Evaluating the Value of Information in the Presence of High Uncertainty

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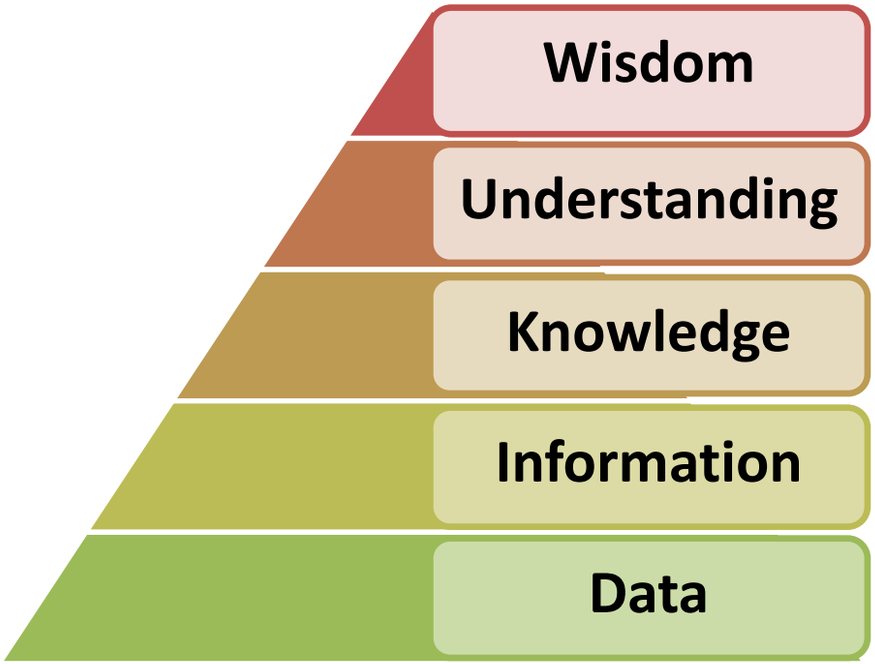
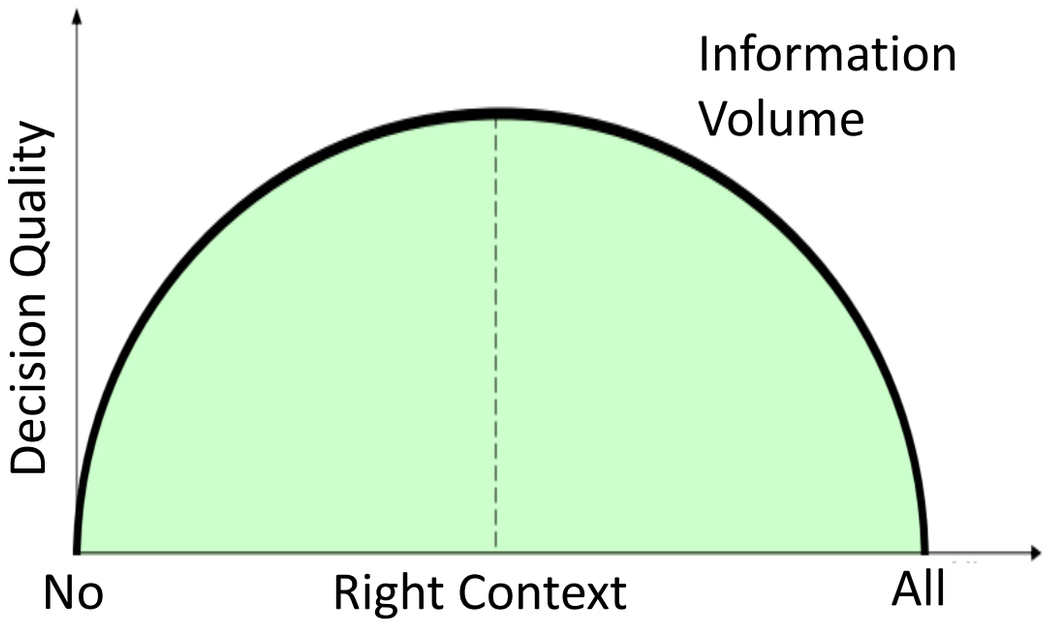
Outline

- What is the Value of Information (VOI)?
- Focus on Counter-Piracy Problem Domain
  - Growing Importance to the Navy
  - Availability of Expertise in the Reach Back Cell
- Problem Formulation
  - Maximize Probability of Interdiction
  - VOI Metrics
- Interdiction Results
- VOI & Sensitivity Analysis
- Conclusion & Future Work

What is the Value of Information?





- The Navy has identified a need to quantify the value of data to be delivered to decision makers (DMs)
- **Goal**: Eliminate unnecessary information and unclog the information super highway
- Allow for faster conveyance of proper context to the decision maker → faster, better informed and superior decisions

- Mastering information dominance requires acquisition, integration, and transfer of the

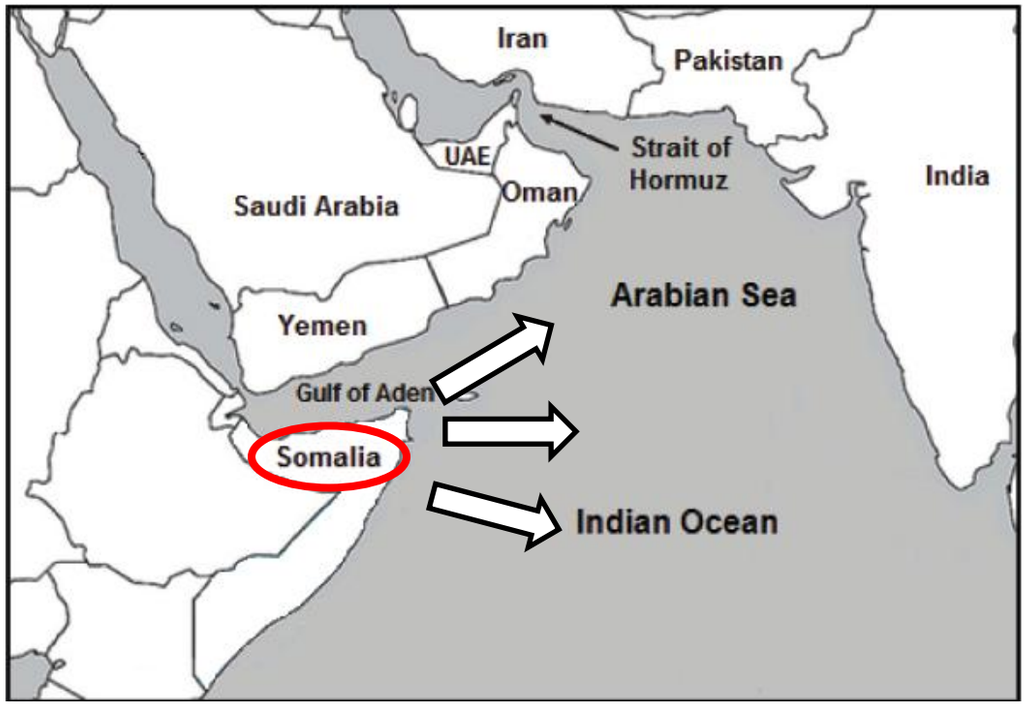
6R
1. **R**ight data/information/knowledge/wisdom from the
2. **R**ight sources in the
3. **R**ight context to the
4. **R**ight DM at the
5. **R**ight time for the
6. **R**ight purpose

