Utilizing Network-Enabled Command and Control Concepts to Enhance ASW Effectiveness

The Ninth International Command and Control Research and Technology Symposium
Copenhagen, Denmark
September 14-16, 2004

Dr. Ralph Klingbeil
Mr. John Shannon
Mr. George Galdorisi

Naval Undersea Warfare Center Newport
and
Space and Naval Warfare Systems Center, San Diego

Outline

- **Background and analysis objective**

- **Analysis of two net-centric ASW concepts**

  - **Shared Situational Awareness (SSA)**

  - **Collaborative Information Environment (CIE)**

- **Summary of findings**

**The Technical
Cooperation Program
AU, CA, NZ, UK, US**

Background and Context

TTCP – OSD Sponsored long-term effort

"Technical" counterpart of AUSCANNZUKUS

Ten Groups in various specialties

MAR – Maritime Systems Group

MAR AG-1: Network Centric Maritime Warfare

  Three year effort

  Extensive operational cross-talk

  Goal: Define: "What's a pound of C4I worth?"

Real World ASW Challenges

- **Submarines are difficult to detect, in part because their signatures are low, i.e. quiet diesels on battery**

- **Littoral operating regions are often plagued by false contacts**

- **Larger and more powerful sensors (larger detection ranges) can sometimes exacerbate the false contact loading problem**

- **The classification capabilities of most shipboard sensor operators is not as robust as that of experienced acoustic analysts**

Can network-centric techniques mitigate some of these challenges?
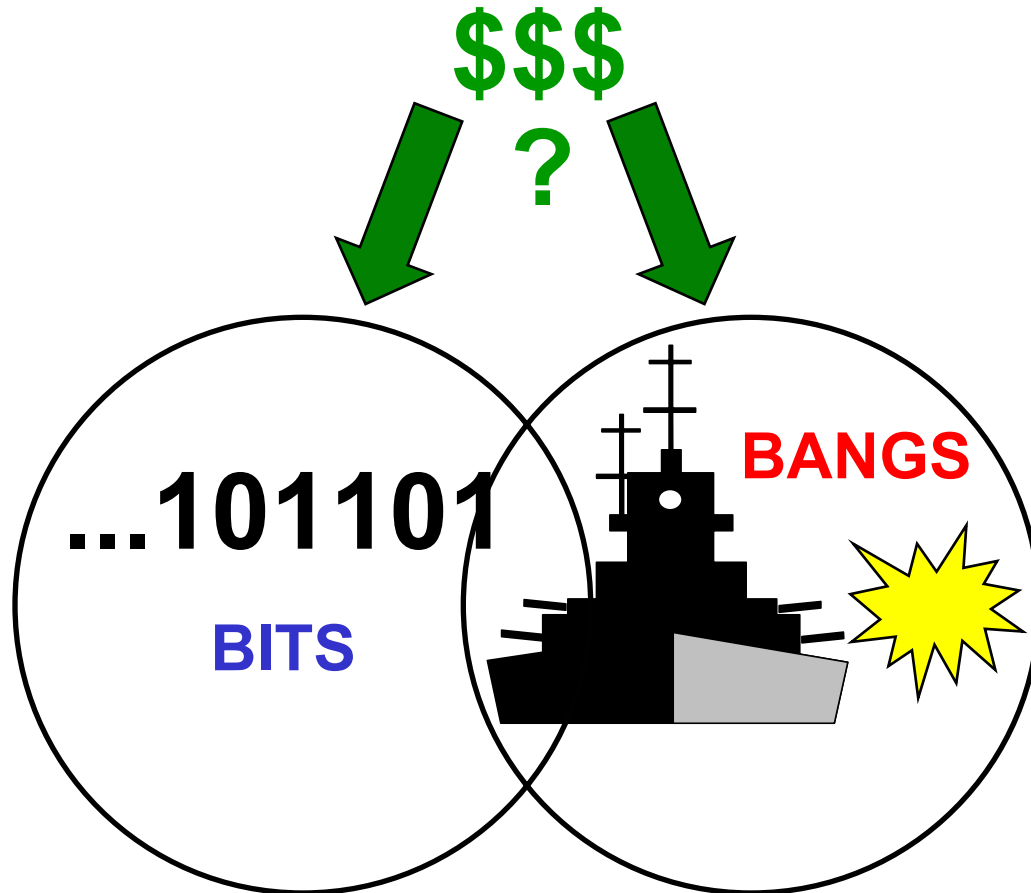
$$$

?

...101101

BITS

BANGS

Hard choices need to be made between investments in information infrastructure and the combat systems themselves.
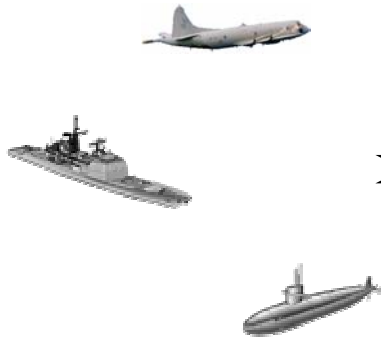
This is an extreme dilemma, because combat systems, without timely, relevant information, are useless.

On the other hand, a target can't be taken out with just information.
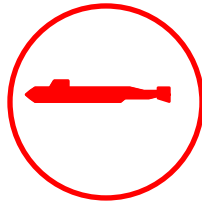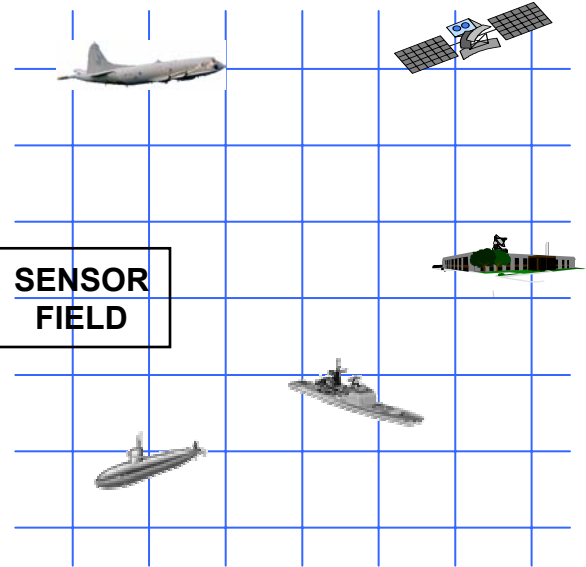
To be successful, we need to strike a balance between "shooters" and "information systems."

