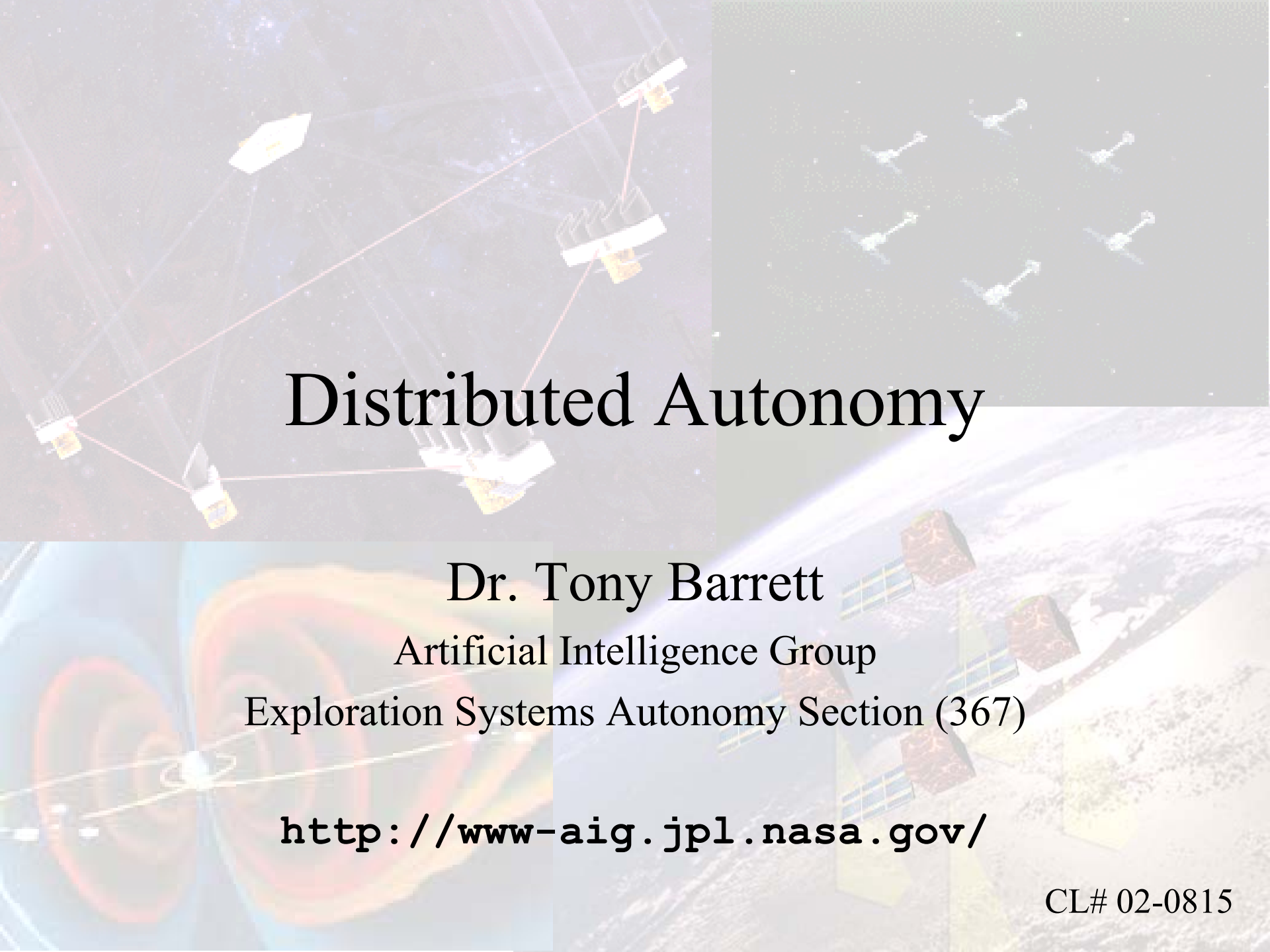

Distributed Autonomy

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Artificial Intelligence Group

Exploration Systems Autonomy Section (367)

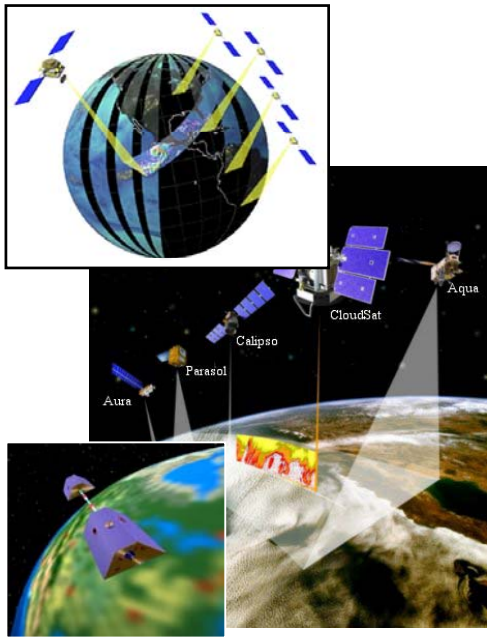
http://www-aig.jpl.nasa.gov/

CL# 02-0815

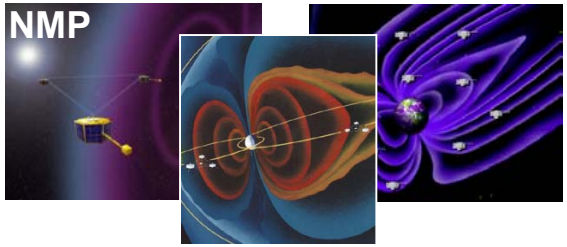
Motivation

- Why should you be interested?
  - Multi-platform missions are coming!
  - How can we cost-effectively manage them?

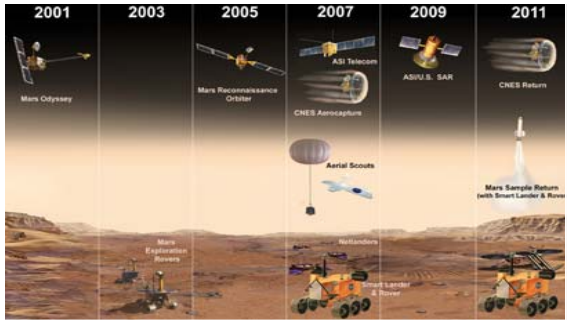
Earth Observing System



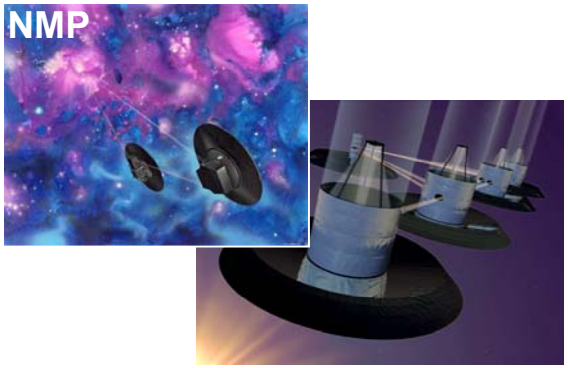
Sun-Earth Connections



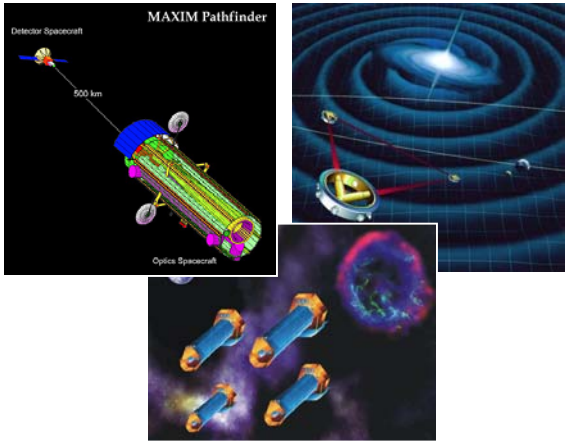
Mars Network



Origins Program



Structure & Evolution of the Universe



JPL

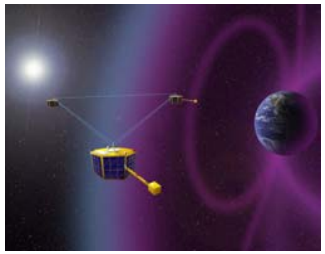
Outline

- What kinds of distributed missions are there?
- How does single-spacecraft autonomy evolve to adapt to distributed missions?
- How can we make multiple autonomous spacecraft work together?

