increasing the time allowed to reach its objective; or changing its objective to a closer location; or reducing its priority. Any reserve forces allocated to downgraded attack become candidates for reassignment to higher priority attacks, or the superior may decide to accept a higher level of risk for the unsubstantiated attack. The latter course of action usually resulted in either the execution or promotion of the superior officer during World War II.

Outline

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- ❑ SEAS
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  - Origin of COFM
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  - ➡ SEAS implementation
  - Additional decisionmaking logic
- ❑ Scenarios, C4ISR Capabilities, and Decision Spaces
- ❑ Results

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Next we describe the autonomous C2 decisionmaking agents and algorithms that we have implemented in SEAS.

SEAS Implementation: Ground Force Commander Decisionmaking

- **Autonomous decisionmaking implemented at two levels of ground force C2 hierarchy**
  - Division and brigade (some vehicle-level capability)
  - Both Red and Blue sides
- **Operational-level command emulating COFM**
  - Estimates of enemy combat capability developed by operational commanders for specific areas of the battlefield
    - based on the COP
- **Compare the location of self and subordinate units to movement plan goals and subgoals**
- **Modify their movement plan, orientation, and weapons readiness state based on analysis of the COP**
- **Direct subordinates to change their plans and state**

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In order to implement COFM using SEAS, we set up a scenario that contains the features listed in the chart above.

Namely, both Red and Blue forces have autonomous decisionmaking capability at both the division and brigade level.

At the operational level, decisions were made based upon calculated COFM values. These values were based on estimates of enemy combat capability developed by commanders for specific areas of the battlefield.

Each unit compares the location of itself and its subordinate units to movement plan objectives and subobjectives. Each unit also uses sensed data from its Common Operational Picture (COP) on enemy positions and mass to modify its movement plan, orientation, and weapons readiness state, and directs subordinates to change their plans and state.

COFM Implementation in SEAS

- Baseline attack or defense plans for Blue and and Red ground forces
  - Offense vs. defense for unevenly matched forces
- Plans include
  - Two levels of objectives (intermediate and ultimate)
  - Two levels of command (division and brigade)
  - Multiple echelons
    - 1st echelon
    - Reserve (2nd echelon) forces

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In the baseline scenario we used in the analysis, Red is the attacker and Blue is the defender. Red has two objectives: an intermediate objective located just past Blue's defensive position and an ultimate objective located slightly beyond Blue's base.

When Blue units are overrun, they retreat to Blue's base. From there, Blue attacks any Red force that approaches within a given distance.

For each side there are both division and brigade levels of command, as well as second and third echelons of reserve forces.

COFM Implementation in SEAS (2)

COFM rule sets implemented for two levels of command in SEAS 2.2

- ❑ **Brigade and division commanders**

Test resulting command decisionmaking behavior in simple 2-step battle vignette

- ❑ **Vehicles equipped with only organic sensors and unit communications**
- ❑ **Adjust rule set**

Incorporate appropriate interfaces to "off-board" ISR communications

- ❑ **Adapt rule set, test, and adjust**

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The COFM rule sets are implemented in the following way.

Red and Blue vehicles are equipped with their own Forward Looking Infrared (FLIR) sensors and communications devices. Red and Blue brigades are also equipped with off-board sensors that provide additional data on the disposition of opposing forces in the close battle area.

Detections by a sensor assigned to a given region (e.g., a brigade area of operations) are restricted to those vehicles within its assigned region. This restriction allows the data for only a given brigade and its strike sector to be passed up to the division level. At the division level, these data are used to calculate COFM factors. Based on the value of COFM calculated, the division commander decides whether to continue the attack or to withdraw.

COFM Implementation in SEAS (3)

Develop full COFM rule set for operational-level warfare in SEAS 2.2.

- ❑ Use vertical slice where 9 platforms are represented by 1*

Test resulting command decisionmaking behavior in multistep battle vignettes

- ❑ Equip operational level commander with theater-level ISR capabilities

Develop Blue operational-level COFM rule set to take advantage of advanced battlefield awareness and other IS systems

- ❑ Adapt rule set, test, adjust, and refine

*For a discussion of the vertical slice technique, see *Evaluation and Evolution of the System Effectiveness Analysis System (SEAS)*, Moore et al., Santa Monica, CA: RAND, AB-266-1-AF, 1999.

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We developed the simple scenario just described into an operational-level scenario involving a multistep battle vignette.

Such a development involves incorporating the COFM rule set into the operational-level decisionmaking process. By incorporating the effect of operational-level battlefield awareness, we can test the effect advanced IS systems have on combat outcomes.

Division Commander Decisionmaking Engine

The division commander's rules are functions of

- ❑ **Force ratios, time, and distance estimates that depend on ISR architecture performance**
- ❑ **Brigade location estimates transmitted to and used by division**
  - **Depend on communications performance**
- ❑ **Heuristics for phase change**
  - **e.g., thresholds to change from attack to defend, or retreat**
  - **Changes in operational objectives, risk factors**

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The Division commander follows a simple set of rules:

(1) Each brigade's attack is checked in priority order.

(2) If the COFM for a brigade is above or below its minimum required value (δ_{min}) and the brigade is attacking or defending, respectively, then the brigade attack/defense is said to be substantiated and nothing is done.

(3) If the brigade attack is not substantiated, then available reserves are allocated to substantiate the brigade's attack. Similarly, if the attack is substantiated, then the defense allocates reserves (if possible) to unsubstantiate the attack.

(4) If the brigade attack cannot be substantiated, then the attack's priority and objectives are downgraded.

(5) If enemy units break through, then the objectives for the next phase of the overall attack replace the objective for the successful attack. This means that Blue units will retreat from a defense that has been broken and Red units will attempt to push onward to their final objective. Such attacks are likely to get additional reserves since the priority for the attack will be upgraded.

Division Commander Decisionmaking Engine Outputs

- ❑ **Allocates reserve forces to support specific attacks**
- ❑ **Issues attack, defend, or retreat commands to brigades**
  - **Determine where to confront the enemy using estimates of probable location and condition**
- ❑ **Issues phase changes in operational objectives**
  - **Defend at front**
  - **Retreat and defend at points in rear area**
  - **Identify breakthroughs and reinforce**

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Shown above are the outputs of the division commander decisionmaking engine.

Brigade Decisionmaking Engine

- Reports attack COFM to Division
- Executes commands issued by Division
- Issues commands to subordinate units
  - Unit movement commands
    - Advance, retreat, defend at current position, etc.
  - Force disposition commands
    - Change in unit formation
    - Dig in
    - Retreat when suffering level of casualties or damage (not implemented)
- Controls tactical disposition of subordinate units
  - Permit/not permit tactical divert
- Synchronizes and controls dynamic tactical maneuver operations of subordinates (partially implemented)

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Shown here are the main features and functionality of the brigade decisionmaking engine. Each brigade reports its COFM to the division and executes commands issued to it by the division. The brigade commander in turn issues commands to his subordinate units (in this case, individual tanks). The menu of possible commands are shown above. Brigades can also execute tactical maneuver operations. In this version of the model, only a tactical divert maneuver was implemented. More sophisticated maneuver operations will be incorporated into future versions of the model.

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Next we describe the logic we implemented for individual tanks to simulate the decisionmaking of tank commanders given access to off-board situation awareness information.

Divert Maneuver Logic

- ❑ **Executed by individual vehicles in groups or separately**
- ❑ **Vehicles divert to target location received from off-board sensors and attack if**
  - **Own vehicles are moving and opposing vehicles are moving away, OR**
  - **Own and opposing vehicles are stationary**
  - **Distance to target is not greater than maximum permitted divert radius**

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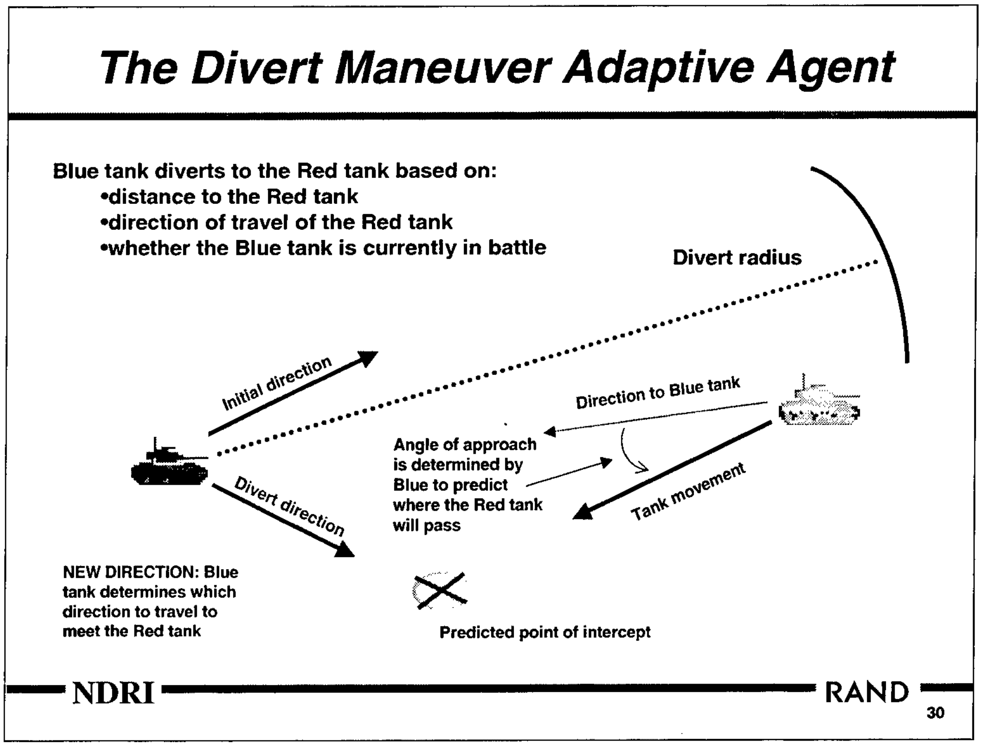
Each tank can execute a dynamic divert maneuver based on off-board situation awareness information it may receive (that is, the tank or brigade might not directly sense the target or targets with its own organic sensors), even if the tank is moving toward a preestablished goal (as directed by its division or brigade commander).

Tanks can divert to the estimated target location if certain criteria are satisfied. The divert criteria are briefly summarized above. Tanks will not divert if they are currently engaged in battle but will if both they and their target are stationary or if they are chasing the enemy (i.e., if both are moving and the enemy is moving away from the friendly forces). Details on how the divert maneuver is accomplished for moving targets are discussed in the next chart.



The divert maneuver is an example of an adaptive system or agent. The code for the divert maneuver is entered in the orders of individual tanks. Based on sensed data, a Blue tank would make a decision whether to divert from its objective path and attack a Red tank. With the Red tank position passed to the Blue tank, the decision to divert from its course (or its static location) is made based on (1) if the distance to the Red tank is within the "divert radius," (2) if the direction of travel of the moving Red tank will not bring it close to the blue tank, and (3) if the Blue tank is currently not in battle. All three criteria need to be fulfilled for the Blue tank to divert.

The distance to the Red tank can be calculated by the Blue tank based on target information passed from another platform. This allows the Blue tank to divert to another tank that is outside of its own sensing range. The user input "Divert Radius" controls how far the Blue tank will be permitted to divert. The direction of travel of the Red tank is determined by estimating its velocity using successive target locations over a two-minute period. The Blue tank then makes a calculation of where the Red tank will pass. If the Red tank will pass within the Blue tank's sensor and weapon ranges, it will wait for the Red tank. If not, it will divert to a calculated leading intercept point and engage the Red tank there. The Blue tank will not divert if it is currently in battle (e.g., under fire or firing its weapons).

Outline

- Introduction
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In this section we describe the notional division-level scenario developed for this analysis, the C4ISR capabilities assumed, and, because this scenario is largely unscripted, the decision space or space of possible unit movements and decisions associated with this scenario.

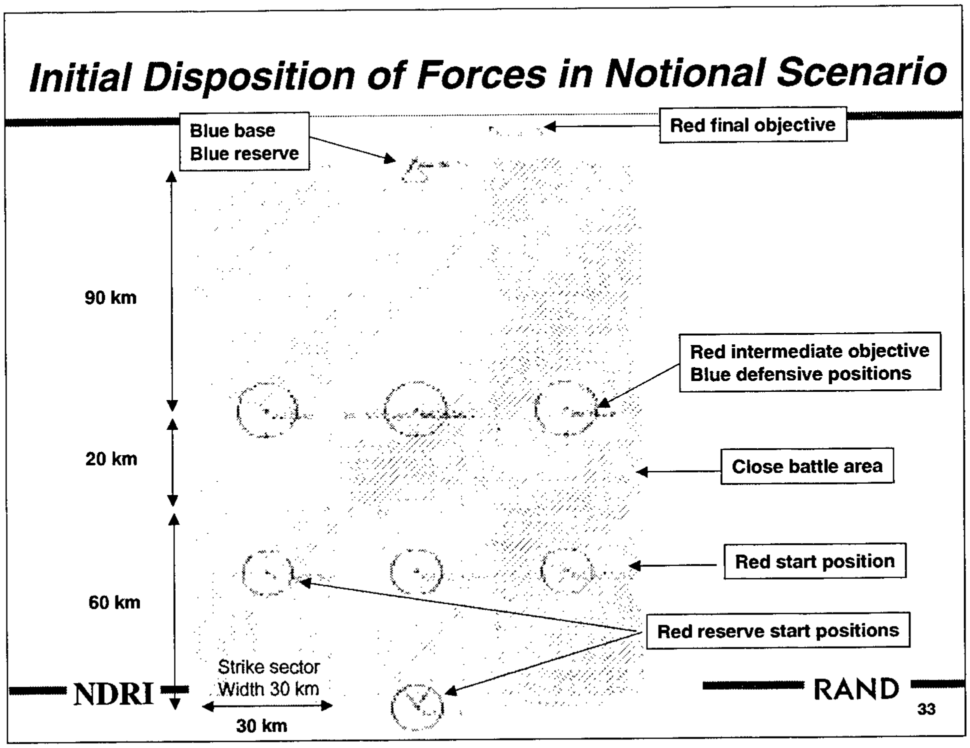
Notional Division Scenario

- Division area of operations with second echelon on Blue side and second and third echelons on Red side
- Red has an overall 1.75:1 force advantage
- Blue and Red both have near-perfect ISR in the close battle area
  - Excursion cases in which Blue has perfect ISR in deep battle area
- Red and Blue tank capabilities
  - Equal weapon Pks and onboard sensor Pds
  - Blue tanks twice as fast as Red

NDRI RAND 32

The notional scenario we consider in this analysis has Red and Blue forces opposing each other over a front of division-level width, and includes rear areas with second echelon forces on the Blue side and second and third echelon forces on the Red side. Red has a numerical force advantage of almost 2 to 1. In this proof-of-concept analysis, we focused on the C2 and decisionmaking capabilities of Red and Blue forces. Consequently, we assumed that both Red and Blue sides had near-perfect ISR capabilities or near-perfect battlefield awareness in the close battle area (as depicted in the next chart). For this scenario there was no indirect fire or air support, and we assumed no effects on the battle due to weather and terrain, although these options may be explored in future expansions of this scenario.