* Adapted from A Washburn, "bits, Bangs, or Bucks? The Coming Information Crisis, 66th MORS Symposium, NPS, Monterey, CA June 1998

Platform- and Network-Centric ASW

PLATFORM-CENTRIC ASW

NETWORK-CENTRIC ASW

SENSOR FIELD

INFORMATION GRID

ASW FUNCTIONS

AVOID

DETECTION → **CLASS** → **LOC/TMA** → **MONITOR / FOLLOW**

REDETECT/ ATTACK

DECLARE OP AREA SAFE
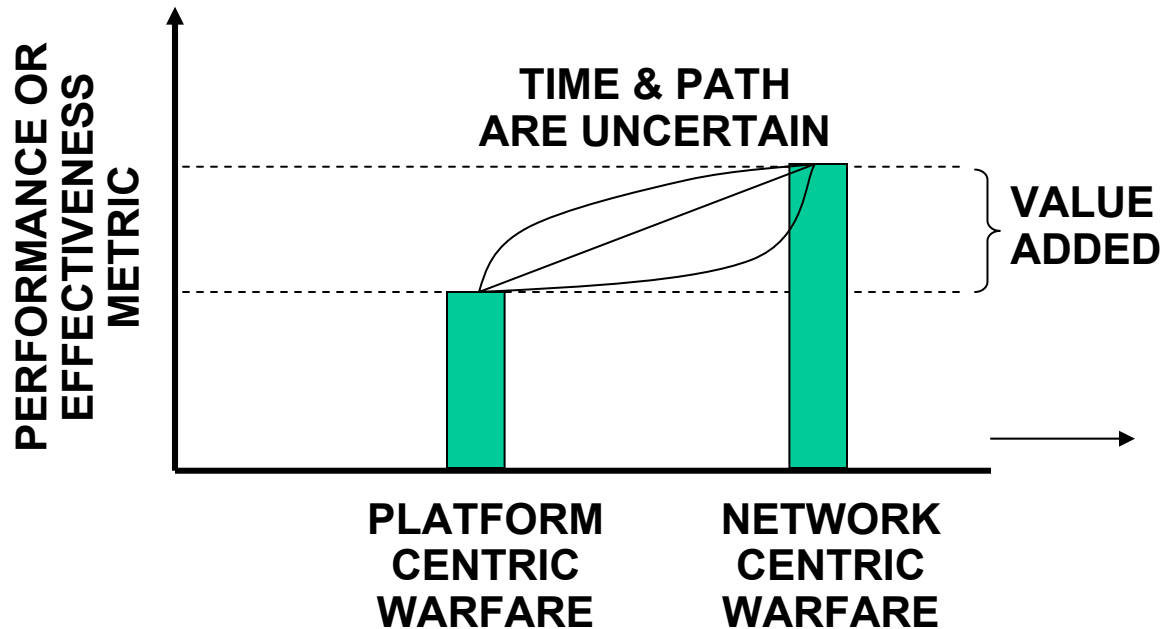
ASW FUNCTIONS
- SEARCH
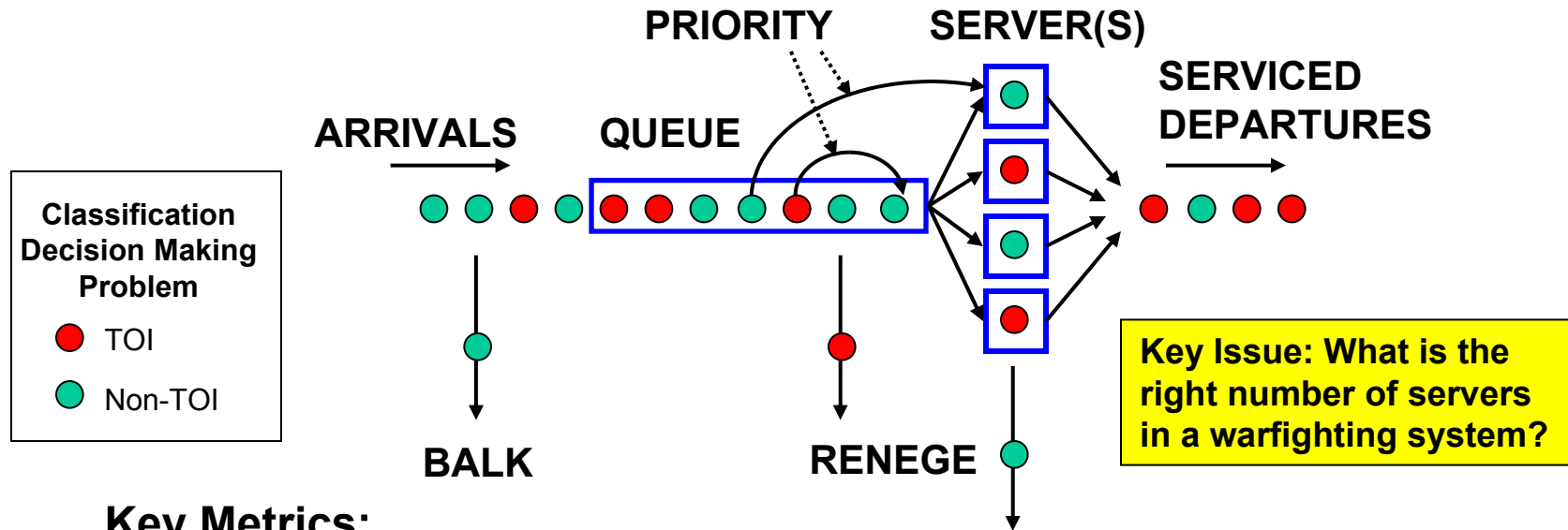- LOCALIZATION
- ATTACK/ CONTACT INVESTIGATION

Whether network-centric or platform-centric, the basic ASW functions/tasks need to be performed; thus the ASW MOEs are the same.

Objective of this Analysis

To provide insight to decision makers, derived from quantitative analysis, on the military value of maritime network infrastructure and NCASW concepts

Description of a Queuing System and Key Queuing Metrics

PRIORITY **SERVER(S)**

SERVICED DEPARTURES

ARRIVALS **QUEUE**

Classification Decision Making Problem

🔴 TOI

🟢 Non-TOI

BALK **RENEGE**

Key Issue: What is the right number of servers in a warfighting system?

