Princeton SATELLITE SYSTEMS

Edgewater Solutions, LLC

VOSB

Satellite Planner for Execution And Reconfiguration

SPEAR

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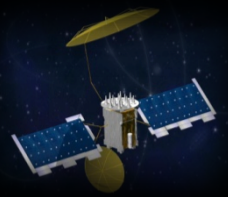
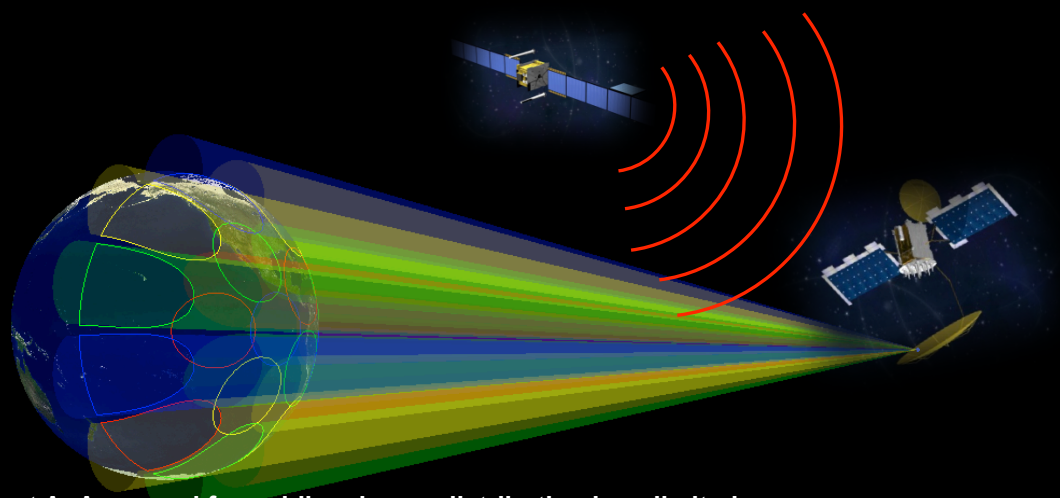
$$\begin{aligned} \min_{x} \quad & J(x) = c^T x + (v_0^T x + v_0) + x^T P_0 x + f(x) \\ \text{Subject to} \quad & Ax \le b \\ & A_{eq} x = b_{eq} \\ & \|S_0 x + t_0\| \le u_0^T x + v_0 \\ & \|S_l x + t_l\| \le u_l^T x + v_l \quad l \in [1, C_l] \\ & x^T P_k x + q_k^T x + r_k \le 0 \quad k \in [1, Q_l] \\ & g_i(x) \le 0 \quad i \in [1, M_0] \\ & h_j(x) = 0 \quad j \in [1, N_0] \end{aligned}$$



Problem Statement

- We rely on satellites for vital communications and sensing
  - Disruptions can have a severe impact on missions
  - Timely response to threats and failures is critical
- On-orbit reconfiguration of systems and payloads can mitigate risk
  - Myriad of options
  - Complex physical and operational constraints
  - Competing objectives from different stakeholders

Need for effective decision support tools

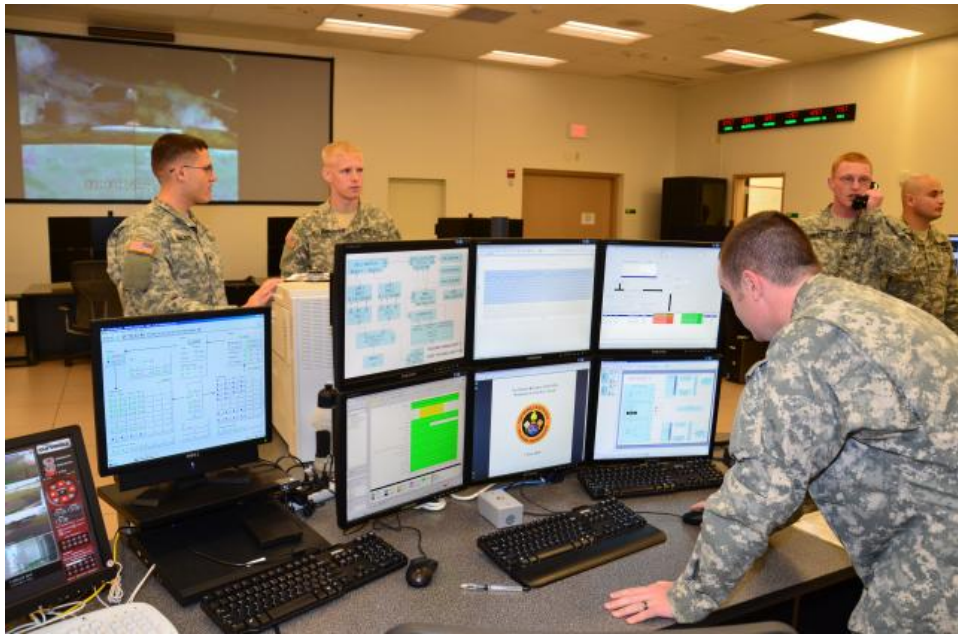


Who Can Benefit?

