Draper Laboratory Overview of Rendezvous and Capture Operations

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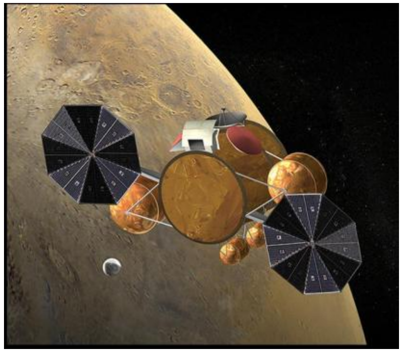
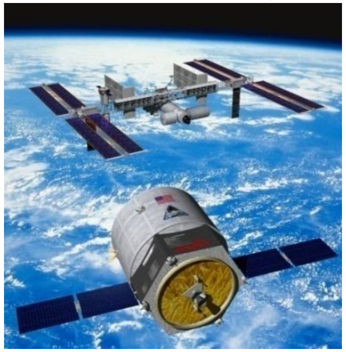
Motivation for Rendezvous

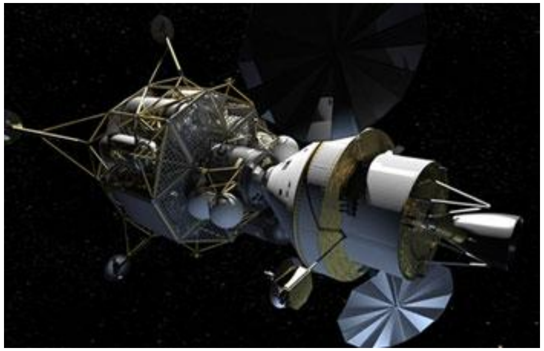
Autonomous Rendezvous is a critical capability