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

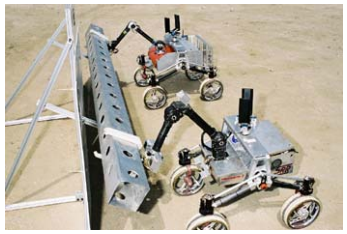
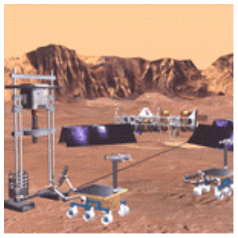
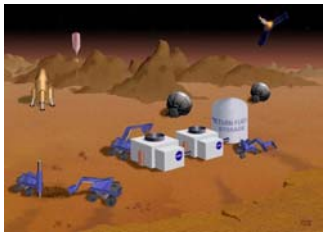
Restriction to Science Missions

- Science missions to observe phenomena
  - Example: Each ST-5 spacecraft has a magnetometer that measures local magnetic field strength and the mission transfers that data to a scientist's workstation for analysis.



Signals: Magnetic field vectors
Source: Points in the magnetosphere
Destination: Scientist's workstation

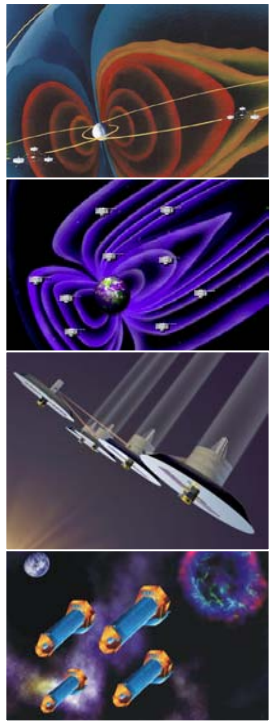
- Concepts not addressed here:


- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Motivation for a Science Mission

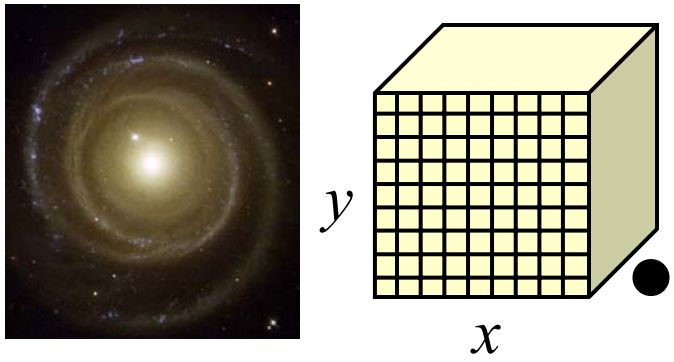
- Science missions are flown to answer questions.
  - What are the processes that permit and control the reconnection of magnetic field lines across collisionless plasma boundaries? (MMS)
  - How does the magnetotail store, transport, and release matter and energy? (MC)
  - What are the compositions of the atmospheres of terrestrial planets orbiting nearby stars? Is water or carbon dioxide present? (TPF)
  - What happens near a black hole? (Constellation-X)



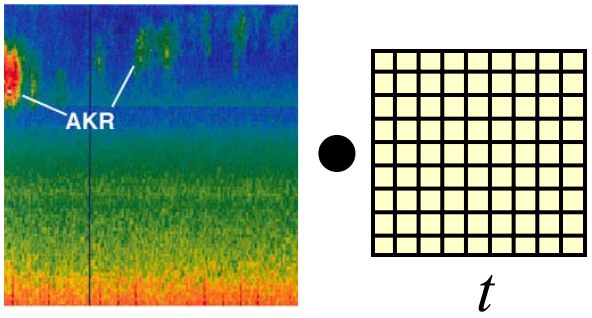
- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Classification of Phenomena (Underlying Scientific Questions)

Signals from Celestial Sphere



Signals from Magnetosphere

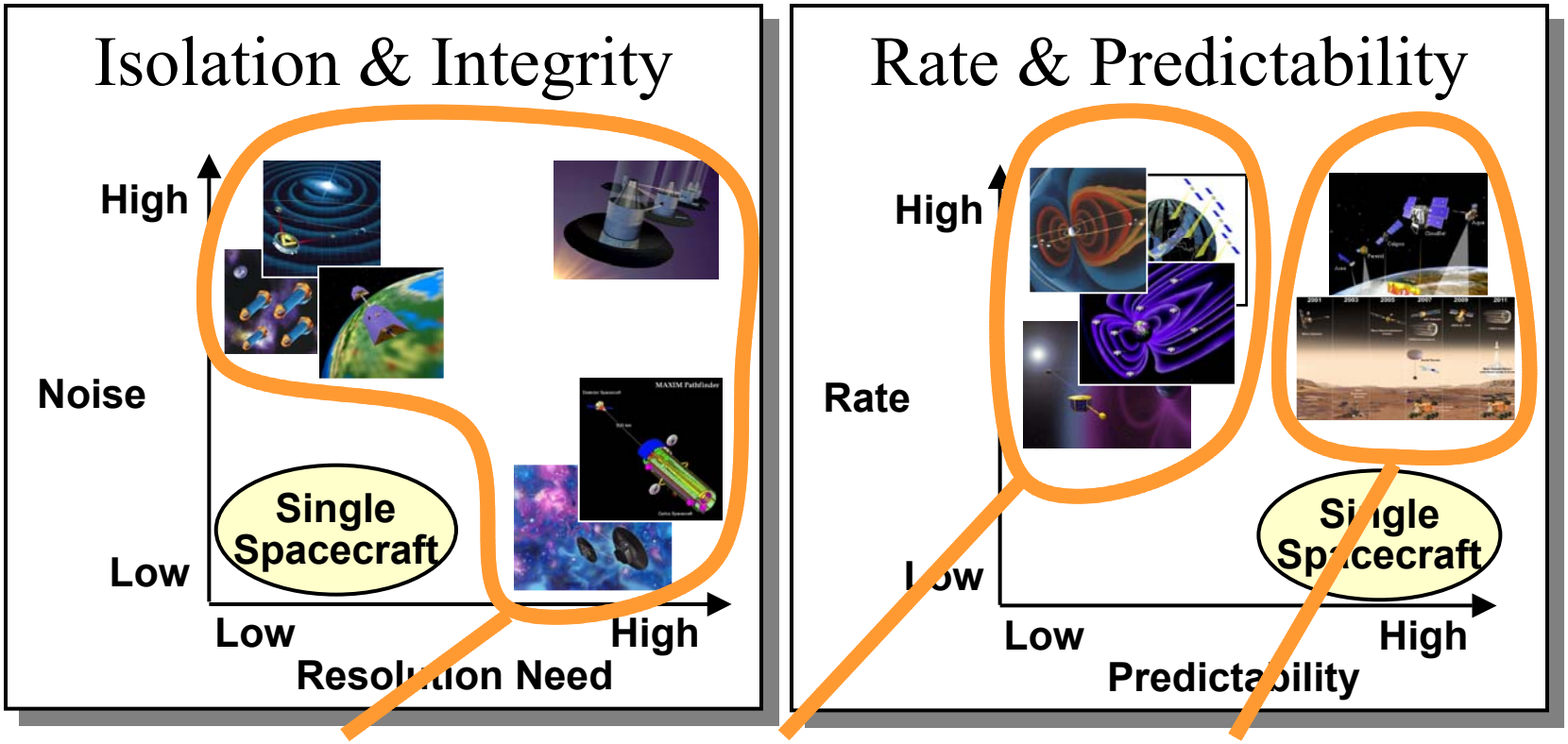


Five Classification Metrics

- Signal Location
  - **Where are the signals?**
- Signal Isolation
  - **How close are distinct signals in phenomenon?**
- Information Integrity
  - **How much noise is inherent in each signal?**
- Information Rate
  - **How fast do the signals change?**
- Information Predictability
  - **How predictable is the phenomenon?**

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

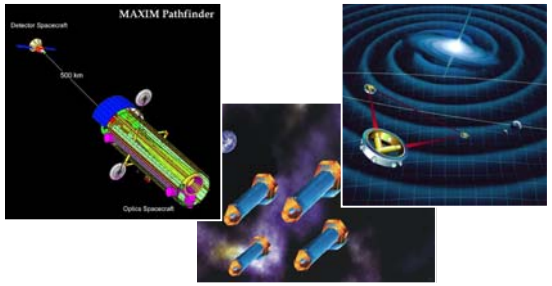
Multiple Platform Mission Types



Signal Separation Missions

Origins Program

Structure & Evolution of the Universe



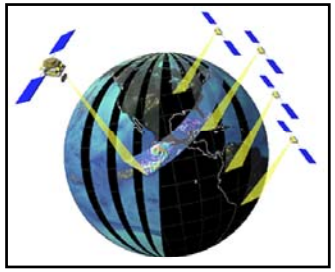
Earth Observing System

- Motivating issues
  - Separate signals from each other and/or from noise.
- Observation characteristics
  - Spacecraft coordinate to take a single observation.
- Control characteristics
  - Activity coordination
  - Precise formation flying

