Search Modeling and Optimization in USCG's Search and Rescue Optimal Planning System (SAROPS)

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History and Background

- **As a result of air-sea rescue operations during the WWII, the US Coast Guard established the Air Sea Rescue Agency in 1944**
  - Used “Methods of Locating Survivors at Sea on Rubber Rafts” US Navy Hydrographic office, 1944 for planning searches – influenced by Koopman’s work in ASWORG later reported in “Search and Screening” 1946.
  - In peace time this became Search And Rescue (SAR)
    - USCG published first *Search and Rescue Manual* in 1959 based on Koopman’s 1956 -7 articles on search theory in *Operations Research*
    - Manual method given in this publication remained basic technique until 1967
  - SARP – Search And Rescue Planning program - 1970
    - Computer version of manual methods with some additions
- **Computer-Assisted Search Planning (CASP) developed in early ’70’s.**
  - Deployed in 1974 on a CDC 3300 in Washington, DC
  - Monte-Carlo simulation
  - Search Planning aid was primarily a display of cellular distributions.
  - In use until March 2007!

History and Background

- **SAROPS development began in October 2003. Designed to take advantage of better**
  - Environmental data information – winds, currents, visibility, cloud cover
  - Models for
    - Drift and leeway of search objects
    - Detection capability of search sensors
  - Theoretical developments in search planning
    - Search for moving objects, multiple search object types, survivor search
  - Computer capabilities and geographic displays
- **SAROPS became operational in March 2007.**
  - Developed by Metron, Applied Science Associates (ASA), and Northrop Grumman

Basic Components of SAROPS

- **Environmental Data Server (EDS) developed by ASA**
  - Gathers and provides environmental products for SAROPS
- **Simulation (SIM) developed by Metron**
  - Produces and updates probability distributions for location of search object
- **Planner developed by Metron**
  - Recommends search patterns for ships and aircraft to maximize detection probability (probability of success).
- **Graphical User Interface (GUI) developed by Northrop Grumman**
  - Uses ArcGIS as basis for GUI

Maritime Search Planning Challenges

- **Search object location is uncertain and moving**
- **Motion is indeterminate due to uncertainty in**
  - Currents, winds, and leeway
- **Object type maybe uncertain**
    - Boat? Raft? Person in Water? - differing motion and detection characteristics
- **Detection capability depends on**
  - Platform, sensor, environment, and object type
- **Both searcher and search object are moving during search**
- **Search platforms have operational constraints**
  - Search areas must be rectangular and can't overlap
  - Search paths must be equally spaced and parallel

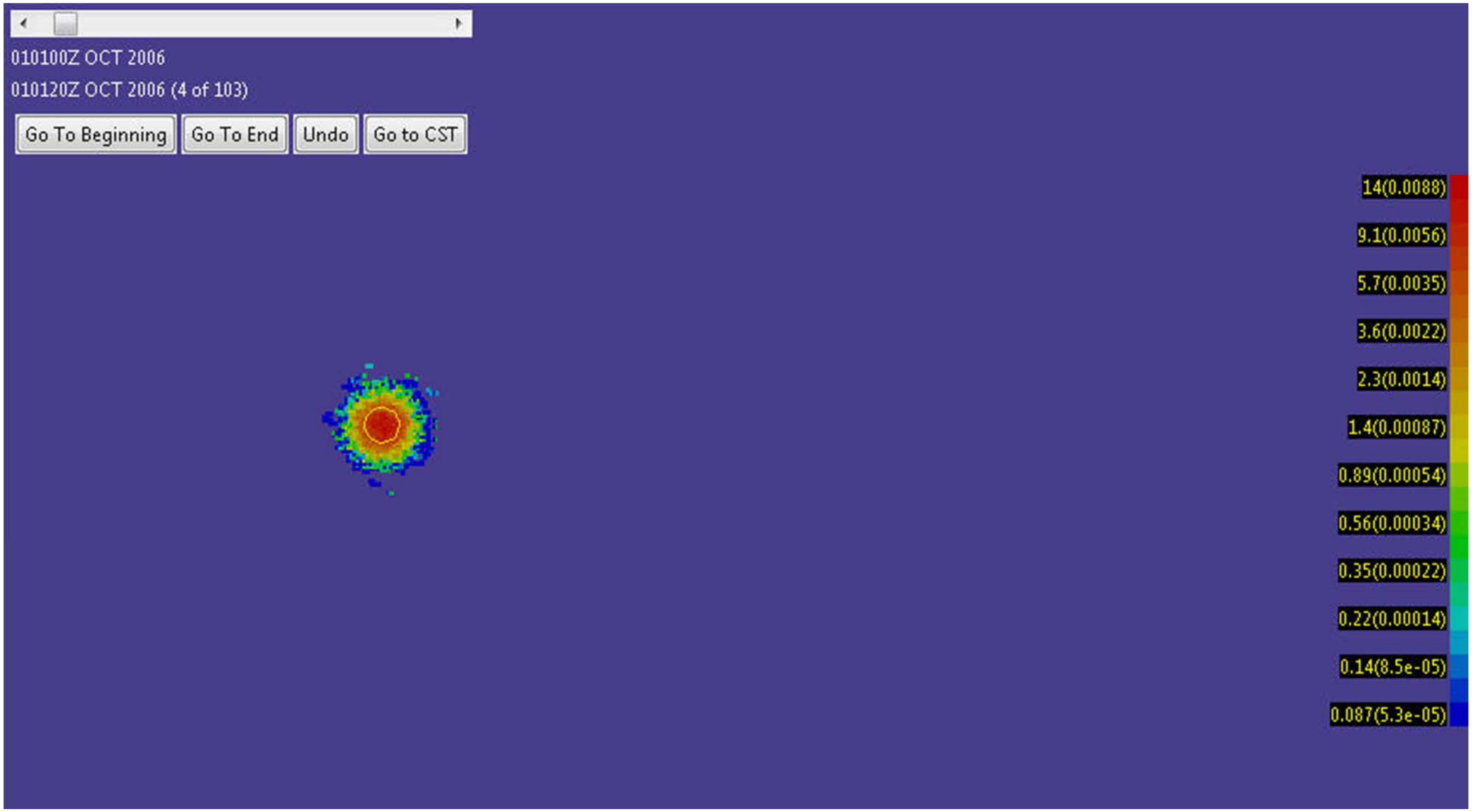
Approach - Bayesian

- **Use SAROPS Simulator (SIM) to compute probability distribution for search object location and type as a function of time**
  - Output is weighted set of particles – possible paths for search object
    - An object type is assigned to each path - type may change over time
- **Use Planner to recommend “optimal” search plans**
  - Recommended plan maximizes increase in probability of success for
    - Specified set of Search and Rescue Units (SRUs) and search times
  - Planner recommends set of non-overlapping search rectangles
    - Specifies search paths within rectangles
  - Planner accounts for
    - Previous unsuccessful searches – uses Bayesian posterior distribution from SIM
    - Detection capability of each SRU for each object type – includes environment
    - Motion of search object and searcher during search

