

**AFRL-VA-WP-TM-2003-3074**

**QUALITY OF INFORMATION  
METRICS FOR AUTONOMOUS  
DECISION MAKING**



**Russell Purtell**

**Northrop Grumman Corporation  
Air Combat Systems  
One Hornet Way M/S 9L40/W6  
El Segundo, CA 90245-2804**

**Ravi Prasanth, Joao Cabrera, and Raman Mehra  
Scientific Systems Company, Inc.**

**Robert Smith  
AFRL/VACC**

**SEPTEMBER 2003**

**Final Report for 15 September 2003 – 18 September 2003**

**Approved for public release; distribution is unlimited.**

**AIR VEHICLES DIRECTORATE  
AIR FORCE RESEARCH LABORATORY  
AIR FORCE MATERIEL COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542**

**20031126 099**

# REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YY)</b> September 2003		<b>2. REPORT TYPE</b> Conference Presentation		<b>3. DATES COVERED (From - To)</b> 09/15/2003 – 09/18/2003			
<b>4. TITLE AND SUBTITLE</b> QUALITY OF INFORMATION METRICS FOR AUTONOMOUS DECISION MAKING				<b>5a. CONTRACT NUMBER</b> F33615-02-C-3207			
				<b>5b. GRANT NUMBER</b>			
				<b>5c. PROGRAM ELEMENT NUMBER</b> 62201F			
				<b>5d. PROJECT NUMBER</b> 2403			
				<b>5e. TASK NUMBER</b> 06			
<b>6. AUTHOR(S)</b> Russell Purtell (Northrop Grumman Corp.) Ravi Prasanth, Joao Cabrera, and Raman Mehra (SSCI) Robert Smith (AFRL/VACC)				<b>5f. WORK UNIT NUMBER</b> 68			
				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>		<b>10. SPONSORING/MONITORING AGENCY ACRONYM(S)</b> AFRL/VACC	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Northrop Grumman Corporation Air Combat Systems One Hornet Way M/S 9L40/W6 El Segundo, CA 90245-2804		<b>Scientific Systems Company, Inc.</b>  AFRL/VACC					
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Air Vehicles Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7542							
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited.							
<b>13. SUPPLEMENTARY NOTES</b> This Conference Presentation was presented at 2 <sup>nd</sup> AIAA "Unmanned Unlimited" Systems, Technologies, and Operations – Aerospace, Land, and Sea Conference and Workshop & Exhibit in San Diego, CA, 15-18 September 2003.							
<b>14. ABSTRACT (Maximum 200 Words)</b> This effort explores the management of information flows in a UAV. It is research into the information requirements for flying a UAV and how the quality of that information might be ascertained. This presentation looks at early results using information theory constructs to evaluate different information flows.							
<b>15. SUBJECT TERMS</b> information, UAV, quality of information, reliability							
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT:</b> SAR	<b>18. NUMBER OF PAGES</b> 28	<b>19a. NAME OF RESPONSIBLE PERSON (Monitor)</b> Robert Smith <b>19b. TELEPHONE NUMBER (Include Area Code)</b> (937) 255-8429		
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified					



# **Quality of Information Metrics for Autonomous Decision Making**

**Russell Purtell, Ravi Prasanth, Joao Cabrera,  
Robert Smith and Raman Mehra**

**Presented at the**

**2nd AIAA "Unmanned Unlimited" Systems, Technologies, and  
Operations—Aerospace, Land, and Sea  
Conference and Workshop & Exhibit**

**San Diego, California  
15 - 18 Sep 2003**

**Scientific Systems Company, Inc.**

**NORTHROP GRUMMAN**  
*Integrated Systems*



## Outline



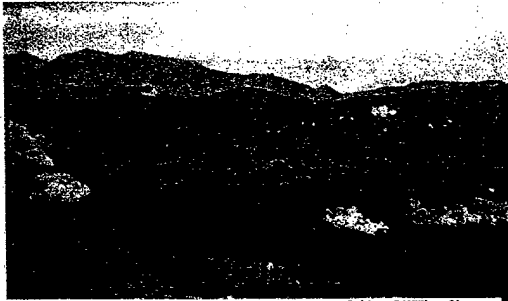
- **Distributed Infocentric Reliable Control Technology (DIReCT) Program**
- **Quality of Information (QoI)**
  - **Problem statement, measure of QoI**
  - **Autonomous QoI computations**
  - **QoI Demonstration Example 1**
    - **Strike UAVs exchange position information for collision avoidance**
    - **Autonomous detection of channel changes**
  - **QoI Demonstration Example 2**
    - **Tactical ISR to Strike UAV communication of Combat ID**
    - **Autonomous assessment of QoI of discrete-valued data**
- **Conclusions and Future Work Directions**