The capabilities of Red and Blue tanks are as indicated, with Blue tanks having a maximum speed of 60 kilometers per hour and Red tanks having a maximum speed of 30 kilometers per hour.



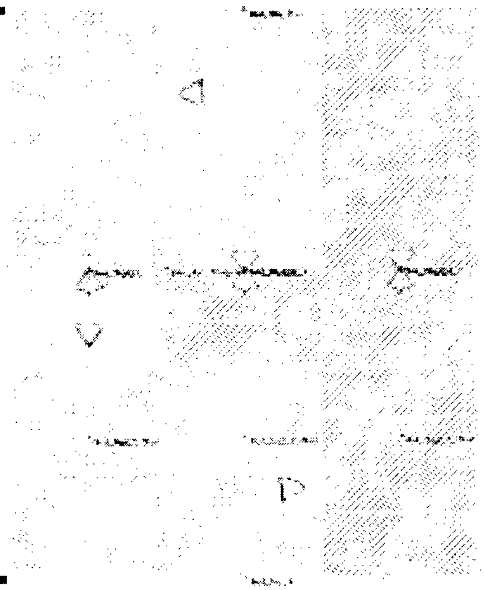
This screen shot from a SEAS run illustrates the geometry of the battlefield and key points or objectives relevant to the scenario. The start positions, intermediate objectives, and final objective for Red are shown. Likewise, the Blue defensive positions and the Blue base are labeled. A single brigade occupies each start and defensive position. On the front lines, three Blue brigades are dug in and face three Red brigades that move northward and attack at the start of the scenario. A single Blue reserve brigade occupies the Blue base and is not committed at the beginning of the scenario. Also shown are the starting locations of two Red reserve brigades. Two additional Red reserve brigades have starting locations further back in the third echelon and are not shown. In all of the cases that were run, Blue starts out in a defensive posture and Red attacks.

The hash-marked regions indicate two types of areas: the three strike sectors that span the entire region from north to south and smaller tactical areas of operation (TAOs) that define the close and rear battle areas in each of the three strike sectors. For the purposes of this proof-of-concept analysis, it was assumed that both Red and Blue had perfect battlefield awareness in the close battle area defined by the central TAOs located in each of the strike sectors. For most of the excursions run, Blue also had perfect battlefield awareness in its own deep operating areas. An excursion case was also run in which Blue also had perfect battlefield awareness in the Red rear area.

Also shown on the chart are the maximum coverage ranges of the ISR sensors used in this proof-of-concept model (as indicated by the large circular arcs). Six redundant sensors provide coverage of the three close battle TAOs (one each for both Red and Blue forces in these TAOs). One long-range ISR sensor provides coverage of the Blue deep battle area. Target sightings from the long-range ISR sensor are transmitted to the division headquarters, relayed to brigade headquarters, and then sent to individual tanks. Target sightings from the shorter-range sensors are transmitted to the brigade headquarters and relayed to the tanks of each brigade. Tanks on both sides have access to off-board sensor information that provides them with battlefield awareness information beyond the range of their own organic sensors. Thus, individual tanks in the model have access to a Common Operational Picture (COP). Targets on the COP can be time delayed depending upon the characteristics of the communications channels connecting the tanks to off-board ISR sensors and the loading on the communications channel. When the tanks are stationary (as indicated in the slide), each tank's organic FLIR sensor is time averaged to have 360-degree coverage. This corresponds to the tanks fully rotating their turrets while stationary.

Because running simulations involving entire brigades of tanks would be far too time consuming, we instead used a subset of the forces called a *vertical slice*, which models the conflict with an equal proportion of forces taken from all levels (brigade, division, etc.) from each side. In the vertical slice approximation used in this analysis, each brigade is composed of 15 tanks (approximately a 9 to 1 vertical slice).

Blue Reserve Brigade Takes the Initial Red Feint



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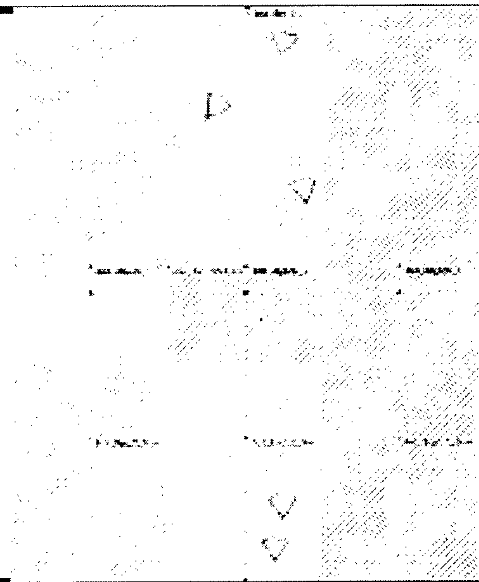
Shown in this chart are the opening moves of the scenario in which the Red frontline brigades have advanced to the Blue frontline positions. When the tanks are on the move, they shift their time-averaged coverage to a forward-looking sector that is 60 degrees wide. As is evident from this chart, all tanks are on the move at the particular time this simulation snapshot was taken.

In this run, the first Red reserve brigade has moved into the close battle area of the first strike sector (the sector on the left). This is one of the few scripted moves in this scenario. This move by Red prompts the Blue reserve brigade to reinforce the frontline unit in the first strike sector (as directed by the Blue division COFM decisionmaking engine). However, three additional Red reserve brigades are now on the move, of which only one is visible on the chart. The latter Red reserve unit is on its way to the third strike sector as directed by the Red division commander, i.e., the Red COFM decisionmaking engine. The move by the initial Red reserve brigade in the first strike sector is a feint that in most runs diverts the Blue reserve from the main Red attack that later occurs in the second (central) or third strike sector with the force of the other three Red reserves. It is important to note that the Red division commander can modify his attack plan and change the location of the main attack after the initial engagements have occurred. This is just one example of the dynamic decisionmaking on both sides that occurs in the model.

Red Breakthroughs in Two Sectors



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This chart shows a simulation screen snapshot from a point later in the battle. In this case Red has broken through in two strike sectors, and all of the Blue frontline brigades have been wiped out. The remnants of two Red brigades are advancing from their intermediate objectives to their common ultimate objective. The Blue reserve has retreated as directed by the Blue division decisionmaking engine to defend the Blue base. One can also see the two rearmost Red reserve brigades advancing to the front. In this case the Red division commander is reinforcing success and using the division's overwhelming numerical force advantage by directing all remaining Red forces to advance in the central strike sector toward their ultimate objective.

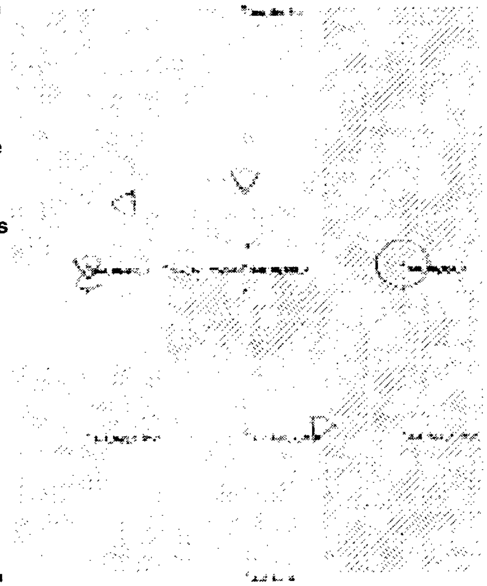
This vignette serves to point out one simplification that was used in building the decision engines used in the model. All brigades fight to the death or to the last tank unless directed to retreat by the division commander. This decisionmaking behavior is simplistic and unrealistic, and will be remedied in the next version of the model in which more realistic disengagement criteria will be used.

Temporary Lack of Force Synchronization

Simultaneous Blue reinforce and retreat operations

But Blue reserve brigade has time to reinforce

Red slow to take advantage of Blue retreat in central strike sector



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Shown in this chart is an interesting example of lack of force synchronization and an example of some of the unexpected, unscripted behavior the model can exhibit due to the fact that many autonomous decisionmaking agents are interacting stochastically in the simulation model and using communications links with time delays. In this particular case the Blue division commander has directed the Blue reserve to reinforce in the first strike sector where a fierce fire fight is going on. The Red frontline brigade in the third strike sector has defeated the frontline Blue unit there and has come to a halt. The Blue frontline unit in the central strike sector has defeated the frontline Red unit there but has begun to retreat as directed by the Blue division commander, evidently because of the perceived force imbalance in the second and third strike sectors. One could hypothesize that if the Blue forces were better synchronized, then by reducing Blue communications net time delays and Blue division commander decision delays, the Blue unit in the central strike sector would instead have been ordered to assist in the battle taking place in the first strike sector, as the remaining Red reserve brigades are still far from the front and the other frontline Red brigade had halted at its intermediate objective.

One can also see an interesting phenomenon occurring in the central strike sector. Red does not take advantage of the retreating Blue force by moving its reserve unit directly up the central sector. This is because Red does not have deep ISR coverage of Blue territory and so does not "see" the retreating Blue force.

Rich Model Decision Space

- Scenario decision space =

  no. of units x no. of possible positions

  = 96 (Blue) x 216 (Red) = 20736

  - not including tactical diverts and maneuvers

- Vast majority of decisions are bad and lead to disaster for one side or the other
- Decisionmakers must identify good decisions out of a sea of many bad decisions
  - some obvious, some not

NDRI RAND 38

In the preceding charts, we have shown only a few snapshots of the many engagements and maneuvers that take place in a single simulated battle. Rarely do two battles proceed exactly alike. Because of the stochastic nature of SEAS, the series of decisions made by individual commanders can differ substantially from one simulation run to another. This in one respect is not surprising: War is intrinsically an enterprise with substantial uncertainty, and this uncertainty is reflected in the wide variability of intervening events in each simulation run.

One way to characterize this variability is to consider the space of possible decisions that Red and Blue commanders can make in the scenario. If one adds up all possible moves of all units and multiplies them together, one gets a maximum estimate of the model decision space: over 20,000 states. Only the opening dozen or so moves in the scenario are scripted. It should be realized that the vast majority of the states in the decision space are disastrous. The decision space of interesting states is much smaller, perhaps being only 1 or 5 percent of all possible moves. But this still leaves 200 to 2,000 interesting moves where information can play a crucial role in selecting the right move for either Blue or Red. In other words the C4ISR systems employed by either side should help decisionmakers to identify the few good decisions that can win the war out of the sea of many bad decisions that can easily lead to defeat. Just as in chess, a bad decision made early on, such as taking the Red feint at the start of the conflict, may ultimately lead to defeat.

Outline

- ❑ Introduction
- ❑ SEAS
- ❑ Autonomous C2 Decisionmaking and the Correlation of Forces and Means
- ❑ Scenarios, C4ISR Capabilities, and Decision Spaces
- ➡ ❑ Results

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Next we discuss the results obtained using the model for a series of runs to be described below.

Cases Run

Red Decision Delay/ Blue Decision Delay	1	15	20	30
1				
15				
20				
30				

With ~ 1 Red and ~1 Blue Comm delay *100 repetitions*

Red Comm Delay/ Blue Comm Delay	1	15	30
1			
15			
30			

With ~1 Red and ~1 Blue decision delay and with 30 Red and 1 Blue decision delays
100 repetitions

NDRI RAND 40

Shown here are the major cases run, each with 100 repetitions using the SEAS ground force C2 simulation model we have developed.

In the first set of cases, Red and Blue decision time delays were varied as indicated in the chart. In the second set of runs, communications time delays for both Red and Blue communications networks were varied. For runs where decision delays were varied, the time delays in Red and Blue communications networks were set to the minimum value of approximately 1 minute.

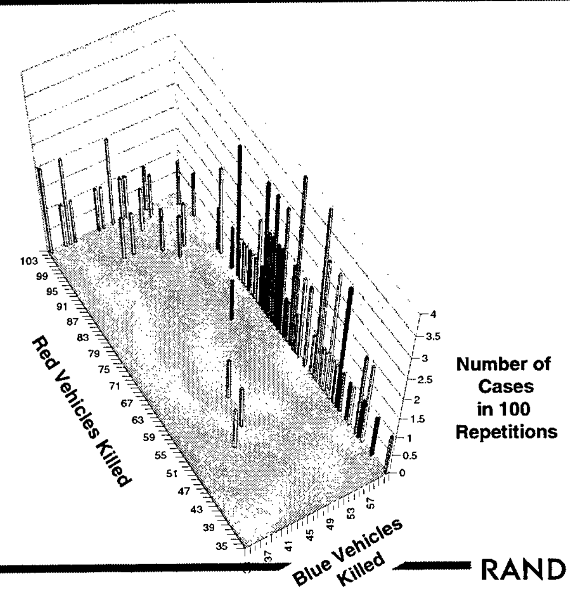
For cases where communications time delays were varied, two decision delay cases were run. In one, Red and Blue decision delays are both set equal to approximately 1 minute, and in the other Red decision delay is set to 30 minutes and Blue decision delay is set to approximately 1 minute.

A few additional excursions were run as well and are described later in this section.

Results for the 30-min Blue and Red Decision Delays Case

Weak convergence to case where Blue loses all its tanks and Red loses ~ 75/105 vehicles

A few cases where Blue wins



NDRI — RAND 41

Shown here are results for the case where both Red and Blue division commanders have a 30-minute decisionmaking delay. In this case both commanders proceed with their plan in 30-minute time blocks. At the end of each time block, they can decide to maintain their previously determined course and not make any changes, or they can direct their subordinate units to change their current maneuver operations based on the battlefield situation awareness data available at that time.

In this case, where both sides have substantial decision delays, Blue loses most of the time. The results fall into a broad, one-dimensional distribution where Blue loses all of its tanks and Red loses about 75 percent of its force (with substantial variation in the number of Red tanks killed). However, there are a few unusual cases where Blue wins (i.e., when the Red force is wiped out and Blue is not) that are not a part of the primary distribution.