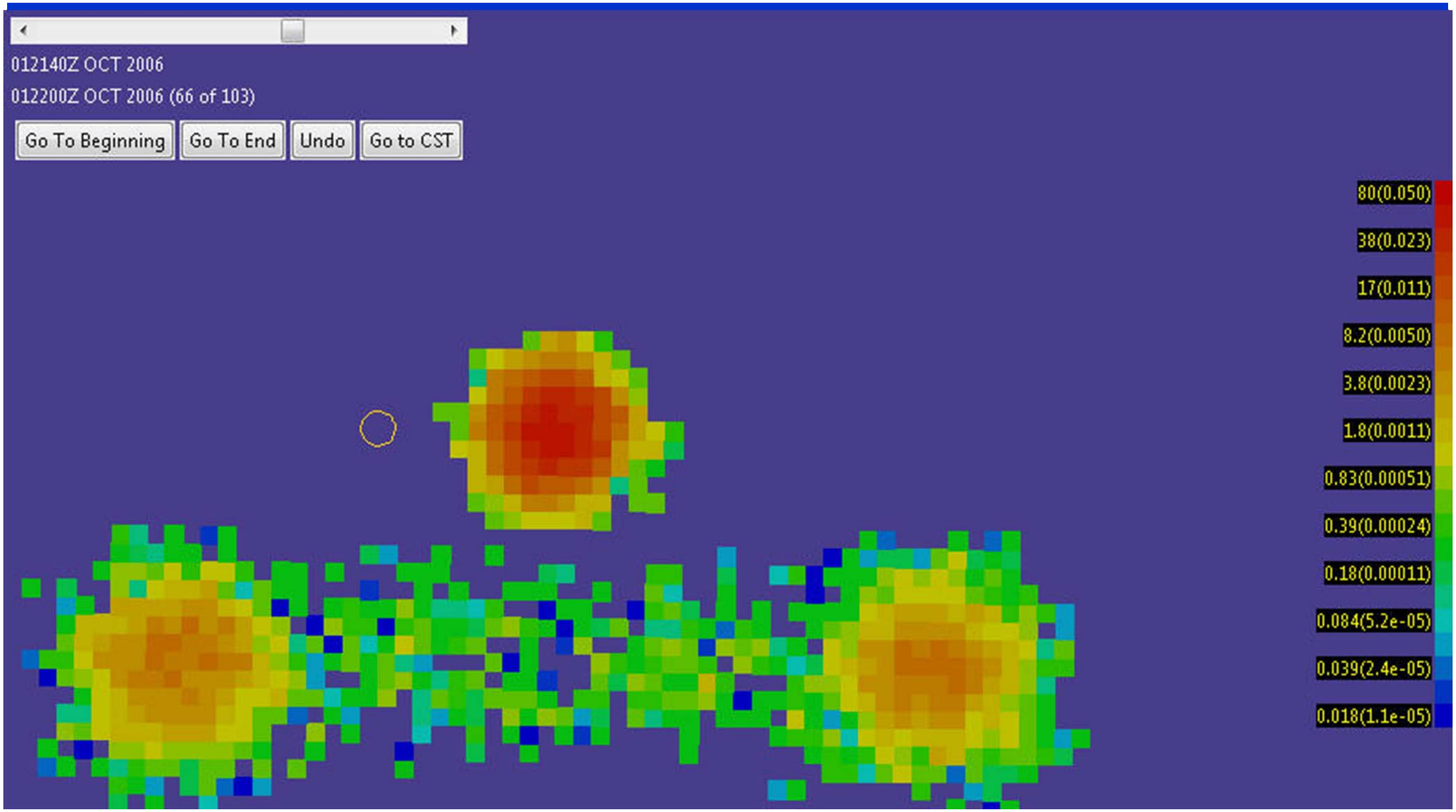
Optimization Example

- **Single Scenario – Distress call at 01 0000**
  - Last Known Position (Circular Normal) at 01 0000
- **Two Search Object Types and Motion Models**
  - Search object in a raft (P=0.25) or in the water (P=0.75) (called PIW)
    - Former case; position is more influenced by the winds (out of the north)
    - Latter case: position is more influenced by the currents (flowing east)
- **Snapshots**
  - 1. Distribution at 01 0120 – shortly after distress call
  - 2. Distribution at 01 2140 - start of search
    - Raft particles went south - gibing effect causes 2 modes in the SE and SW
    - PIW particles went east
  - 3. Recommended plan for this search
  - 4. Posterior distribution assuming recommended search fails