 **Scientific Systems Company, Inc.**

**NORTHROP GRUMMAN**  
Integrated Systems



## Fog of War

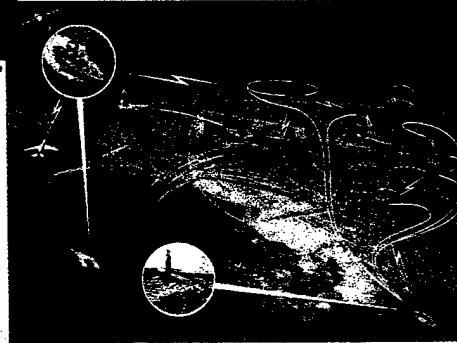


"The Light Bridge," William Simpson

**"Intelligence Reports ... are  
Contradictory, More are False and  
Most are of Doubtful Character"**

**-- Carl von Clausewitz (1780-1831)  
Prussian Military Strategist**

**Lack of Situational Awareness,  
Limited Reasoning Abilities, and  
Information Complexities Will  
Increase the Vulnerability of  
Modern Unmanned Systems to  
Fog of War Realities**



 Scientific Systems Company, Inc.

**NORTHROP GRUMMAN**  
Integrated Systems

Basic story here is that unmanned systems face the same Fog of War as do any military unit and we need to account for it.



## DIReCT Program Objectives

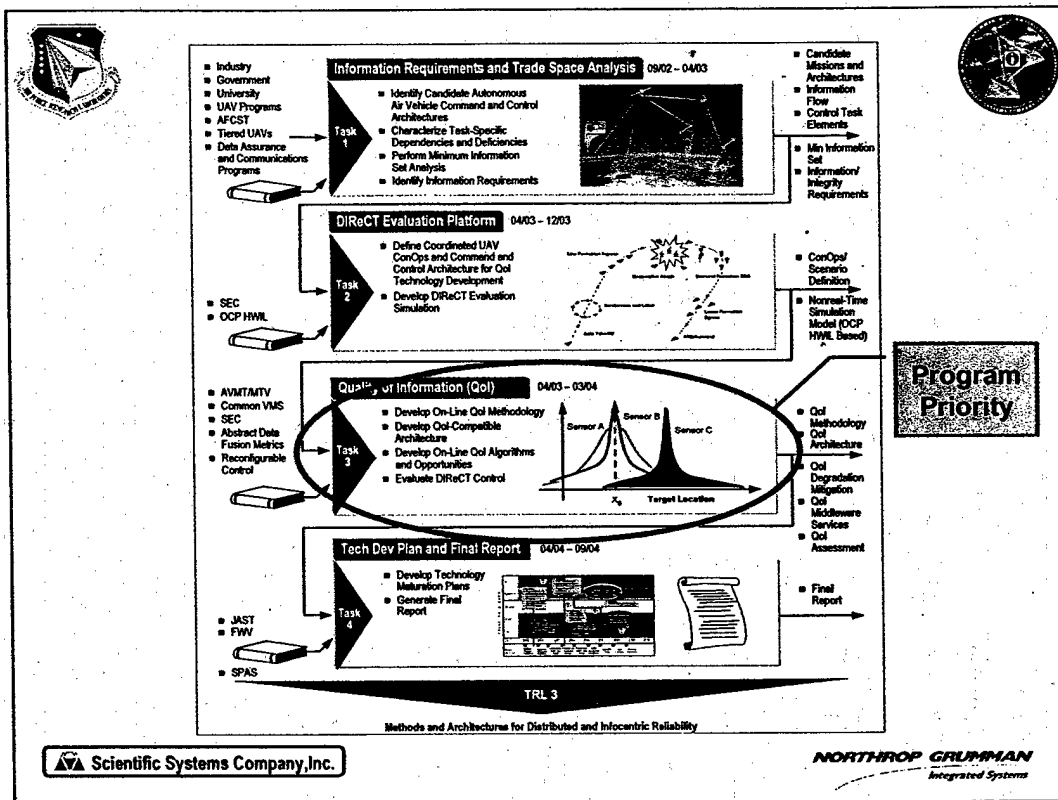


- **Develop Methodologies and Architectures that Enable Single and Multi-Vehicle UCAV Systems to Manage the Information Degradation Resulting from the Fog of War**
- **Key Areas**
  - Information Requirements
  - Qol & Vol Methodologies
  - Qol Compatible Architectures
  - Qol Degradation Opportunities

 Scientific Systems Company, Inc.