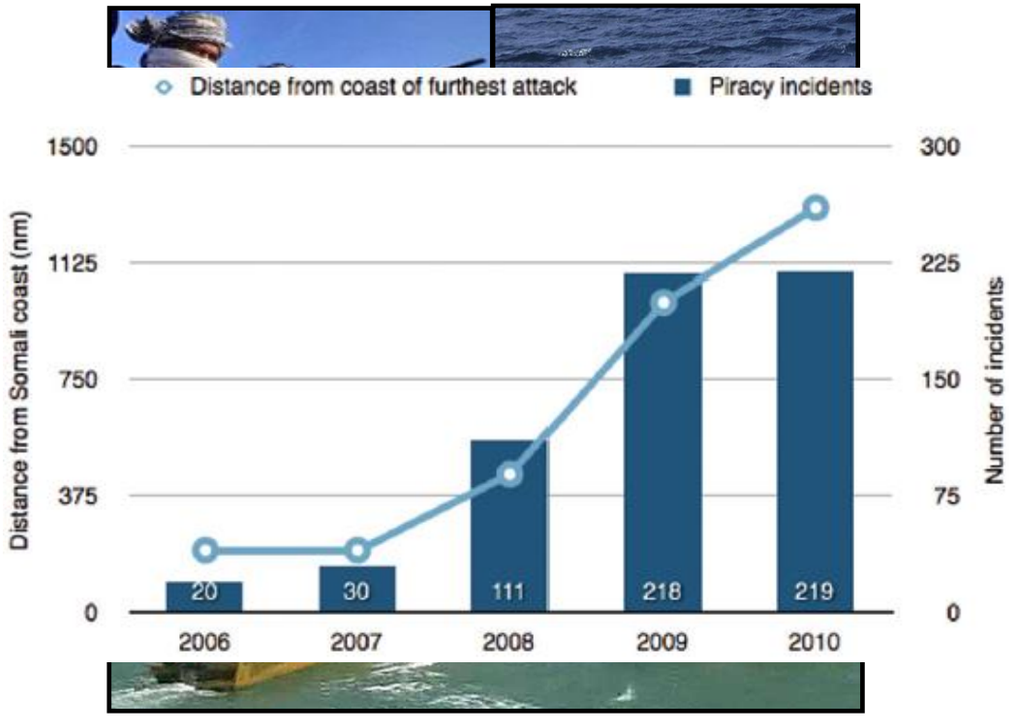
1 – J. G. Morrison, (2011, December 1) Data to Decisions or Decisions to Data? A Human System Perspective on D2D, [Online]. Available: http://www.ictas.vt.edu/cnavs/presentations/data_to_decision/4morrison.pdf.

2 – A. Smirnov, (2006, January 24) Context-Driven Decision Making in Network-Centric Operations: Agent-Based Intelligent Support. Russian Academy of Sciences, St. Petersburg, Russia.

Rise in Somali Piracy

- Piracy has become a major international problem, costing the global economy and maritime security ⇒ Higher insurance rates, delivery delays, ransom payments, etc.

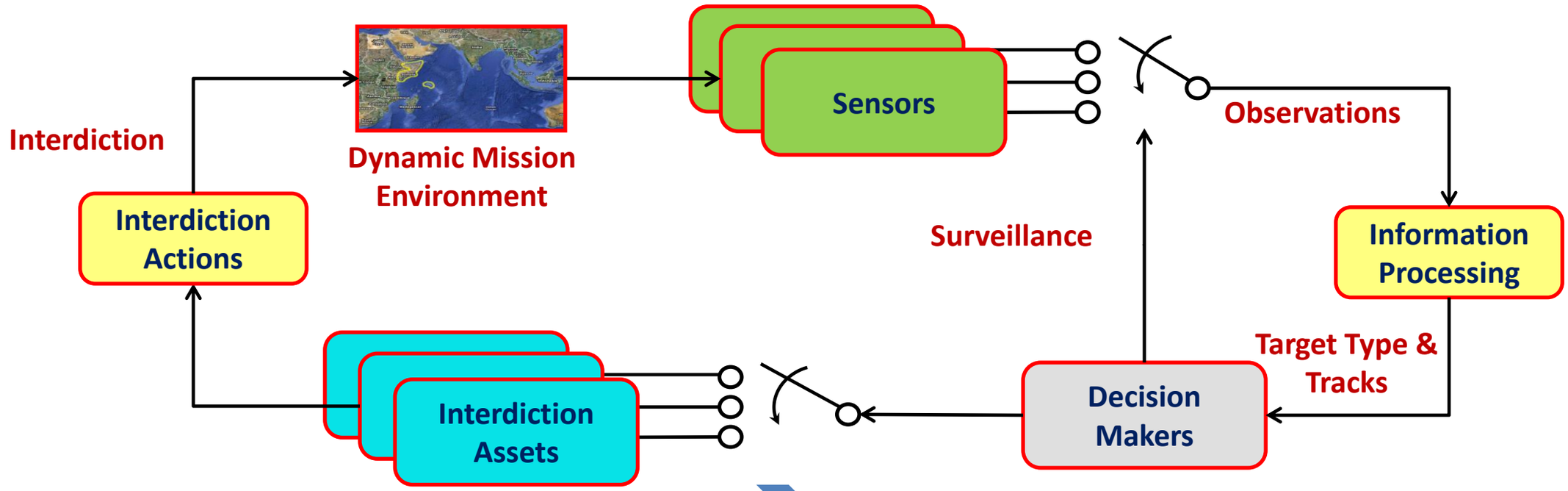




- Pirates continue to increase geographic range of their attacks
- A response to these threats requires:
  - Integration of intelligence and effective surveillance to detect and identify threats in order to gain situational awareness, followed by effective allocation of resources for interdicting the potential threats (Dynamic Resource Management Problem)

Reference: Rick "Ozzie" Nelson, Scott Goossens, 'Counter-Piracy in the Arabian Sea: Challenges and opportunities for GCC Action", Gulf Analysis Paper, CSIS, May 2011

Dynamic Resource Management for Counter-Piracy Operations



Interdiction

- Objective: Maximize interdiction probability of likely pirate attacks over a planning horizon
- Operational level
  - Asset positioning over time
- Tactical level
  - Patrolling Paths
  - Visit, board, search, and seizure (VBSS) decisions
  - Revisit frequency