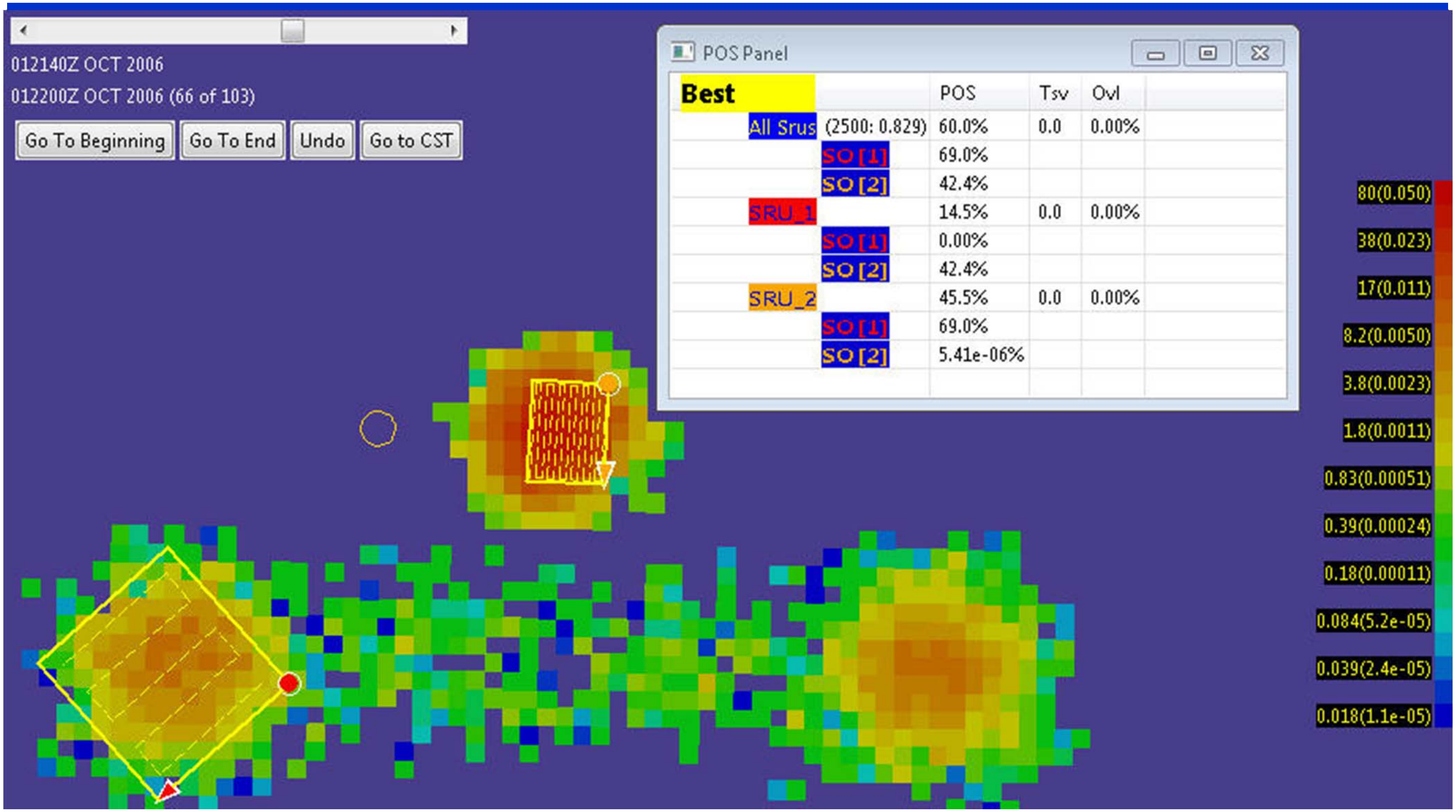
Distribution at 01 0120
After 1hr 20 minutes of Drift