**NORTHROP GRUMMAN**  
Integrated Systems

We're developing information management tools/algorithms to deal with the Fog of War.

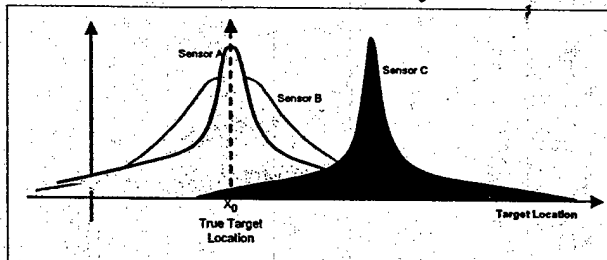


Eye chart showing program inputs and outputs and identifying the part that will be focused on in this presentation.



## Quality of Information (QoI)

- Consider three target location sensors A, B and C
- True target location is a delta function at  $X_0$



- Which sensor is giving better quality information ?  
Sensor A is better than Sensor B since it has lower variance  
Sensor A is better than Sensor C even though Sensor C has lower variance because of its bias.

Desirable Property for QoI measures: If A provides information closer to ground truth than B, then  $QoI(A) > QoI(B)$

Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems

Basic concept of Quality of Information: many sources with different outputs, which is better?



## QoI Measure – Kullback-Leibler

**Kullback-Leibler (KL) Information Distance**

$$K(f, g) = \int f(x) \log \left( \frac{f(x)}{g(x)} \right) dx$$

Shannon entropy is equal to  $-K(f, u)$  where  $u$  is uniform pdf

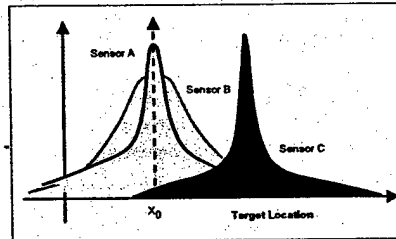
**Important properties:**

**K measures information distance between densities, and is always greater than or equal to zero.**

$$K(f, g) \geq 0$$

**K is zero if and only if  $f(x) = g(x)$ .**

$$K(f, g) = 0 \Leftrightarrow f = g$$



Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems

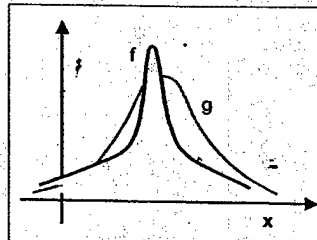
Information theory way to measure differences in probability density functions.



## QoI Measure – KL Distance



- More generally, consider random variable  $x$  with pdf  $f$  and a sensor for  $x$  with pdf  $g$
- If  $g$  is equal to  $f$ , then sensor is providing complete information.
  - $K(f,g)$  is zero in this case.
- If  $g$  is not equal to  $f$ , then sensor is not providing complete information.
  - $K(f,g)$  is strictly positive in this case.



When we say that a sensor is providing information of high quality, we really mean that the sensor is providing information that is close in some sense to the ground truth.

$K(f,g)$  is a measure of the information being supplied by the sensor as compared to the ground truth  $f$ .