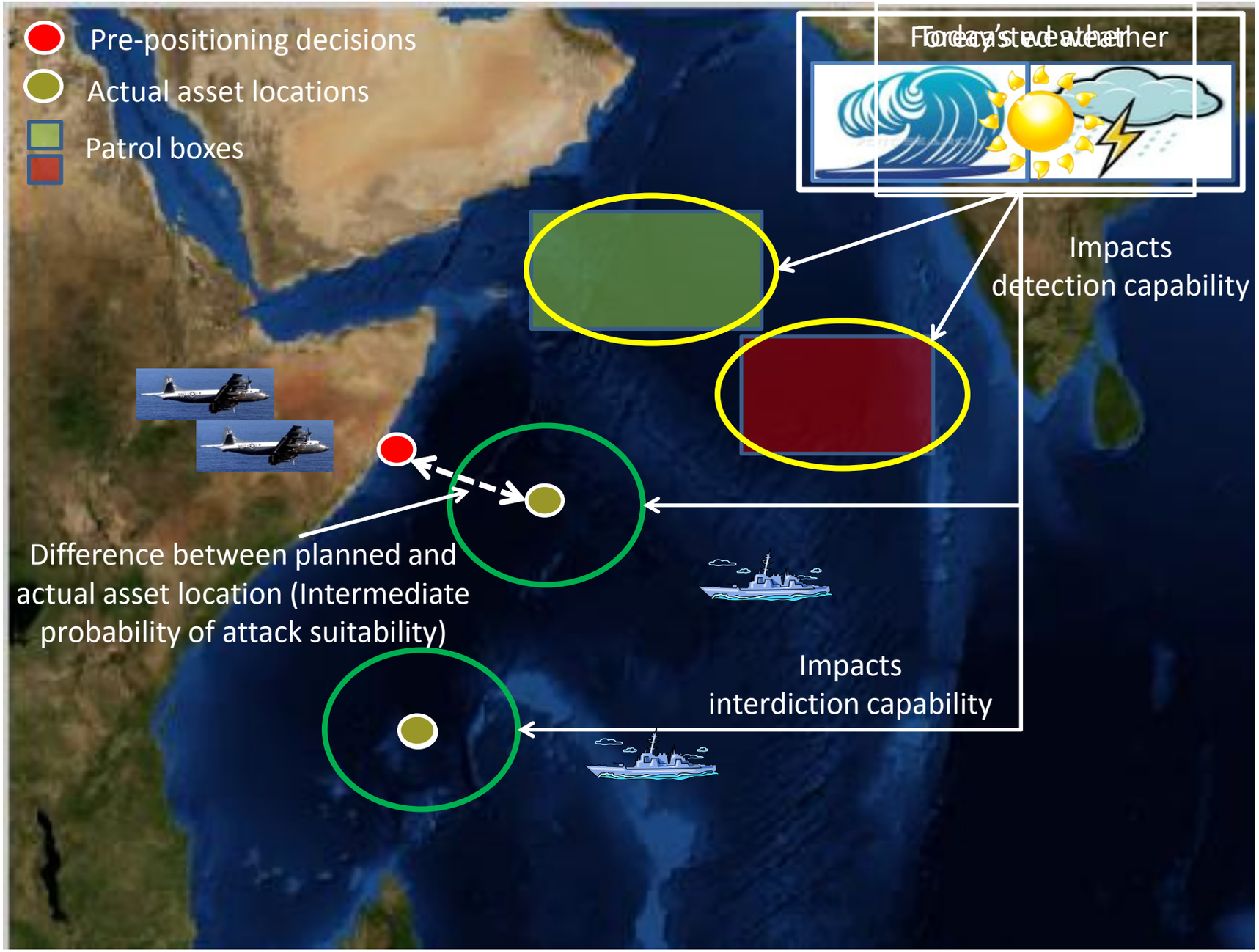
Constraints

- Mission environment (e.g., weather)
- Asset availability
- Coordination/ synchronization
- Asset capabilities (e.g., range, speed,..)
- Sensor assignment (e.g., Many-to-one,..)

Surveillance

- Objective: Maximize probability of pirate detection over a planning horizon
- Operational level
  - Which asset?
  - Where to search (Search box) ?
- Tactical level
  - Search paths
  - Detect, identify, and track
  - Revisit frequency

Counter-Piracy Problem in a Nutshell

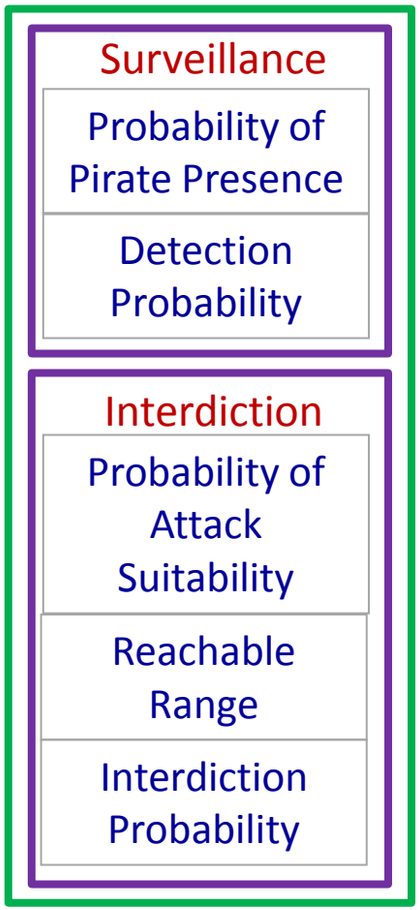


Counter-Piracy Problem in a Nutshell

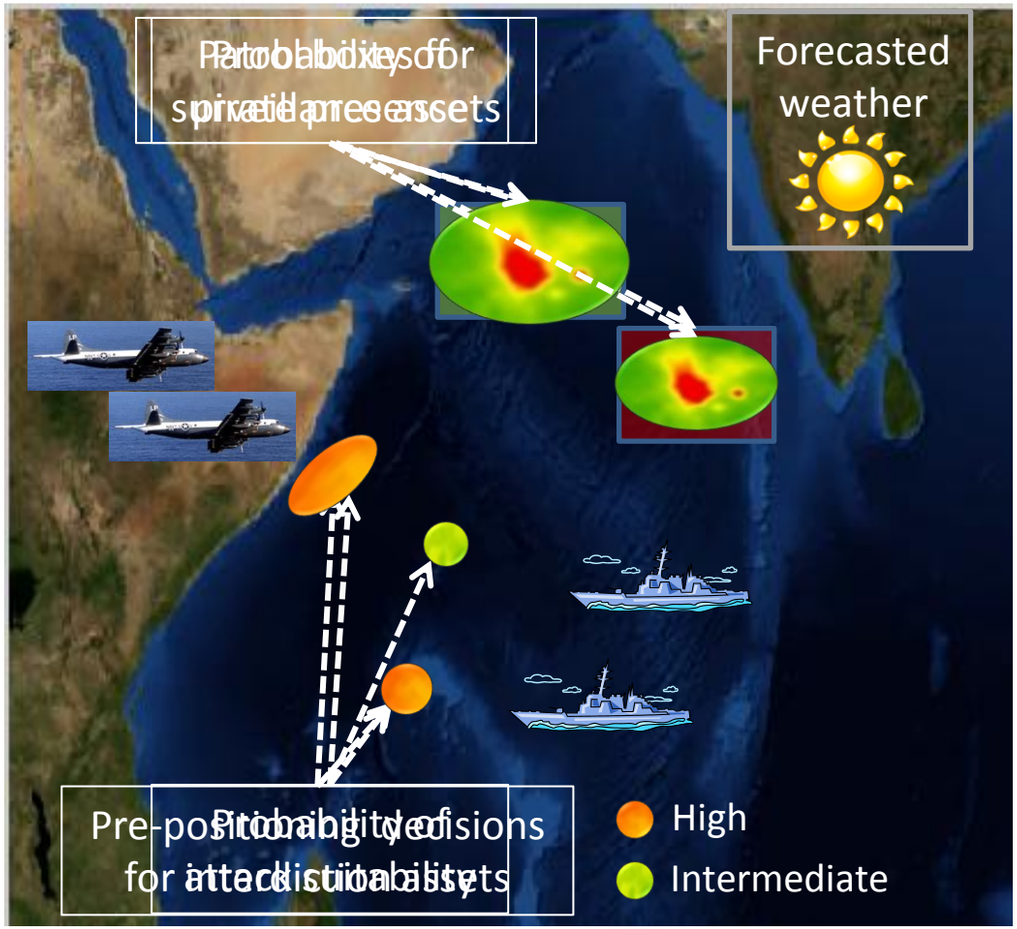
- Objective: Allocate interdiction and surveillance assets over a planning horizon to minimize the likelihood of successful pirate attack, including ensemble forecast uncertainties associated with Pirate Attack Risk Surface (PARS), asset capability, and effects of uncertain weather on reachable cells by each asset