Key Metrics:

- **Probability of a customer acquiring service**
- **Waiting time in queue until service begins**
- **Loss rate due to either balking or reneging**

Queuing Theory can provide an intuitive mathematical and physical framework for the analysis any military system or operation that can be characterized as a "waiting line" or a "demand-for-service." ASW can be analyzed using Queuing Theory

Outline

- **Background and analysis objective**

- **Analysis of two net-centric ASW concepts**

  – **Shared Situational Awareness (SSA)**

  – **Collaborative Information Environment (CIE)**

- **Summary of findings**

NCASW Concepts and Hypotheses

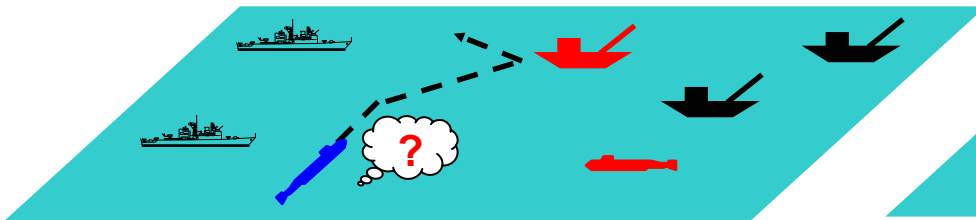**1** **Shared Situational Awareness (SSA)**

Network-enabled Shared Situational Awareness (SSA) can reduce false contact loading thereby increasing ASW effectiveness.

2 **Collaborative Information Environment (CIE)**

Sensor operators in a network-enabled collaborative environment can reach-back to ASW experts to improve target and non-target classification performance.

Shared Situational Awareness (SSA) Concept

PLATFORM-CENTRIC ASW (LIMITED SSA)

NETWORK-CENTRIC ASW (IMPROVED SSA)

Submarine's search track plan is interrupted due to false contact investigation

Submarine avoids unnecessary false contact investigation due to SSA

- Congestion of sonar, high workload
- Time to investigate false contacts
- Reduction of effective search rate
- Missed detections of targets

- Information is essential
- System to remove specified sensor contacts
- Can possibly lower detection threshold
- Increased probability of target detection

- Use sensor correlation across all appropriate platforms in a task group to reduce the number of non-target contacts presented to sensor operators.

- Reduce non-object false contacts, such as reverberation spikes and wrecks, by using acoustic models, in situ data, and local data bases.

Metric for SSA Concept Analysis

Reduce false contact loading on the ASW system by improving Shared Situational Awareness (SSA)

$$P_{ASW} = P_{DET} * \underline{P_{CLASS}} * P_{LOC} * P_{ATK}$$

$$P_{CLASS} = P_{ACQ\ CLASS} * P(T|t)$$

$P_{ACQ\ CLASS}$ = probability that the target acquires classification service

$P(T|t)$ = probability of recognizing the target contact as the actual target of interest (experimental data required)

T = THREAT DECISION

t = true target

There are queuing aspects (waiting line/ demand for service) in each of the terms in P_{ASW}

Sample Result: Effect Of Improved SSA and Service Time on $P_{ACQ\ CLASS}$

Improved SSA reduces the arrival of false contacts which increases the probability of successful target classification

Legend:
- MEAN SERVICE TIME = 15 min
- MEAN SERVICE TIME = 30 min
- MEAN SERVICE TIME = 60 min
- MEAN SERVICE TIME = 120 min

MEAN TIME TO RENEGE = 15 min

$P_{ACQ\ CLASS}$ IMPROVEMENT

VALUE ADDED

SSA IMPROVEMENT

Y-axis: $P_{ACQ\ CLASS}$ (0, 0.2, 0.4, 0.6, 0.8, 1)

X-axis: CONTACT ARRIVAL RATE (contacts per hr) (0, 2, 4, 6, 8, 10)

Note: Example is not based on actual system data

Sample Result: Effect of Number of Classifiers on $P_{ACQ\ CLASS}$

Chart:

- Y-axis: $P_{ACQ\ CLASS}$ (0 to 1)
- X-axis: CONTACT ARRIVAL RATE (contacts per hr) (0 to 10)

$P_{ACQ\ CLASS}$ can be increased by increasing the number of contact investigation units (more servers)

VALUE ADDED

ASSUME FIXED PARAMETERS:
- MEAN CI TIME = 60 min
- MEAN TIME TO RENEGE = 15 min

— 1 SERVICE UNIT
— 2 SERVICE UNITS

Note: Example is not based on actual system

Findings: Shared Situational Awareness (SSA) Concept

- Network-enabled Shared Situational Awareness (SSA) of an accurate surface picture among ASW units can reduce false contact loading, thus improving target classification performance, resulting in improved ASW effectiveness.

- Queuing theory can provide a framework for the analysis of the SSA NCASW concept because this is a "demand-for-service" process.

- The Queuing Theory framework can be used to analyze the tradeoff in benefits between SSA and force size (i.e. "bits" vs. "bangs").

NCASW Concepts and Hypotheses

1   **Shared Situational Awareness (SSA)**

In coalition force ASW, network-enabled Shared Situational Awareness (SSA) can <u>reduce false contact loading</u> thereby increasing ASW effectiveness.

2   **Collaborative Information Environment (CIE)**

Sensor operators in a netted force can <u>reach back to ASW experts</u> to improve target and non-target classification performance.

Collaborative Information Environment (CIE) Concept

Organization for Reach-back to ASW Expert

NCASW RBC organization

```
┌─────────────┐        ┌─────────────┐        ┌─────────────┐
│ Battlespace │        │             │        │             │
│  Entities   │◄──────►│ Theater ASWC│◄──────►│ Evaluation &│
│ (e.g., CSG  │        │ & Reach-Back│        │  Analysis   │
│ & ESG Units)│        │    Cell     │        │   Centers   │
└─────────────┘        └─────────────┘        └─────────────┘
```

Reach-back to expert for collaborative analysis

Value of Networking?