- **JSpOC**
  Joint Space Operations Center
- **GSSC**
  Global SATCOM Support Center
- **NAVSOC**
  Naval Space Operations Center
- **Prime Contractors**
  - Satellite Bus
  - Payloads

Baseline Technology

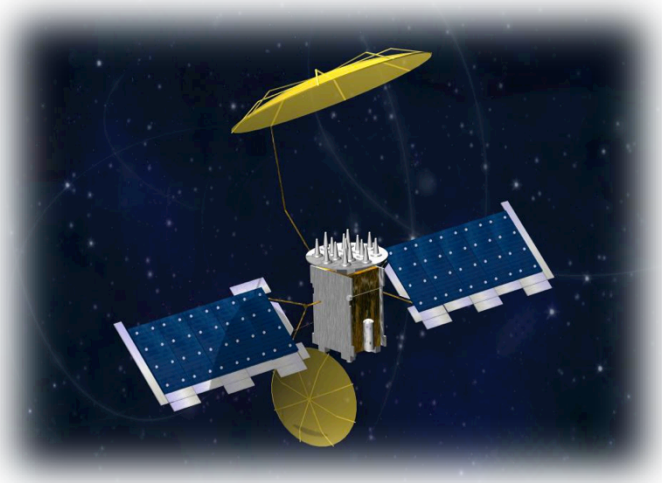
- Satellites built to 10-year-old requirements
  - Cannot design for every possible scenario
- Operation teams not well-equipped for rapid re-planning
  - Ad hoc
  - Overly conservative



- Existing planning and analysis tools…
  - Isolated problems
  - Fixed mission sets
  - Little connection to commander priorities

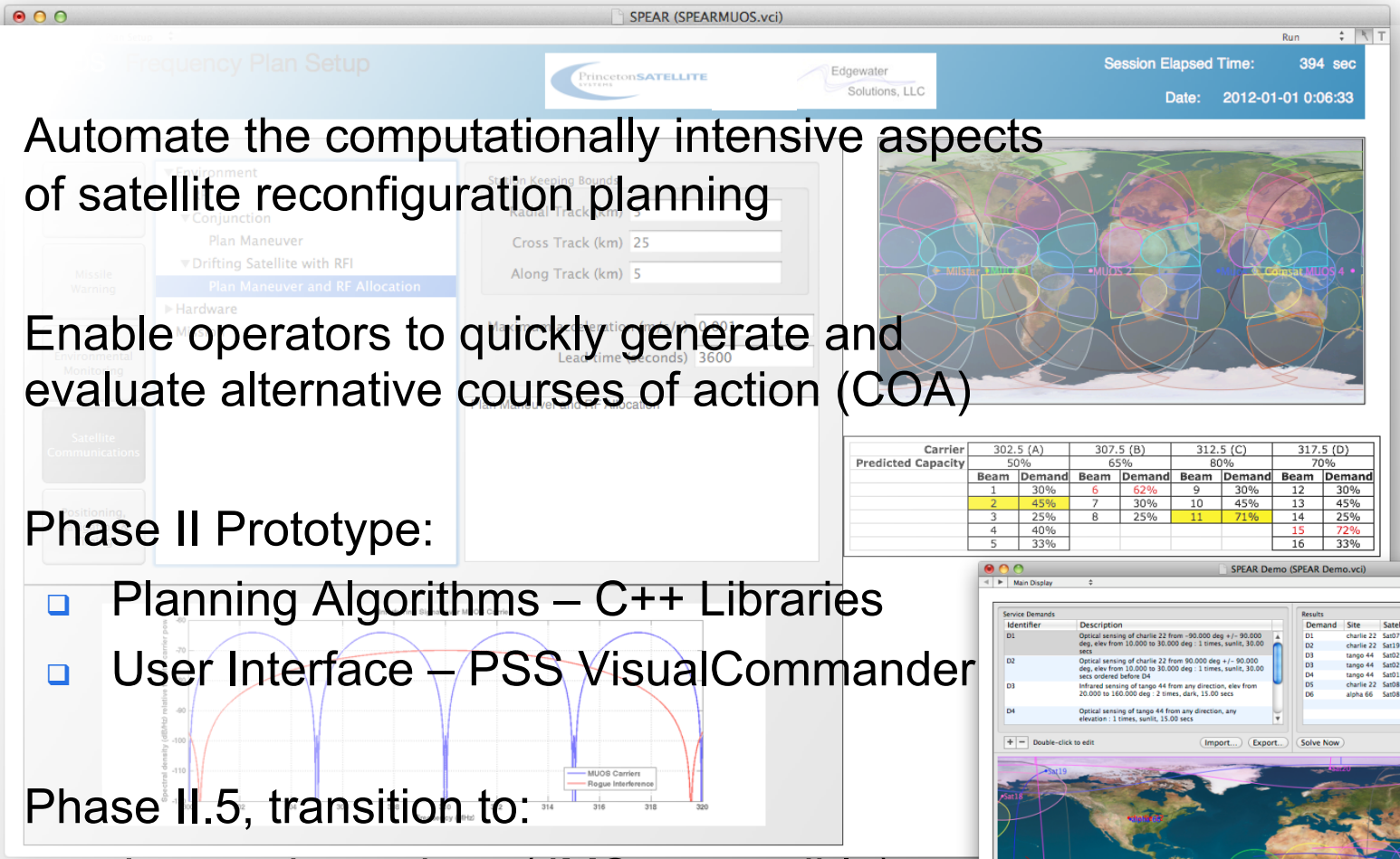
Customer Needs

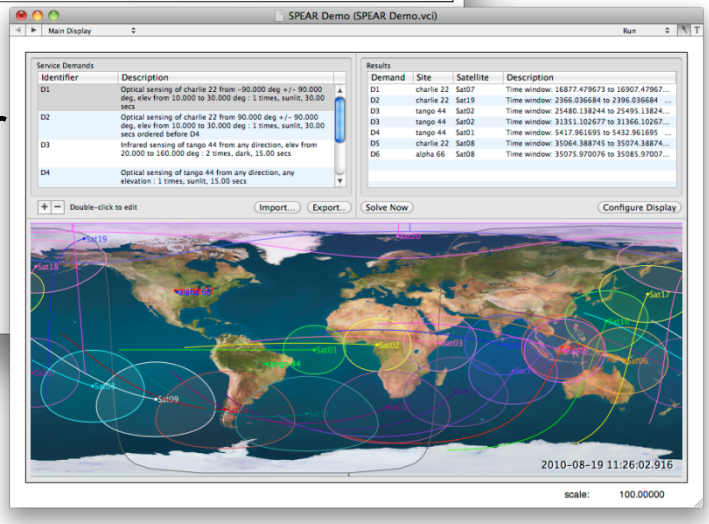
- Enable **reconfiguration** of satellite systems to support the warfighter
- Generate multiple **courses of action** for consideration
- Present ranked potential trade-offs to facilitate **decision-making**
- Employ **open interfaces** and standards for interoperability
- Support **collaboration** across multiple C2 sites / AOR:
  - GSSC
    - NAVSOC
      - JSpOC
- Target Acquisition Program: **MUOS**