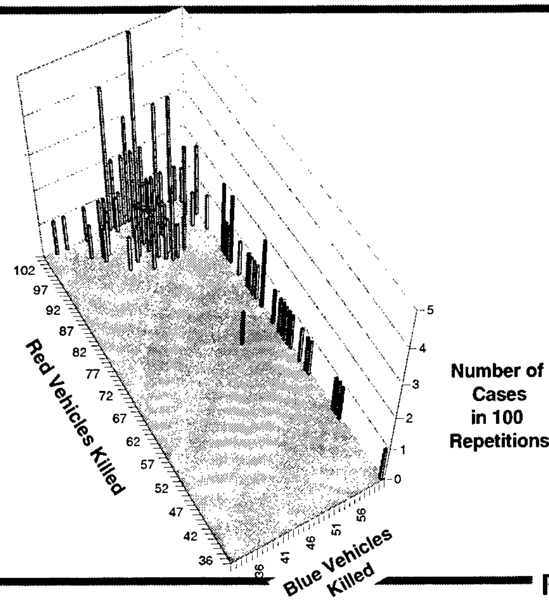
Note that the rules of disengagement and conflict termination employed in this proof-of-concept model are that both sides fight to the death. With more realistic rules of disengagement and conflict termination, the resulting distribution described above may be broad in both dimensions and extend into the interior of the histogram rectangle shown (this conjecture will be investigated in future research).

In intermediate cases where the difference between Red and Blue decision delays are significant, the distribution of results is much more complex than those shown here and may follow a bimodal distribution.

Results for the 1-min Blue and 30-min Red Decision Delays Case

Convergence to case where Blue wins and Red loses majority of its vehicles

A few cases where Red wins



NDRI RAND

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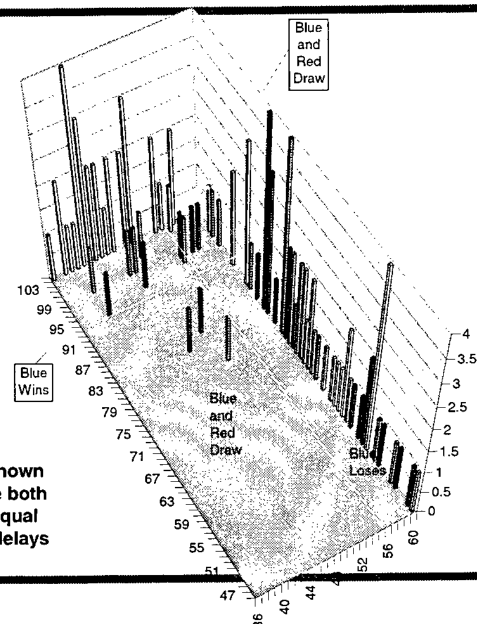
Shown here are the results for the case where Red has a 30-minute decision delay and Blue has about a 1-minute decision delay. In this case the Red division commander proceeds with his plan unaltered in 30-minute time blocks. At the end of each time block, the Red commander can decide to stay the course and not make any changes, or he can direct subordinate units to change their current maneuver operations based on the battlefield situation awareness data available at that time. In contrast, in this case Blue has a much shorter decision cycle and can decide to change course every few minutes.

In this case Blue wins most of the time, although there are a number of cases where Red wins (evidently because Blue makes one or more critical decisions that result in defeat). For this case the results fall into a broad distribution where Red loses most of its tanks and Blue loses about 45 of its tanks (that is, only about one-quarter of the Blue force survives). It is interesting that in this case the main distribution is broad in both dimensions, despite the fact that the same disengagement and conflict termination rules are used in this case as in the case shown on the prior slide.

Win and Loss Criteria



Results histogram shown is for the case where both Red and Blue have equal 15-minute decision delays

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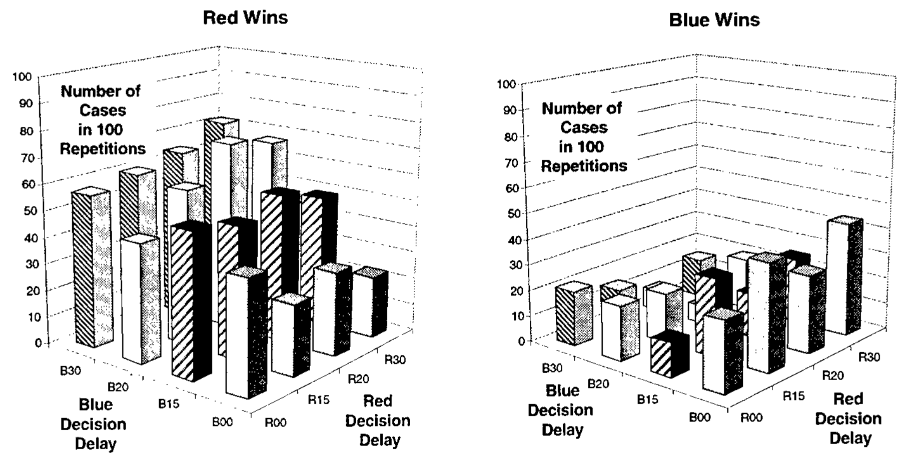
The histograms shown in the prior two charts provide some insight into the spread of possible combat outcomes for a specific case, i.e., specific decision delays. However, it is difficult to compare combat outcomes for several cases using these histograms. Hence, we developed an aggregation method for capturing some of the main features of the histograms shown in previous charts. This aggregation approach is based on battle win and loss criteria with which we have divided the loss-exchange ratio (LER) results space into four quadrants as indicated above. Blue wins if the LER falls into the upper left-hand quadrant. Blue loses if the LER falls into the lower right-hand quadrant. The battle is a draw if the LER falls into one of the other two quadrants.

The histogram above used to illustrate the win and loss criteria corresponds to the case in which both Red and Blue have equal 15-minute decision delays.

Summary of Results for the Decision Delay Cases



NDRI RAND
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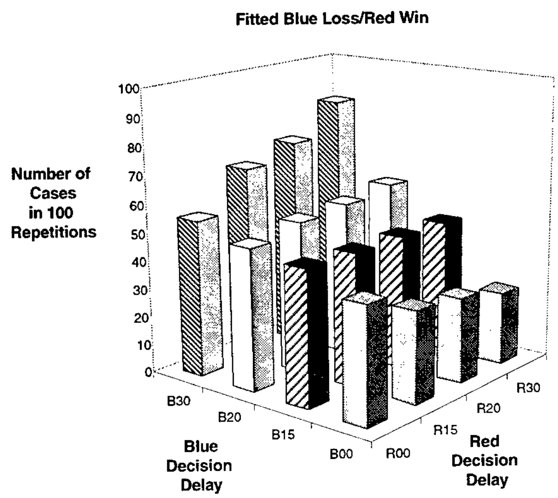
These charts summarize results for all of the decision delay cases considered where comm delays were held to a minimum. Battle results were grouped into four bins: Blue wins, Red wins, Blue and Red both win, and draws. If a side loses 90 percent or more of its vehicles, that side loses. Otherwise, the side wins or draws. If neither side loses, the battle is declared a draw. Not shown is the number of times that Blue and Red draw. Draws occurred 20 to 30 percent of the time.

From the charts it is evident that if Blue has a decision delay of 15 minutes or more, it loses most of the time. On the other hand, if Blue has a short decision delay (the B00 case, which corresponds to approximately a 1-minute decision delay), then Blue has a much better chance of winning, especially if Red suffers from a substantial decision delay.

It is interesting to note that Red has less dependence on decision delay than does Blue if Blue suffers from a decision delay of 15 minutes or more. In many such cases, Red has a greater chance of winning with a longer decision delay. In these cases it would appear that if Red simply sticks to its plan and does not try to outmaneuver Blue, it can take better advantage of its numerical force advantage.

Note that Blue wins four times as often in the B00R30 case as in the B30R00 case.

Summary of Smoothed Results for the Decision Delay Cases

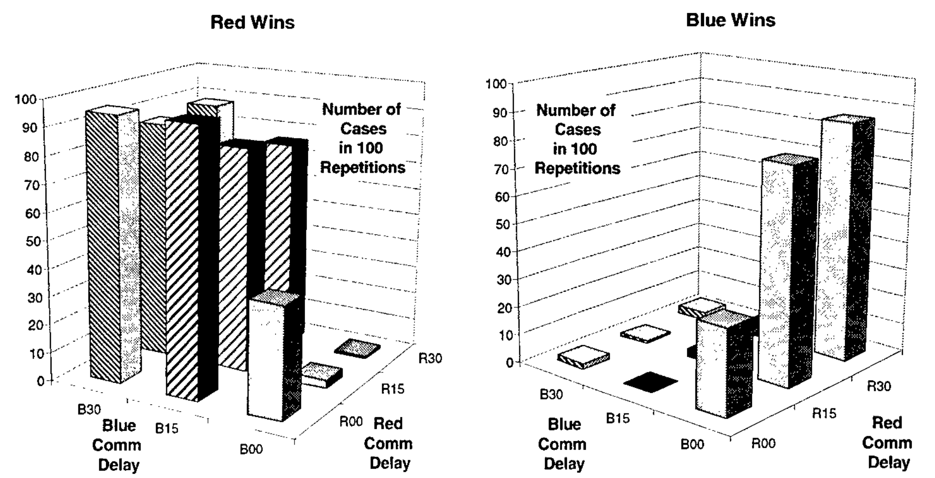


NDRI RAND 45

Shown here are smoothed battle outcome results for the matrix of decision delay cases that were considered. Data smoothing was accomplished using regression analysis. The inverse dependence of Red and Blue on decision delay is highlighted by the regression analysis. Blue loses less often when it has very short decision delay and as Red decision delay increases. On the other hand, Red wins more often if Blue has a large decision delay and as Red decision delay increases.

One striking result is that Blue has about a four times greater chance of losing if the Blue decisionmaking delay time increases from 1 to 30 minutes and if Red decisionmaking delay is 30 minutes. On the other hand, Blue's chance of winning is much less strongly dependent on its decisionmaking delay if Red decision delay is a minimum (about 1 minute).

Summary of Comm Delay Results for Minimum Red and Blue Decision Delays



NDRI RAND

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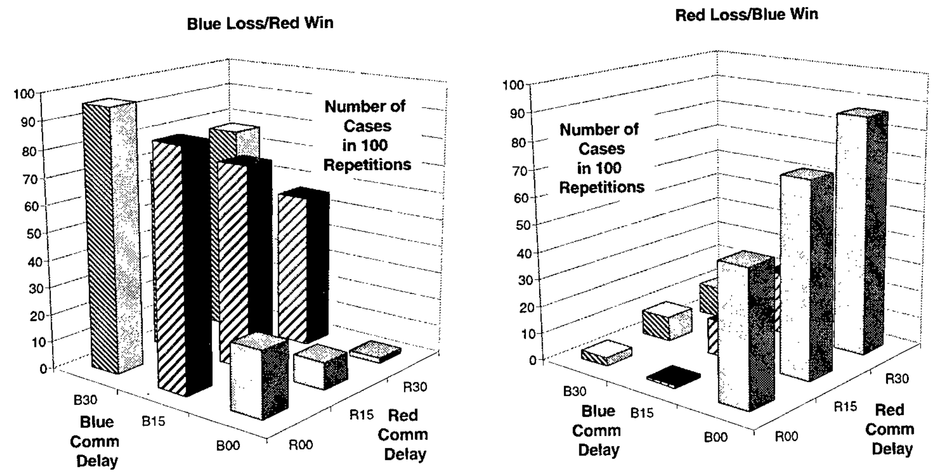
Shown here is the summary of communications delay results for the case where both Red and Blue have minimum decisionmaking delay. In this case Blue has very little chance of winning if there is any sizable comm delay in Blue communications networks. On the other hand, Blue wins in most runs if it has no comm delays and if Red comm networks have a message delivery time delay of 15 minutes or more. What is striking about these results is the major change in outcome as function of relative comm delay. There is a sharp "knee in the curve" somewhere between Blue time delays of 0 and 15 minutes indicating a strong nonlinear dependence of combat outcome on communications time delay. More sensitivity analysis is needed to determine exactly where this knee in the curve is.

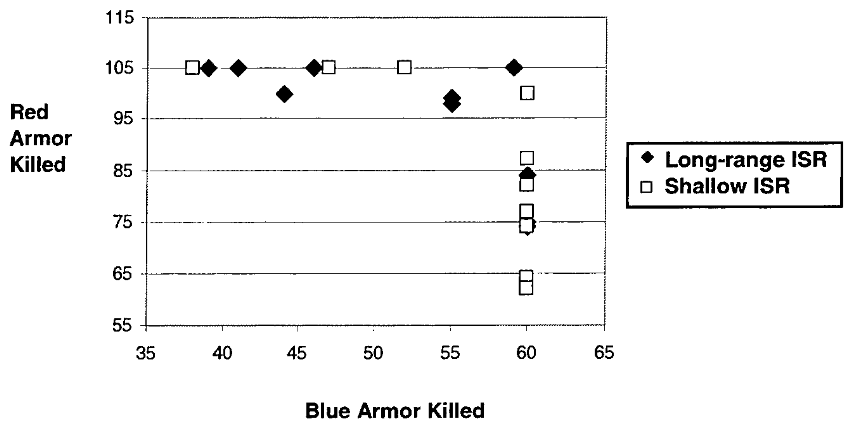
Summary of Comm Delay Results for the Red 30 and Blue 1 Decision Delay Cases



NDRI RAND 47

Shown here are results for the comm delay cases in which Blue also has a 30-minute advantage in decision delay. As is evident from the chart, the same strong dependence on relative comm delay difference is as evident as in the prior results. However, if Blue's comm delay is set to a minimum, its chance of winning is even greater with a greater relative advantage in decision delay.

*Impact of Deep vs. Shallow ISR on Ground Force Decisionmaking**



** No stand-off or deep fires to take advantage of deep ISR coverage.*

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Shown here are the results for an excursion case in which Blue has long-range ISR coverage that extends deep into the second and third echelon of Red. These long-range ISR capabilities enable Blue to see the reserve Red brigades and, it is hypothesized, to not be fooled by the initial Red feint maneuver. With only shallow ISR coverage, Blue cannot see the allocation of Red reserves until it is too late to recover from a misallocation. With long-range ISR coverage, Blue wins more often and loses less often than with only shallow ISR coverage.