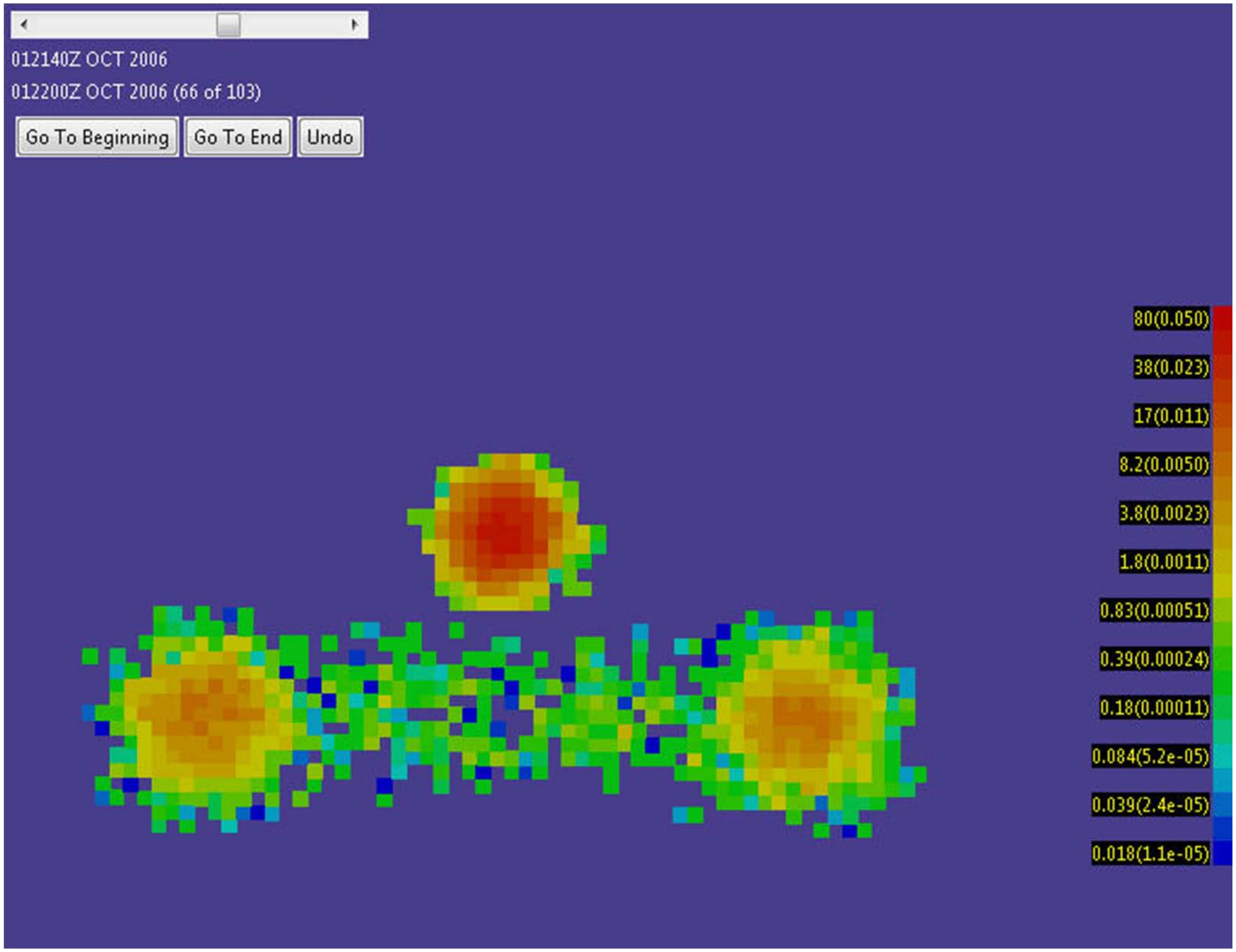
Distribution at 01 2140
Start of Search



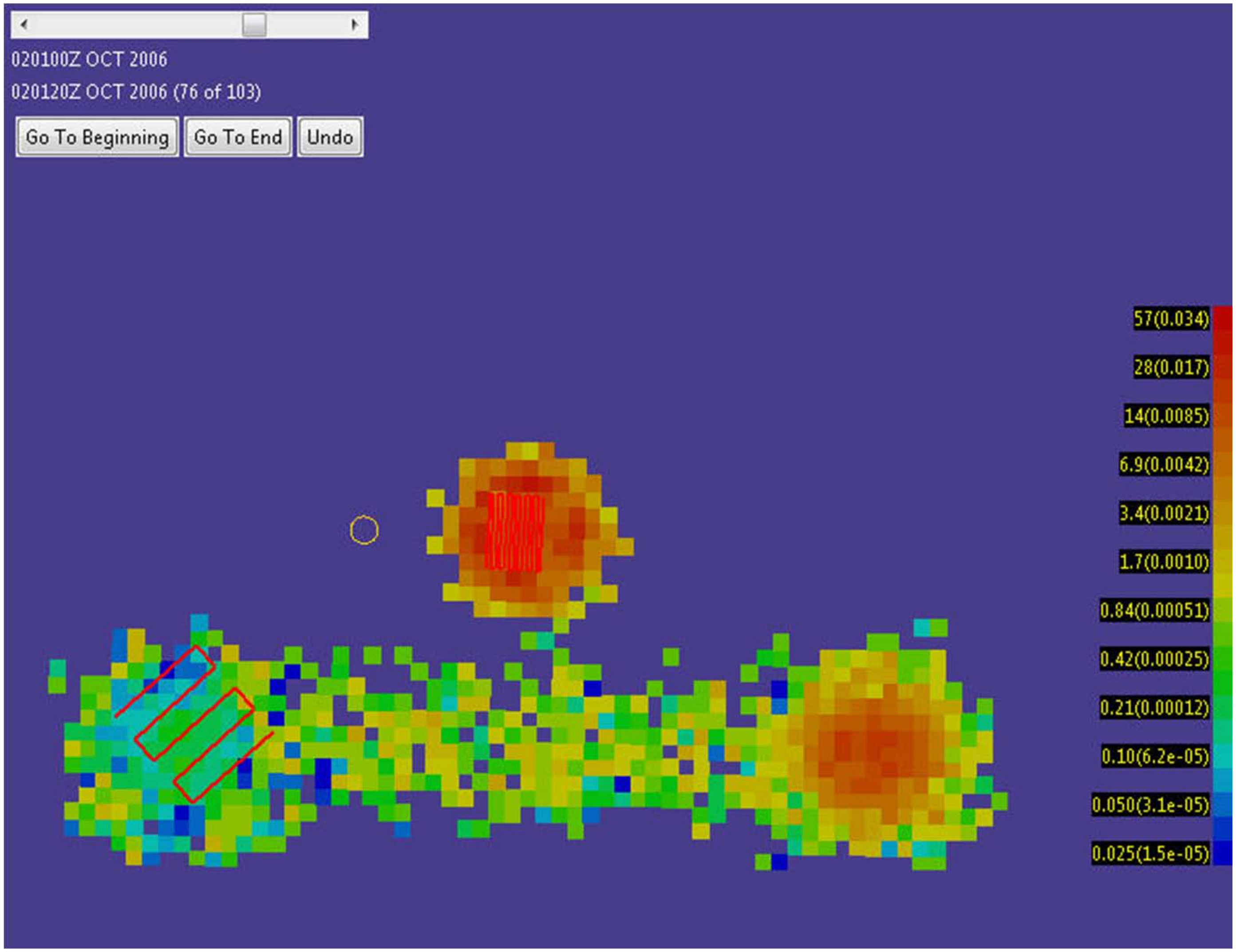
Planner Solution



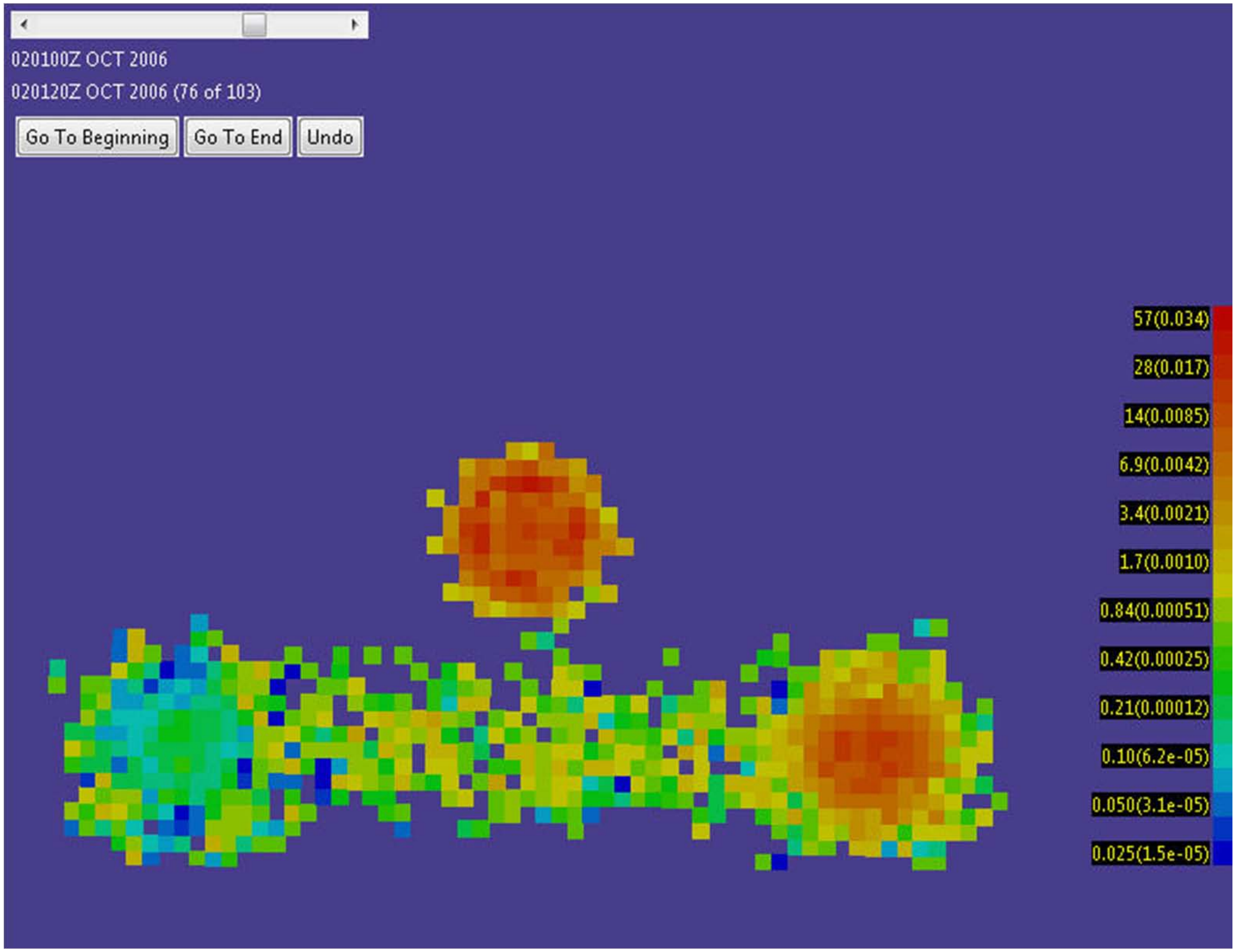
Distribution at 01 2140
Prior to Search



Distribution at 02 0120
Assuming Search Fails



Distribution at 02 0120 without Tracks Assuming Search Fails



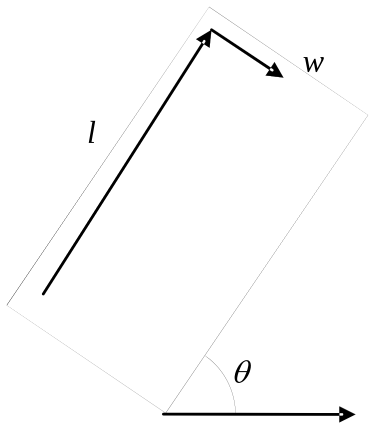
Planner

- **A set of SRUs is specified for the search**
  - SRUs may have different detection characteristics for each object type
    - These are characterized by lateral range curves as discussed below
  - Each SRU has a time on scene, endurance, speed

- **Planner assigns a rectangle to each SRU**
  - An allowable rectangle induces a parallel path search plan for an SRU

- **Planner seeks to maximize Probability of Success (POS) by placing the rectangles intelligently**

Search Paths from Rectangles



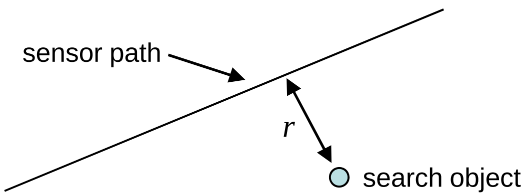
- **A Rectangle is defined by 5 variables:**
  - Center (x, y), orientation θ, length l, and width w
- **Each SRU has a *path-length*** L
- **The set of *allowable* rectangles is constrained as follows**
  - The track spacing s, leg length t, and path length L must satisfy

    $$s_{\min} \leq s \leq t, \quad t + s = l, \ l = L / n \text{ where } n \text{ is an integer, and } w = Ls / l$$

    where $s_{\min}$ is the minimum allowable track spacing
  - Rectangles can not overlap
- **An allowable rectangle (almost) specifies a search path**

Calculating POS for a Search Plan

- **SRU Search paths consist of K straight-line legs**
  - Sensor on SRU (visual, radar, lidar) is characterized by a lateral range function λ
    - λ gives probability of detection as a function of r, distance at point of closest approach
    - Detection prob is function of object type, sensor (altitude), environment – clouds, sea state



  - Let d_k be the distance a the point of closest approach of the k th leg to the path of particle p during the time of the leg. Then

$$pfail(p, SRU) = \prod_{k=1}^{K} (1 - \lambda(d_k))$$