Reachback

Reachback /Forward deployed



Decision Layer superimposed on Mission Environment



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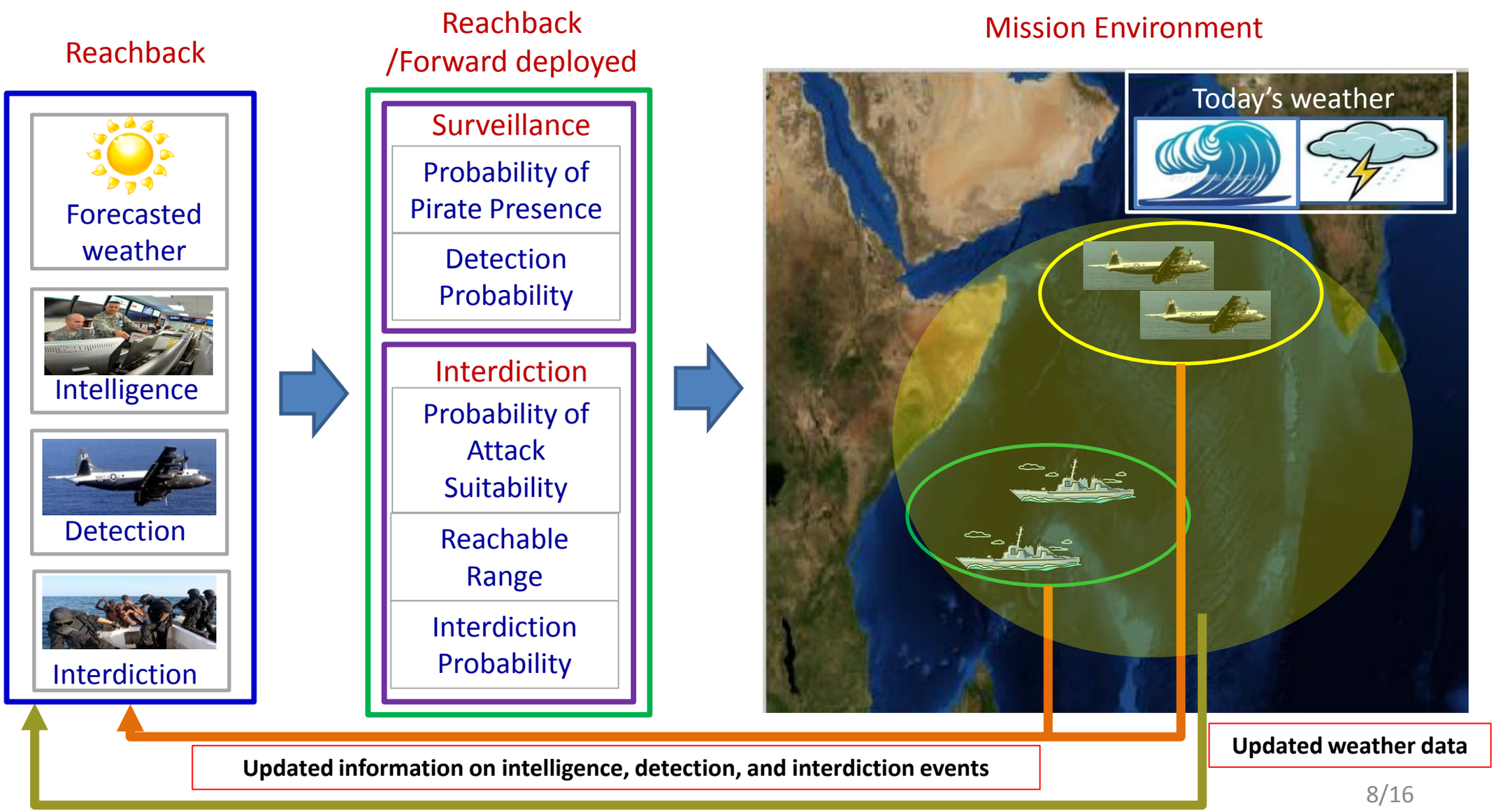


Probability of Interdiction & VOI Metric

- Current time period *k* corresponds to the beginning of a 12 hour duration between updates
- The DM decides allocation for the next *K* periods, *k*=1, 2,…,*K*
- $x_i(k)$ denotes interdiction assets indexed by $i \in I_k$ at time epoch *k*
- I_k denotes the set of available interdiction assets at time epoch *k*

Probability of Interdiction

$$PI_i\left(x_i(k),g\right)=\begin{cases}\dfrac{2r(i,\tau)}{dist\left(x_i(k),g\right)}, & r(i,\tau)<\dfrac{dist\left(x_i(k),g\right)}{2}\\ 1, & r(i,\tau)\geq\dfrac{dist\left(x_i(k),g\right)}{2}\end{cases} \quad (1)$$

Performance Degradation:

$$\frac{CPI_H-CPI_L}{CPI_L}\times 100\% \quad (4)$$

- CPI_H – cumulative probability of interdiction obtained when the PARS has low uncertainty
- CPI_L – cumulative probability of interdiction obtained when the PARS has low uncertainty