Op 1

Op 2

Op N

RBC

Expert

Queue of requests may form

Multiple operators seeking assistance

Networking between sonar operator and RBC expert, via a CIE, is expected to significantly improve P_{CLASS}

Metric for CIE Concept Analysis

Improve target and non-target classification performance by reaching back to experts in a Collaborative Information Environment (CIE).

$$P_{ASW} = P_{DET} * P_{CLASS} * P_{LOC} * P_{ATK}$$

$$P_{CLASS} = P_{ACQ\ CLASS} * P(T|t)$$

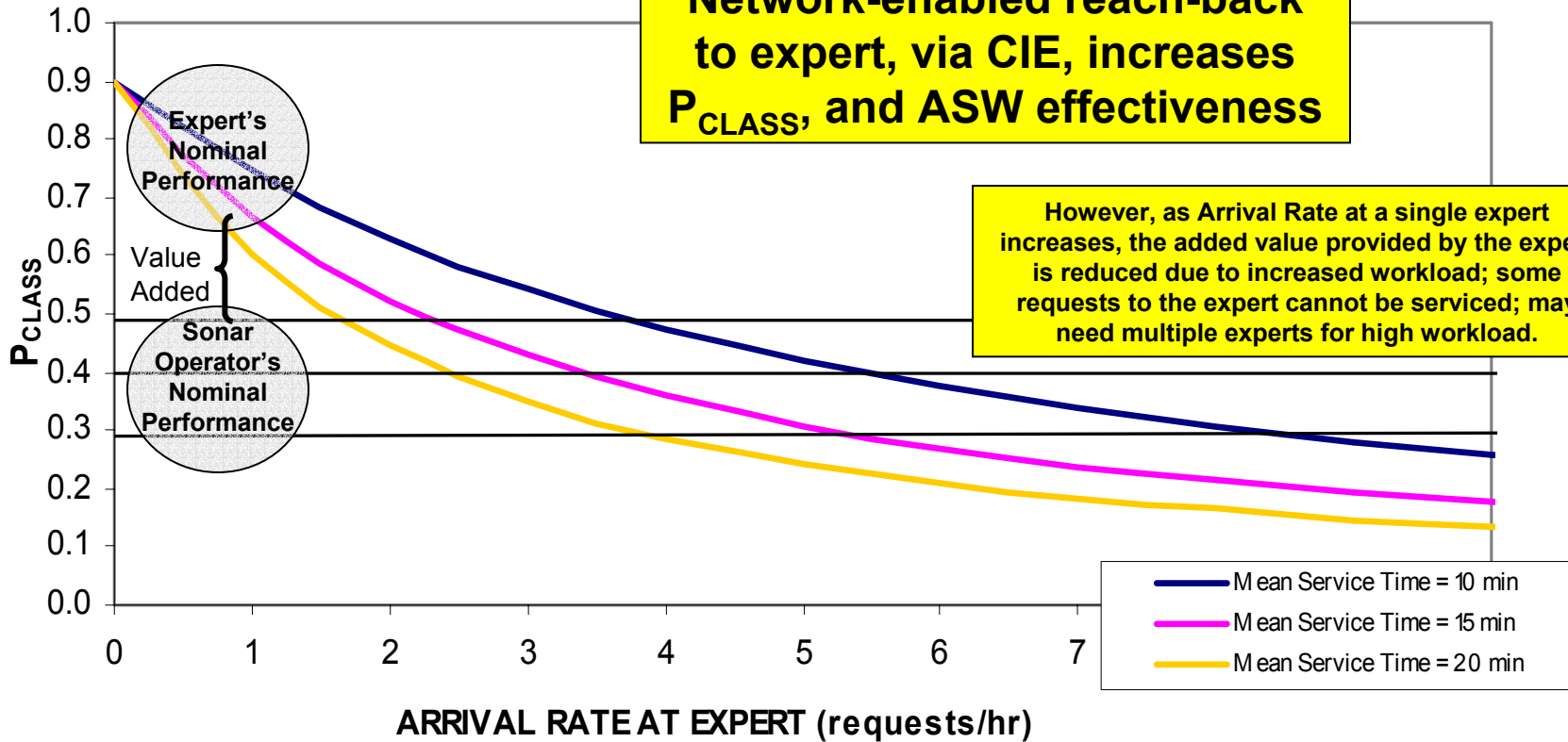$P_{ACQ\ CLASS}$ = probability that the target acquires classification service

$P(T|t)$ = probability of recognizing the target contact as the actual target of interest (experimental data required)

T = THREAT DECISION

t = true target

There are queuing aspects (waiting line/ demand for service) in each of the terms in P_{ASW}

Sample Result: Effect of Arrival Rate at Expert (via Reach-back using CIE) on P_{CLASS}

Network-enabled reach-back to expert, via CIE, increases P_{CLASS}, and ASW effectiveness

However, as Arrival Rate at a single expert increases, the added value provided by the expert is reduced due to increased workload; some requests to the expert cannot be serviced; may need multiple experts for high workload.

Chart labels:
- Expert's Nominal Performance
- Value Added
- Sonar Operator's Nominal Performance
- P_{CLASS} (y-axis)
- ARRIVAL RATE AT EXPERT (requests/hr) (x-axis)
- Mean Service Time = 10 min
- Mean Service Time = 15 min
- Mean Service Time = 20 min

CIE = Collaborative Information Environment

P_{CLASS} = Probability of Classification

Assumptions:
- One contact is already in classification process
- Inverse Gaussian Service Time Distribution
- Mean Time to Renege = 15 min

Findings: Collaborative Information Environment (CIE) Concept

- Network-enabled "reach-back" to ASW experts, via a Collaborative Information Environment (CIE), can improve target classification performance of sonar operators, resulting in improved ASW effectiveness.

- Queuing Theory can provide a framework for the analysis of the value of the sonar operator - expert CIE because this collaboration is a "demand for service" process.

Outline

- **Background and analysis objective**

- **Analysis of two NCASW search concepts**

- **Summary of findings**

Primary Findings: NCASW Concepts

- **Network-enabled Shared Situational Awareness (SSA) of an accurate surface picture among ASW units was shown to reduce false contact loading, thus improving target classification performance, resulting in improved ASW effectiveness.**

- **Network-enabled "Reach-back" to ASW experts, via a Collaborative Information Environment (CIE), was shown to improve target classification performance of sonar operators, resulting in improved ASW effectiveness.**

Additional Findings

- Queuing Theory provides an intuitive mathematical framework for a quantitative analysis of ASW functions and NCASW concepts because they can be readily characterized as "demand-for-service" processes.

- The Queuing Theory framework can be used to analyze the tradeoffs and benefits between networking/information sharing capabilities and force size (i.e. "bits" vs. "bangs").