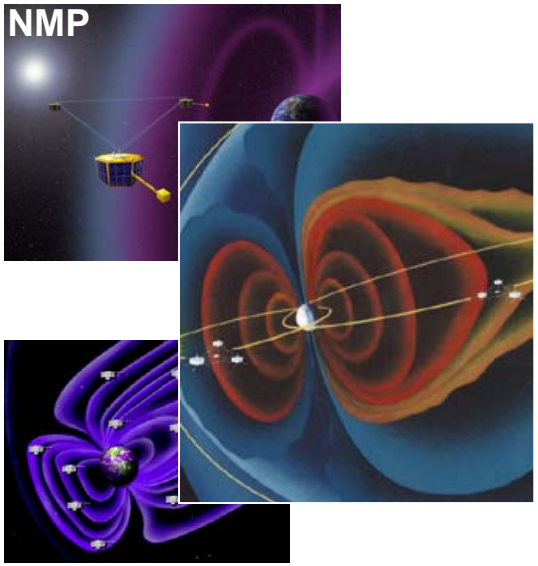
- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Signal Space Coverage Missions

Earth Observing System



Sun-Earth Connections

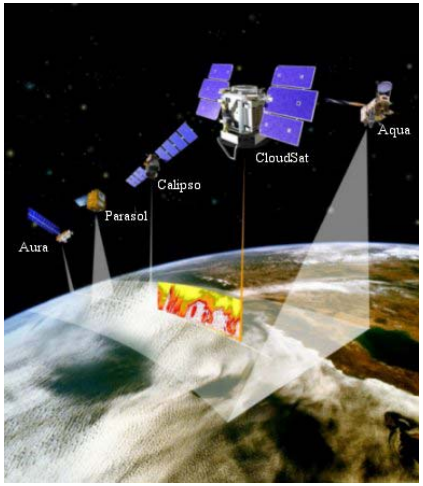


- Motivating issues
  - Capture all rapidly changing signals even if unpredictable.
- Observation characteristics
  - Identical spacecraft take observations that are subsequently correlated.
- Control characteristics
  - Either no coordination or coincident observations.

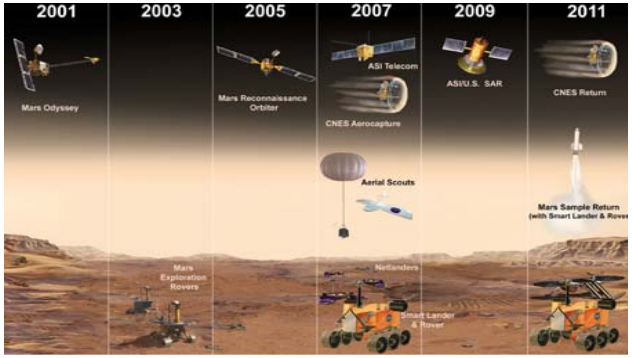
- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Mission Combination

Earth Observing System



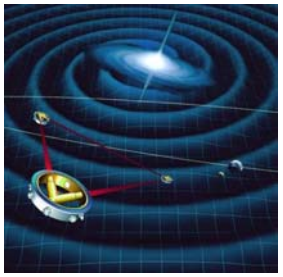
Mars Network



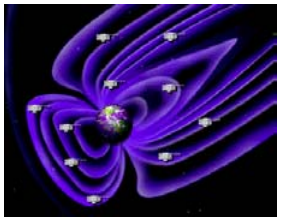
- Motivating issues
  - The collection is greater than the sum of the parts. (Engineering)
- Observation characteristics
  - Multiple mission spacecraft coordinate to improve results.
- Control characteristics
  - Inter-mission coordination
  - Formation knowledge

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

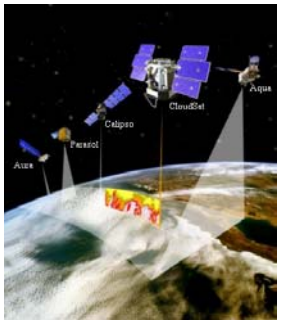
Multiple Platform Issues (not a complete list)



- Signal Separation Missions
  - Distributed control (e.g. formation flying)
  - Distributed fault protection: SAFE-MODE unsafe



- Signal Space Coverage Missions
  - Huge observation&telemetry data volume
  - Commanding large populations that slowly turn heterogeneous due to wear



- Signal Combination Missions
  - Distributed control for coincident observations
  - Inter-mission negotiation

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

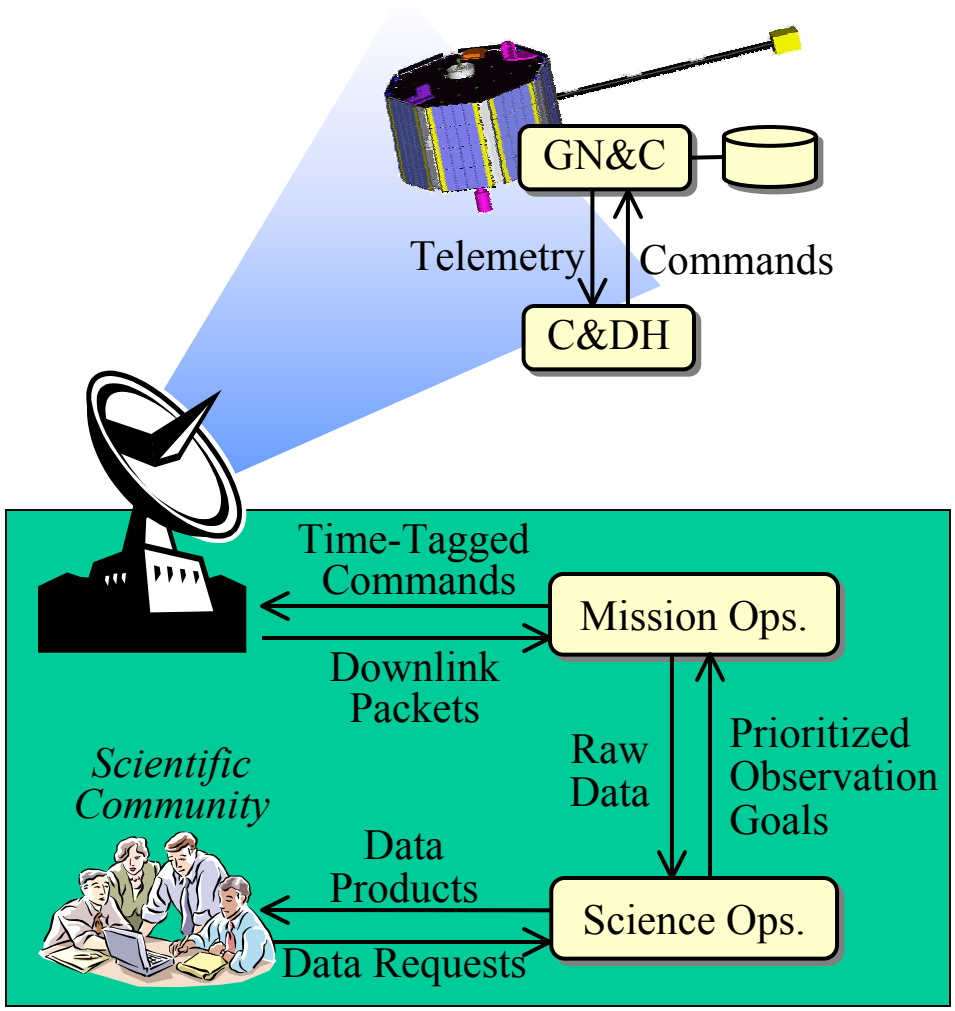
How does autonomy evolve to adapt to the three different kinds of missions?

Why Autonomy?