Summary

- ❑ **We have developed a sophisticated model of dynamic C2 decisionmaking**
  - Command structures and decision engines have general applicability
  - C2 decisions causally linked to comm and ISR system performance
- ❑ **Results indicate strong nonlinear dependence of combat outcomes on C3ISR architecture performance**
  - Decision or comm delay advantage is critically important to Blue, much less important to Red
  - Blue wins most of the time if it has significant decision delay advantage
  - Blue wins or draws most of the time if it has zero comm delays in its networks
- ❑ **Deep battle surveillance valuable for more than deep targeting**
  - Model can assess the operational level advantages provided by situation awareness of the deep battle area

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We have developed a two-sided model of ground warfare that includes adaptive agents that can simulate dynamic C2 and decisionmaking processes. Adaptive agents have been implemented at both the division and brigade levels. The decisionmaking logic implemented is based upon COFM. Because of the flexibility inherent in COFM, this model has general applicability beyond the notional scenario used in this proof-of-concept analysis. Further, command decisionmaking processes are causally linked to C4ISR system performance in this model because the decisions made by simulated commanders are based on the situation awareness information delivered to those commanders by onboard sensors and by communications links to off-board sensors.

The results obtained from the model indicate a strong nonlinear dependence of combat outcome on decision and communications time delays. As indicated above Blue is more dependent on superior C4ISR system performance and decisionmaking advantages than is Red because of Blue's numerical force disadvantage. Despite this disadvantage Blue wins 80 percent of the time if it has an advantage in both decisionmaking and communications network performance. These results hold when both Red and Blue have very good ISR coverage of the close battle area, and neither side has any ISR coverage of the opposing side's rear area.

An excursion case was also run in which Blue has deep ISR coverage of the Red rear area. Even without long-range strike capabilities (as was the case in this analysis), Blue derives a significant operational advantage from having deep surveillance capabilities. These results also suggest that good Intelligence Preparation of the Battlefield (IPB) information is important not only for the strike mission but also for ground maneuver warfare. We hope to examine this relationship quantitatively in future research.

Next Steps

- ❑ **Enhance the C2 decisionmaking engine by including**
  - **Corps-level C2 decisionmaking processes**
  - **Effects of attrition in C2 decisionmaking at all echelons**
  - **Planning and execution monitoring functions**
  - **IPB information into C2 decisionmaking processes**
- ❑ **Include long-range fires, attack helicoptors, and associated C2 decisionmaking processes**
- ❑ **Most realistic representations of C4ISR systems**
- ❑ **Use a more realistic and operationally complex scenario**
  - **Multiple Red and Blue objectives**
  - **Greater spatial and temporal depth**
  - **Sequential deployment of Blue forces**

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Shown in this chart are the next steps planned in Phase II of this research project. These steps will enhance the C2 decisionmaking engines used in the model in the ways indicated. In Phase I, the C2 decisionmaking engines emulated Red and Blue commanders who fight to the death regardless of the attrition their forces suffer. In Phase II simulated commanders will be given attrition thresholds that will alter their decisionmaking. For example, a Blue commander may order certain units to disengage or retreat if they suffer significant attrition. Red and Blue decisionmaking engines will also be enhanced so they can make use of IPB information.

Long weapons and more realistic representations of C4ISR systems will also be included.

Finally, a completely new and more realistic scenario will be used in Phase II that will have more operational complexity. This more realistic scenario will enable both Red and Blue to employ different high-level strategies and to alter these as the scenario unfolds during simulation runs. Depending upon the operational situation and how it degrades or improves, Red and Blue commanders will be able to alter their overall strategy at the corps level in order to accomplish their ultimate objectives.

Appendix A: System Effectiveness Analysis Simulation (SEAS)

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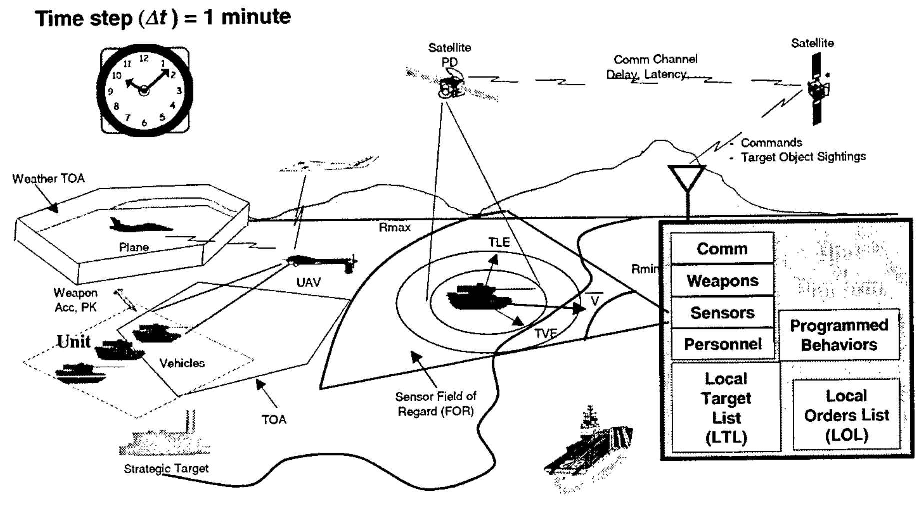
This appendix provides an overview of SEAS and a discussion of its key elements. SEAS version 2.2 was used for the analysis in this document. The previous version of SEAS, version 2.0, has been accepted into the Air Force Modeling Tool Kit. Throughout this discussion we refer to SEAS 2.2 as SEAS II or SEAS.

SEAS Models ISR Collection and Data Dissemination and Weapons Employment in a Realistic Operational Environment



Two- and three-dimensional Tactical Areas of Operations (TAO) to characterize unit and sensor operations in specific regions or weather.

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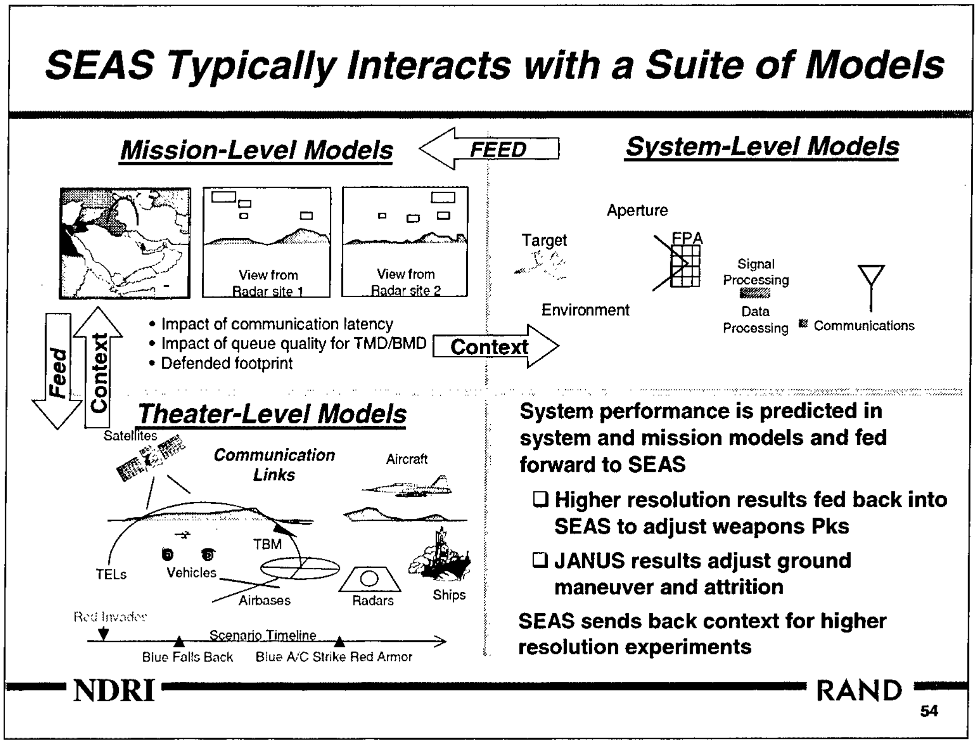
SEAS II is an entity-based, time-stepped, stochastic, multimission-level model designed to help evaluate the military utility of airborne and space-based communications and ISR assets. SEAS II supports quick reaction analysis (QRA) and exploratory analysis.

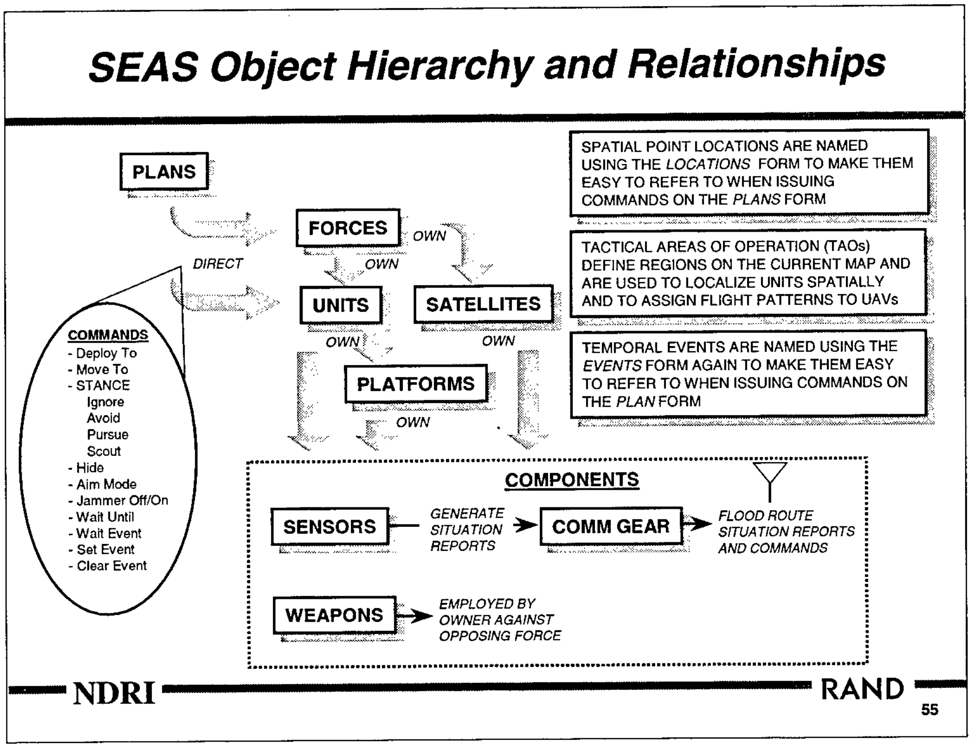
SEAS II entities are *devices* mounted on *platforms* and are governed by *settings*. Platforms are collected into *units*. Units are collected into superior units and, ultimately, *forces*. Devices interact stochastically with other entities. They may be sensors or weapons that detect or kill objects with probabilities given in detection probability (Pd) or kill probability (Pk) tables, respectively. Communications channels are devices that send and receive messages. Platforms may be vehicles that move on the battlefield such as aircraft, UAVs, tanks, and satellites. They may be C2 entities (headquarters) that control units. Movement scripts, force descriptions, Pd and Pk tables, and satellite traces are some examples of *settings* that govern the behavior of SEAS entities.

A representation of a sensor-to-shooter chain is incorporated into SEAS. Target detections by any sensor on a platform are reported on the platform's communication channels. Platforms having access to that channel (directly or via their command hierarchy) will shoot mounted weapons at the reported target if it is within weapon range and satisfies other constraints based on the number of rounds on hand, firing interval, shot coordination, and weapon-target priority rules.



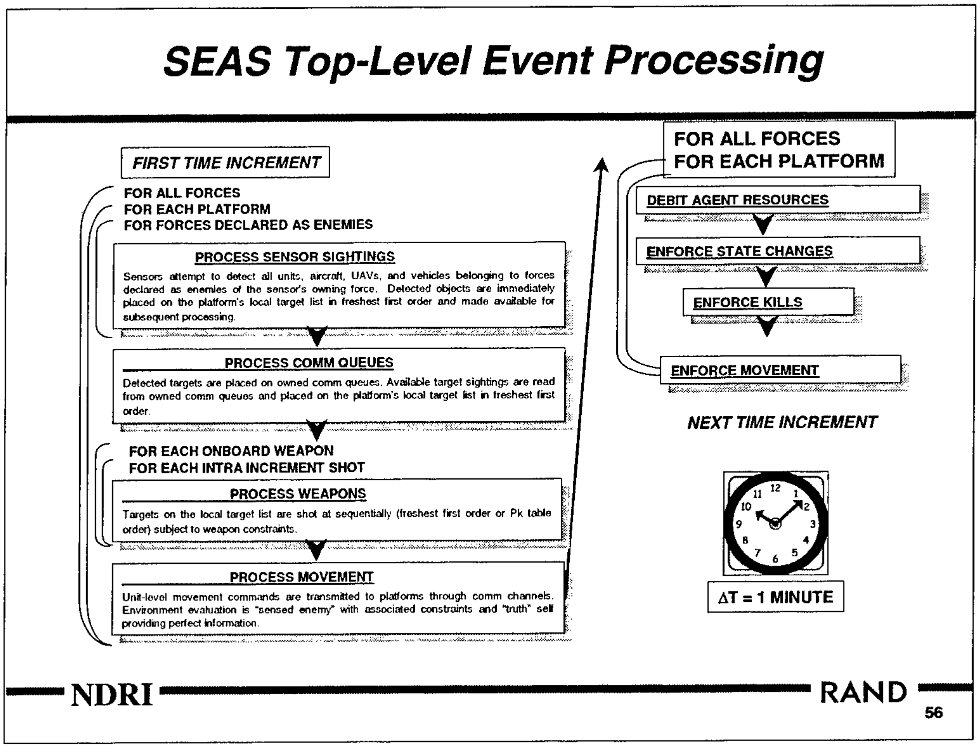
SEAS can and should be used in concert with a suite of analytical simulations. Ideally, such a suite should include detailed engineering and systems performance simulations, engagement- and single-mission–level simulations, aggregate campaign or operational-level simulations, and quickly executing, exploratory simulations such as SEAS. The more detailed and higher-resolution simulations provide measures of performance (MOPs) for the situations and context derived by the other lower-resolution models. The exploratory models conduct analyses in breadth to determine interesting areas for experimentation that are passed to the campaign model for in-depth analysis. The in-depth analysis refines and confirms the insights of the exploratory model. Campaign models output aggregate measures of effectiveness (MOEs) and measures of outcome (MOOs) of the issues under analysis. The exploratory models output MOE and may produce MOO as well.