$1/K$  is thus a measure of QoI

Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems

Apply that distance measure to Quality of Information



## QoI Computation



- Suppose  $f$  and  $g$  are Gaussian:

$$f(x) = \frac{1}{(2\pi \det P)^{n/2}} \exp\left(-\frac{1}{2}(x-a)^T P^{-1}(x-a)\right)$$

$$g(x) = \frac{1}{(2\pi \det Q)^{n/2}} \exp\left(-\frac{1}{2}(x-b)^T Q^{-1}(x-b)\right)$$

- Then,

$$K(f, g) = \frac{1}{2} \log \frac{\det Q}{\det P} + \frac{1}{2} \text{Tr}(PQ^{-1}) - \frac{n}{2} + \frac{1}{2} \text{Tr}(Q^{-1}(a-b)(a-b)^T)$$

- Quadrature formulas can be used in general case.
- Suppose  $f$  and  $g$  are discrete probability distributions. Then, KL is just a sum:

$$K(f, g) = \sum_{k=1}^N f_k \log \left( \frac{f_k}{g_k} \right)$$

Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems

One way to implement the measure



## Family of QoI Measures

- General form of information distance measures (Csiszar, 1967)

$$d(p_1, p_2) = g \left( E_{p_1} \left[ f \left( \frac{p_2}{p_1} \right) \right] \right) \quad \begin{array}{l} f \text{ convex, } g \text{ increasing and } E \\ \text{denotes expectation} \end{array}$$

- Some special cases that will be considered

### Variational Distance

$$f(x) = |1-x|, g(x) = x/2$$

$$d(p_1, p_2) = \frac{1}{2} \int |p_1(x) - p_2(x)| dx$$

### KL Information

$$f(x) = -\log x, g(x) = x$$

### KL Divergence

$$f(x) = (x-1)\log x, g(x) = x$$

### Bhattacharyya Distance

$$f(x) = -\sqrt{x}, g(x) = -\log(-x)$$

$$d(p_1, p_2) = -\log \left( \int \sqrt{p_1(x)p_2(x)} dx \right)$$

### Chernoff Distance

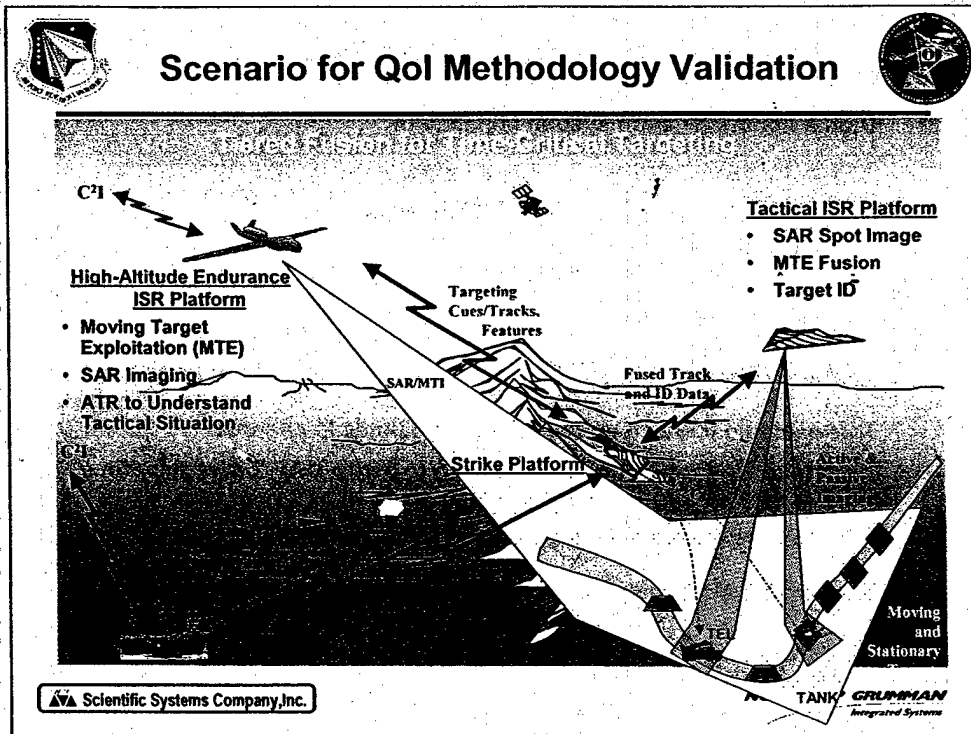
$$f(x) = -x^{1-r}, g(x) = -\log(-x), 0 \leq r \leq 1$$

$$d(p_1, p_2) = -\log \left( \int p_1(x)^r p_2(x)^{1-r} dx \right)$$

Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems

Several approaches to measuring information distance.