Sample Return

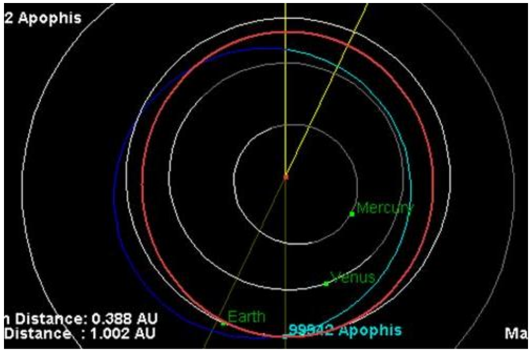
Re-supply



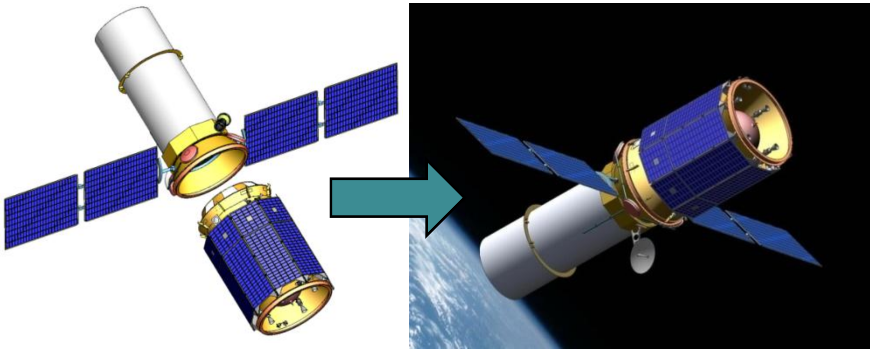


Exploration

Asteroid

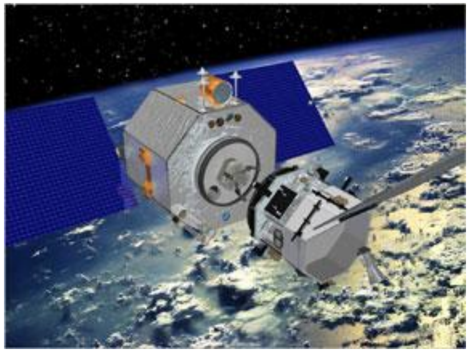


Re-constitution

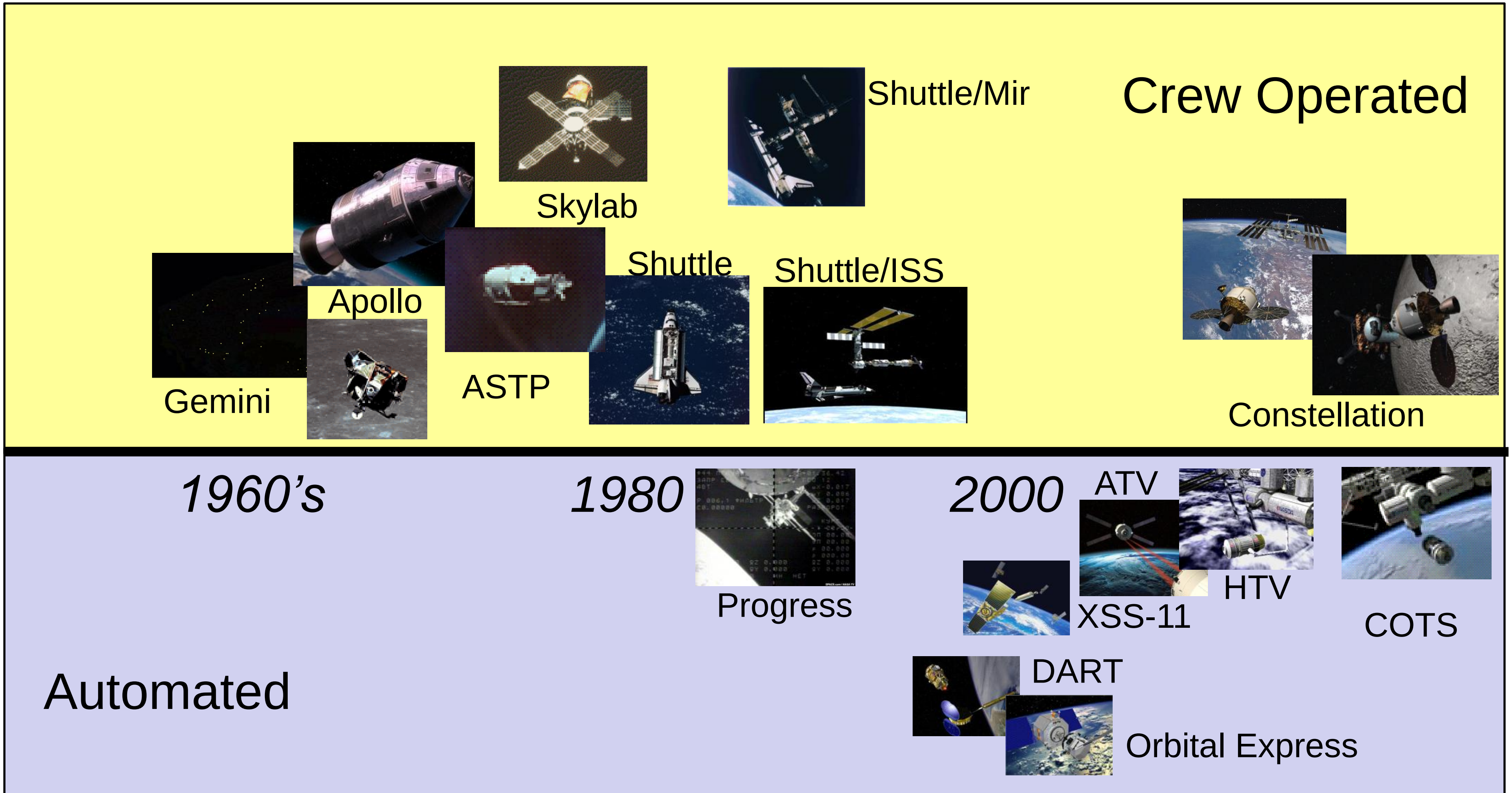


Inspection/Escort

Servicing



Rendezvous Flight History



Crew Operated

Gemini

Apollo

Skylab

ASTP

Shuttle

Shuttle/Mir

Shuttle/ISS

Constellation

1960's

1980

2000

Progress

ATV

HTV

XSS-11

COTS

DART

Orbital Express

Automated

Draper has been involved in all US rendezvous programs

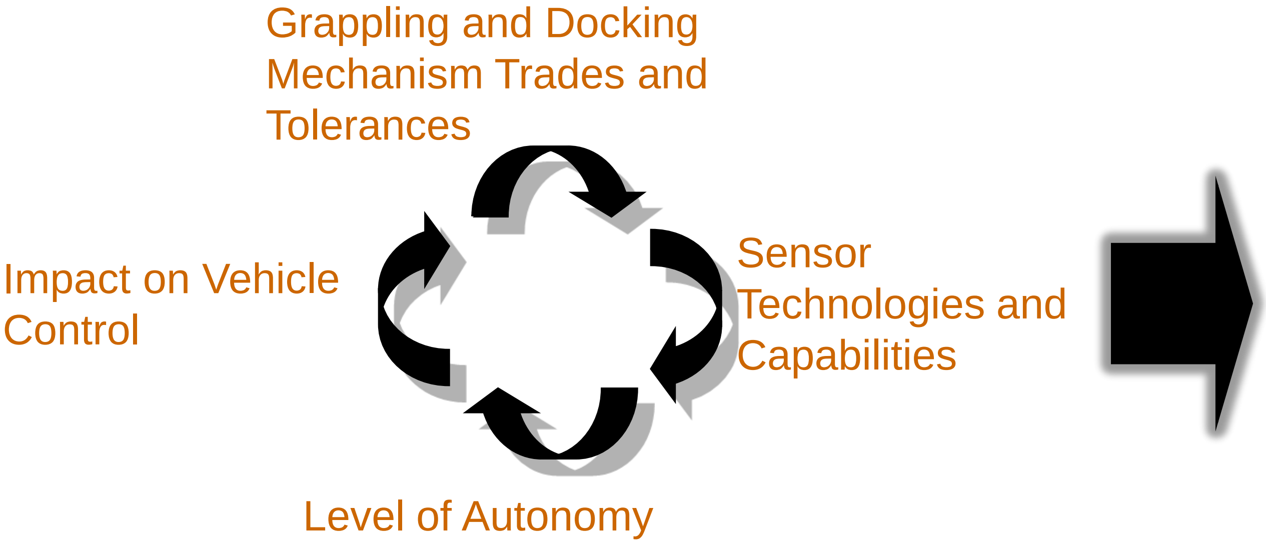
State-of-the-Art and Key Technologies

- All Systems developed are mission-unique (e.g., human-rated systems require human-in-the-loop activity for flight ops)
- Sensor Technologies and Capabilities - provide position and attitude knowledge for relative navigation across different ranges and mission profiles
- Level of Autonomy (On-board Mission Manager)
  - Provide capability to automate operations but maintain positive control
  - Evolutionary approach to permit increasing autonomous control
    - Initial capability for nominal control and failure detection
    - Subsequent incorporation of contingency rules for off-nominal cases
    - Eventually leading to rendezvous re-planning capability
- Grappling and Docking Mechanism Trades and Tolerances
  - Low-force capture reduces contact-collision force and increases safety
  - Androgynous system - Identical units on each side of interface
- GN&C Algorithms are mature, cover most applications, need to be tailored

Primary challenge is to perform the required unique integrated system design, analysis, and testing

Issues and Needs

- The GN&C system interacts with nearly every other sub-system in the vehicle, resulting in complex system trade-offs