SEAS is not suitable to measure the performance of a particular system as it uses MOPs as inputs. However, it can provide MOEs of systems in the context of a particular set of missions and determine the relative effectiveness of more or less of an asset. Since SEAS is not a theater-level model, it cannot predict the "outcome of the war." SEAS can be used to explore changes in MOPs of assets; for instance, a sensor's probability of detection, range, or accuracy or the effectiveness of a given type of a weapon-platform combination against a particular type of target.



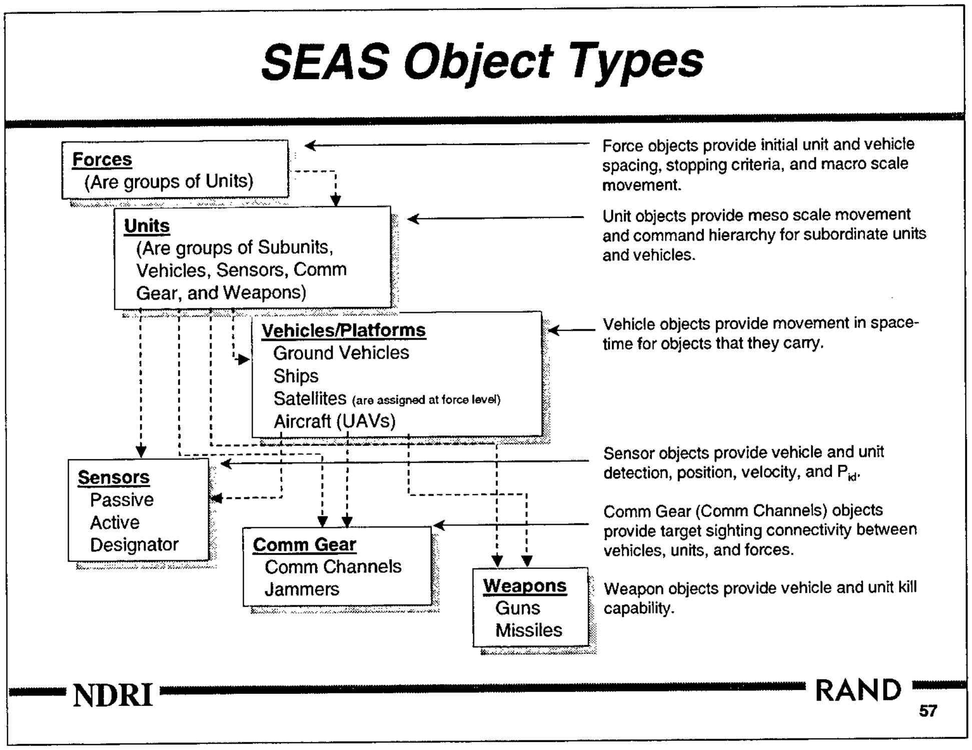
The hierarchy for the SEAS simulation is very similar to the actual organizational structure of most military forces in the world today. Forces own units, which own subordinate units, which own the people and hardware necessary to conduct war.

At the very start of the war file, the analyst must decide the Forces involved and the Concepts of Operation (CONOPS) for the battle. These decisions result in commands that are written to the Forces and their subordinate units. These Forces own units and satellite resources that are used to gain ISR concerning the enemy. The units own platforms (vehicles, planes, UAVs, ships) that serve to provide mobility for the sensors, weapons, and comm gear necessary to conduct the battle. Locations, TAOs, and temporal events are used to define the scenario and location of the battle.

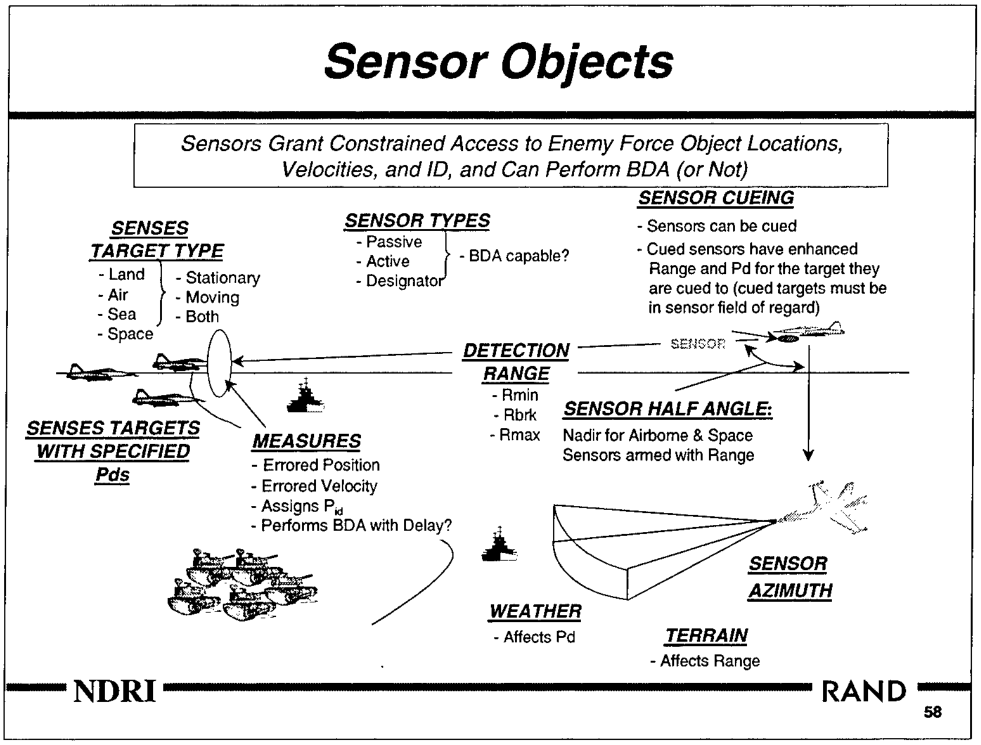


Actions in SEAS are accomplished within a discrete-time simulation with the time step set to equal one minute. Actions in the simulation are governed by modules that define the interactions of various parameters such as environment, sensors, weapons, vehicles, satellites, etc. The order in which modules are adjudicated in the simulation are as shown in this chart. The first step is processing the sensor sightings for both sides, then the communication queue status, etc., with movement being the last action taken before the next time increment.

As subsequent time steps occur, the modules account for movement; use of resources; attrition of both enemy and allied forces; constraints on sensors, weapons, communication, movements of units, vehicles, or satellites; the actions and interactions of agents, and the interactions of all other appropriate parameters. These activities are repeated until the battle is declared over as a result of time or unit attrition.



The hierarchical force structure in SEAS permits easy programming of scenarios. A SEAS unit reflects an actual combat unit in regard to access to sensors, communications ability, platforms, and weapons. A SEAS unit can own other units, which in turn may own other units The unit can own a sensor or multiple sensors. It can own single or multiple communications channels, as well as different types of platforms and weapons. The same is true of subunits.



SEAS sensors are endowed with defined abilities and limitations by the user. These abilities and limitations provide the owner of the sensor constrained access to information concerning the object of the sensor. The environment can adversely affect the sensor by reducing the probability of detection of the sensor object. Cueing the sensor enhances the Pd, making it easier for the sensor to find the target. Again, this models reality where a Moving Target Indicator (MTI) sensor on a satellite might cue a Synthetic Aperture Radar (SAR) sensor having enhanced resolution.

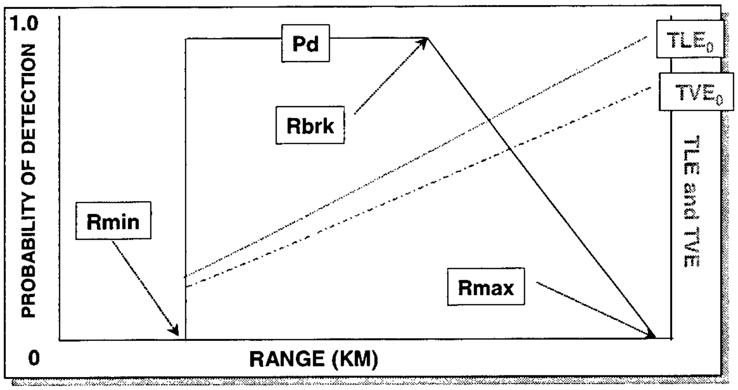
Sensor-Target Interaction (Detection Range)

For each enemy target Rmin <= Rt <= Rmax, a uniform random draw is made between 0 and 1. A draw above Pd is a detection

Range is slant 3-D slant range, not range projected into plane of battlefield

TLE and TVE are 1 sigma point on Gaussian truncated at 6 sigma

TLE and TVE are specified for max range and vary linearly toward zero ($s = r\theta$)



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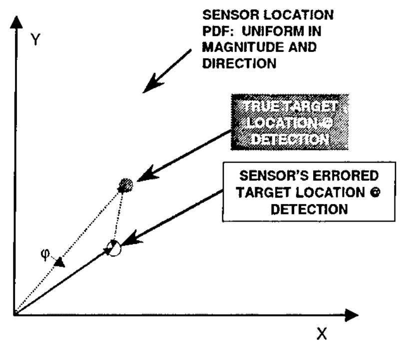
Sensors are utilized to locate objects. The effectiveness of the sensor is user-defined by indicating the probability of finding a particular object. The probability can be modified based on the range of the sensor to the object sensed. The minimum target detection range for a sensor is denoted Rmin. This accounts for sensors like SAM radars that have minimum range constraints. Rmin is also used to create nadir holes for space-based sensors (note: these nadir holes do not display). Detection probability degrades linearly to zero from the break range (Rbrk) to the maximum range (Rmax). The Target Location Error (TLE) and the Target Velocity Error (TVE), which are specified by the user, are also linearly dependent with distance to the target. This creates a classic duality. Getting closer is good because it increases the likelihood of killing the target due to better target location. However, getting closer also exposes the shooter to additional enemy weapon systems. The user-specified values apply at Rmax. If Rbrk is not specified, then Rbrk = Rmax.

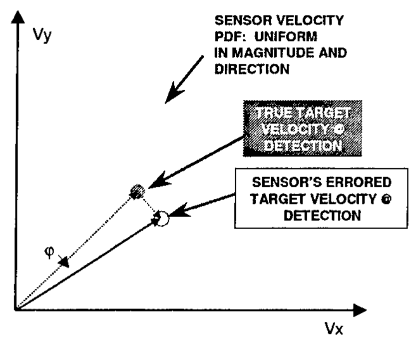
Sensor-Target Interaction (Location & Velocity)

- ONCE A SENSOR DETECTS A TARGET, A SIGHTING MESSAGE IS CREATED THAT CONTAINS AN ERRORED TARGET LOCATION AND AN ERRORED ESTIMATE OF TARGET VELOCITY

LOCATION



VELOCITY



NDRI RAND

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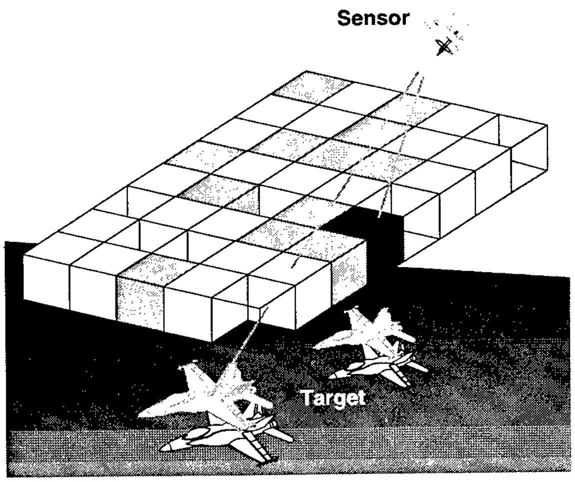
Errors on sensed target location are generated using a Gaussian random draw on both the x and y axes using the user-specified TLE as a one sigma value. The probability of finding the target within the TLE value is .63. The TVE is computed in a similar fashion utilizing assumed velocity errors in the x and y directions.

Based on the initial target location and speed, SEAS projects an assumed target location over time to the point at which a weapon is fired. The location error increases as the time from sensing to weapon firing increases.

Weather Impact on Sensors



User Defines:
- Size, Shape, & Location (TAO)
- Min Alt, Max Alt (km)
- Pd reduction factor (0 - 1)
- Start time and End time

This "patch" of weather is assigned to a sensor explicitly

Affects detection probability for line of sight (LOS) vectors passing through the defined weather region

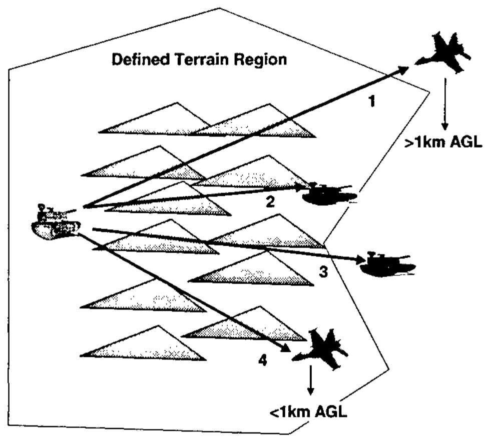
Multiple weather TAOs can be defined and assigned to the same sensor

Multiple weather TAOs can overlap (worst-case value is enforced)

NDRI RAND 61

The user is able to account for the effects of weather on sensors. The "weather" area is defined as a polygon located between two altitudes (min and max). This area of weather can be defined to reduce the effectiveness of certain sensors but not others. The reduction in sensor capability can be defined for each sensor by stipulating a multiplication factor for the Pd. Multiple weather databases can be defined and turned on and off at different times to simulate changing weather conditions. If the same sector is covered by multiple polygons with different Pd reduction factors, the weather condition with the greatest effect will control the sector until it disappears based on the user-defined duration. In this way the user can simulate a reduction in weather conditions (an increase in Pd up to the defined Pd) as the scenario progresses. Weather conditions can also affect a vehicle's maximum speed based on a multiplicative parameter between 0 and 1.