Challenging information scenario

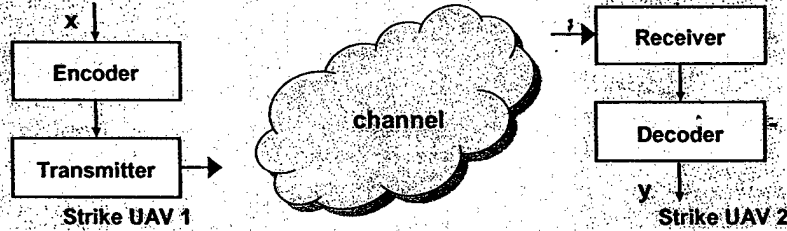
-tiered: multiple levels and sources of information

-Time-critical: timeliness is an important factor



## QoI Demonstration Example 1

- Digital communication system consists of

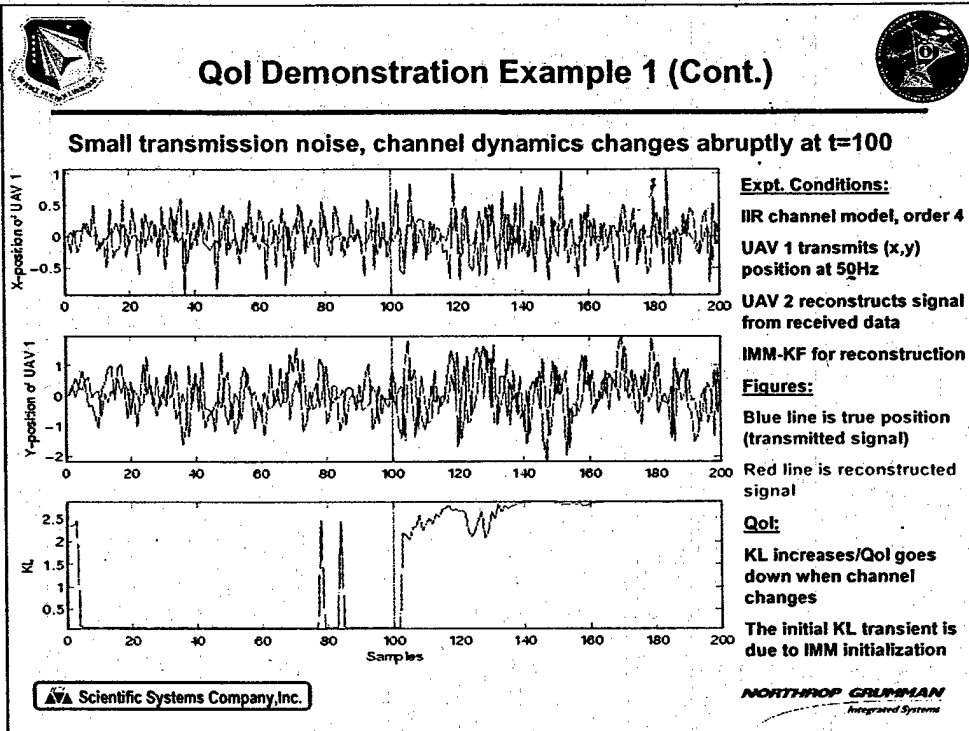


- This example focuses on the effect of changes in channel
  - Strike UAV 1 transmits its position to Strike UAV 2 at regular time intervals for collision avoidance
  - Changes in channel causes distortions in received signal
- Can strike UAV 2 detect channel changes using QoI measures ?