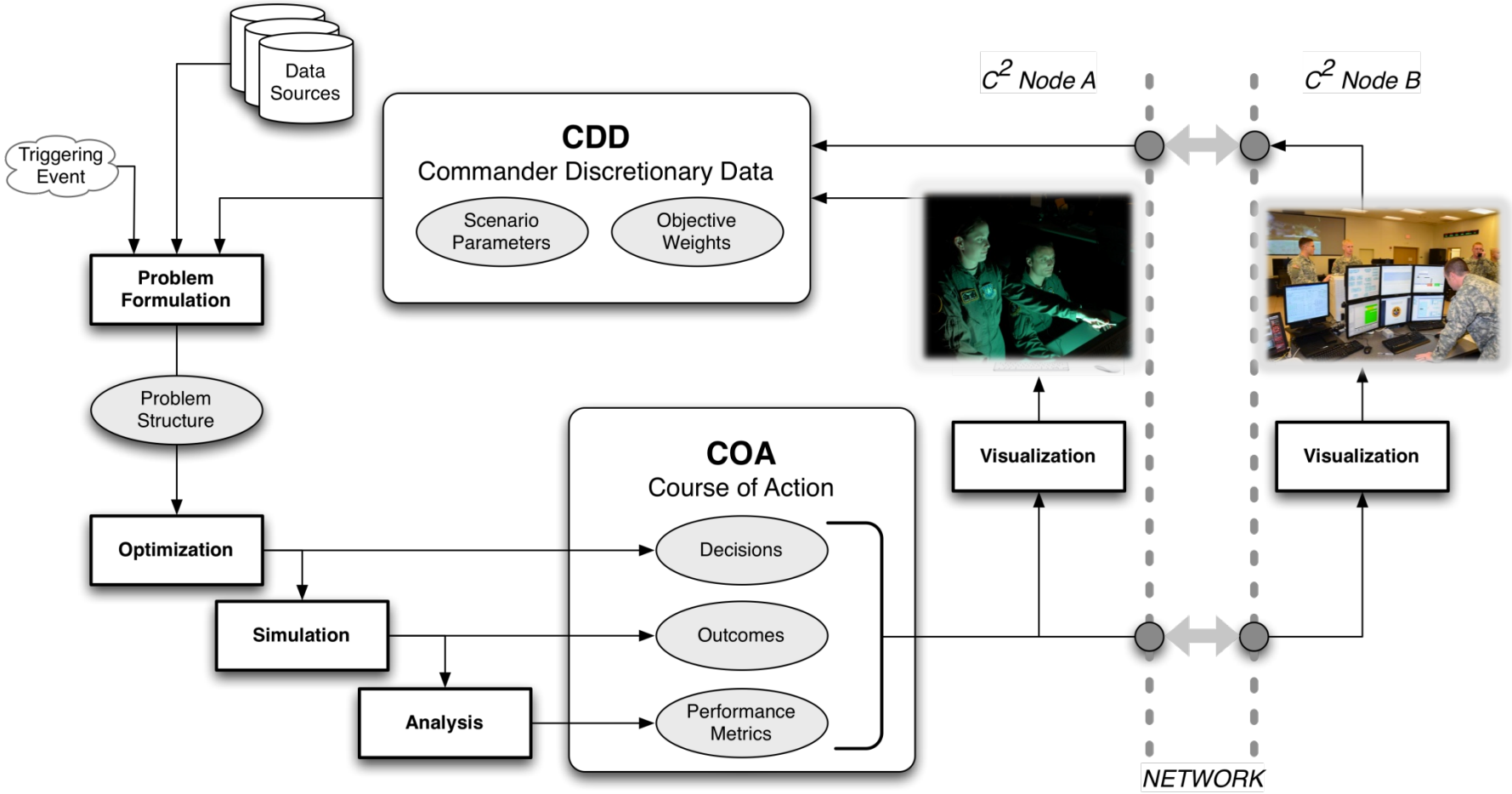
SPEAR

- Automate the computationally intensive aspects of satellite reconfiguration planning
- Enable operators to quickly generate and evaluate alternative courses of action (COA)
- Phase II Prototype:
  - Planning Algorithms – C++ Libraries
  - User Interface – PSS VisualCommander
- Phase II.5, transition to:
  - Java web services (JMS compatible)
  - UDOP (user defined operational picture)