Terrain Impact on Sensors



User Defines:
- Size, Shape, & Location (TAO)
- Pd reduction factor (0 - 1)

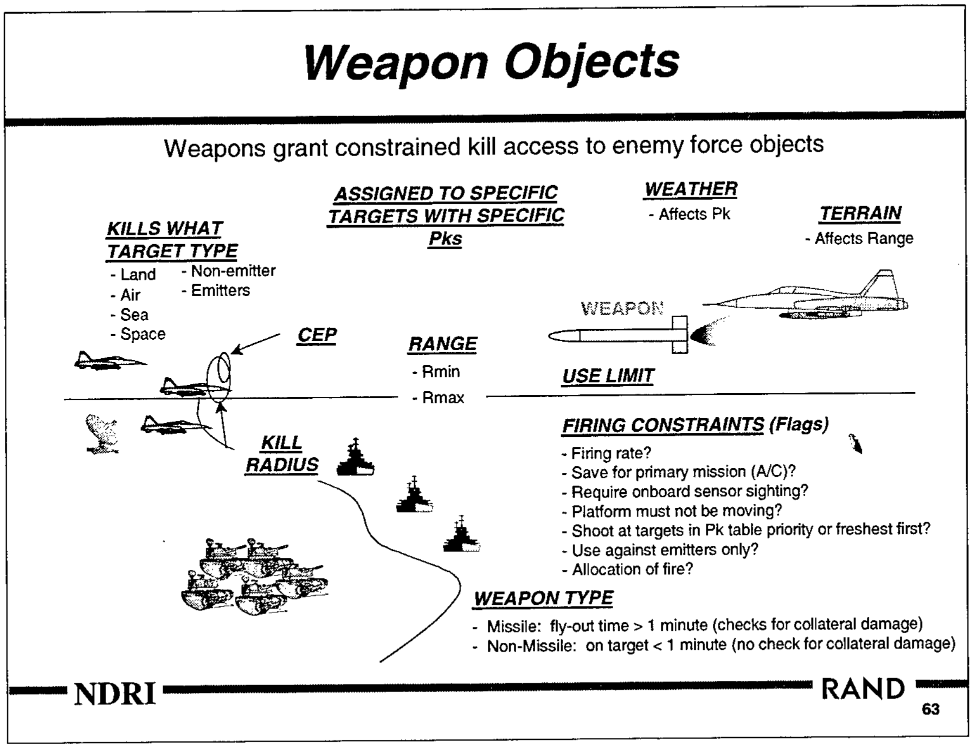
This "patch" of terrain is assigned to a sensor explicitly

Affects detection probability for line of sight (LOS) vectors passing into the defined region

Multiple terrain TAOs can be defined and assigned to the same sensor

NDRI RAND 62

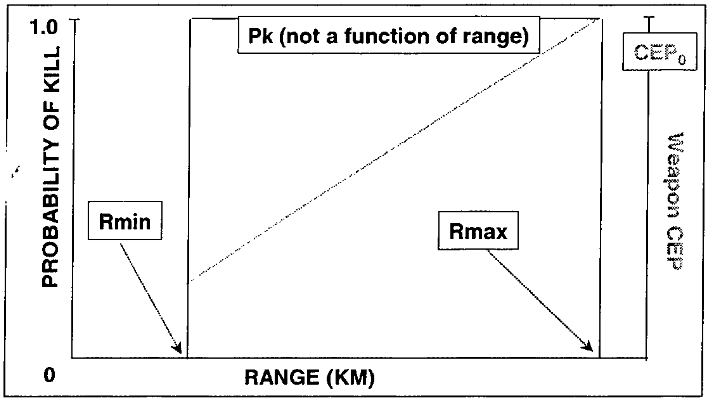
The terrain database structure defines a region bounded by a closed polygon and a reduction factor associated with the enclosed region. This factor scales the sensor detection range for platforms whose line of sight (LOS) intersects this polygon when either the sensor, target, or both are in the TAO. If both the sensor and target are outside the TAO and the LOS happens to pass through the TAO, the Pd is similarly affected. Platform altitude is used to determine when the reduction factor is applied. Sensor platforms above 1 kilometer, either in or out of the TAO, do not have this factor applied.



Weapons are assigned to specific targets through the use of Pk tables. The effects of weather on the Pk and the effects of weapons range due to terrain can be accounted for by the user. Further constraints on weapon utilization can be programmed through the use of various flags that can be set by the user. These flags can account for firing rate, whether a weapon platform can be moving or not, whether an onboard (platform) sensor must detect a target before firing, the type of target that can be killed, etc.

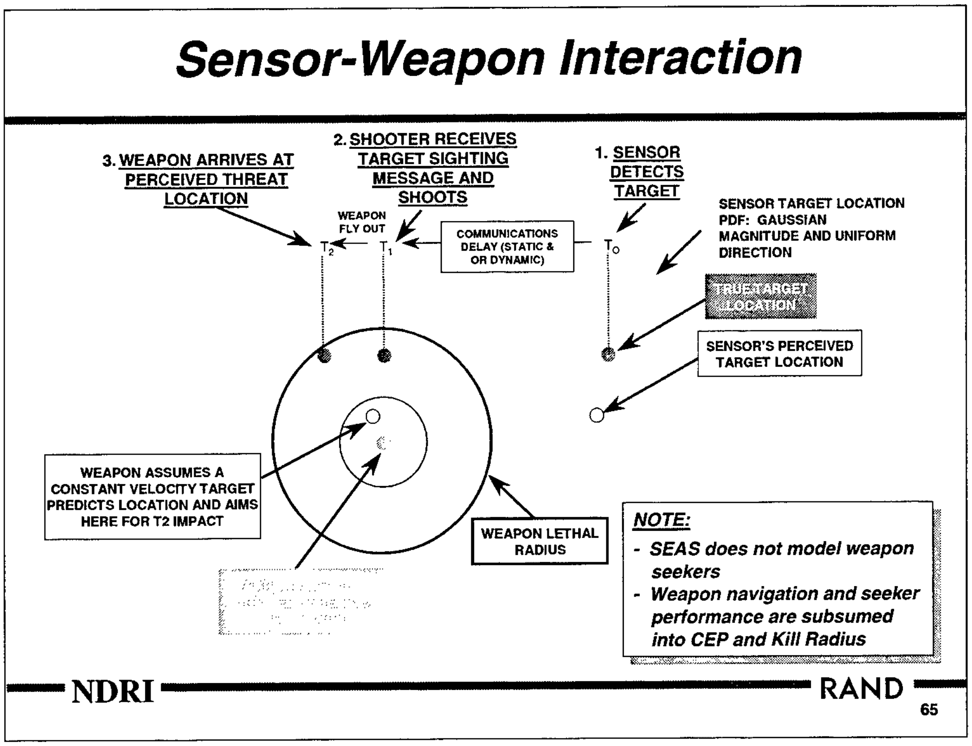
Weapon CEP Versus Range Variation

- For each enemy target Rmin <= Rt <= Rmax, a Pk draw is made based on the weapon target pair in the Pk table
- The user-specified CEP starts at max range and decreases linearly to min range ($s = r\,\theta$). CEP is defined as 1 sigma of Gaussian PDF truncated at 6 sigma



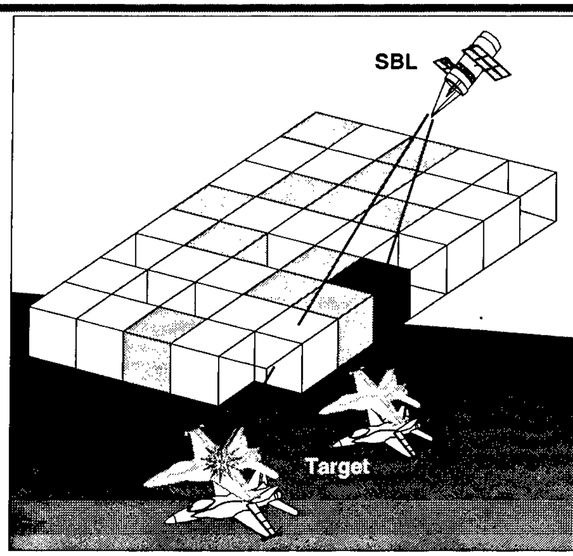
NDRI RAND 64

Range does not affect the Pk. Between the minimum and maximum range of the weapon, the Pk is constant based on the initial Pk draw from the Pk table. However, the CEP (Circular Error Probability) does vary with range. The CEP is at the maximum value specified for the weapon at maximum weapon range and varies linearly to zero as the firing range is reduced.



The chain of events from target sensing to weapon hit considers the errors and delays inherent in the sensor to weapon impact links. As shown in previous charts, the sensor error is accounted for in two components: the TLE and TVE. This errored information is passed via a communications system that has inherent delay in receiving and retransmitting information. During this communication delay, the target is proceeding along an assumed track that is computed based on the sensor information. The weapon fired at a "perceived" target location has a certain targeting error. The summation of all these facts and errors concerning the sensor/target/weapon chain determines whether the weapon will kill the target. Subsequent detections replace previous detections. This assumes perfect target track correlation.

Weather Impact on Weapons



User Defines:
- Size, Shape, & Location (TAO)
- Min Alt, Max Alt (Km)
- Pk reduction factor (0 - 1)
- Duration (min)

This "patch" of weather is assigned to a weapon explicitly

Affects kill probability for weapons passing through the defined weather region

Multiple weather TAOs can be defined and assigned to the same weapon

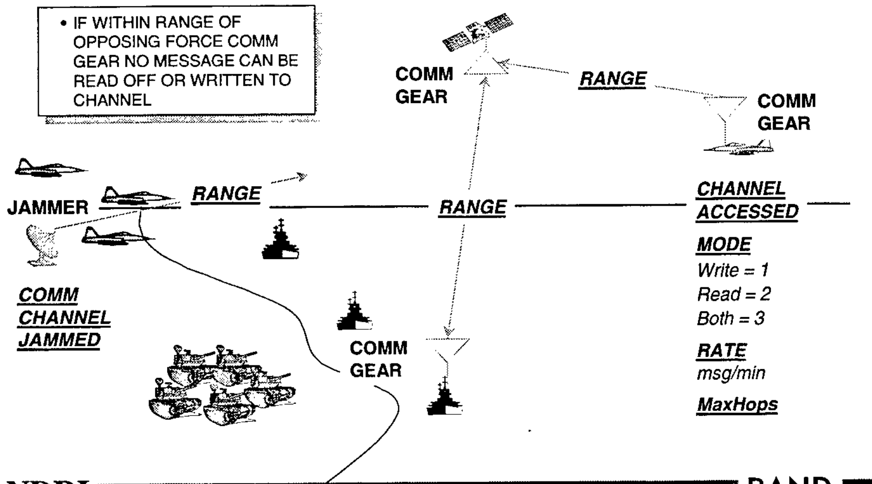
Multiple weather TAOs can overlap

NDRI RAND 66

Just as weather affects the detection probability of a sensor, it can also affect the kill probability of a weapon. The user defines the weather area and how it affects individual weapons targeted against individual types of targets. The Pk is then reduced by the specified reduction factor if the weapon must pass through the weather area to attack the target. As in sensors, multiple-weather TAOs can be defined to account for time variation of weather over a defined area.

Communication Terminals (Gear)

- *COMMUNICATION GEAR GRANTS CONSTRAINED ACCESS TO COMMUNICATION CHANNELS*

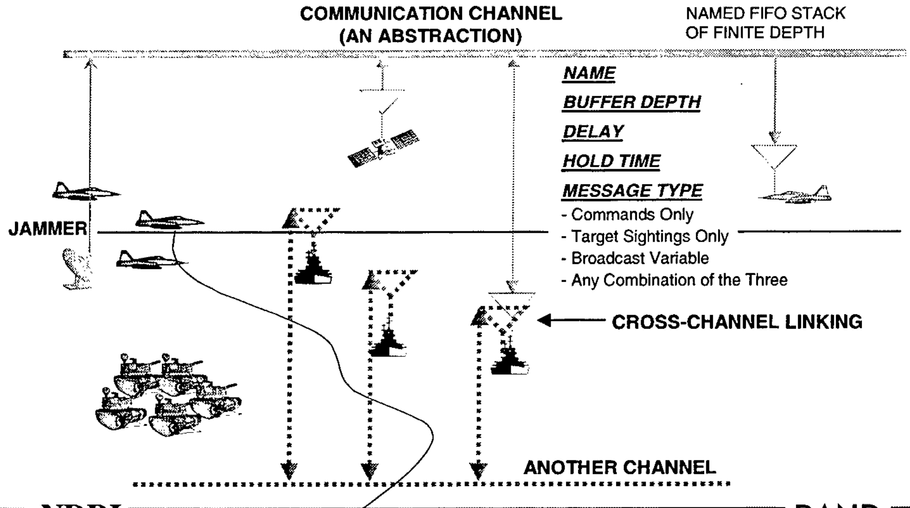


NDRI RAND 67

Communication is the means by which information about targets as well as commands are transmitted and received by units and platforms (agents). Communications systems can be jammed reducing or totally eliminating information flow. The communications mode (write, read, or both) is user specified. Communications channels have a range. When transmitters and receivers are outside the specified range, no messages get through. The user can control how many channel nodes a target sighting can traverse. This is used to control the flow of target-sighting messages through the communications network. For example, one would want to prevent a tank commander from squawking target sightings back to CONUS via a satellite comm channel that is four echelons above him. A piece of communications gear can be defined as a jammer. A jammer blocks *all* reads and writes to the channel it jams when it is within its specified range of a platform trying to access that channel.