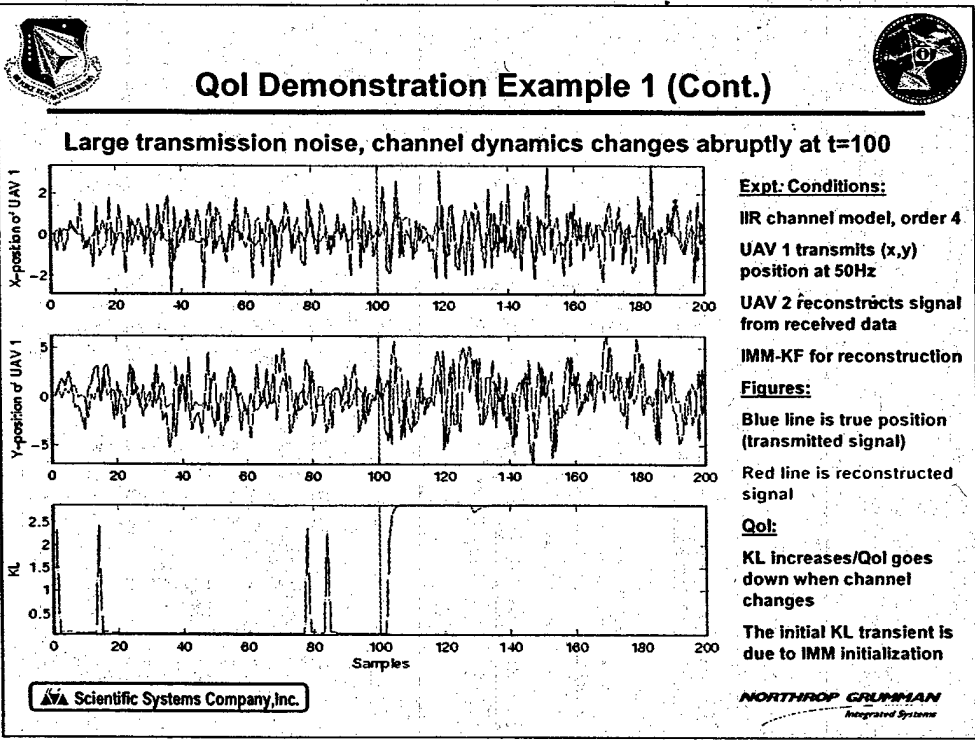
Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems

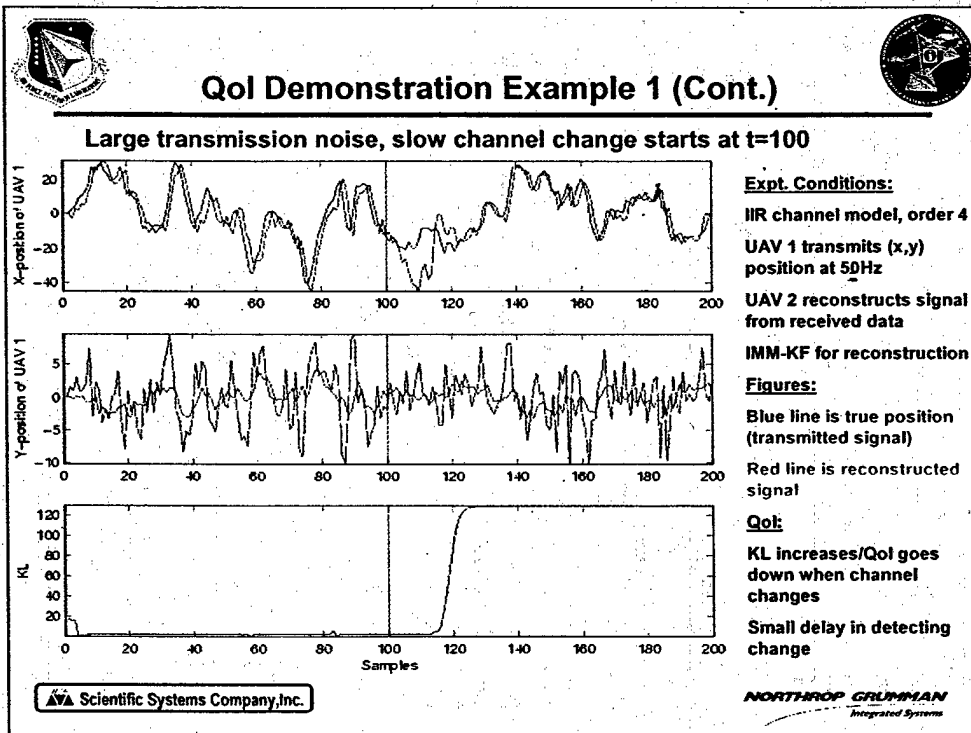
How might these concepts be applied to a simple communication system