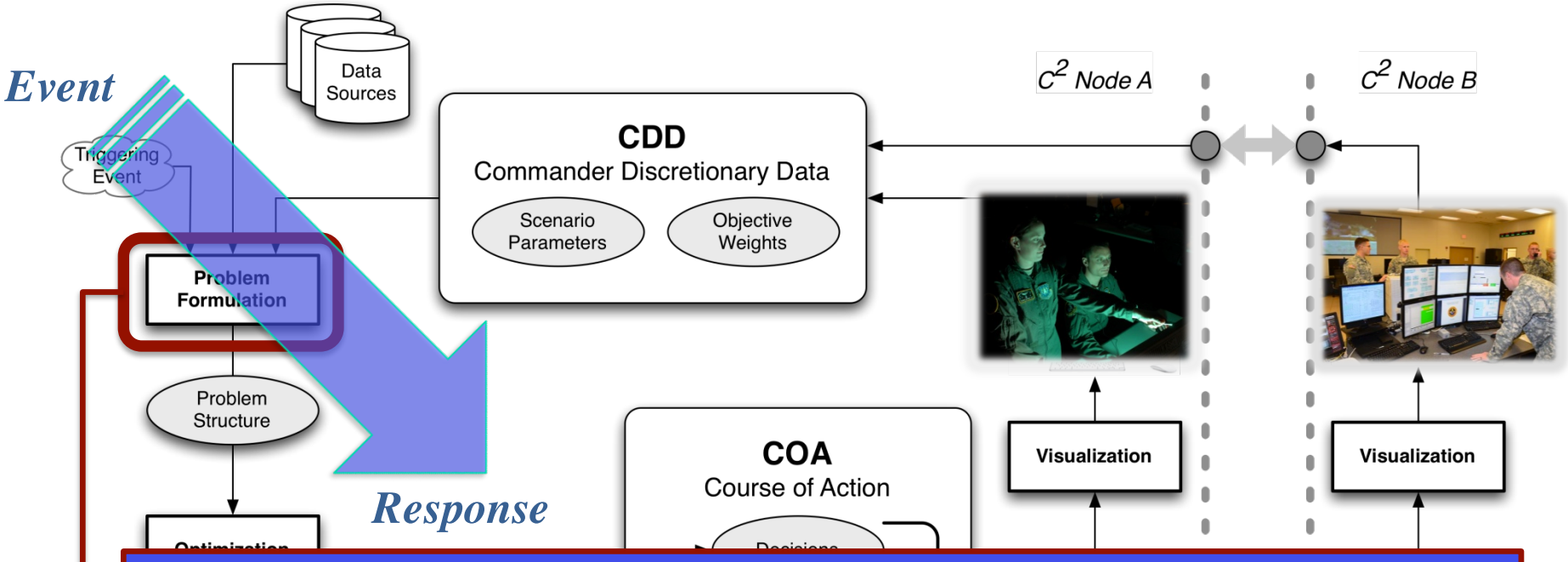




SPEAR Architecture



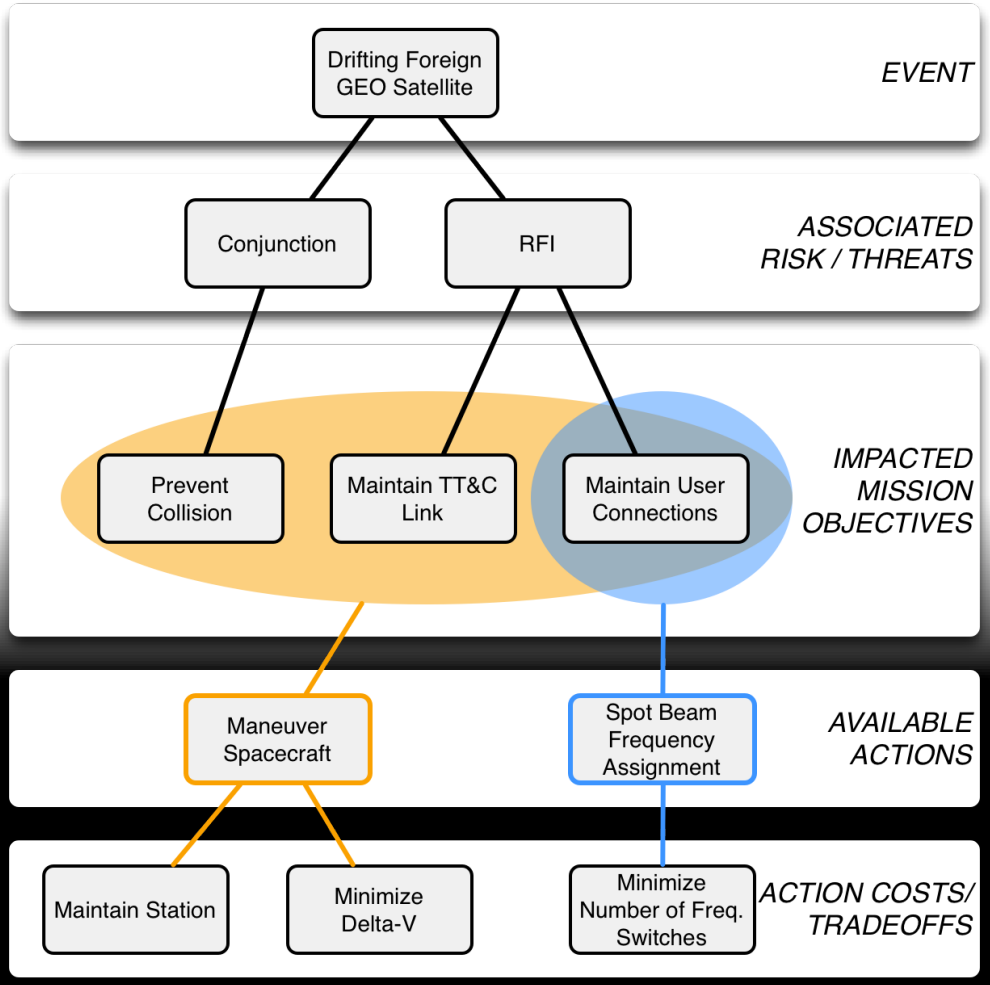
SPEAR Architecture



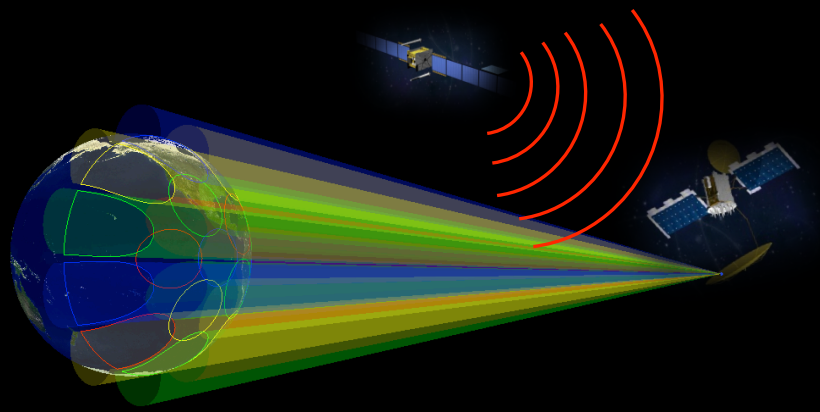
Automated Problem Formulation –

1. **Identify pre-designed abstract problem formulation for this event.**
2. **Populate with required data from available data sources**
3. **Construct formal optimization problem in a standard data structure**