- Phenomena with high information rates and low predictabilities motivate autonomy.
  - There is just too much data to downlink it all.
  - An autonomous system identifies the important data to
    - reduce downlink volume by discarding uninteresting data and
    - improve information availability by performing follow-up measurements depending on the data.
- Examples of such phenomena:
  - Martian imagery passing under Odyssey with evidence of water.
  - Dynamic plasma interaction processes in the Magnetosphere.
  - *Telemetry surrounding a spacecraft anomaly…*

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

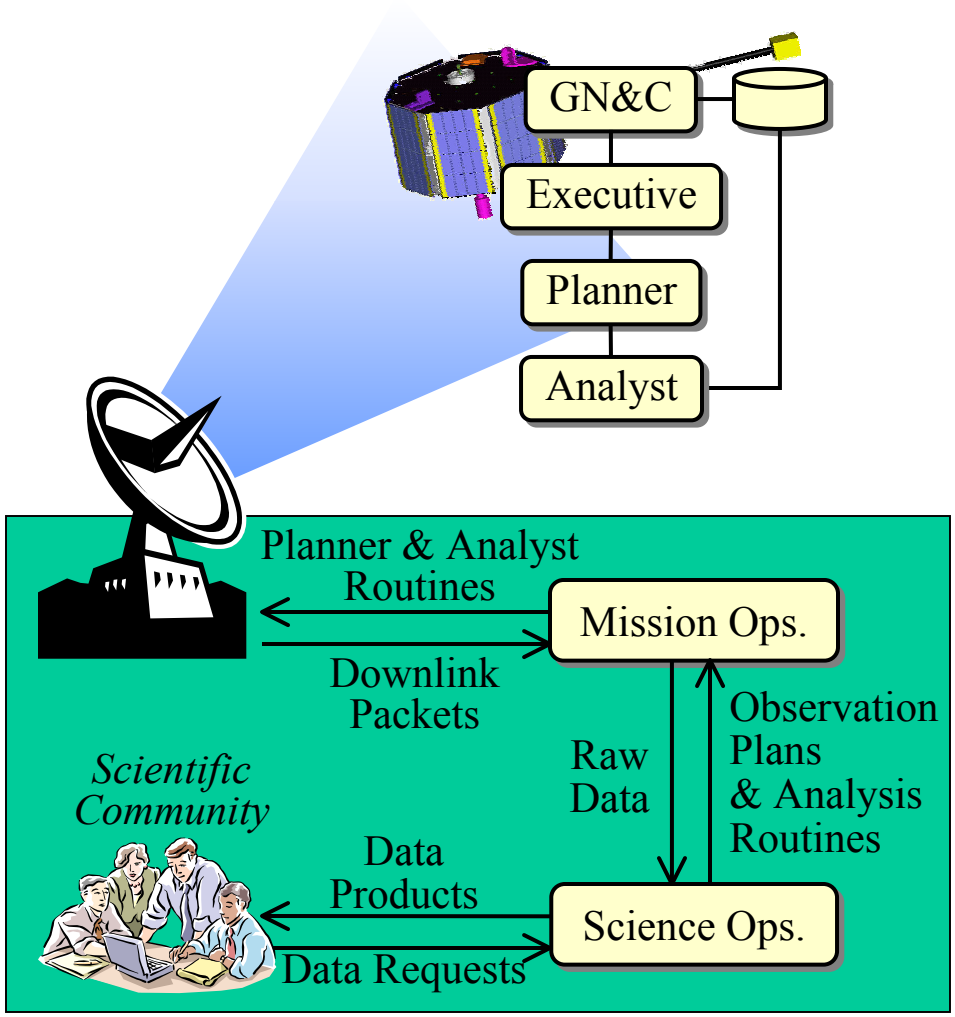
"Standard" Operations



1. Mission & Science Ops. turn data requests into time-tagged commands for the C&DH.
2. C&DH feeds commands to make GN&C collect and downlink both observation data and spacecraft health telemetry.
3. Mission Ops. evaluates telemetry and passes raw observation data to Science Ops.
4. Science Ops. processes the raw data into validated data products.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

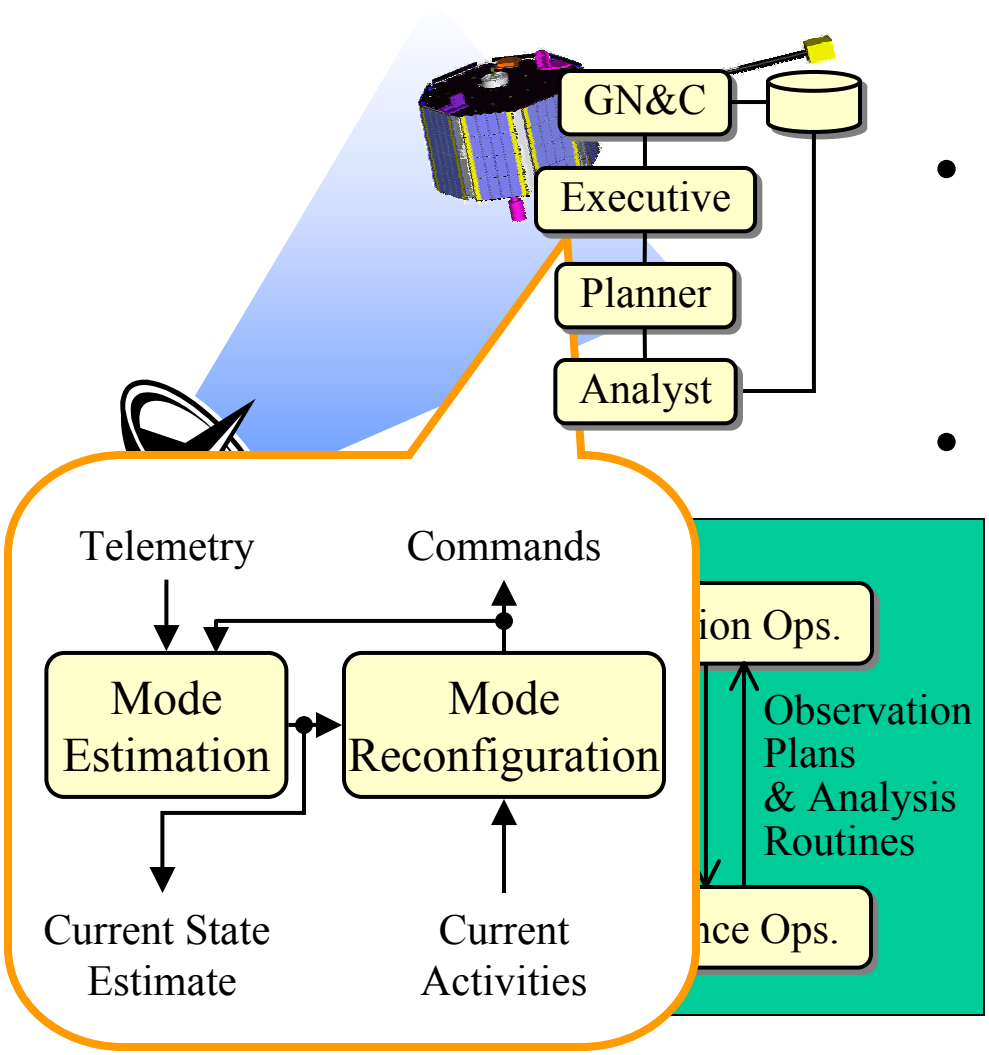
Autonomous Operations



1. Mission & Science Ops. turn data requests into onboard planner and analyst routines.
2. Analyst, Planner, and Exec. subsystems robustly command the spacecraft to collect-analyze-downlink interesting observations & telemetry
3. Mission Ops. evaluates telemetry and passes raw observation data to Science Ops.
4. Science Ops. processes the raw data into validated data products.