is the probability that the SRU fails to detect the particle p during its search

- **Let $w(p)$ be the probability on path p. Then**

$$POS(p) = 1 - \prod_{sru} pfail(p, \text{SRU}) \text{ and } POS = \sum_p w(p) POS(p)$$

Computing POS for Planner

- **Probability of Success (POS) is computed 3 ways:**
  - Method A: Exponential detection function
    - Compute sweep width W of sensor by $W = \int_{-\infty}^{\infty} \lambda(r)\, dr$
    - A = *area of rectangle,* s = speed, T = search time, P_C = cont Prob
    - POS = $P_C\left(1 - \exp\left(-\frac{sTW}{A}\right)\right)$
  - Method B: Reduced Sample – compute POS the "correct" way but use a small subset of particles
  - Method C: "Exact – use full set of particles (Used to report the results)

Mathematical Formulation

- **Constrained Optimization problem with 5*n* variables,**
  - *n* is the number of SRUs.
- **Use iterative techniques for "solving" the problem**
- **Need initial solution**
- **Need algorithm for iterating to better solutions (higher POS)**

Five Step Strategy

- **Step 1.** Obtain initial solution
  - Rectangles may overlap a bit and have Track Spacing Violations (TSVs)
- **Step 2.** Refine solution to eliminate overlap and TSVs
- **Step 3.** Perturb rectangles to improve POS while introducing as little overlap as possible and no TSVs
- **Step 4.** Go to Step 2 if reasonable
- **Step 5.** Otherwise, create another initial solution and then go to Step 2
- **Stop after some period of time**

Step 1: Initial Placement

- Greedily place the first SRU:
  - Align with the mean drift
  - Look for a rectangular array of cells by starting with the highest prob cell and adding/subtracting rows and columns until we can’t improve the POS, using method “A” to approximate POS.
- Update the probabilities of the particles.
- Place the second SRU.
  - Allow overlap, but only *some* overlap.
    - Goal is to have a fixable amount of overlap for step 2
- Place third and remaining SRUs similarly.
- At each step, maintain admissibility
  - Admissible sets can have their overlaps cleared with small adjustments.