SPEAR – Drifting Satellite Scenario for MUOS

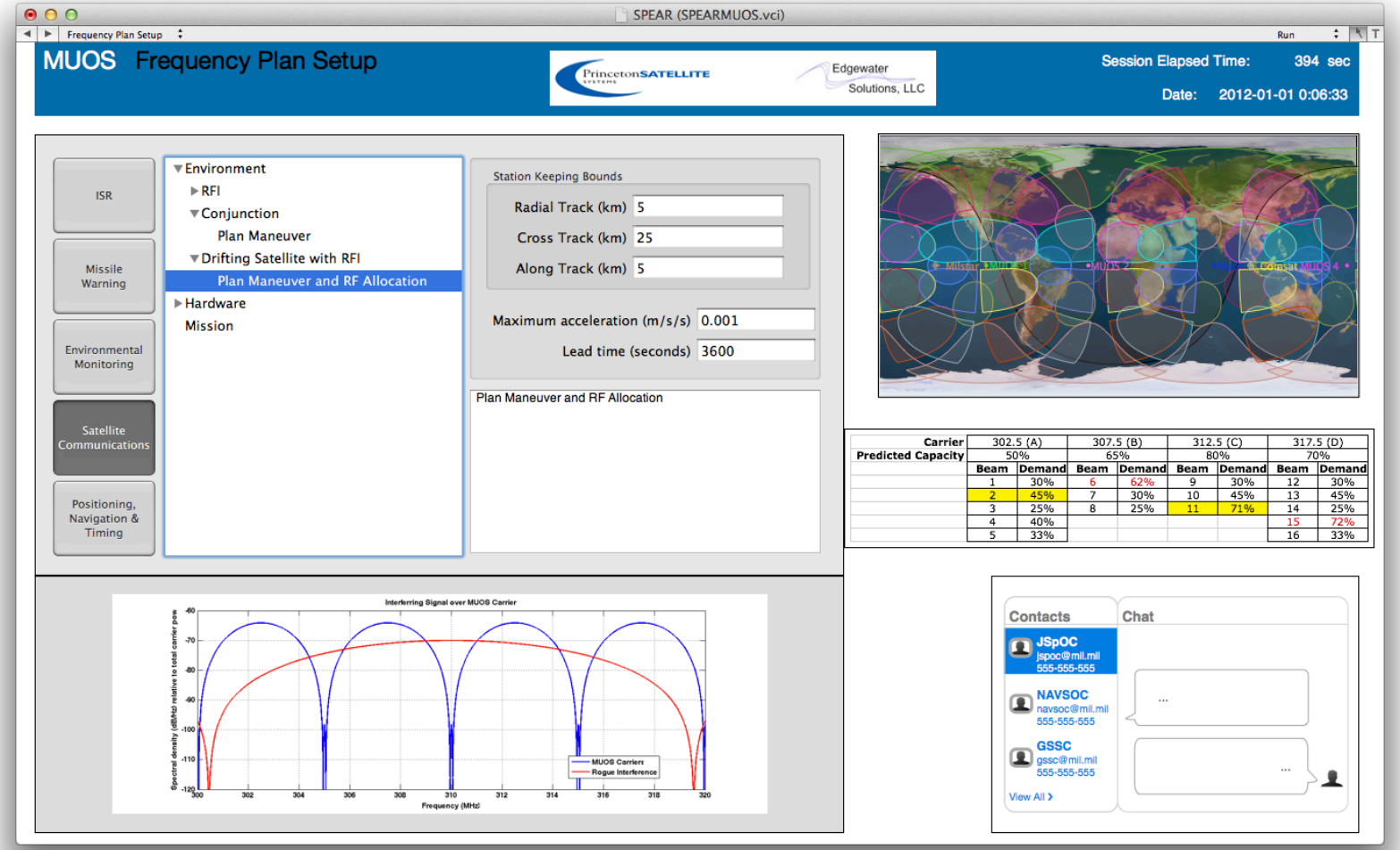


- Galaxy 15 – April 2010 (example)
  - Stopped responding to ground control
  - Eastward drift, continued broadcast
- Objectives
  - Avoid collision and RFI
  - Maintain station
  - Minimize Delta-V
- Reconfigure
  - MUOS orbit and comms payload