Backup Material

False Contacts Interfere with Observing Targets of Interest

PASSIVE SONAR	ACTIVE SONAR	RADAR
Surface vessels	Surface vessels	Surface vessels
Own ship lines	Reverberation	Sea surface structure
Consort signatures	Fish schools & whales	Navigation buoys
Decoys	Bottom pinnacles	Fishing buoys
Biologics	Shallow water wrecks	Fixed man-made structures
	Decoys	Garbage
	Wakes and knuckles	
	Fronts and eddies	

COSTS ASSOCIATED WITH FALSE TARGETS:

- Reactive forces may be employed unnecessarily

- Fuel, sonobuoys, and weapons may be expended unnecessarily

- Reactive forces may not be available when needed

- Prosecution of real targets may be delayed or missed

> "War, as the saying goes, is full of false alarms."
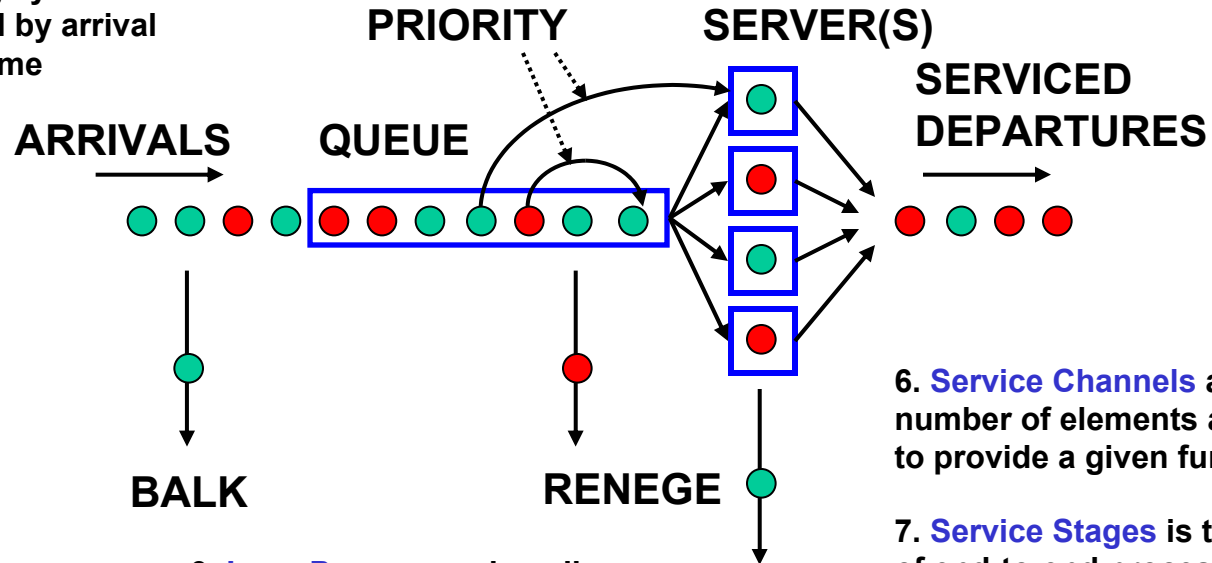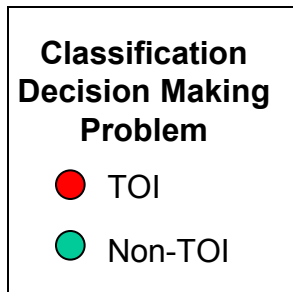> *Aristotle: Nichomachean Ethic, iii, c. 340 BCE*

Description of a Queuing System

4. **Queue Discipline** describes how a customer is selected for service once in queue (FIFO, priorities, etc.)

5. **System Capacity** is the maximum size of a queue; finite or infinite

2. **Service Pattern** is described by service rate or service time

1. **Arrival Pattern** describes the input to the queuing system and is typically specified by arrival rate or interarrival time

PRIORITY

SERVER(S)

SERVICED DEPARTURES

ARRIVALS

QUEUE

Classification Decision Making Problem

- 🔴 TOI
- 🟢 Non-TOI

BALK

RENEGE

6. **Service Channels** are the number of elements available to provide a given function

3. **Loss Processes** describe how customers can be lost (balking and reneging)

7. **Service Stages** is the set of end-to-end processes for completion of service

Queuing Models for Computations

- **Closed-form equations for exponential distributions**
  - **C Ancker and A Gafarian,** *Queuing with Impatient Customers Who Leave at Random*, **Journal of Industrial Engineering** <u>13</u>, **84-90, 1962**
  - **C Ancker and A Gafarian,** *Queuing with Reneging and Multiple Heterogeneous Servers*, **Naval Research Logistics Quarterly** <u>10</u>, **125-149, 1963**
  - **R Bedow,** *Queuing Models for Use in ASW Analysis*, **Shearwater, Inc report for NUWC, November 1985**

- **Simulations for other distributions (e.g., inverse Gaussian in decision making)**
  - **K Sullivan (NUWC) and I Grivell (DSTO, Australia),** *QSIM: A Queuing Theory Model with Various Probability Distribution Functions*, **NUWC TD 11,418, March 2003**
  - **Commercial software (e.g.,** *Extend* **by Imagine That Inc) implemented at NUWC by M St Peter and M Jarvais**

ASW Effectiveness Metric

$$P_{ASW} = P_{DET} * P_{CLASS} * P_{LOC} * P_{ATK}$$

P_{ASW} = probability of successfully attacking the threat before it attacks (ASW success metric)