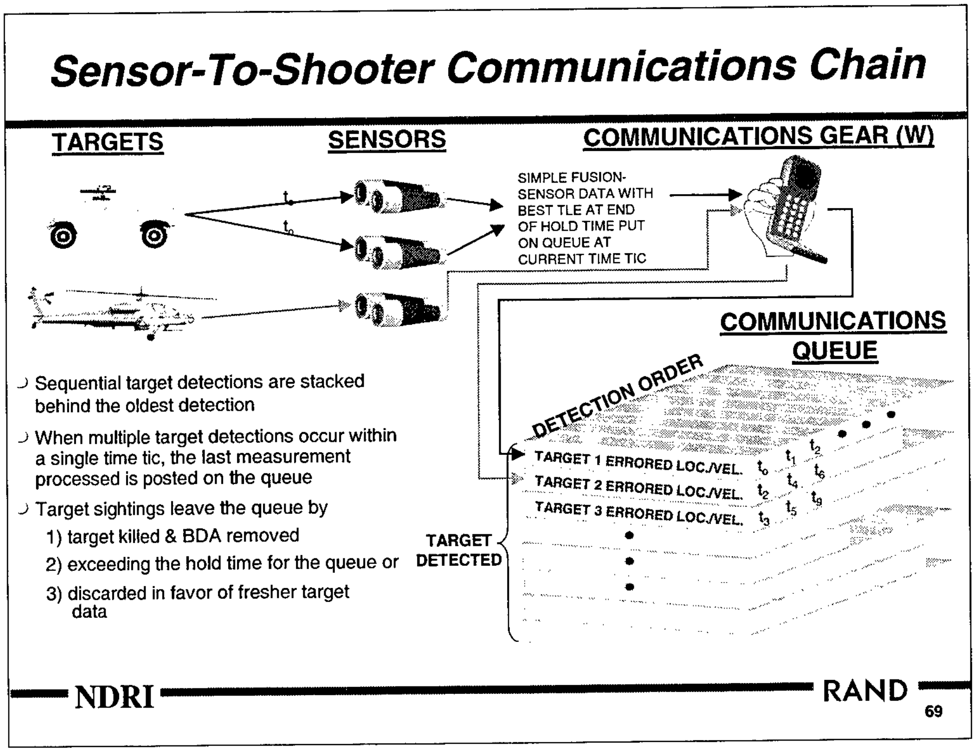
Communication Channels

- COMMUNICATION CHANNELS PROVIDE CONSTRAINED LINKS BETWEEN COMMUNICATION GEAR



NDRI RAND 68

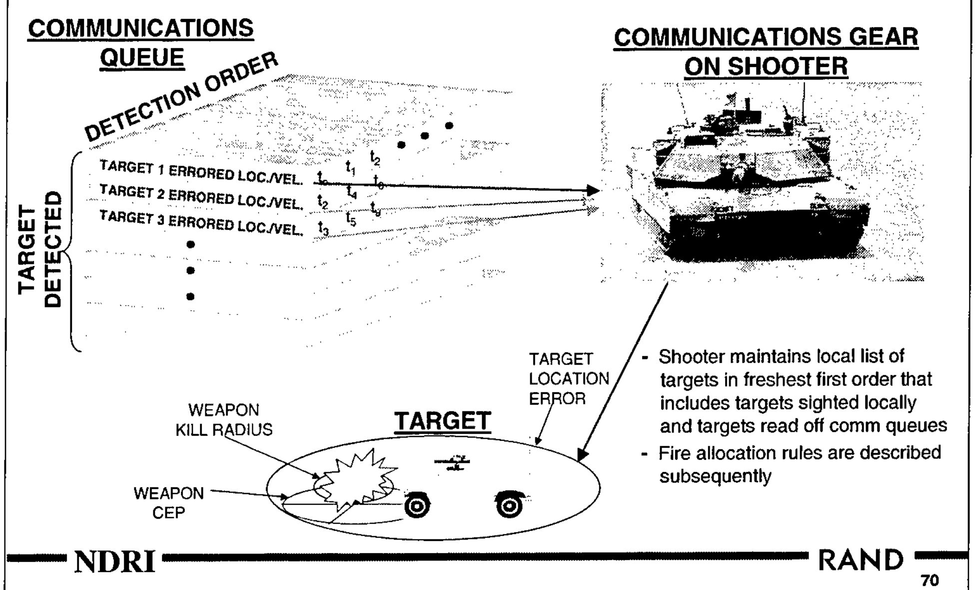
Multiple pieces of comm gear can be specified for a single unit or platform. This allows cross-linking of communications channels. Messages received on one channel are retransmitted on all other channels owned by that unit or platform. Hold time specifies how long a message stays on the communications queue once it is available for reading. The comm gear has both a static delay time that applies to all messages entering the cue and a dynamic delay that is an exponential time added to the static delay. No message can be read until it has aged on the queue for the delay time specified for that queue. The buffer depth controls how many messages can be on the queue at any one time. Messages written to the queue once it is full are lost. SEAS passes three types of messages on communications channels: target sightings, commands, and broadcast variables. The message type flag controls which type of messages this channel can carry.



The sensor-to-shooter communications chain is based on the concept of placing target information on the communication queue such that the freshest target information is stacked behind the older target information. As previously discussed under weapons, the fresher the information, the smaller the targeting error at the time the weapon is fired. When two sensors locate the same target at the same time, the target with the smallest TLE is placed on the queue while the information from the other sensor is discarded. The information on the communications queue is discarded when the target is confirmed destroyed, when the specified hold time for target information is exceeded, when older target information is displaced by fresher data, or when the fusion flag conflates the sightings.

There is one sensor fusion option currently. If the fusion flag is set at the Unit or Vehicle level, and two sightings at different times are recorded on a local target list, the route sum of squares (RSS) of the location and velocity errors is performed and a new sighting is returned to the list. This simple calculation rewards multiple sightings of a target with decreasing errors in the location and velocity.

Sensor-To-Shooter Communications Chain (Cont.)



A weapon platform maintains an onboard local target list that is refreshed with data obtained from local sensors as well as remote sensor information that is relayed to the platform via the communications system.

SEAS contains "fire allocation rules" that spread fire across multiple targets. This is to avoid the possibility that a platform would fire all available weapons against a single target. The "fire allocation" system will be discussed later.

Platform Objects

- Platforms enable onboard equipment (sensors, comm gear, weapons) to change location in space and time

SATELLITES

PLATFORM MOVEMENT:
- Explicit commands
- Hard wired behavior
- Agent rule sets
- External file (sats only)

WEATHER
- Affects Speed

TERRAIN
- Affects Speed

AIRCRAFT
- Attack targets
- Linear flyouts
- Can divert to other targets

UAVs

FLY ALONG POLYGONS (TAOs)

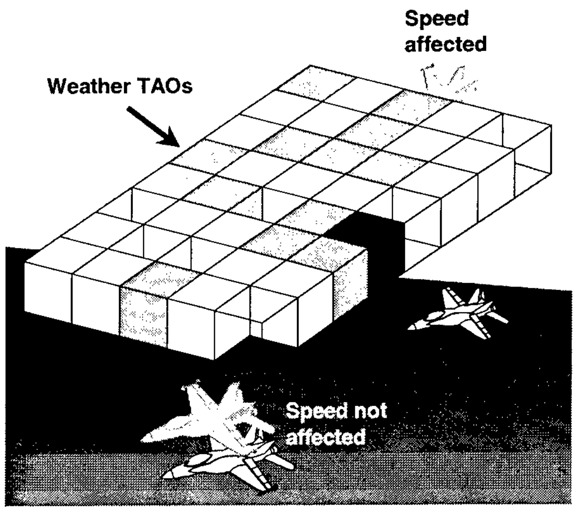
SURFACE VEHICLES
- Stay within polygons (TAOs) or
- Follow along polygon (Patrol)
- Follow explicit and agent based movement orders
- Move at half speed at night
- Can be denied movement after shooting for a delta time (shoot & scoot)

- Each platform maintains a local target list that defines the targets it knows about
- Targets enter this list from onboard sensors or comm links
- Target engagement priorities can be assigned as freshest first or Pk table order under weapon objects

NDRI RAND 71

Platforms are mobile SEAS constructs that carry sensors, weapons, and communications gear. Movement can be done using explicit commands input by the user, by "hard wired" behavior written into the SEAS code, as a result of the agent rule sets (to be discussed later), or by the use of an external data file that is read into SEAS during execution. This last option is currently used for satellite files only.

Weather Impact on Platforms (Vehicles & A/C only)



User Defines:
- Size, Shape, & Location (TAO)
- Min Alt, Max Alt (km)
- Speed reduction factor (0 - 1)
- Duration (min)

This "patch" of weather is assigned to a vehicle or plane explicitly

Affects speed of vehicles and planes passing through the defined weather region

Multiple weather TAOs can be defined and assigned to the same platform

Multiple weather TAOs can overlap

NDRI RAND

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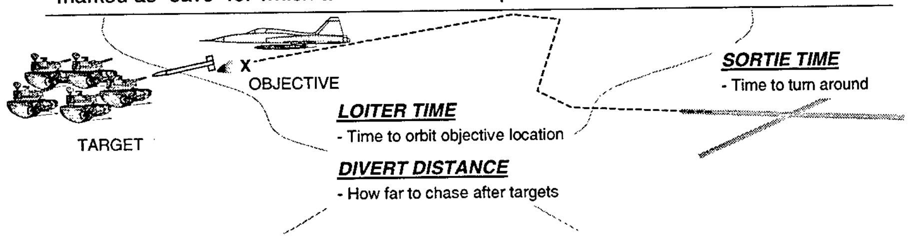
Weather can be defined to affect the speed of platforms. As in previous discussions about weather effects on sensors and weapons, all necessary parameters are input by the user. Any platform entering the defined weather area for which there is a defined interaction will have its maximum speed multiplied by the weather factor. A platform inside both a weather and terrain region will have both factors applied sequentially to its speed. The factors can affect the speed either positively or negatively, depending on the desired interaction.

Aircraft Platforms

- Aircraft platforms can have sensors, weapons, and comm devices
- Orders are given to an aircraft or group of aircrafts to "fly" to a designated location. The loiter time (once the aircraft reaches the target) and turnaround time (for refueling, etc.) are controlled by the user
- When the aircraft reaches its objective it will engage any target for which it has a weapon subject to that weapon's constraints
- The aircraft can "chase after" targets that are on its local target list out to a distance specified as its "Divert Range"
- Targets encountered before reaching the objective will be engaged with any weapon not marked as "save" for which a Pk table match-up exists



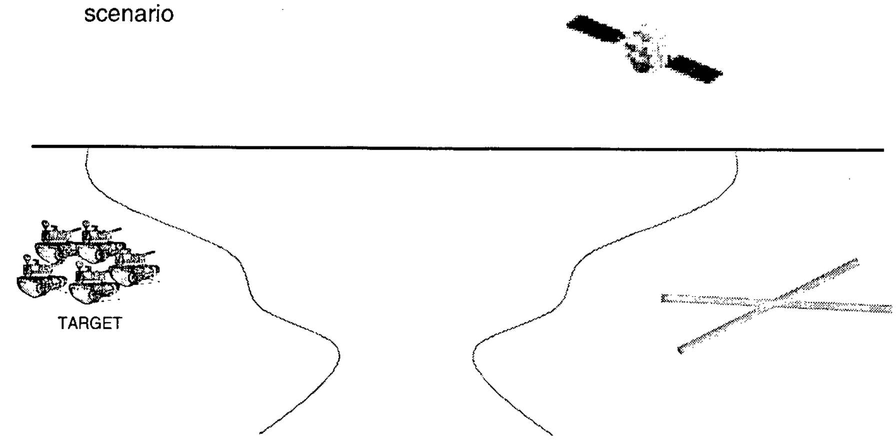
NDRI RAND 73

An aircraft's movement is controlled by the "fly" orders assigned to it. The orders specify the location for a single trip to be taken. As the aircraft encounters its objective, targets consistent with weapons able to attack the specified targets are engaged. As the scenario run progresses, the aircraft flies out to the specified fly location and begins to search for the assigned targets. If it locates a target appropriate for its weapons load, it will attack the target. It can leave its assigned fly objective to attack targets for which it has weapons as long as these other targets are located with the "divert range" that is specified for the platform.

During fly out, the platform can engage targets for which it has weapons, unless the user specifies through a "save" flag that it should not do so. In this case the weapon is saved for a specific target controlled by the user. In all cases the aircraft will attack targets of opportunity when it is returning from the fly location to base.

Satellite Platforms

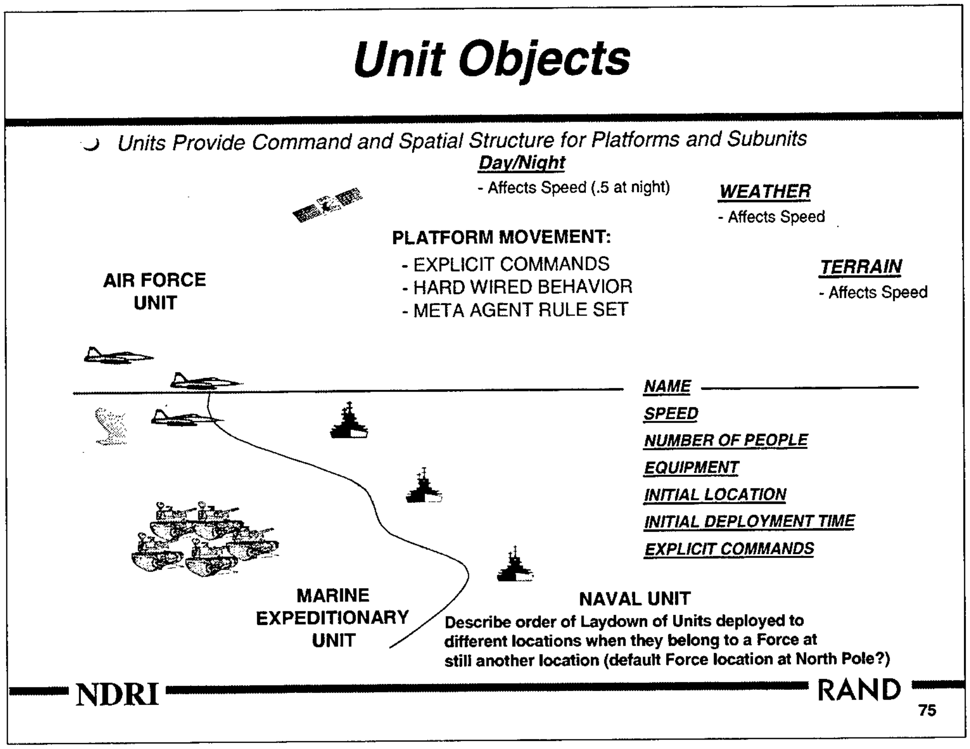
- The motion of satellite platforms may be defined in SEAS or is passed into SEAS by specifying a path to an ASCII file containing longitude, latitude, and altitude of the satellite at one-minute intervals over the duration of the scenario



NDRI RAND 74

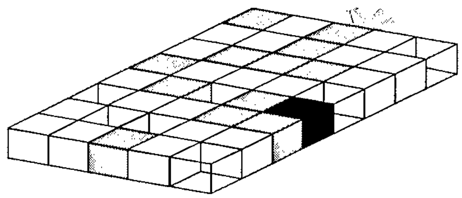
Satellite platforms are assigned at the force level and can have sensors, weapons, and comm devices attached to them. Their movement can be controlled by two means. Satellite files that provide longitude, latitude, and altitude in one-minute intervals are the only types of files read by SEAS from an external source (other than the input.war file). SOAP, a program that computes Keplerian orbits, can be utilized to create a text file readable by SEAS that provides this information.

SEAS also has an internal subroutine that allows simple orbit calculations and can be used instead of the position files noted above. The user specifies the satellite period (min), eccentricity, inclination (deg), longitude of rising node (deg), true anomaly (deg), argument of perigee (deg), and epoch. SEAS then generates the necessary files to move the satellite during the scenario.