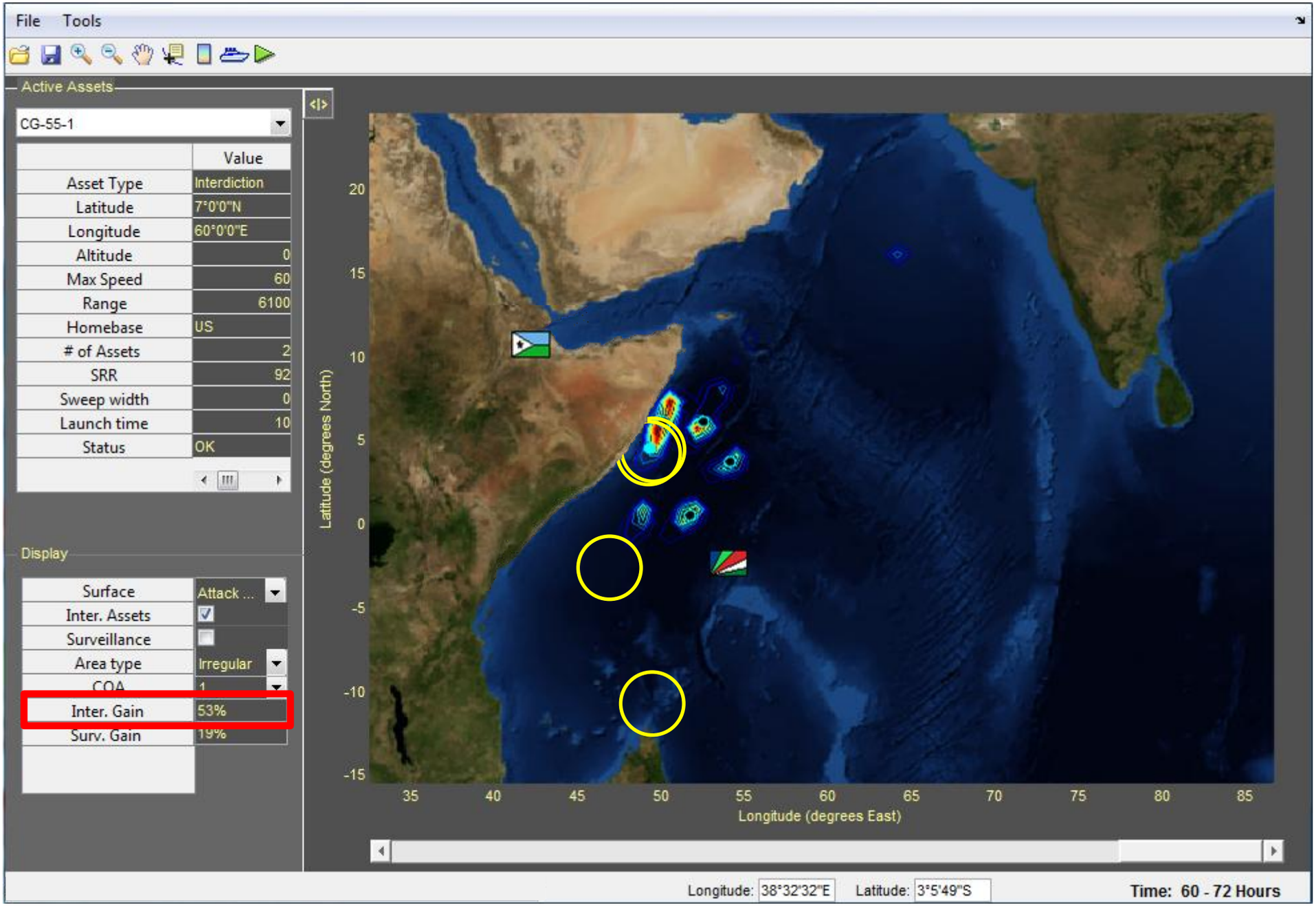
Distance (km) Covered During Time τ (s)

$$r(i,\tau)=\begin{cases}v_i\tau, & \tau\leq t_i^h\\ v_it_i^h+v_i^h\left(\tau-t_i^h\right), & \tau>t_i^h\end{cases} \quad (2)$$

VOI Metric: Cumulative Probability of Interdiction

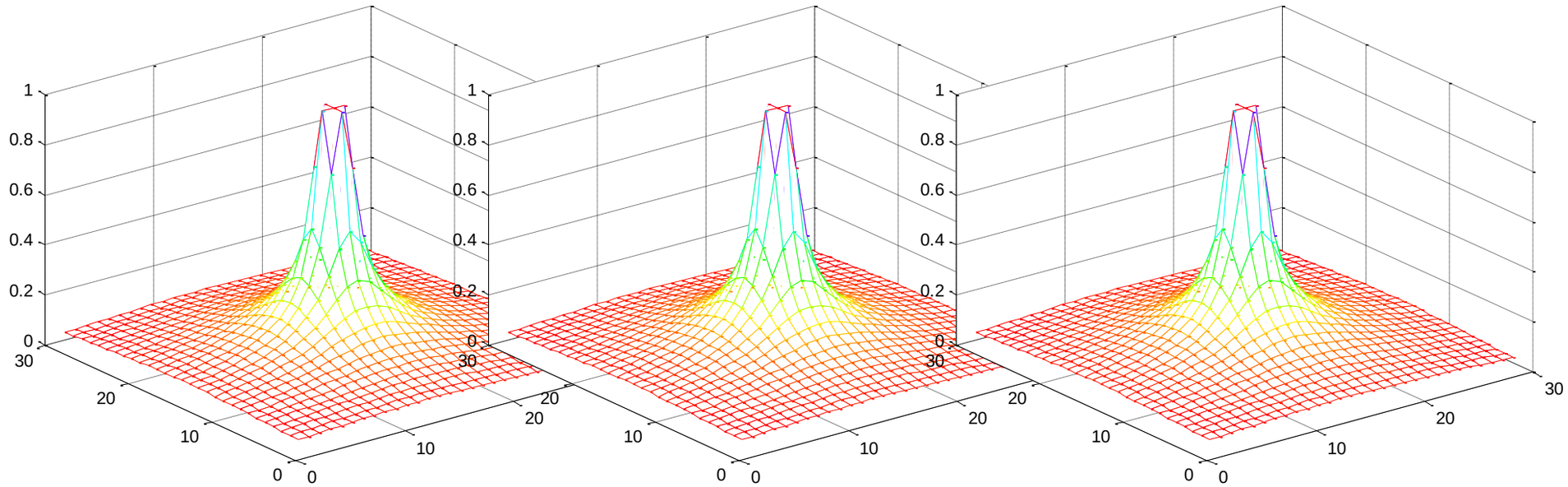
$$CPI=\sum_{k=0}^{K}\sum_{i\in I_k}\sum_{g\in G}PI_i\left(x_i(k),g\right) \quad (3)$$

Experimental Environment (Counter-Piracy Tool)



Degradation in the Quality of PARS Map

- Suppose we get probability maps for surveillance & interdiction at time *k*=0 for *k*=1,2,3, then for *k*=2,3,4 at *k*=1, etc.
- Assume "good future estimate" when we are at any given time period (i.e., good estimate at *k*=1 when we are at *k*=0,…)