Step 2: Eliminate Overlap and TSV

- Minor Moves - each SRU rectangle has 20 possible minor moves.
  - Examples: Move up ¼ NM; Expand to the right; Contract from the left
- Overlap Elimination
  - For each SRU, check each congruent minor move.
    - Make move if it decreases overlap, and doesn't decrease POS (Method B)
    - Otherwise make move with smallest decrease in POS
  - Continue until overlap is eliminated
- TSV Elimination
  - For each SRU, check for the best TSV-reducing minor move.
    - Set of TSV minor moves depends on values of Minimum Track Spacing, Current Track Spacing, and Search Leg Length
  - If any TSV-reducing minor moves are made, repeat Overlap Elimination step.
    - Since Overlap Elimination uses congruent moves, TSV does not change
  - Continue until TSV is eliminated

Steps 3 - 5: Improve POS

- **Step 3**
  - Discrete gradient with 20 possible minor moves as in Step 2
  - Use a move if it increases POS with “minimal” increase in overlap
- **Step 4**
  - Go back to step 2
- **Step 5:** If stuck at a local maximum, “Jump” one of the rectangles to new location

Summary

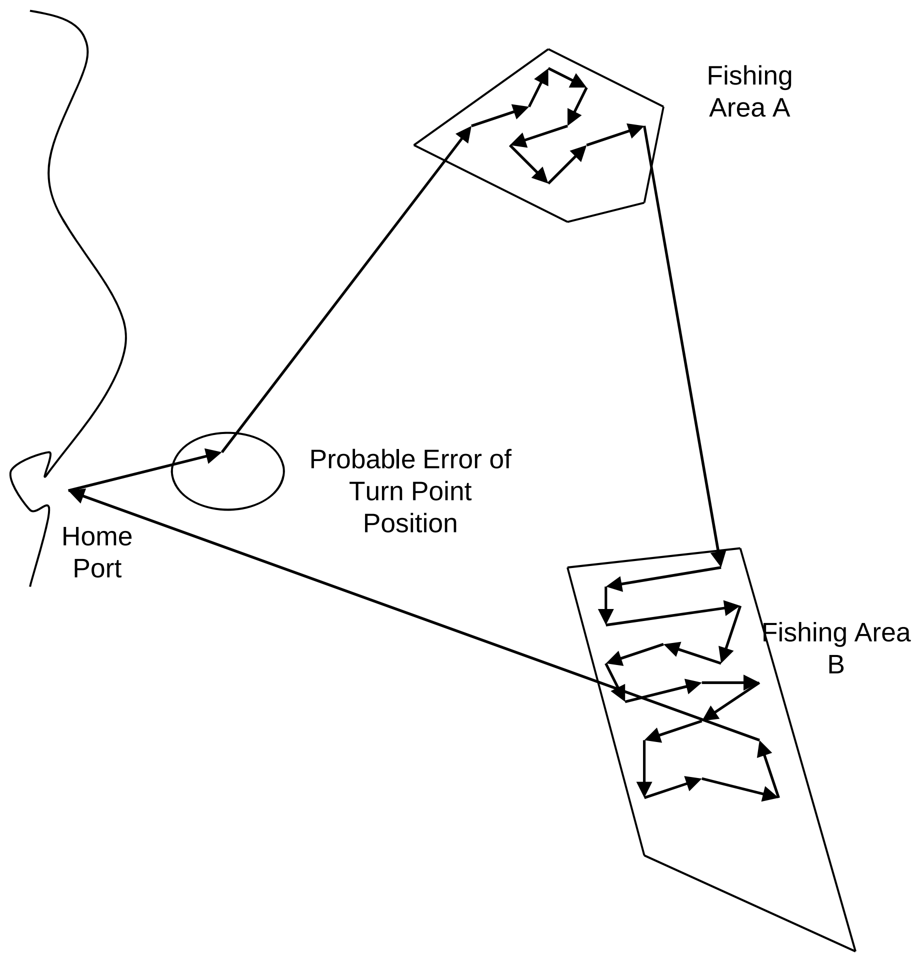
- **SAROPS Planner provides an important new tool for SAR planning**
- **Planner recommends search plans that**
  - Maximize increase in POS for a given set of SRU assets
  - Are operational
    - Parallel path plans – no overlap in search areas
    - Based on time on station, endurance, and speed of SRUs
  - Account for
    - Previous unsuccessful search
    - Detection capability of SRU as a function of target type and environment
    - Multiple target types
    - Target and SRU motion during search
- **Developmental Version of Planner is Interactive**

Backup Slides

Simulator

- **Monte-Carlo simulator produces distribution for location and state of search object – weighted set of particles (paths).**
- **Pre-distress motion is described with *scenarios*.**
  - Examples: Sequence of waypoints, Dead-Reckoning, Last-Known Position. SAROPS has these and other *scenario-types*.
  - Scenarios carry weights.
  - Each Scenario has its own collection of particles.
- **Transition to distress**
  - Draw for when the distress occurred - Influenced by hazard areas
  - Draw for the type of post-distress object
- **Post-distress motion**
  - Moves according to the winds and currents
  - These affect diverse object types differently

Example of Scenario



Updating for Unsuccessful Search

- SIM computes $pfail(p) = \prod_{SRU} pfail\left(p, SRU\right)$ to obtain the probability that search by all SRUs fails to detect p.
- Let $w(p)$ be probability on particle p. Then the posterior probability is

$$\hat{w}(p) = \frac{pfail(p)w(p)}{\sum_{p'} pfail(p')w(p')}$$

- Process of updating for unsuccessful search is followed for each search.
- Posterior distributions are displayed by choosing a display time, gridding the ocean into cells, and computing the sum of the posterior probabilities of the particles in each cell at that time.
  - The distribution is usually displayed in color coded fashion with high probability cells shown in red and low in blue.