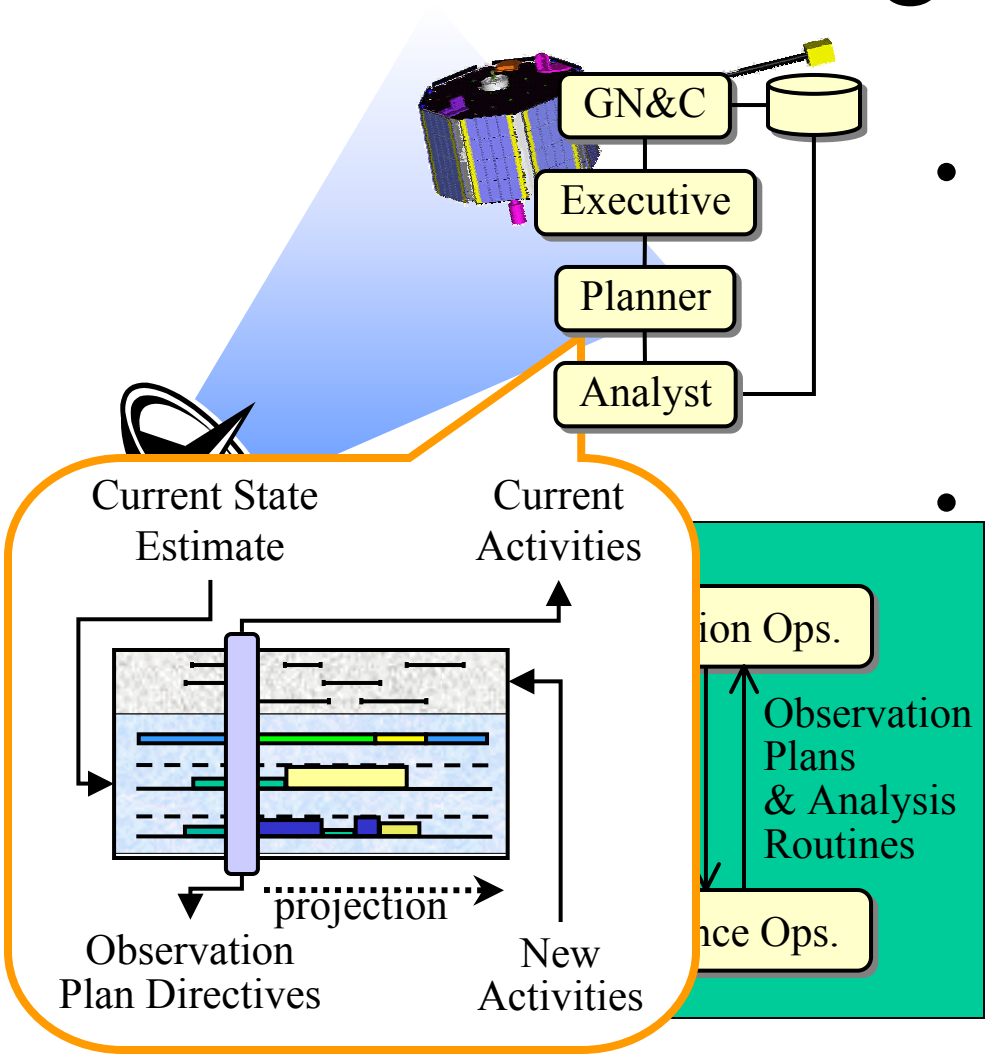
- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Robust Executive



- Motivation
  - To robustly perform required activities.
- Execution Loop
  1. Interpret telemetry in the context of current commands to estimate the current state.
  2. Send new commands to perform the current activities in the context of current state estimate.
  3. Go to 1.

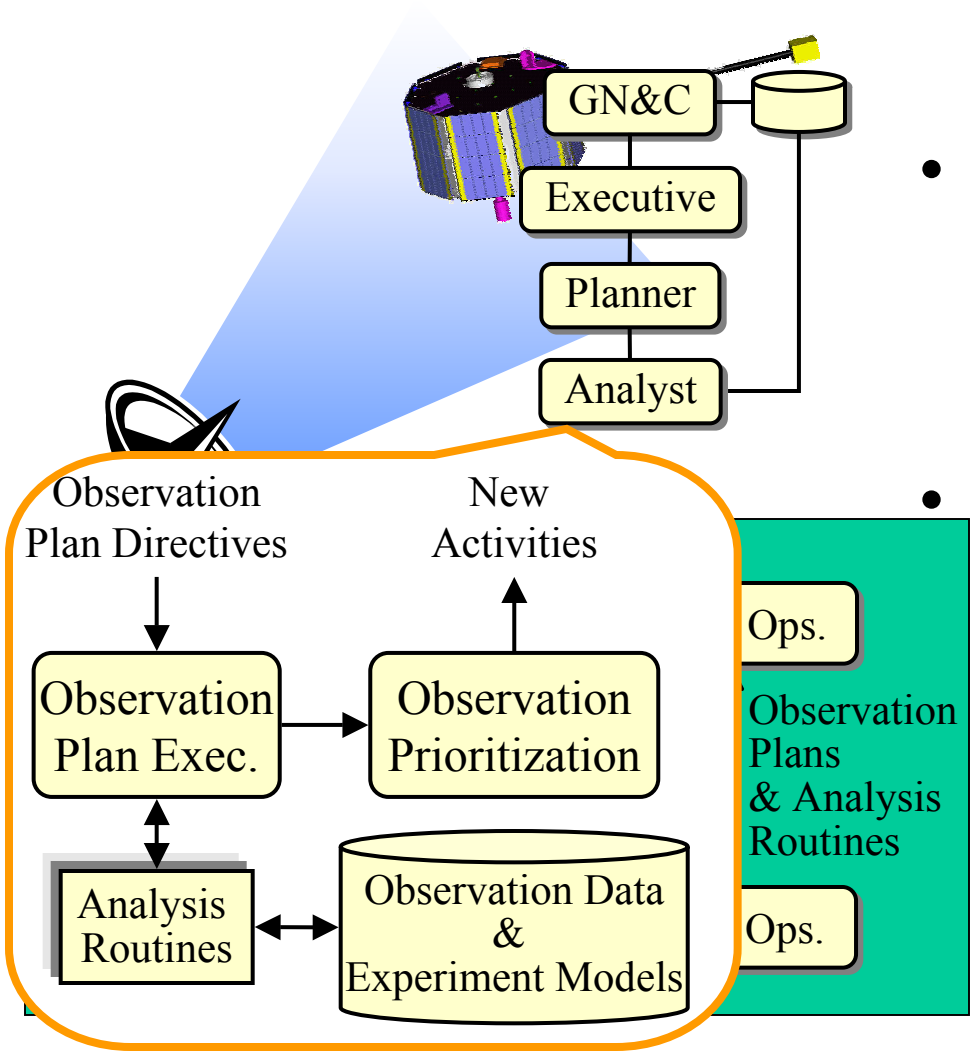
Scheduling Planner



- Motivation
  - Support adding activities and avoiding destructive activity interactions.
- Execution loop
  1. Update projection to reflect activities & current state estimate.
  2. Fix problems found in projection using planner routines
  3. Update current activities & observation plan directives and accept new prioritized activities.
  4. Go to 1.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Science Analyst

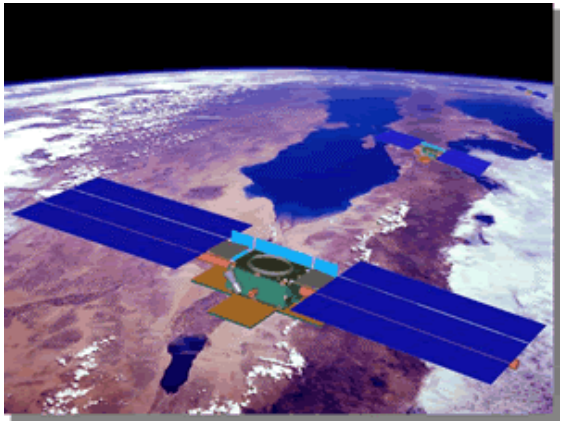


- Motivation
  - Support situation dependent observation plans.
- Execution loop

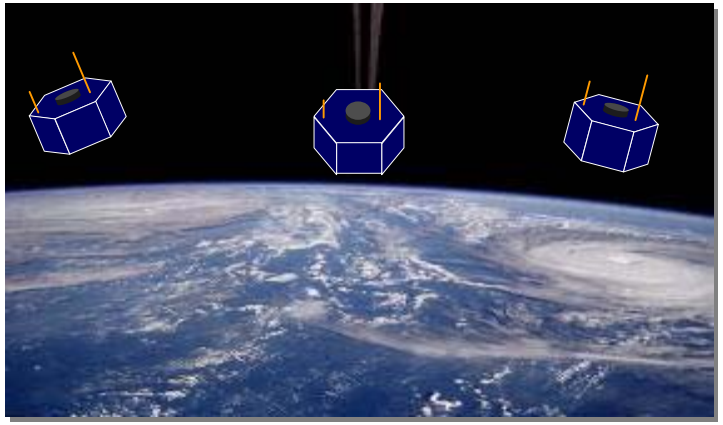
1. Wait for an observation plan directive.
2. Execute observation script that responds to directive by analyzing new data, updating models, and generating new activities.
3. Prioritize activities and pass to planner.
4. Go to 1.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Current Single-Spacecraft Autonomy Experiments



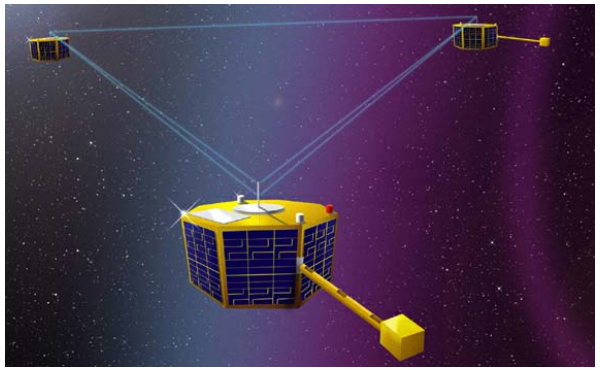
- ST-6 on TechSat21
  - 3 spacecraft with an autonomous master and 2 slaves.
  - Slaves have GN&C components and isolated executives.