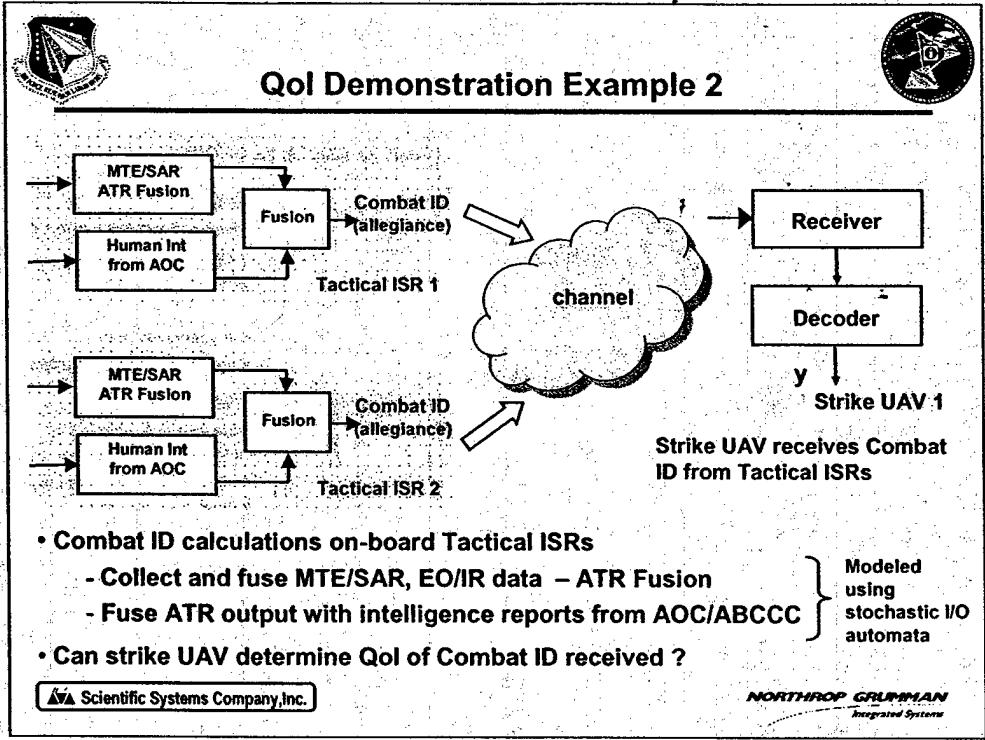
Simulation data showing measurement of QoI when comm channel degrades



Simulation data showing measurement of QoI when comm channel degrades



Simulation data showing measurement of QoI when comm channel degrades

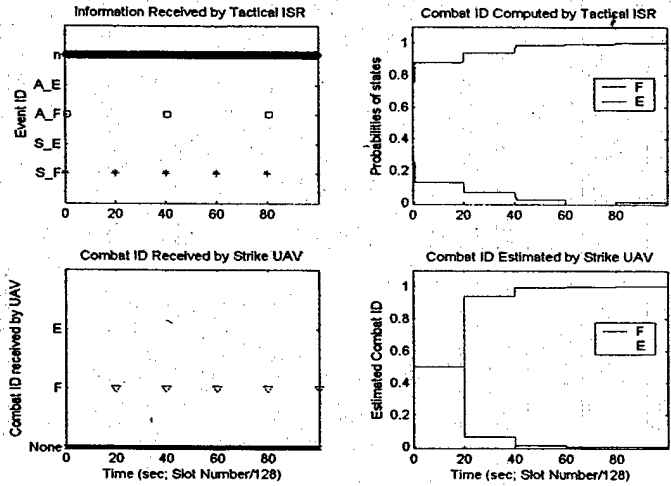


Two sources of combat identification (friend/foe); what is the value of each?



# QoI Demonstration Example 2 (Cont.)

## Tactical ISR 1/Strike UAV Simulation



**Expt. Conditions:**  
 LINK-16/TDMA network  
 Scaled time axis  
 Ground truth is Friend  
 Two report types from AOC & MTE/SAR with specified probabilities

**Figures:**  
 Top left: Reports received by T-ISR 1  
 Top right: Combat ID  
 Bottom Left: Transmitted symbol  
 Bottom Right: Reconstructed CombatID

Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
 Integrated Systems

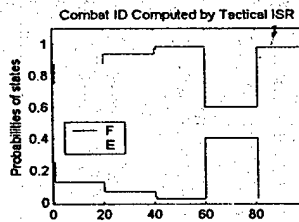
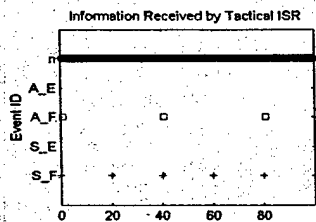
Simulation results: reconstructing from intermittent information