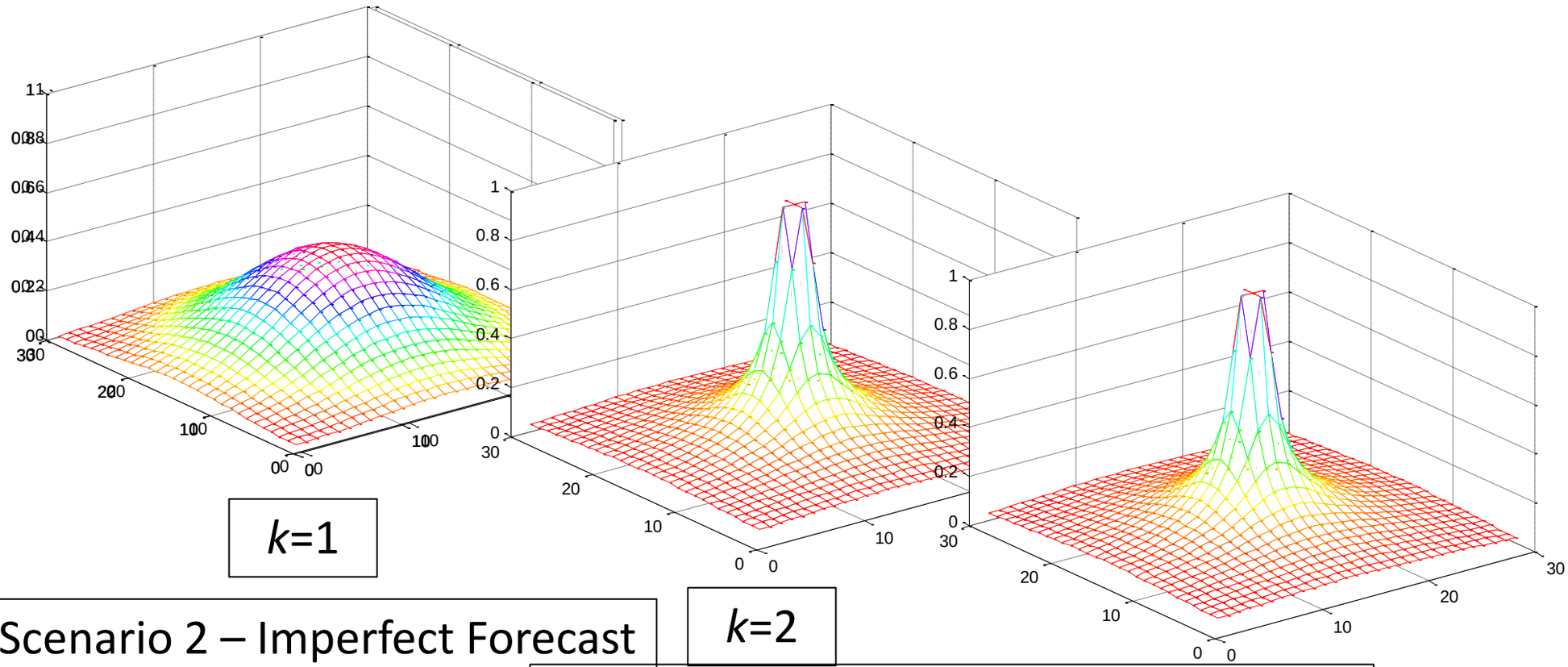
k=1 *k*=2 *k*=3

Scenario 1 – Perfect Forecast

Current time
k=0

Degradation in PARS Map Quality

- Suppose we get probability maps for surveillance & interdiction at time *k*=0 for *k*=1,2,3, then for *k*=2,3,4 at *k*=1, etc.
- Assume "good subsequent estimate" when we enter any given time period (i.e. good estimate for *k*=1 when we enter *k*=0,…)



Scenario 2 – Imperfect Forecast

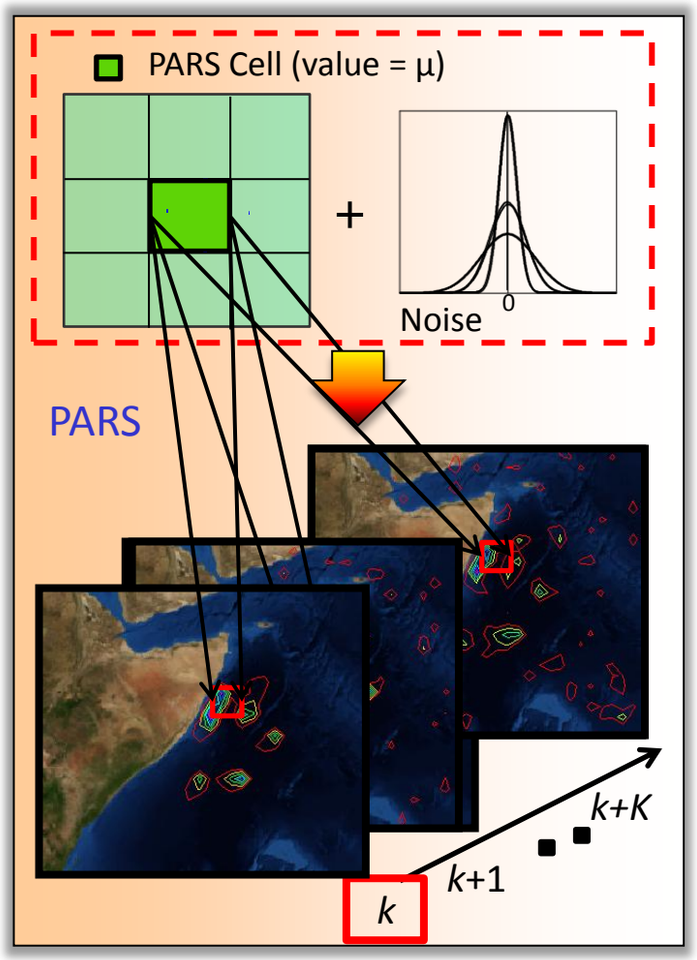
Current time
k=0

The difference between the two scenarios will give us the value of perfect information

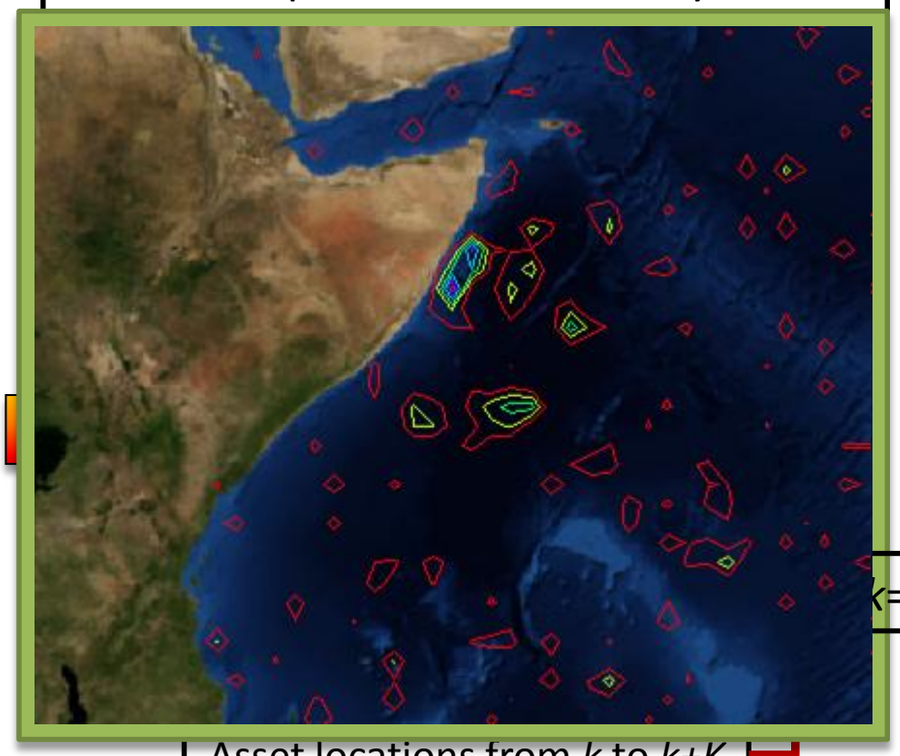
VOI Analysis Using Counter-Piracy Tool

- Objective: Provide a quantitative assessment tool to conduct sensitivity analysis wrt accuracy of PARS and model parameters