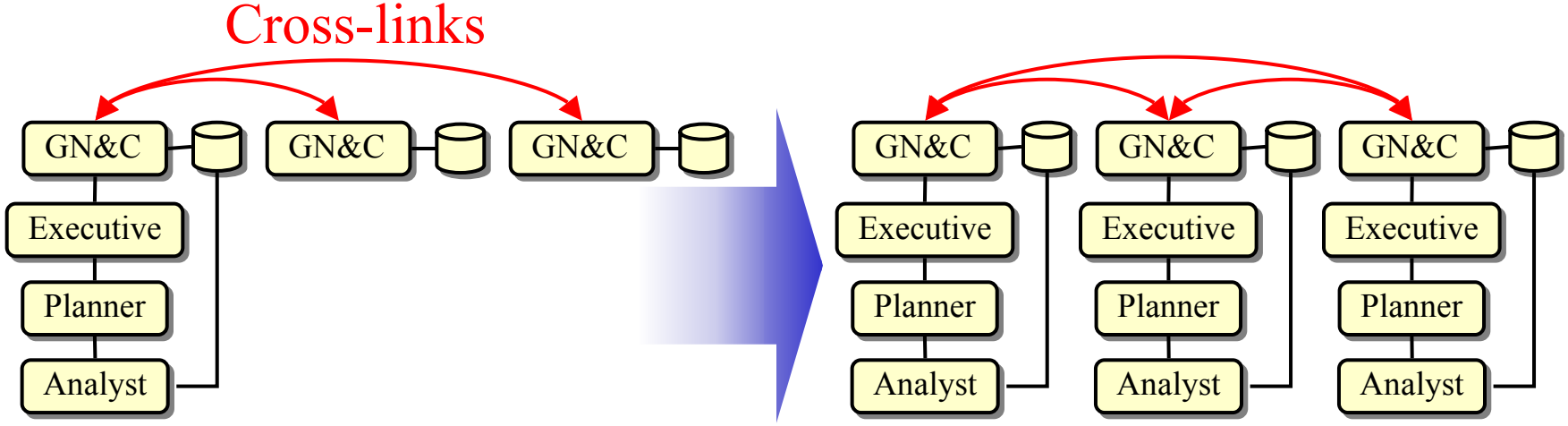


- Three Corner Sat
  - 3 spacecraft with an autonomous master and 2 slaves.
  - Evolves into 3 isolated autonomous spacecraft as they loose the cross-link.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

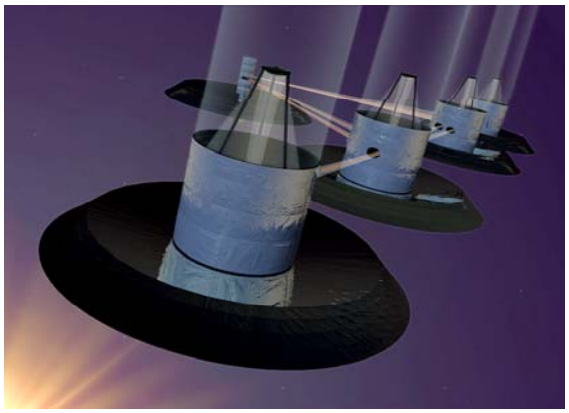
How to Distribute?

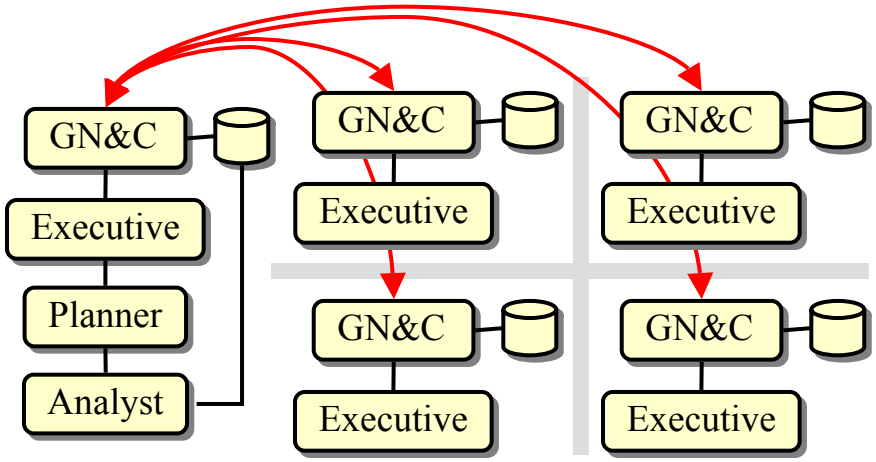




Who gets which components?

Autonomous Signal Separation

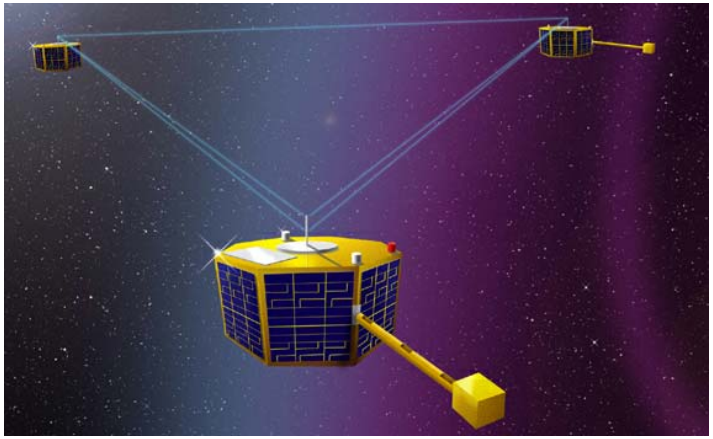


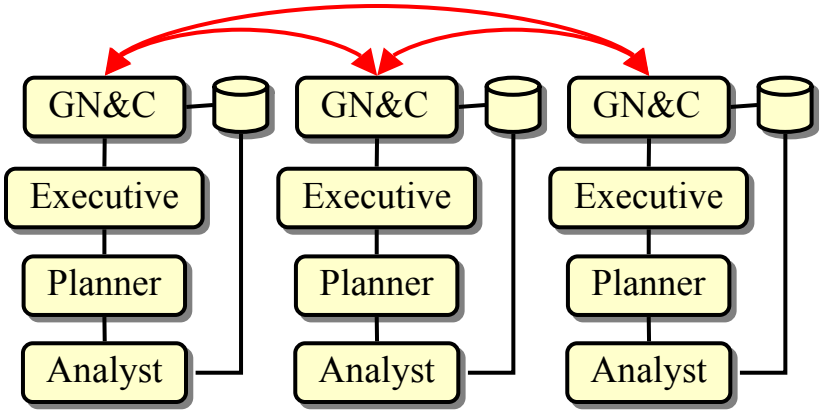


- Why many executives?
  - Each spacecraft can have local anomalies.
  - During an anomaly communications can be lost due to drift.
- Why only one planner?
  - During normal operations the spacecraft are guaranteed to be able to communicate.
  - Since spacecraft join to make an observation, only one analyst is needed.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Autonomous Signal Space Coverage

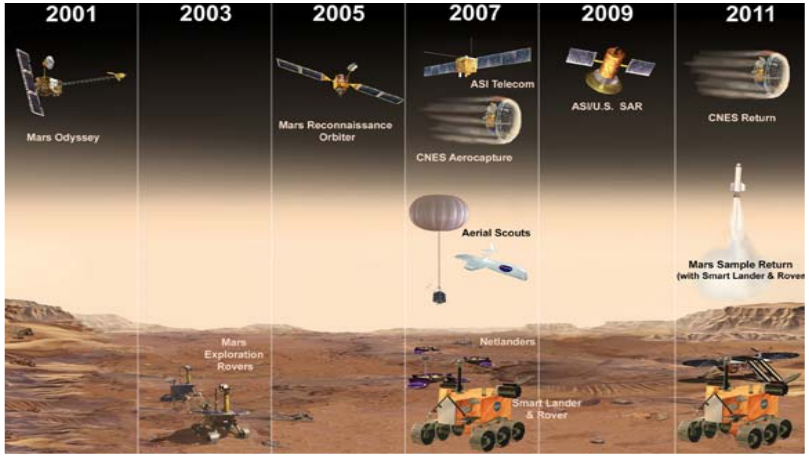


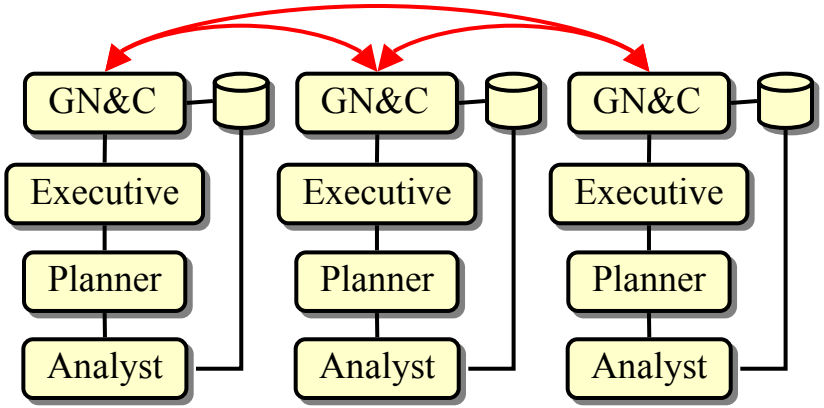


- Why many planners?
  - Cross-link is lost during normal operations, but spacecraft still have to manage local activities and respond to science events.
- Why communicate at all?
  - The value of local measurements is enhanced when combined with data from others. Planners must coordinate over collection.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