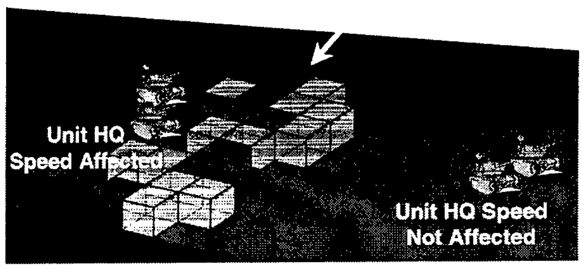


Units are SEAS entities that can own other objects as well as subunits, which in turn can also own objects. The unit object allows the user to specify various parameters for the unit. These parameters include location, speed, number of personnel, and types of equipment such as planes, tanks, missiles, etc. The user can also specify when the unit will deploy, when and where it will move, and other explicit commands.

Weather Impact on Units



Weather TAOs



User Defines:
- Size, Shape, & Location (TAO)
- Min Alt, Max Alt (km)
- Speed reduction factor (0 - 1)
- Start Time / Stop Time

This "patch" of weather is assigned to a unit explicitly

Affects speed of units passing through the defined weather region

Multiple weather TAOs can be defined and assigned to the same unit

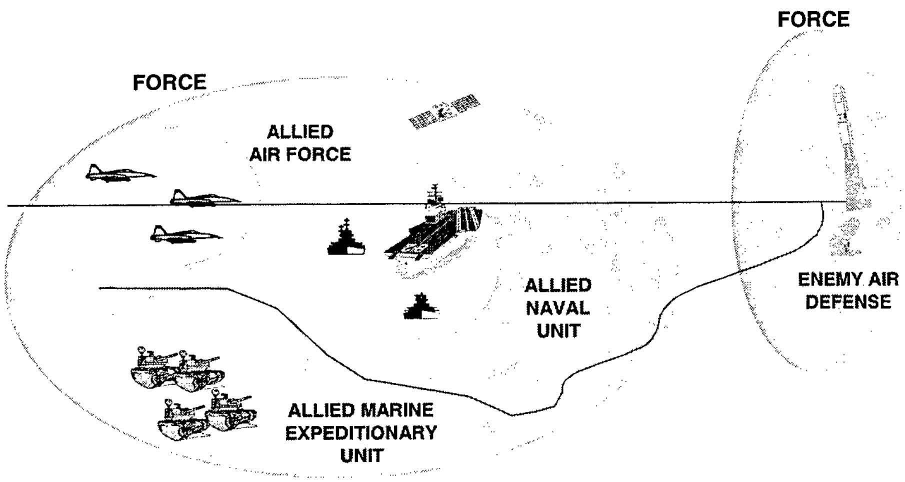
Multiple weather TAOs can overlap

NDRI RAND 76

Weather can impact the speed of a unit as has been previously discussed with weapons, sensors, etc. The definition of necessary parameters is the same as for other weather-affected objects.

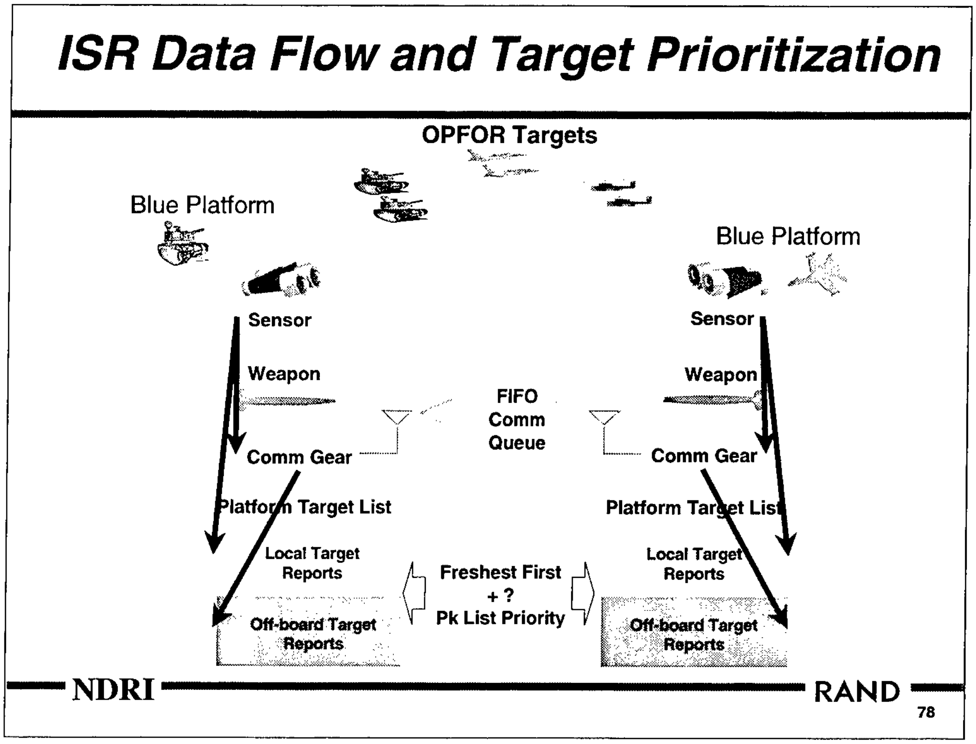
Force Objects

- Force objects collect units into coordinated groups and define relationships between them (Ally, Enemy, Neutral)

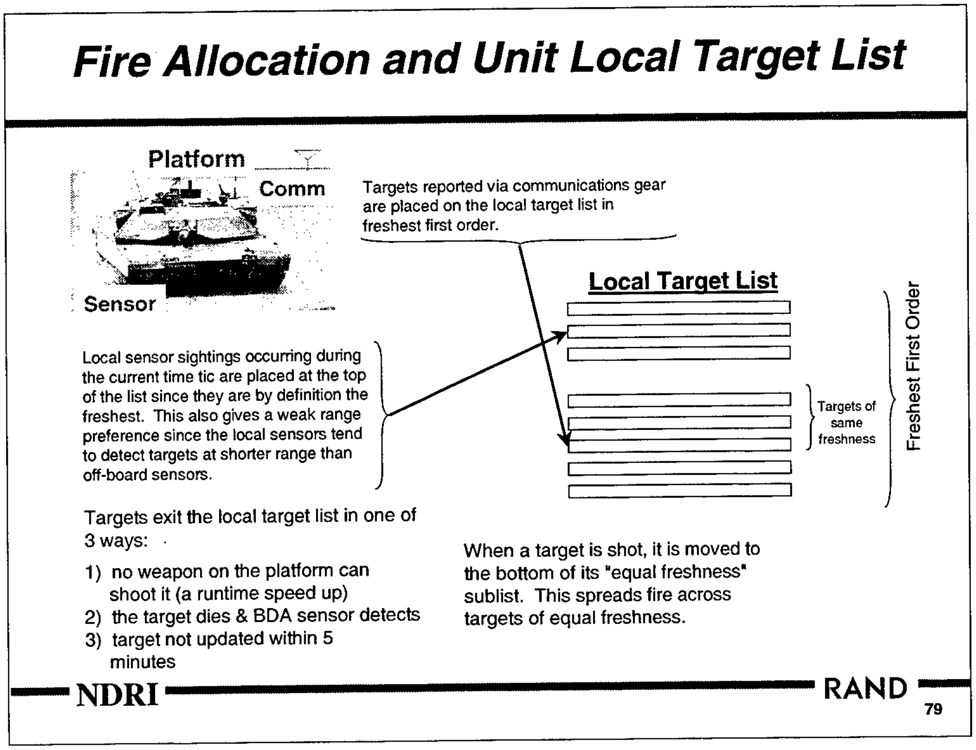


NDRI RAND 77

A force object defines the number and types of units that make up a force. It also allows for definition of what represents an ally and an enemy force/unit. Satellite platforms are assigned directly to forces (not to units or vehicles).



SEAS prioritizes targets on the basis of freshest information first and then best kill probability based on the Pk table. As has been previously discussed, the ability to kill a target in SEAS is predicated on having a weapon with a defined kill radius impact in a target location so that the target is within the kill radius of the weapon. Since there are errors inherent in the sensor data and a growing target location error as time increases, the faster a weapon can get to a target location after sensing, the greater the probability of a kill. Based on this it is imperative that the freshest sensor data be utilized. If the situation arises where two sets of target data are received simultaneously, SEAS will fire the weapon at the target with the highest Pk.



Local target sensors are utilized first in weapons targeting since by definition local sensors provide the freshest data. As previously discussed these data have priority in the local target list when multiple sightings of a target are made (assuming no fusion is performed). Also, since the sensor's range is usually inside the weapon's range, the probability of achieving a target kill goes up. Once a target is "shot-at," it is moved down the equal freshness list so that fire may be allocated to other targets. This spreads the fire across all available targets.

Targets exit the local target list by one of three methods:

(1) An incompatibility between available weapons and targets. For example, if the platform has only anti-radar missiles and no radar-generating enemy source exists.

(2) BDA ascertains that the target has been destroyed.

(3) Information on the target location is not updated within five minutes.

If two sightings of the same target differ in time, the target list will only keep the more recent sighting. This is regardless of the errors associated with the sightings so long as the fusion flag is not set. If it is set, SEAS will calculate the RSS of the errors in the sightings and place the updated location on the list.

Fire Allocation: Weapon / Target List Interaction

	Non Time of Flight Weapon Δt <= 1Minute		Time of Flight Weapon Δt > 1Minute	
	Fire Rate > 1/Min	Fire Rate <= 1/Min	Fire Rate > 1/Min	Fire Rate <= 1/Min
Not Prioritized	Goes down the local target list shooting one shot at each target. When the end is reached it starts back at top until all rate specified shots are taken. **The local target list is always in freshest first order!**	Shoots at first target on local target list and moves it to the bottom of its "equal freshness" sublist. This spreads fire across multiple targets of equal freshness on subsequent time tics.	Shoots one shot at first target on local target list and moves it to the bottom of its "equal freshness" sublist. Won't shoot again until first shot lands.	Same.
Prioritized	Goes down the local target list looking for target that appears first in the Pk table. When it finds one it shoots it and moves it to the bottom of its "equal freshness" sublist. Goes back to the top of the local target list and starts over again. If it exhausts priority 1 targets it moves to priority 2, etc. Continues until all rate specified shots are taken.	Goes down the local target list looking for targets that appear first in the Pk table. When it finds one it shoots it and moves it to the bottom of its "equal freshness" sublist. This spreads fire across targets of equal priority on subsequent time tics.	Shoots one shot at highest priority target on local target list and moves it to the bottom of its "equal freshness" sublist. Won't shoot again until first shot lands.	Same.

Note: Each weapon instance acts independently.

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In SEAS fire allocation differs depending on whether weapon flight time is less than or greater than one minute, weapon firing rate is less than or greater than one per minute, and fire is or is not prioritized.

Flight Time Less Than One Minute

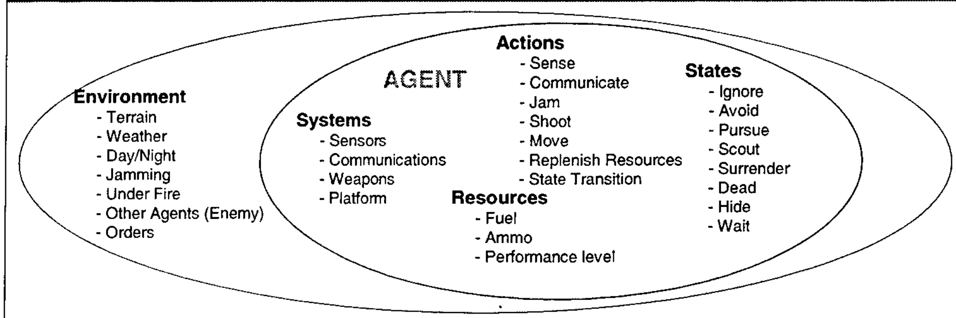
For fire rates greater than one per minute, nonprioritized shooters go down the local target list one target at a time until the end of the list and then return to the beginning. For prioritized fire SEAS will compare the target list with the Pk table and shoot at the target with the highest Pk. It takes this target to the bottom of the equal freshness list and goes on to the next target. It will continue this scheme until it exhausts all priority 1 targets and then will move on to priority 2 targets.

For fire rates less than or equal to one per minute, the nonprioritized weapon goes after the first target on the local target list then moves it to the bottom of the equal freshness list. For the prioritized case, the weapon goes after the target with the highest Pk and then moves the target to the bottom of the equal freshness list.

Flight Time Greater Than One Minute

For any firing rate, nonprioritized weapons will fire at the first target on the local target list and then move the target to the bottom of the equal freshness list. The weapon will not fire again until the first shot lands. For prioritized weapons the weapons will fire at the highest-priority target and then move it to the bottom of the freshness table. It will not fire again until the first shot lands.

Theoretical Context for SEAS Complex Adaptive System Agents



- Agents exist and move in a space-time **Environment**
- Agents possess **Systems** and **Resources**
- Agents are in **States** and take **Actions**
- **Actions** modify the **Environment** and expend **Resources**
- Simple rule sets determine **Actions** based on Agent's sensed **Environment**, **State**, **Resources**, and owned **Systems**

NDRI RAND

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SEAS provides a mechanism by which friendly and enemy forces are modeled and are given the ability to interact and react to situations. This Complex Adaptive System (CAS) is the heart of the simulation. In SEAS, agents are used to model this CAS by allowing the actions of agents to affect the environment (communication, sensor effectiveness, other agents, enemy forces, etc.) and utilize and expend resources. Most objects in the SEAS code contain a description section (containing such things as the number and type of weapons contained on it, the number of people, speed, etc.) and an orders section. The orders section contains the agent-based behavior in addition to scripted moves. For instance, a scripted move would be to move to a given position at a certain time. Agent-based behavior might involve moving to a position that contains a number of enemy tanks above a certain threshold (calculated from, say, target locations taken from sensed data). The difference being that the latter is based on the stochastic nature of sensing and the probabilistic location of targets. Therefore, agents such as airplanes and vehicles can react based on their environment. Their environment is described by such things as the terrain, weather, whether it is day or night, whether they are under fire or not, weapons owned or operating, etc. The agents can act based on their perception, by communicating, shooting, moving, etc. The result is a less scripted scenario providing a more robust set of actions. These same actions affect the environment and the cycle continues.

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