Planner: Remaining Work

- **Better Initial Solutions**
- **Better Choice of *Minor Moves***
  - E.g, Some that are not the movement of a single SRU
- **Re-define what to Maximize**
  - Probability of finding Object AND Object is Alive
- **Use Optimization Libraries**
  - Use real gradient searches by introducing Path-Length as a sixth variable for each SRU, OR
  - Solve problems for a fixed value of length, and combine results

History and Background (3)

- **Team and Roles:**
  - Northrop Grumman is the prime
  - Applied Science Associates: GUI and EDS
  - Metron: Simulator and Planning Algorithms
- **More Information on the Web:**
  - http://www.military.com/news/article/coast-guard-news/cg-assists-in-search-for-air-france.html?col=1186032366581
  - http://en.wikipedia.org/wiki/Search_and_Rescue_Optimal_Planning_System_(SAROPS)
  - http://www.scientificamerican.com/article.cfm?id=people-lost-at-sea-found

Software Component: GUI, EDS, SIM

- ***SAROPS is the overall Program***
- ***Computational Engine (called SIM) is a Service***
- **Workflow**
  - GUI collects information from user:
    - *Where, when, hypotheses on what happened*
  - *Information on winds and currents are gathered from EDS*
  - *Writes the information into an Xml file and environmental data files*
    - *3 files; 1 model file (xml), 1 wind file (netcdf), and 1 currents file (netcdf)*
  - *SAROPS sends SIM the 3 files and SIM creates a file of distributions (one for each 20-minute time period)*
  - *SAROPS gathers more information about the search assets*
  - *SAROPS asks SIM for a suggested search plan*

History and Background

Early CASP Probability Map

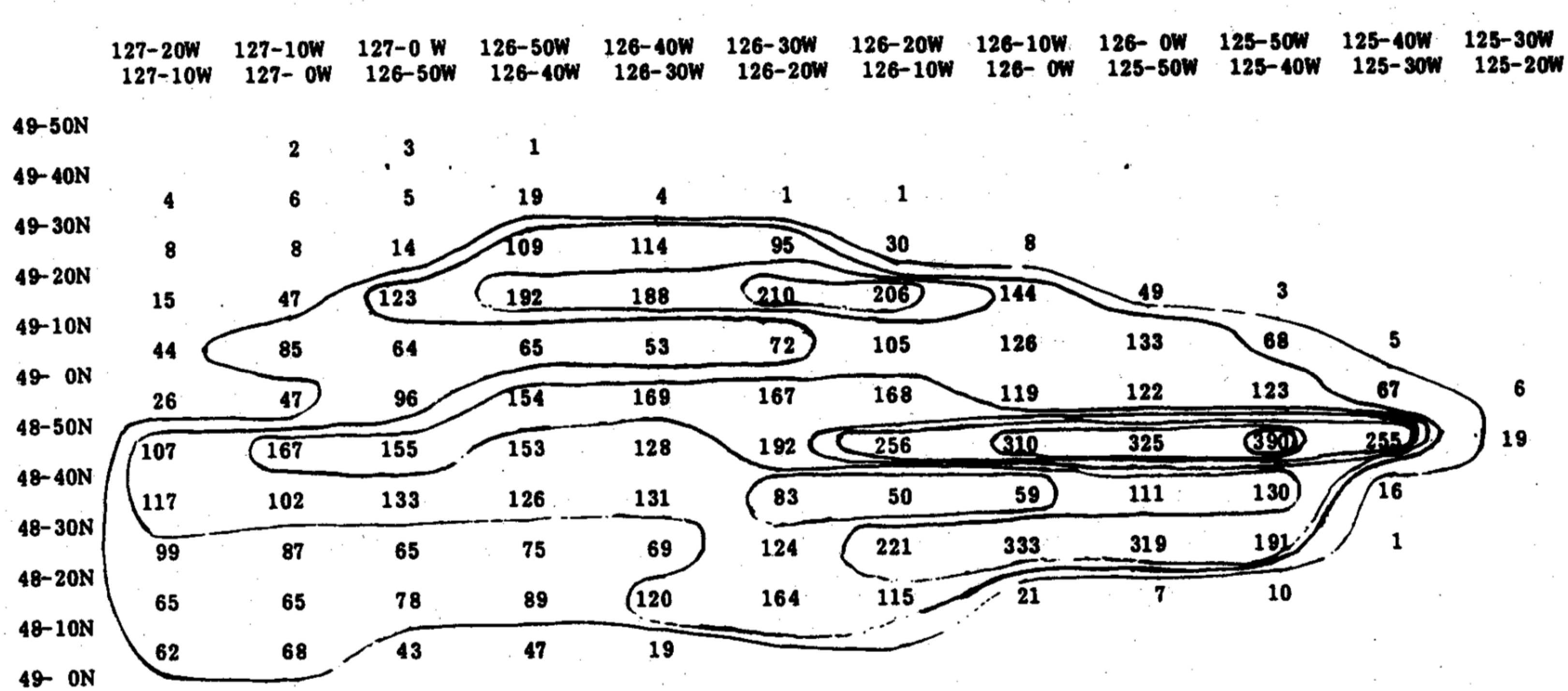


FIGURE 2. Target location probability distribution probabilities are multiplied at 10,000 and truncated