Autonomous Mission Combination





- How does this differ from signal space coverage?
  - Each entity has different capabilities
    - Sensors: radar, optical, IR...
    - Mobility: satellite, rover...
    - Communications abilities.
  - Each mission has its own motivations.
    - There is a competition where each mission wants to optimize its own objectives in isolation.

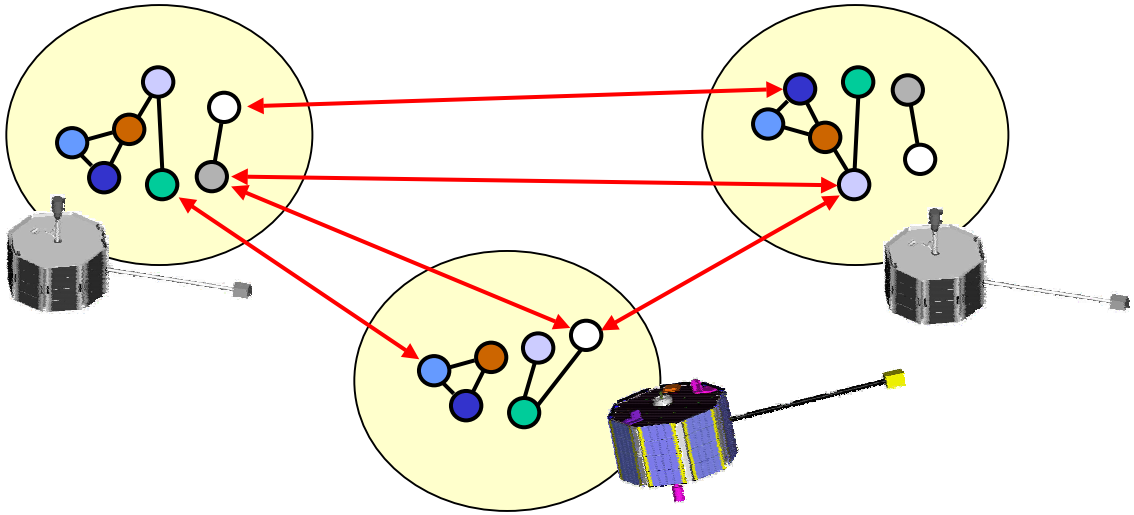
Working Together: The General Problem

- The ultimate motivation for any technology:
  - Reduce cost while increasing value
- An underlying motivation for autonomy
  - Reduce risk&cost while increasing data value
- The general underlying problem for distributed autonomy:
  - Maximize some global value function subject to local constraints.

- What kinds of distributed missions are there?
- How does autonomy evolve to adapt to a distributed mission?
- How can we make multiple autonomous spacecraft work together?

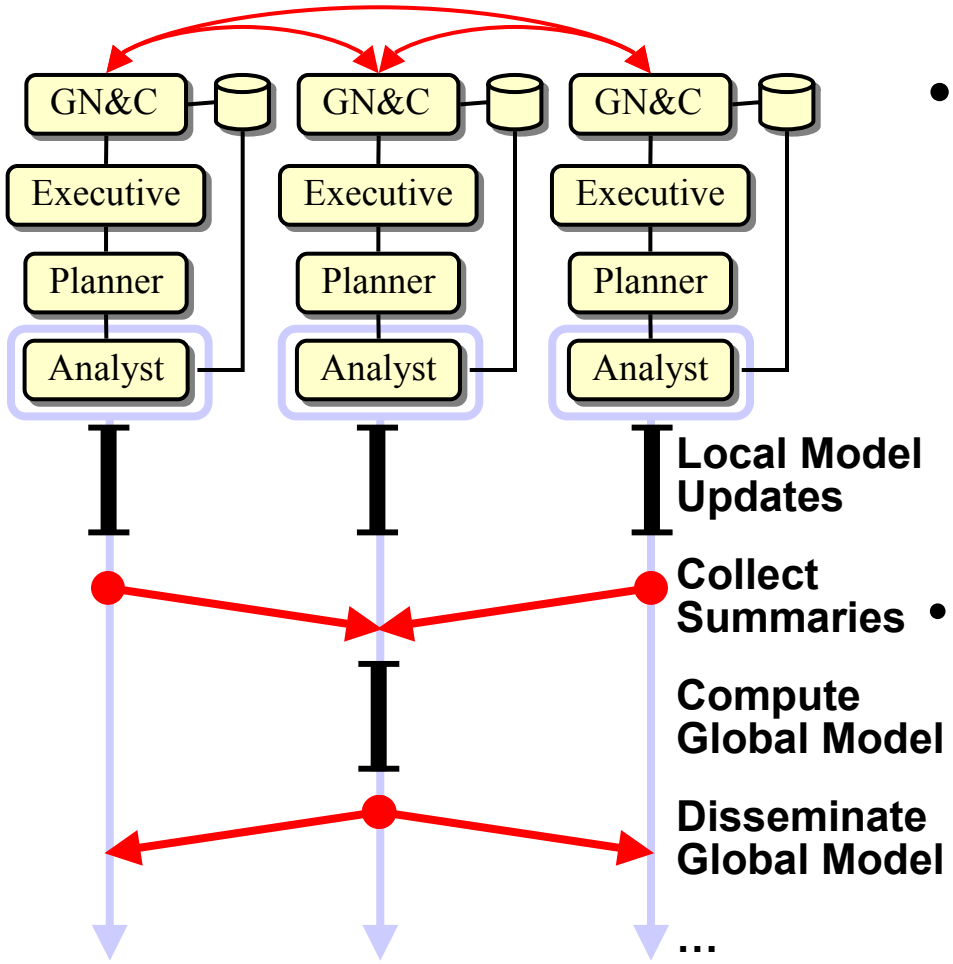
Distributed Constrained Optimization

- Optimize a function of variable assignments with both local and non-local constraints.



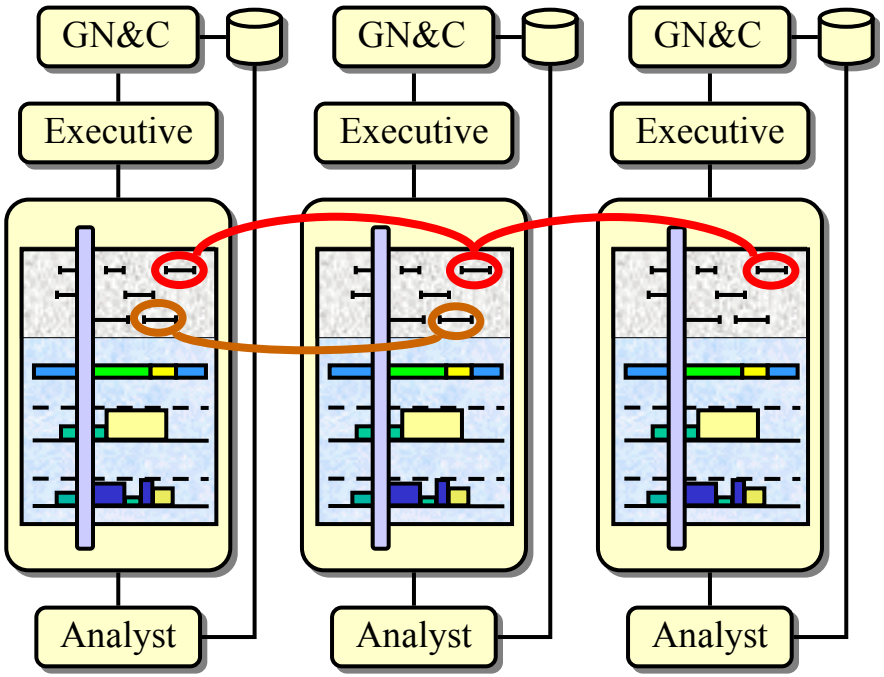
This is a hard problem to solve!