Imperfect PARS Forecast Model



- Model parameters for analysis

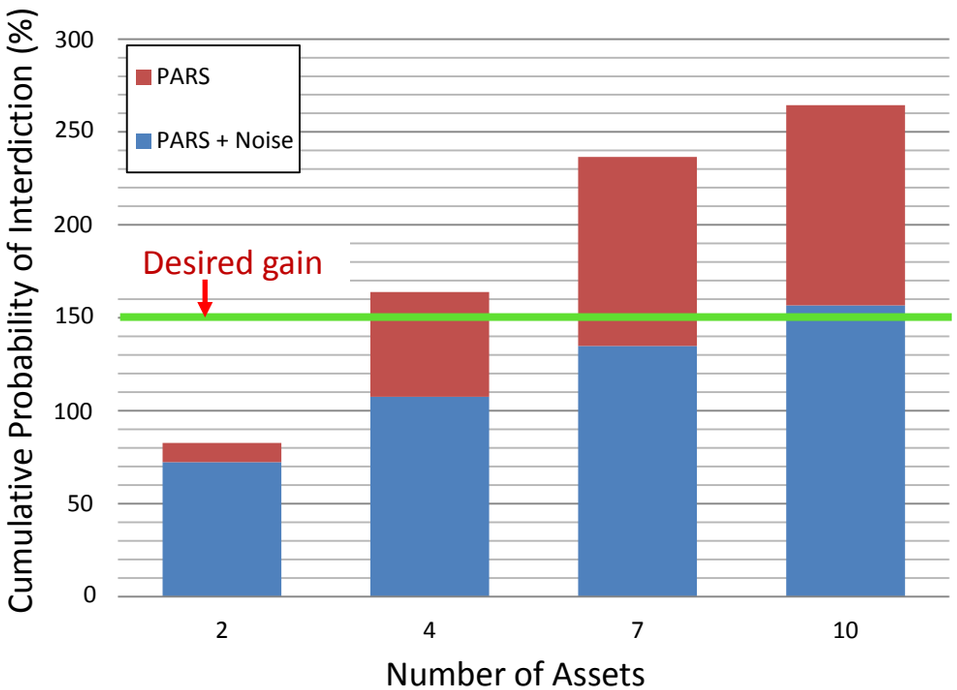


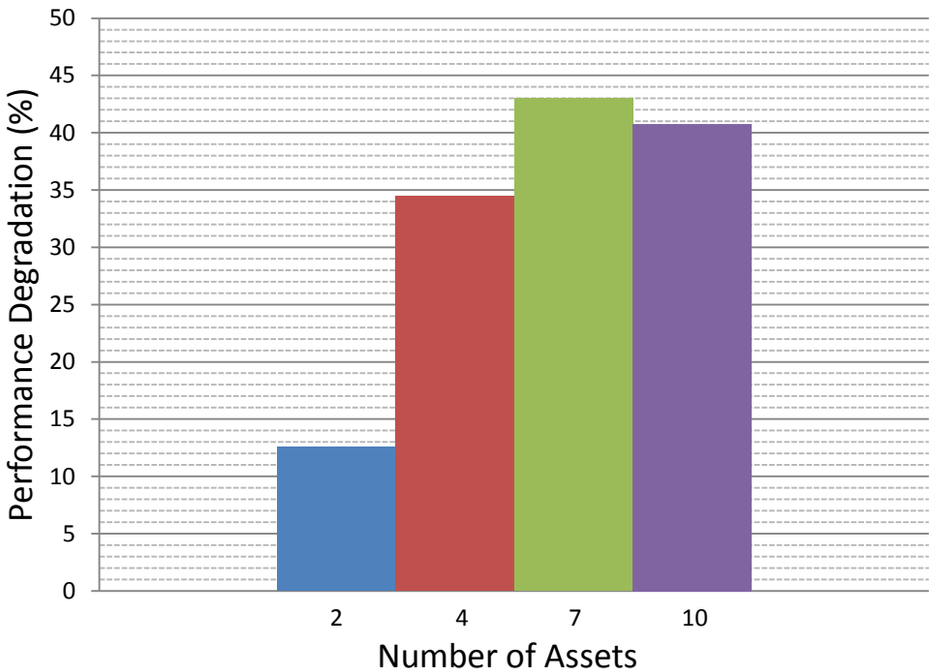
k=k+1

Asset locations from *k* to *k+K*

- As the forecast horizon increases, the variance of the noise added to the PARS increases