## QoI Demonstration Example 2 (Cont.)



### Tactical ISR 2/Strike UAV Simulation: ATR fusion process changes at t=50



**Expt. Conditions:**

LINK-16/TDMA network

Scaled time axis

Ground truth is Friend

Two report types from AOC & MTE/SAR with specified probabilities

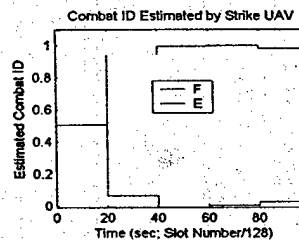
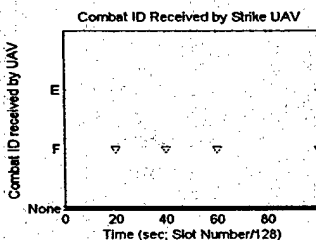
**Figures:**

Top left: Reports received by T-ISR 2

Top right: Combat ID

Bottom Left: Transmitted symbol

Bottom Right: Reconstructed CombatID



Scientific Systems Company, Inc.

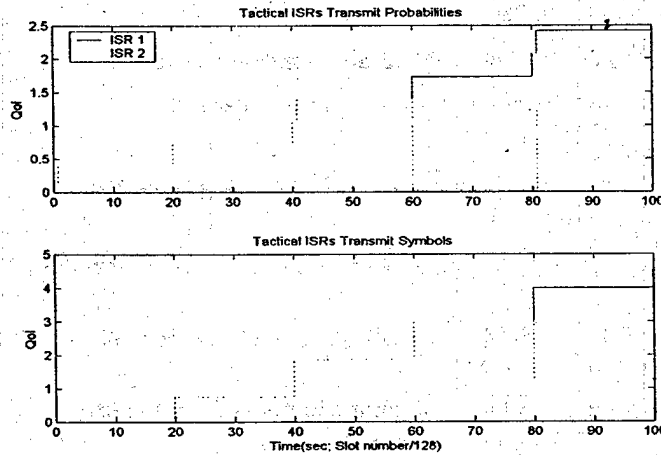
NORTHROP GRUMMAN  
Integrated Systems

Simulation results: reconstructing from intermittent information with a dropout



## QoI Demonstration Example 2 (Cont.)

### Tactical ISR 2/Strike UAV Simulation: ATR fusion process changes at t=50



#### Top Figure:

T-ISRs transmit Combat ID probabilities

Compare each distribution with uniform distribution

QoI decreases with jump in ISR 2

#### Bottom Figure:

T-ISRs transmit Combat ID symbols (F or E)

Reconstruct probabilities with Bayes filter

Compare reconstructed distributions with uniform

QoI decreases with jump in ISR 2

Time delays in detection due to low sampling rate  
Better to transmit probabilities than to reconstruct them at strike UAV

AVA Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems



## Conclusions

- Developed a procedure to autonomously determine QoI of received data.
  - Uses Kullback-Leibler information distance
  - A family of measures applicable to different tasks/missions
  - Applicable to both real-valued and discrete-valued data
- Demonstrated applicability to
  - real-valued data communication between UAVs in a strike package for collision avoidance
  - Combat ID calculation and communication between AOC/Tactical ISR and strike UAV
- QoI methodology is capable of detecting changes in channel as well as the source characteristics.
  - There is some time delay in detecting changes because of the low number of Combat ID measurements (received data)

 Scientific Systems Company, Inc.

**NORTHROP GRUMMAN**  
Integrated Systems



## Future Work

- Detailed modeling of accrual of evidence by Tactical-ISR's
  - How long does it take to bring probability of correctly identifying target as foe above 0.9999999 or reducing false alarm probability to less than  $10^{-6}$  ?
  - How to reduce identification time (hence, overall delay) using communication among Tactical-ISR's, multiple looks, etc ?
  - How to incorporate "rules of engagement" into QoI framework ?
- Detailed modeling of comm. failure mechanisms and their effects on QoI
- Demonstration of QoI methodology on a realistic mission simulation

AVA Scientific Systems Company, Inc.

NORTHROP GRUMMAN  
Integrated Systems