Early SAROPS Success

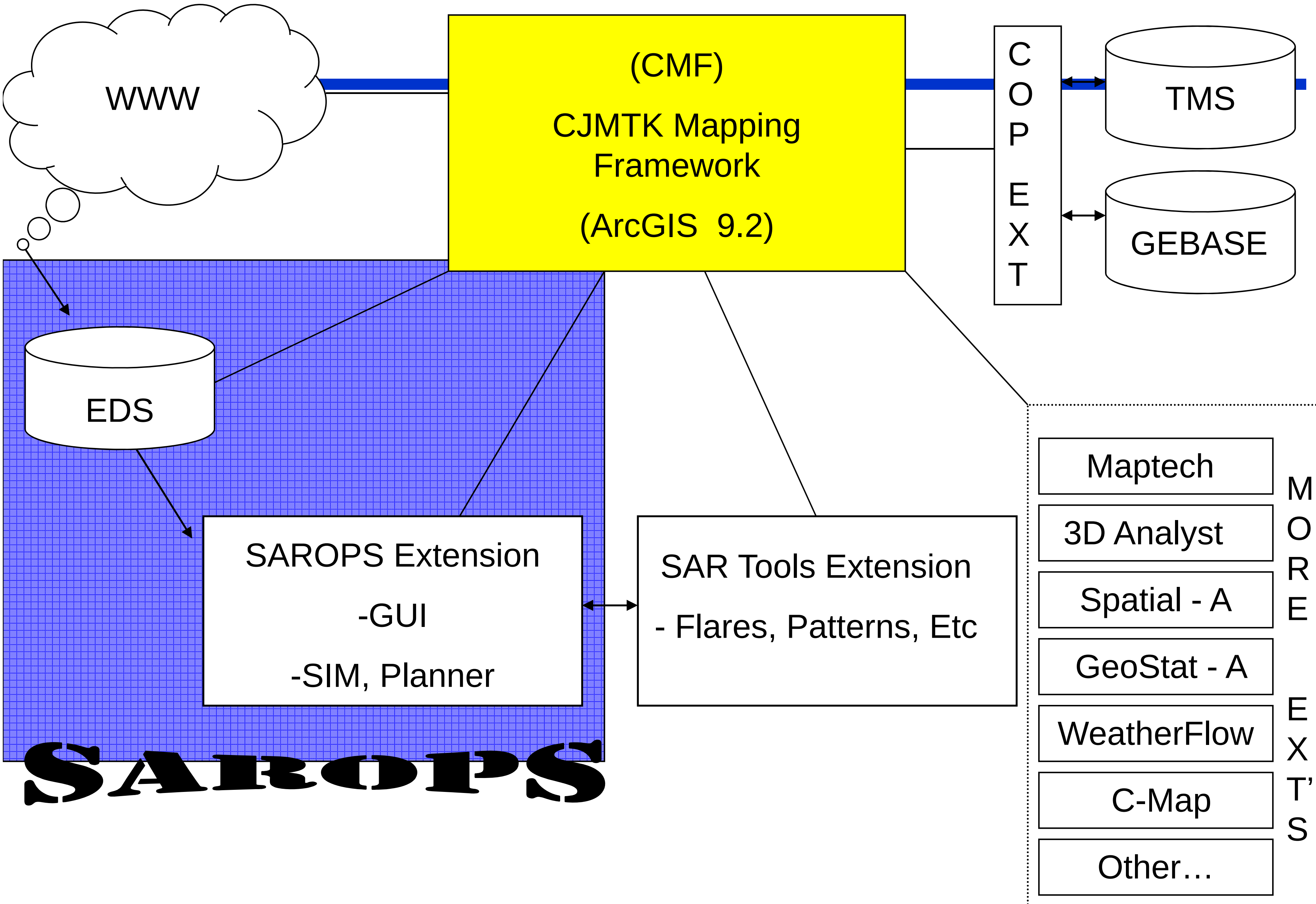
Cruise Ship Passenger Goes Overboard; Is Rescued 8 Hours Later

By Robert Nolin and Ihosvani Rodriguez; South Florida Sun-Sentinel March 17, 2007

- Michael Mankamyer was 30 miles off Fort Lauderdale treading water in choppy seas.
  - **Eight hours earlier, the 35-year-old Orlando man had jumped from a cruise ship balcony**
  - **Rescue officials were at a loss to say why, though a witness said he was drunk.**
- Salvation came at 8:45 a.m., when a lookout on the Coast Guard cutter *Chandeleur*, Petty Officer Ryan Coon, saw Mankamyer in the fresh sunrise about 75 yards away.
- He was shirtless, splashing and thrashing his arms. I knew that was our guy," Coon told reporters Friday evening.
  - **"I hollered out, `Man overboard, portside!'" The crew threw Mankamyer a life ring; he swam up and grabbed it.**
- Nancy Nelsen, a civilian search and rescue specialist in the Coast Guard's Miami office
  - **Credited a new computer model, the Search and Rescue Optimal Planning System, or SAROPS, for helping locate Mankamyer.**
  - **The system analyzes wind and currents and uses an animated grid model to project where a floating person could be.**

SAROPS Methodology - Bayesian

- **Assemble data, information, assumptions**
- **Produce scenarios**
  - Group information into logical “stories”
    - Each story equals a scenario
    - Scenarios can be inconsistent – capture dissonant information
  - Quantify uncertainties using probabilities
  - Produce probability distribution for target location from each scenario
- **Produce Prior Target Location Distribution**
  - Weight scenarios (subjective)
  - Compute prior as weighted sum of scenario distributions
- **Assess Unsuccessful Search**
  - Record search effort
  - Estimate detection capabilities of sensors
- **Update prior location distribution to account for unsuccessful search**
  - Compute posterior distribution for target location given unsuccessful search
- **Use posterior to plan next phase of search**
- **Using the posterior as the prior, repeat last three steps until done**



WWW
(CMF)
CJMTK Mapping Framework
(ArcGIS 9.2)
COP EXT
TMS
GEBASE
EDS
SAROPS Extension
-GUI
-SIM, Planner
SAR Tools Extension
- Flares, Patterns, Etc
Maptech
3D Analyst
Spatial - A
GeoStat - A
WeatherFlow
C-Map
Other…
MORE EXT'S
SAROPS

Example of Scenarios and Object Types

- **Two Scenarios (Pre-Distress Motion)**
  - (P = 0.7) We think he went fishing in fishing area 1 and then on to fishing area 2. In this case, he went 12 kts, …
    - For an individual particle, correlation between the position in fishing area 1 and fishing area 2.
  - (P = 0.3) But we also heard a mayday and it might have been him. In this case, he has been adrift from a roughly circular area, for the last 12 hours, …
- **Two Object Types (Post-Distress Motion)**
  - He got into a raft (P=0.4) or he is in the water (P=0.6)
    - Former case; his position is more influenced by the winds
    - Latter case: his position is more influenced by the currents
- **Post-Distress Motion**
  - Uses environmental data and random fluctuations
  - Fluctuations are correlated over time for a single particle