SPEAR – Drifting Satellite Scenario for MUOS

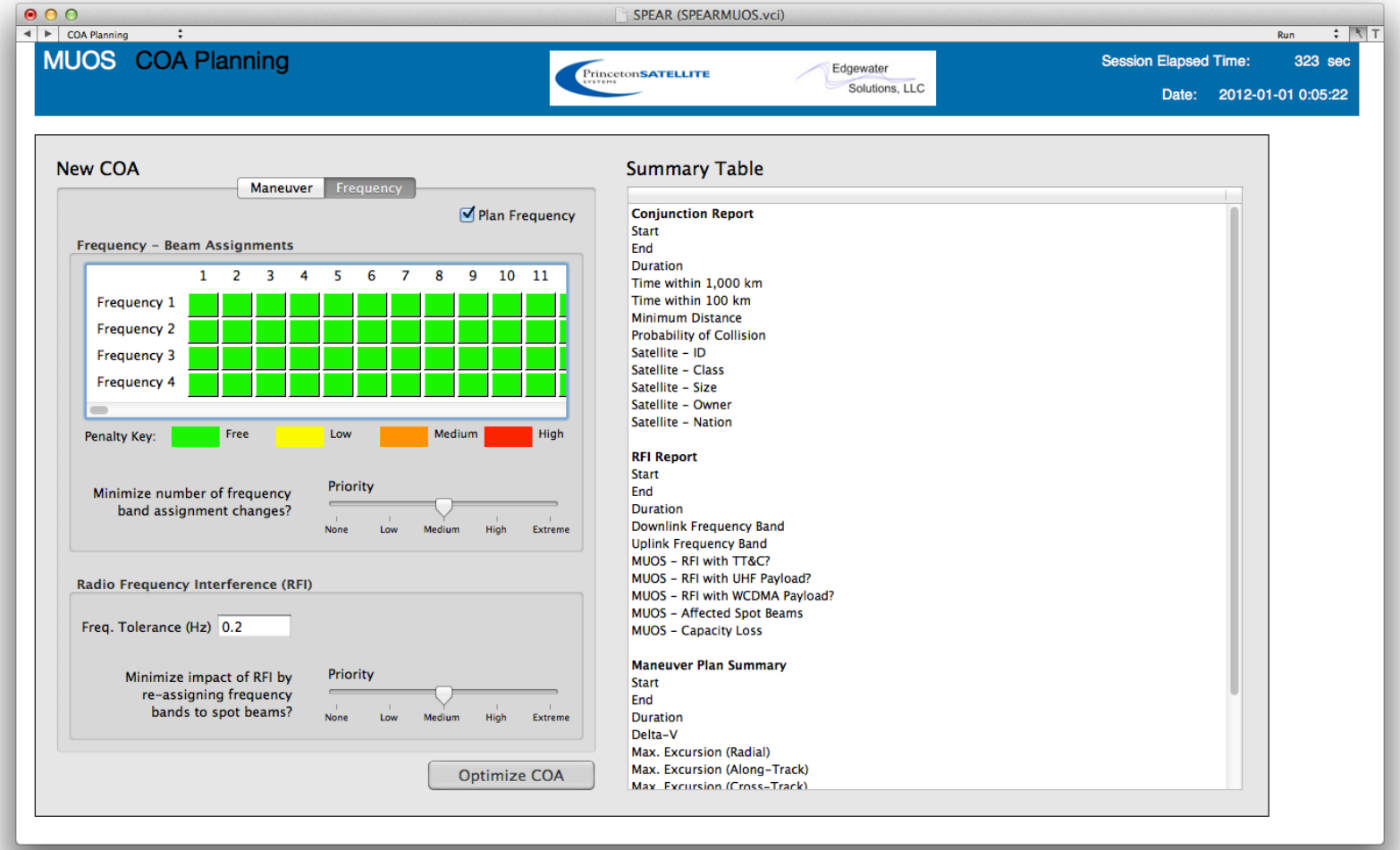
- Select reconfiguration scenario
- Initialize response settings



Carrier	302.5 (A)		307.5 (B)		312.5 (C)		317.5 (D)	
Predicted Capacity	50%		65%		80%		70%	
	Beam	Demand	Beam	Demand	Beam	Demand	Beam	Demand
	1	30%	6	62%	9	30%	12	30%
	2	45%	7	30%	10	45%	13	45%
	3	25%	8	25%	11	71%	14	25%
	4	40%					15	72%
	5	33%					16	33%

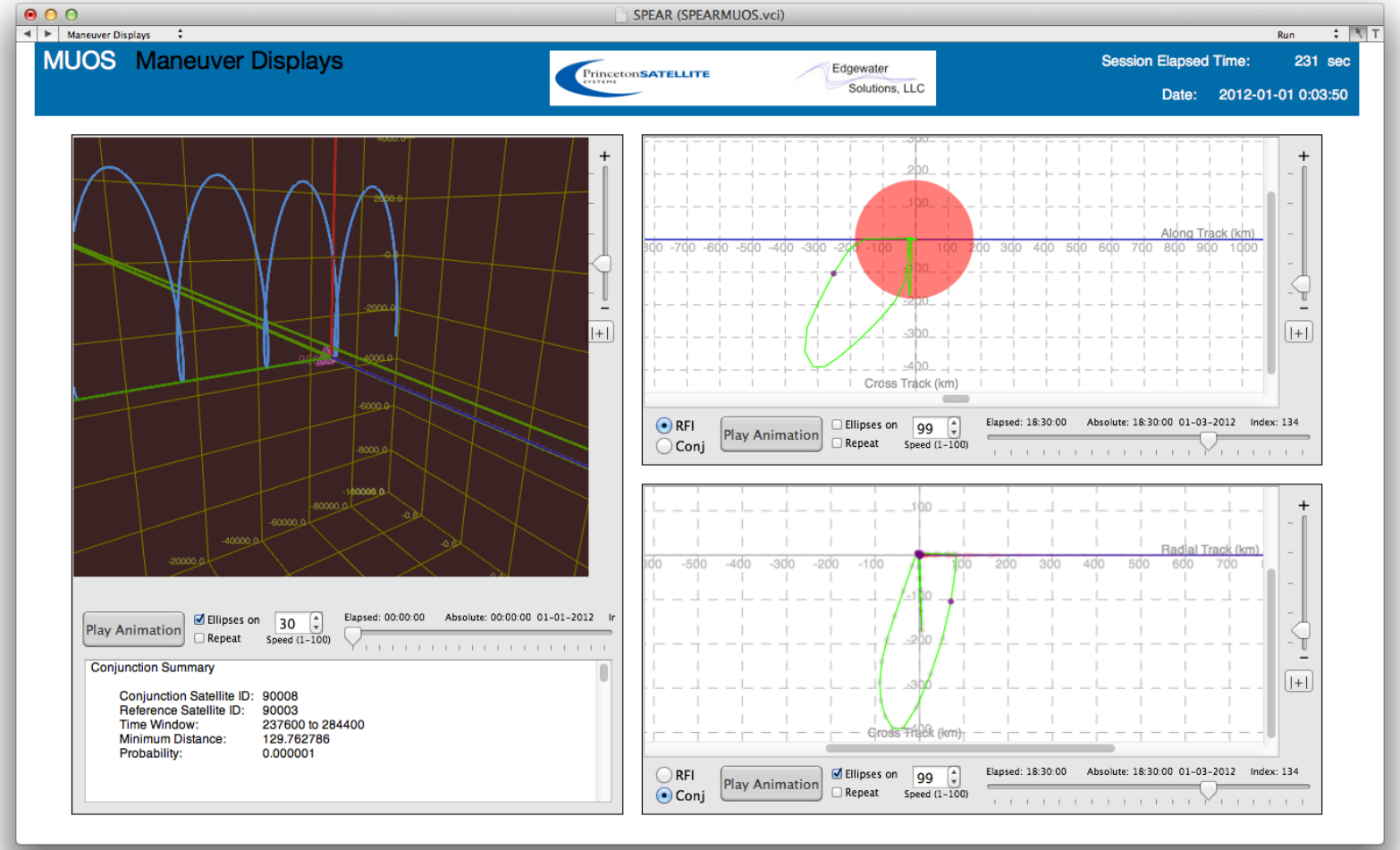
SPEAR – Drifting Satellite Scenario for MUOS