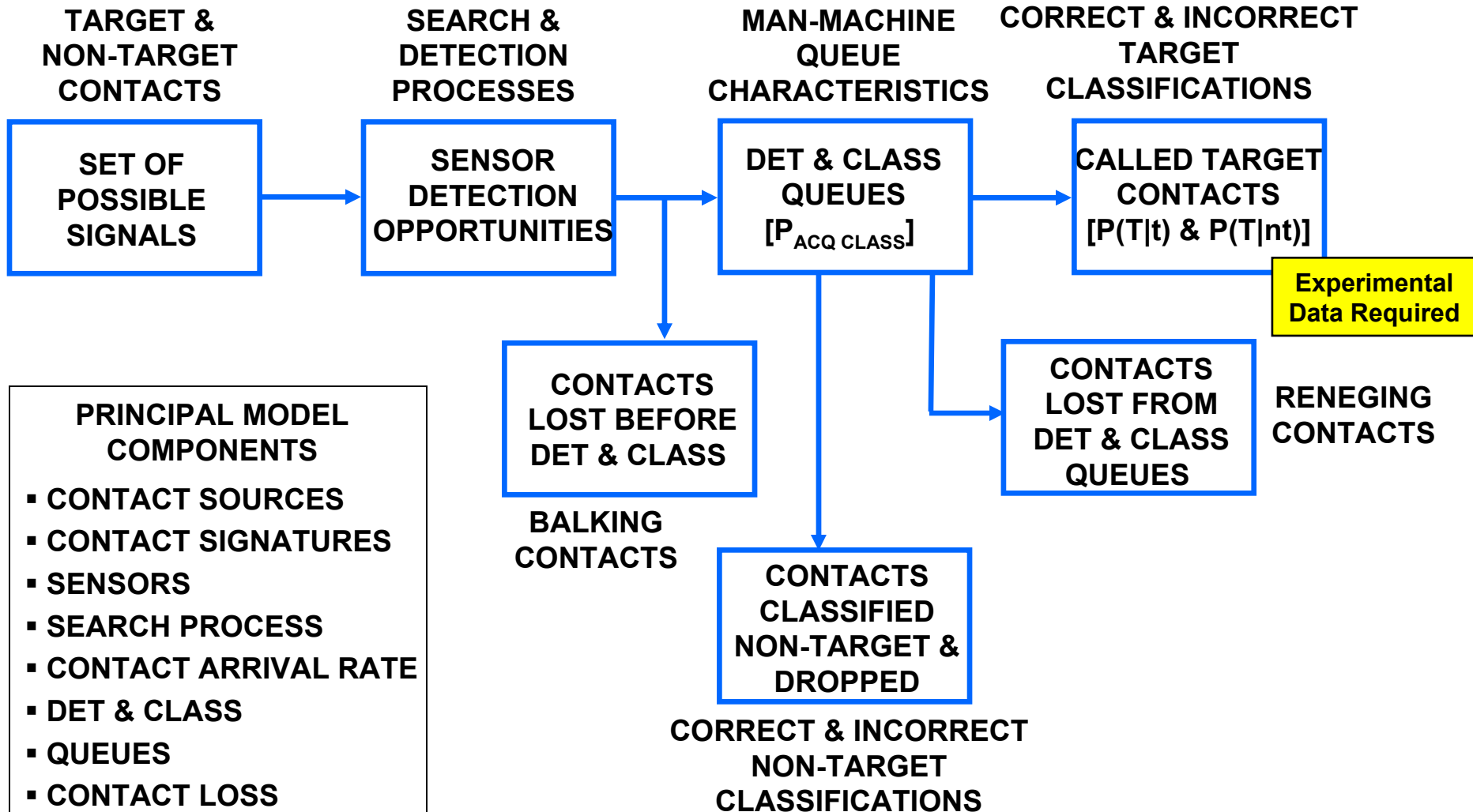P_{DET} = probability of threat detection
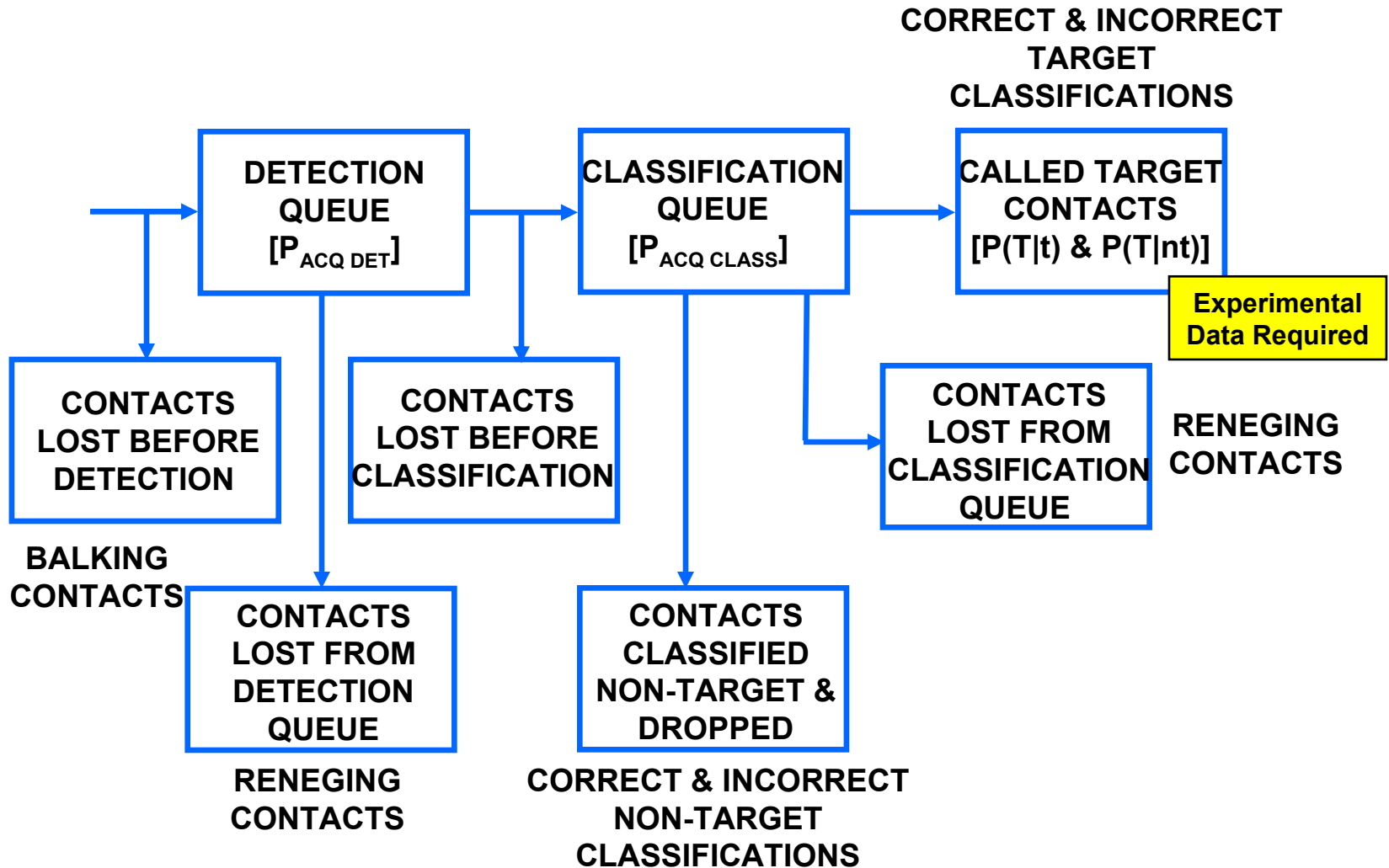
P_{CLASS} = probability of correct classification