Value of the PARS & Performance Degradation

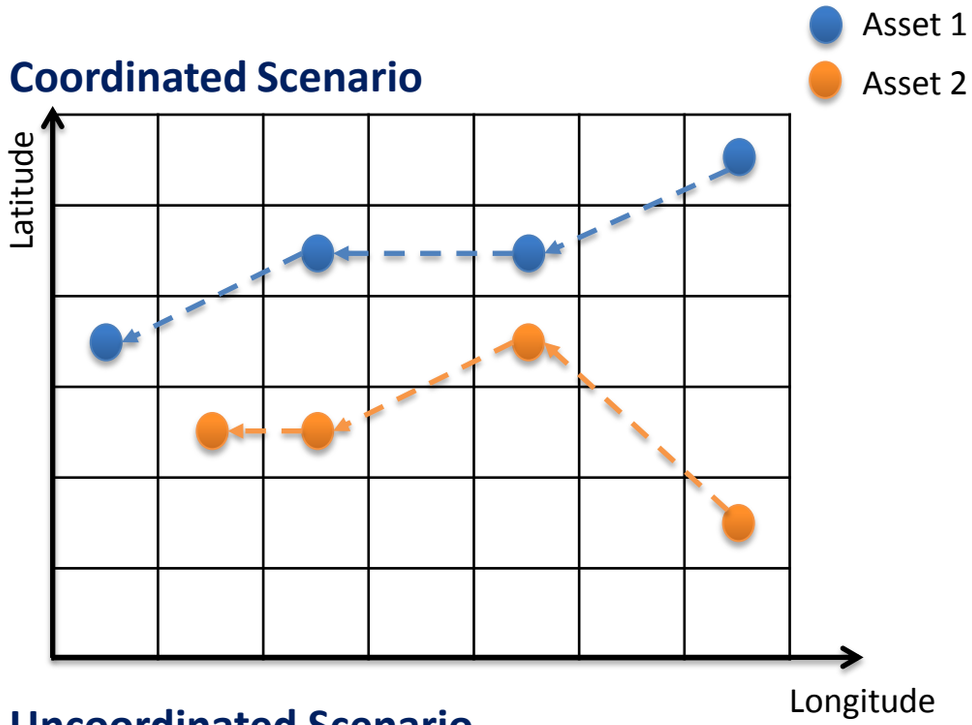


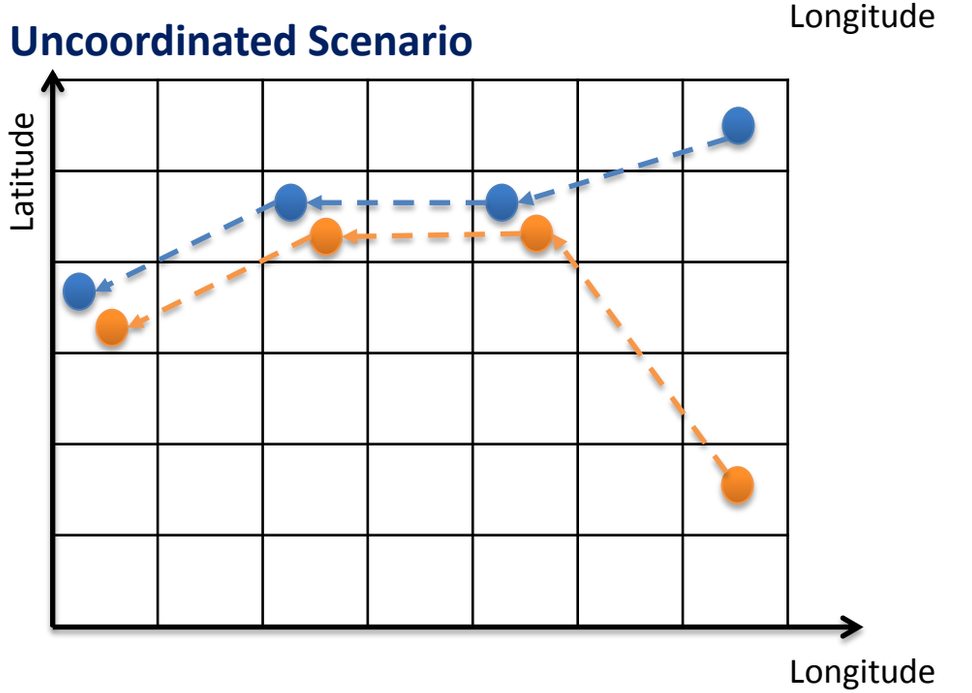


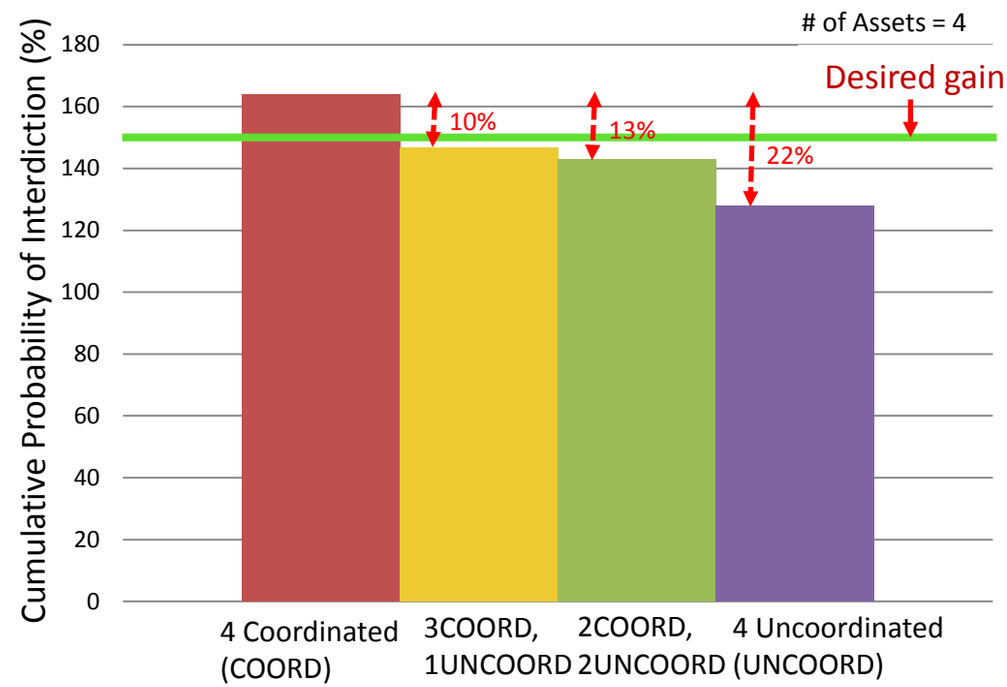
- # of Assets vs. Cumulative Interdiction Probability with PARS and with PARS + Noise
  - Noise with a variance of $(0.04)^2$ added at the current time epoch and variance is increased by a factor of 2 for each subsequent time epoch
  - For a desired cumulative probability of interdiction (say 150%) with a time horizon of 6 days, using PARS requires only 4 assets and PARS + Noise requires 10 assets
  - Rate of increase in the cumulative probability of interdiction with PARS + Noise wrt number of assets is less than that with PARS

- # of Assets vs. Performance Degradation between PARS and PARS + Noise
  - Using PARS with high uncertainty results in a 12% degradation in solution performance with 2 assets and peaks in solution disparity at 7 assets (43%)
  - Degradation is more evident when there are more opportunities to minimize likelihood of pirate attack
  - Performance degradation is a major consequence of adding high uncertainty to the forecast

Sensitivity Analysis of Coordinated vs. Uncoordinated Assets







- Coordinated vs. Uncoordinated Assets
  - Asset coordination is necessary in order for 4 assets to obtain a desired cumulative probability of interdiction of 150%
  - Lack of asset coordination lowers cumulative interdiction gain by 10% or more, resulting in failure to obtain the desired gain
  - Coordinated interdiction strategies improve interdiction gain by as much as 22% over uncoordinated case

Conclusion

- **Summary**: Quantified mission-specific value of information in a counter-piracy mission
  - Used a dynamic interdiction asset allocation algorithm to quantify the value of the PARS maps considering various levels of uncertainty
  - Having a “good” PARS can be extremely economical, ultimately allowing the DMs to forego the operating costs of allocating unnecessary assets
- **Future and Current Work**: Shift to a counter-smuggling mission in the East Pacific and Caribbean Oceans
  - Develop mission performance metrics for quantifying the value of PARS maps (e.g., expected amount of drugs interdicted, expected number of interdictions, etc.)
  - Explore a priori measures of information value (e.g., Bayesian diagnosticity, impact, information gain, etc.)