- Combined maneuver and frequency planning
- Establish priorities and constraints for multiple COAs



SPEAR – Drifting Satellite Scenario for MUOS

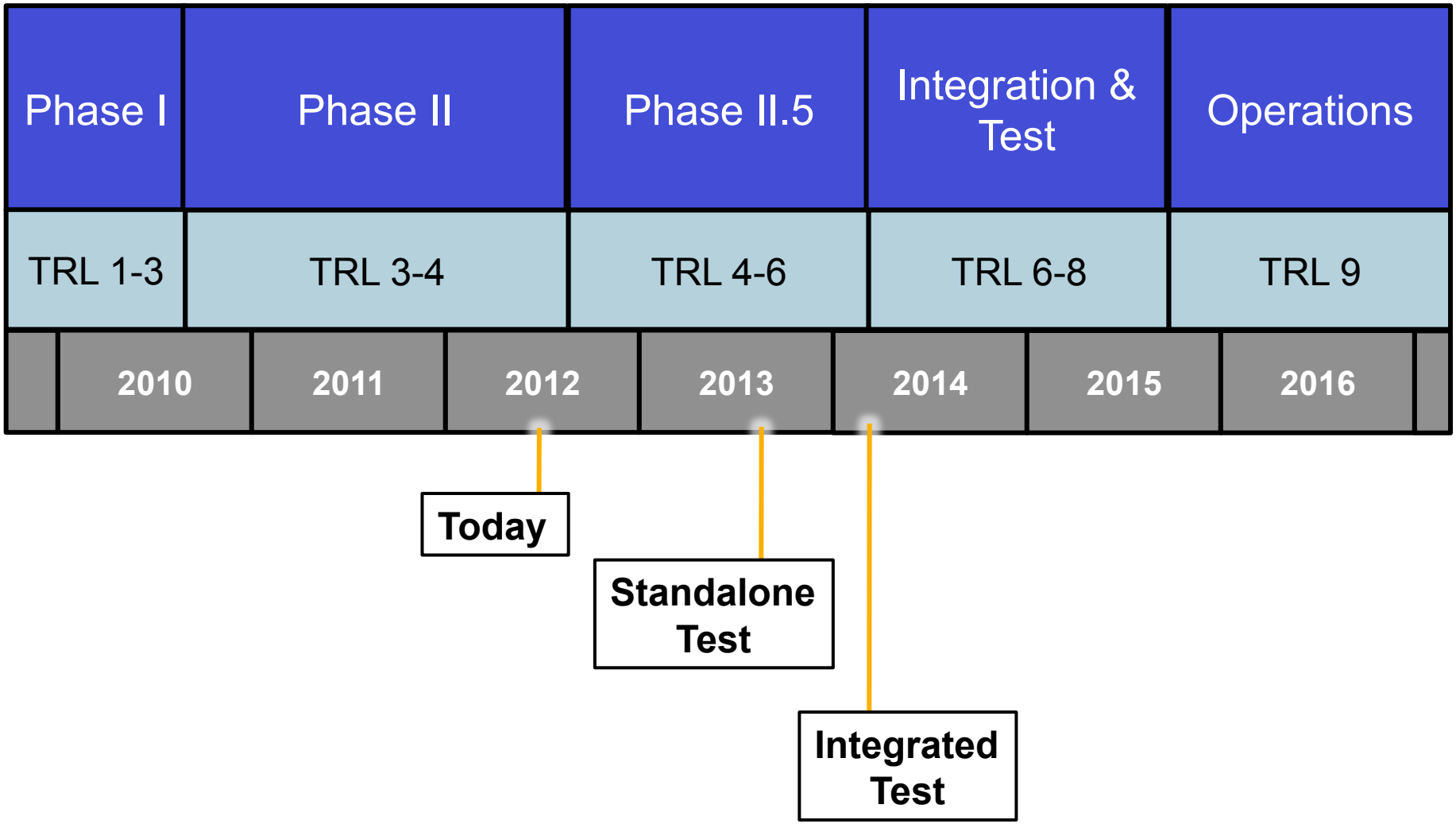
- Visualize each course of action
- Maneuver trajectory with RFI in relative orbit frame



Performance Specs / FAB Table

Features	Advantage	Benefit
Planning formulated as optimization problems	Powerful solvers may be leveraged	Reduces development time and risk
Automates generation of multiple COAs	Operators can explore decision space at a high level	Compare and trade off alternative responses
Performance metrics derived from Unified Joint Task List	Alternative COAs are evaluated in terms of relevant measures	Design traced to formal requirements / objectives