P_{LOC} = probability of successful localization to within weapon launch criteria

P_{ATK} = probability of successful attack, given detection, classification, and localization

There are queuing aspects (waiting line/ demand for service) in each of the terms in P_{ASW}

Method To Calculate P_{ACQ CLASS}

Method To Calculate $P_{ACQ\ CLASS}$

TARGET & NON-TARGET CONTACTS

SEARCH & DETECTION PROCESSES

MAN-MACHINE QUEUE CHARACTERISTICS

CORRECT & INCORRECT TARGET CLASSIFICATIONS

```
SET OF POSSIBLE SIGNALS  →  SENSOR DETECTION OPPORTUNITIES  →  DET & CLASS QUEUES [P_ACQ CLASS]  →  CALLED TARGET CONTACTS [P(T|t) & P(T|nt)]
```

SET OF POSSIBLE SIGNALS

SENSOR DETECTION OPPORTUNITIES

DET & CLASS QUEUES [$P_{ACQ\ CLASS}$]

CALLED TARGET CONTACTS [P(T|t) & P(T|nt)]

Experimental Data Required

PRINCIPAL MODEL COMPONENTS

- **CONTACT SOURCES**
- **CONTACT SIGNATURES**
- **SENSORS**
- **SEARCH PROCESS**
- **CONTACT ARRIVAL RATE**
- **DET & CLASS**
- **QUEUES**
- **CONTACT LOSS**

CONTACTS LOST BEFORE DET & CLASS

BALKING CONTACTS

CONTACTS CLASSIFIED NON-TARGET & DROPPED

CORRECT & INCORRECT NON-TARGET CLASSIFICATIONS

CONTACTS LOST FROM DET & CLASS QUEUES

RENEGING CONTACTS

Detection and Classification Queues

CORRECT & INCORRECT TARGET CLASSIFICATIONS

```
          DETECTION              CLASSIFICATION          CALLED TARGET
          QUEUE                  QUEUE                    CONTACTS
          [P_ACQ DET]            [P_ACQ CLASS]            [P(T|t) & P(T|nt)]
```

Experimental Data Required

CONTACTS LOST BEFORE DETECTION

CONTACTS LOST BEFORE CLASSIFICATION

CONTACTS LOST FROM CLASSIFICATION QUEUE

RENEGING CONTACTS

BALKING CONTACTS

CONTACTS LOST FROM DETECTION QUEUE

CONTACTS CLASSIFIED NON-TARGET & DROPPED

RENEGING CONTACTS

CORRECT & INCORRECT NON-TARGET CLASSIFICATIONS

Reneging Processes

ENTERING/EXITING SENSOR COVERAGE

TARGET TRACK

DETECTION RANGE

$$HT = \pi R / (2 V_{REL})$$
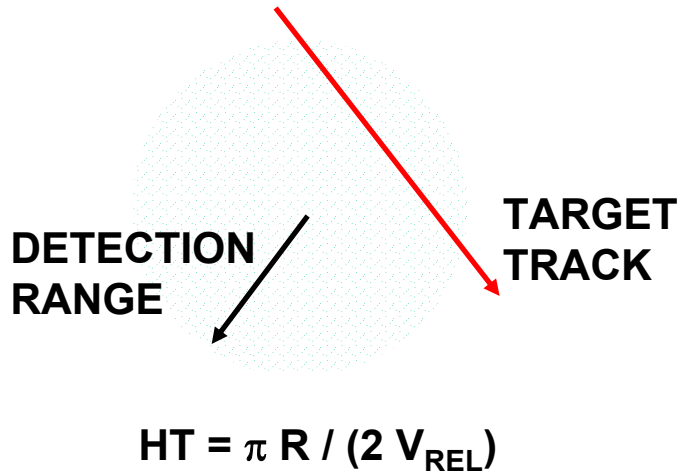
TRANSIENT/TIME-URGENT EVENTS

ON

OFF

e.g., mast exposure
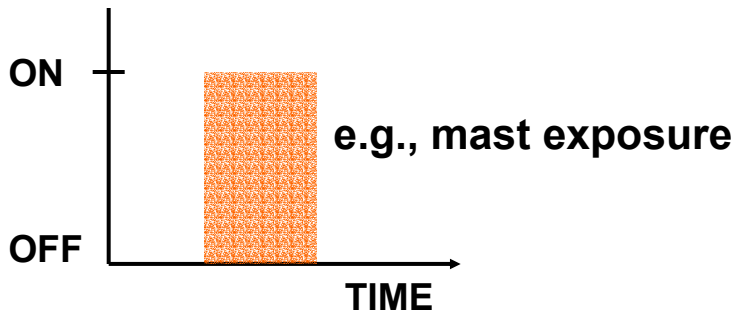
TIME

PROBABILITY OF HOLDING CONTACT

TARGET OR NON-TARGET HT

MEAN HT (min)