Coordinating Analysts



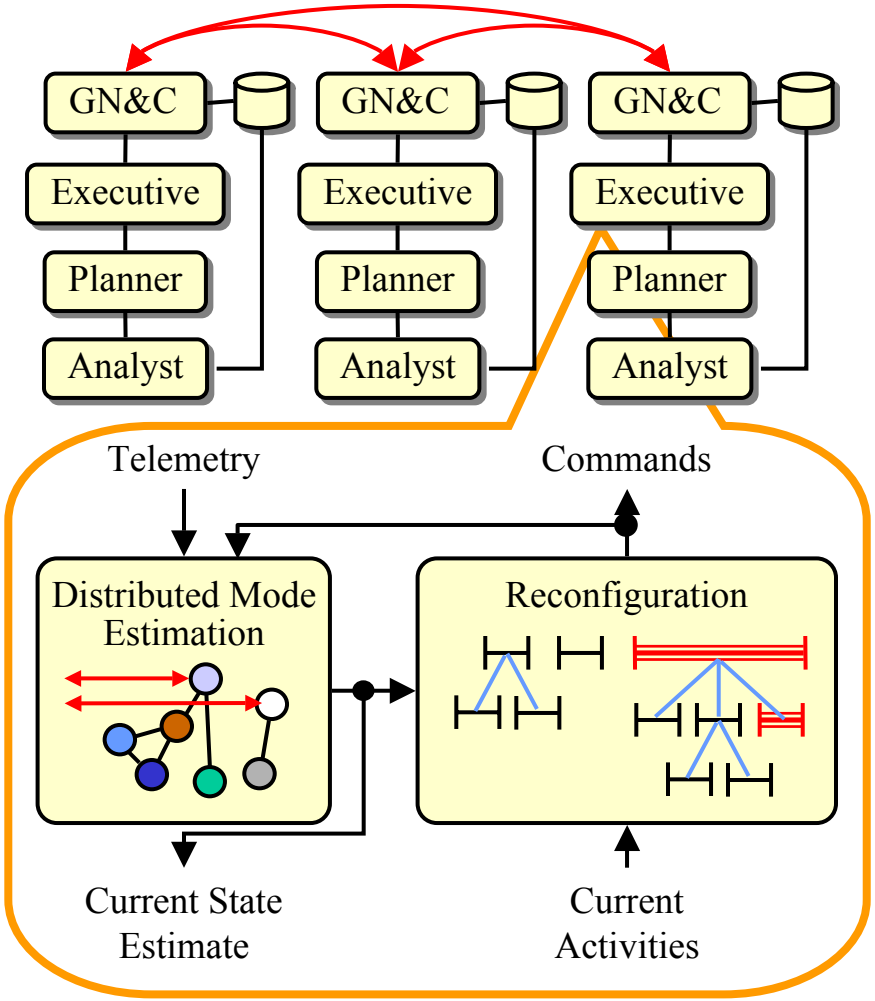
- Problem
  - Maximize total downlinked data value subject to local planning restrictions.
  - The value of an observation depends on both local properties and properties of observations made by others.
- Approach
  - Compute & combine local models of phenomena to focus global data collection.

Coordinating Planners



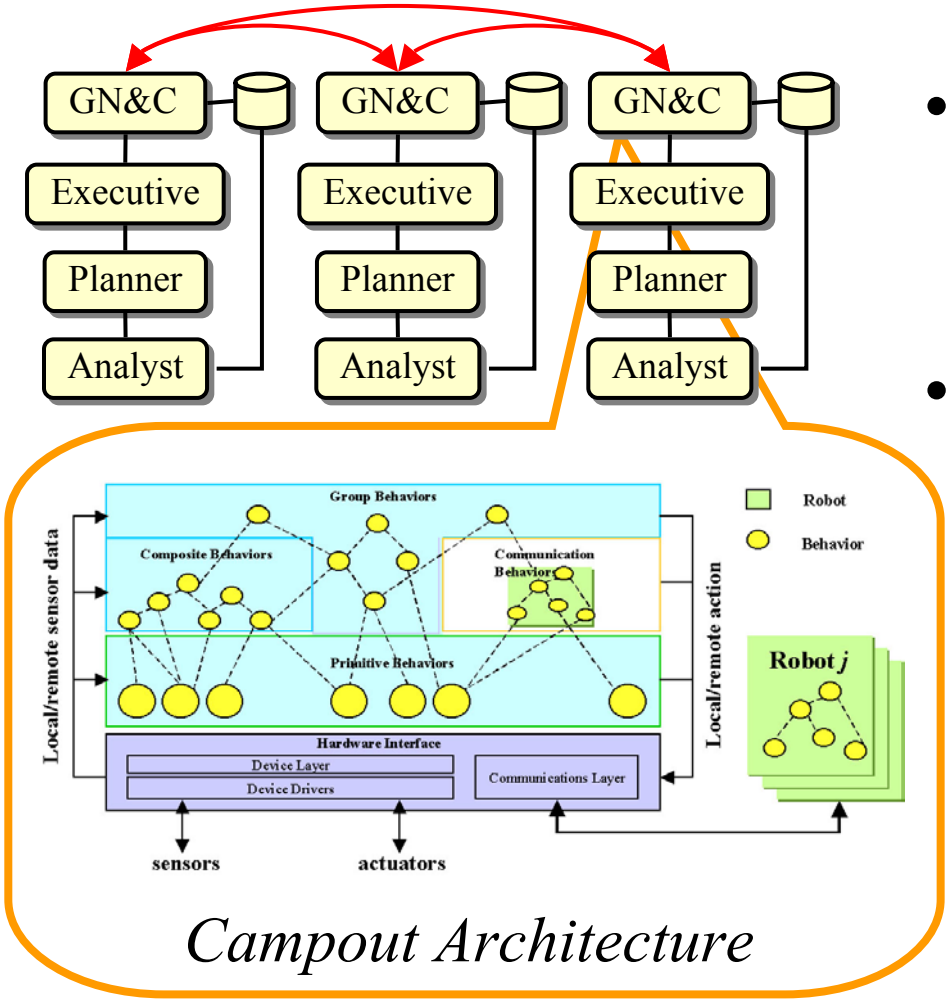
- Problem
  - Maximize priority weighted sum of satisfied goals subject to local constraints.
- Approaches
  - Goal delegation with abstract planning and/or contract networks.
  - Schedule coordination with distributed constraint satisfaction based algorithms

Coordinating Executives



- Estimation Problem
  - Find the local/global mode with the maximal probability subject to local observation constraints.
- Reconfiguration Problem
  - Find the coordinated reconfiguration paths to the target mode that has the cheapest resource cost subject to local constraints.

Coordinating Controllers



Campout Architecture

- Problem
  - Coordinate multiple local and global behaviors for optimal control.
- Approach
  - Subscription-based communications between behaviors on different platforms.
  - Priority&state-based behavior arbitration
  - Behavior fusion based on consensus computation mechanisms

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Technical Conclusions

- What kinds of distributed missions are there?
  - (1) Separation, (2) Coverage, (3) Combination
- How does autonomy evolve to adapt to a distributed mission?
  - It depends on the kind and maps to a component distribution.
- How can we make multiple autonomous spacecraft work together?
  - Getting components to work together is an instance of the constrained optimization problem.

Relevant Research at JPL

(an incomplete list)

Technology	Contact
Distributed analysts	Tara Estlin
Distributed planners	Tony Barrett
Distributed executives	Tony Barrett
Robotic work crews	Terry Huntsberger
Formation flying	Fred Hadaegh
Middleware IPN interfaces	Norm Lamarra
Mars network	Chad Edwards
Spacecraft cross-link protocols	Peter Shames
Distributed sensors	Harold Kirkham
Sensor webs	Kevin Delin

Extra Directions for Improvement

- Capabilities
  - Ground operations control of autonomous systems
  - Fairly arbitrating conflicting demands from different instrument teams, possibly on different missions
  - Functioning in a low power (picosat) environment
  - Autonomous artifact building
  - Learning to improve coordination
- Getting above TRL 3
  - Flight-like multiple platform testbeds are needed to evaluate actual performance of different techniques.
  - System interfaces are currently adhocly defined.
  - Not enough communication between research activities.