Current State of Development



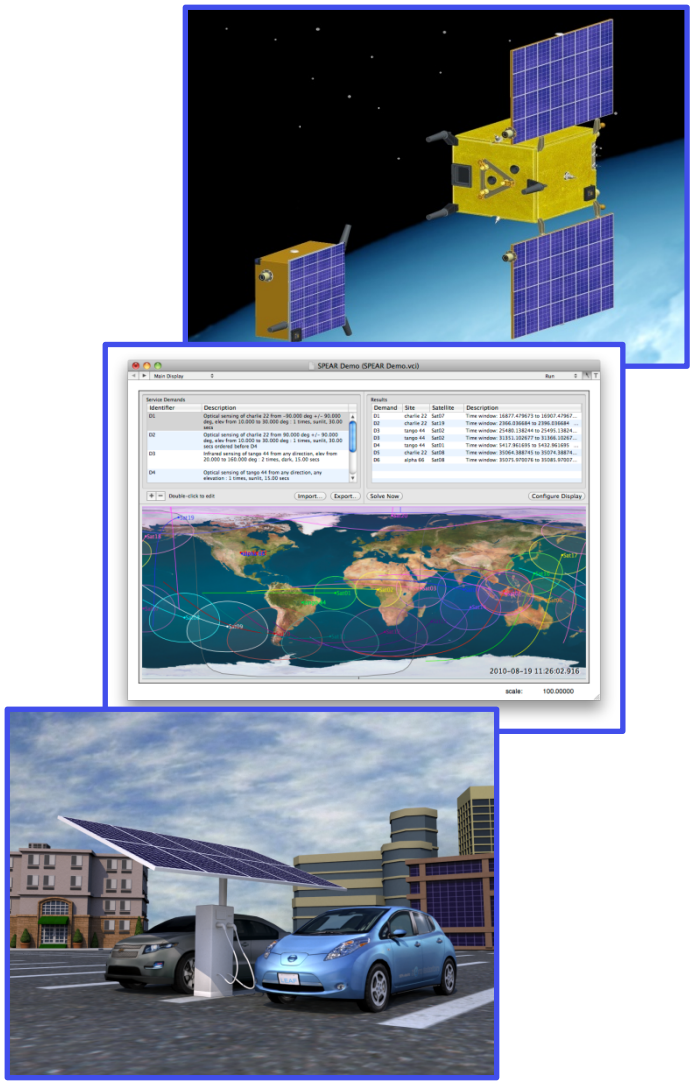
Type of Partners Sought

- **Satellite Operations**
  - NAVSOC
  - General Dynamics
  - Harris OS/Comet
- **UDOP**
  - The Design Knowledge Company
- **JMS**
  - JSpOC
  - Intelligent Software Solutions
- **MUOS**
  - Navy SPAWAR
  - Lockheed Martin

About PSS

Aerospace *Software* *Energy*

- Founded in 1992
- Operational Flight Software
  - **Indostar** – Attitude Control System (Orbital Sciences)
  - **TDRS** – Momentum Management System (Boeing)
  - **PRISMA** – Collision Avoidance System (Swedish Space Corporation)
- Commercial Software Products
  - Spacecraft Control Toolbox
  - Aircraft Control Toolbox
  - VisualCommander
- SunStation™
  - Patented solar-powered EV charging station
- JCLaS – JMS Comprehensive Launch Service
  - Phase II AFRL SBIR through 2013



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Extra slides

Comparison with Other Options

Key Functions	SPEAR	Baseline	Competitive Approach 1	Competitive Approach 2
Operations reconfiguration	Produces COA's that accept warfighter requirements and system constraints	Distributed, manual process with some software support	None, new capability (NAVSOC System)	(JMS)
Threat reconfiguration	Rapidly responds to threat data with inclusion of warfighter requirements	No single system that displays situation awareness and system response options	JMS UDOP provides SA	
System failure reconfiguration	Rapidly responds to system failure with solutions that maximize life and operations	Reconfiguration developed with limited input from warfighter	(NAVSOC System)	
Reconfiguration to multiple changes	Provides courses of action for multiple, simultaneous problems	Distributed, manual process with some software support	(NAVSOC – Satellite system)	(GSSC: communications)

SPEAR - Optimization

Generalized Problem Formulation - *Parameter Optimization*

$$\min_{\boldsymbol{x}} \quad J(\boldsymbol{x}) = \boldsymbol{c}^T\boldsymbol{x} + (\boldsymbol{u}_0^T\boldsymbol{x} + \boldsymbol{v}_0) + \boldsymbol{x}^T P_0 \boldsymbol{x} + f(\boldsymbol{x})$$

Subject to

$$A\boldsymbol{x} \leq \boldsymbol{b}$$
$$A_{eq}\boldsymbol{x} = \boldsymbol{b}_{eq}$$
$$||S_0\boldsymbol{x} + \boldsymbol{t}_0|| \leq \boldsymbol{u}_0^T\boldsymbol{x} + v_0$$
$$||S_l\boldsymbol{x} + \boldsymbol{t}_l|| \leq \boldsymbol{u}_l^T\boldsymbol{x} + v_l \quad l \in [1, C]$$
$$x^T P_k x + q_k^T x + r_k \leq 0 \quad k \in [1, Q]$$
$$g_i(\boldsymbol{x}) \leq 0 \quad i \in [1, M_n]$$
$$h_j(\boldsymbol{x}) = 0 \quad j \in [1, N_n]$$

**** Key Benefits ****

- **Problems can be assembled from component pieces**
- **Automatic Classification of Problem Type**
- **Leverage performance of proven solvers**

LP — Linear Program

SOCP — Second Order Cone Program

QCQP — Quadratically Constrained Quadratic Program

NLP — Non-Linear Program