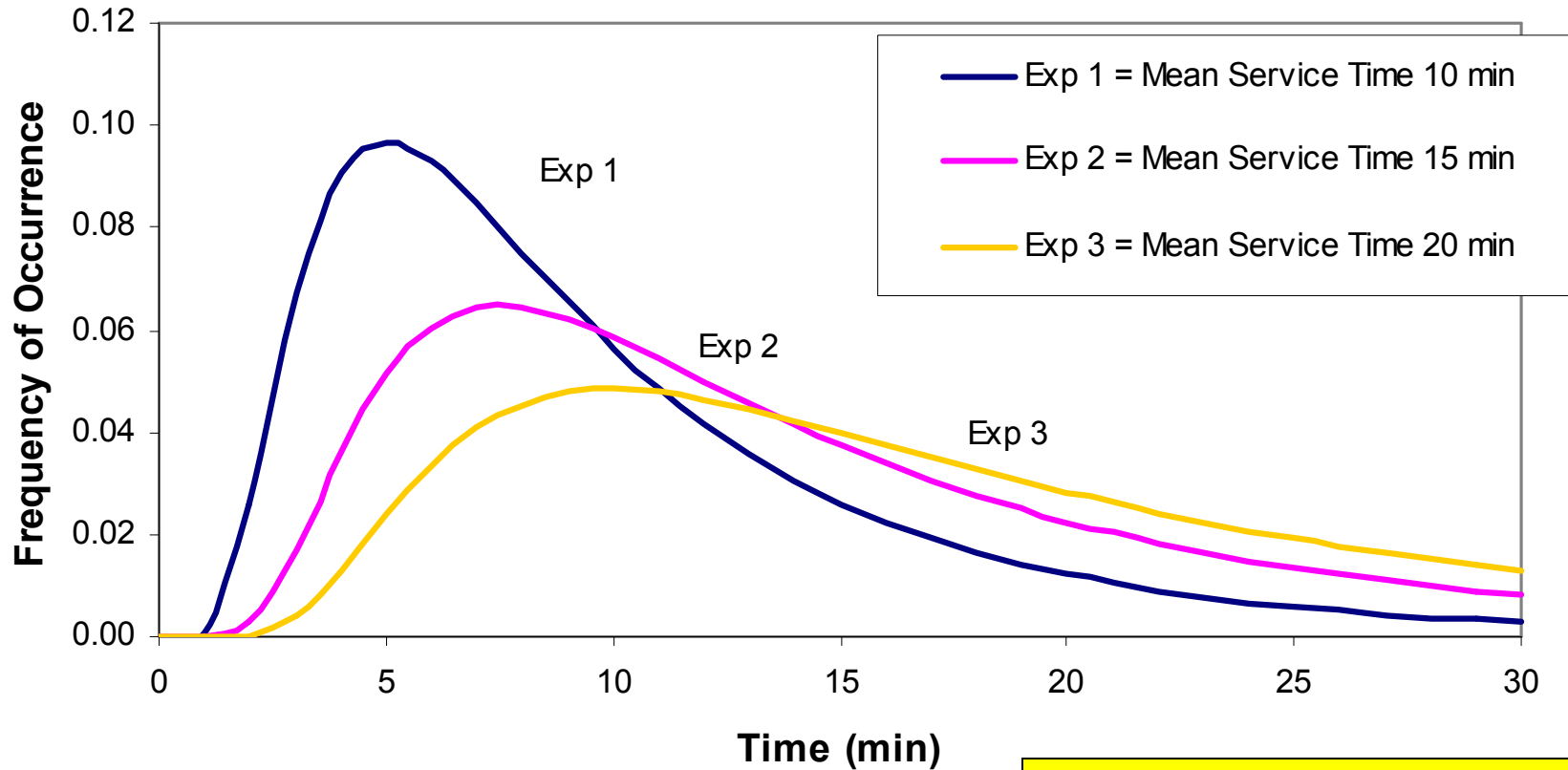|	
———	5
———	10
———	15
———	20
———	25

PHOLD

TIME (min)
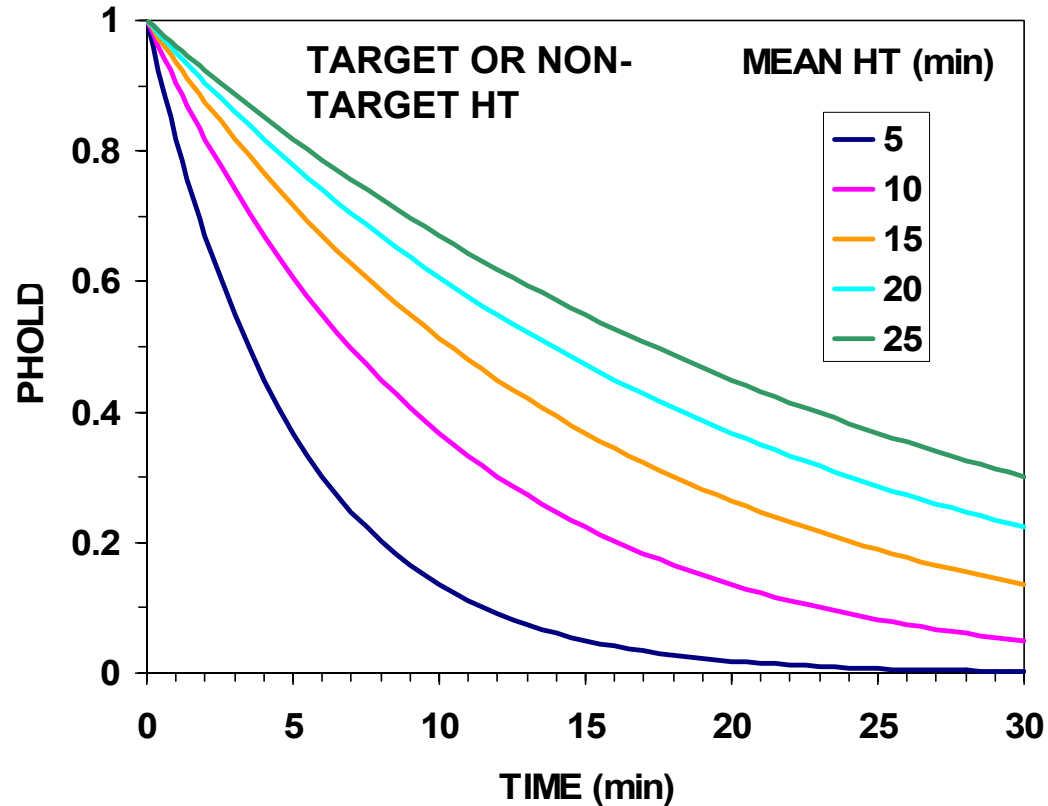
On exponential holding time, see RW Sittler, An Optimal Data Association Problem in Surveillance Theory, IEEE Transactions on Military Electronics, MIL-8, 125-139 (1964)

Inverse Gaussian Representation of Analytical Decision Time

Frequency of Occurrence vs **Time (min)**

Legend:
- Exp 1 = Mean Service Time 10 min
- Exp 2 = Mean Service Time 15 min
- Exp 3 = Mean Service Time 20 min

Inverse Gaussian probability density function is a general representation of decision making time