- Integrated performance analysis is required to assure mission trajectories that meet sensor, clearance and safety requirements while minimizing impacts to the target spacecraft
- Also, robust contingency operations are required



Grappling and Docking Mechanism Trades and Tolerances

Impact on Vehicle Control

Sensor Technologies and Capabilities

Level of Autonomy

Robustness, safety, reliability, operational complexity, heritage

Typical GN&C System Performance Requirements

Performance Parameter	30 km	1.5 km	500m	100m	10m
Attitude Knowledge (3-σ) per axis	0.3 deg	0.3 deg	0.3 deg	0.3 deg	0.3 deg
Attitude Control (3-σ) per axis	0.5 deg	0.5 deg	0.5 deg	0.5 deg	0.3 deg
Attitude Rate (3-σ) per axis	0.2 deg/s	0.2 deg/s	0.2 deg/s	0.2 deg/s	0.1 deg/s
Relative Position Knowledge (3-σ) per axis	100 m	50 m	50 m	5.0 m	0.2 m
Relative Velocity Knowledge (3-σ) per axis	0.08 m/s	0.08 m/s	0.08 m/s	0.02 m/s	0.01 m/s
Position Control (3-σ) per axis	N/A	200 m	40 m	5.0 m	0.1 m
Velocity Control (3-σ) per axis	0.03 m/s	0.03 m/s	0.02 m/s	0.02 m/s	0.003 m/s

Navigation Sensor Types

Phase	Sensor	Range of Operation	Measurement Type	Nav Support	TRL
Orbit	GPS	R > 100m	Inertial position and velocity	Inertial Position	8-9
Orbit	IMU	N/A	Inertial acceleration and attitude rates	Propagated Attitude and Position	9
Orbit	Star Tracker	R > 2 Km	Catalog Matching	inertial attitude	8-9
Acquisition Sensor	RGPS	500 m < R < 35 km	Target and chaser pseudo and delta ranges	Relative pos/vel	8-9
Acquisition Sensor	Optical	100 m < R < 5 Km	Range and bearing to target	relative pos/vel	6
Mid-Range Sensor	Optical LIDAR	50 m < R < 200 m	Relative position and attitude	target rel pos/vel, attitude, rel attitude	~5
Docking Sensor	Optical LIDAR	*** < R < 100 m	Relative position and attitude	target rel pos/vel, attitude rel attitude	~5

Processed Camera Imagery

RGPS

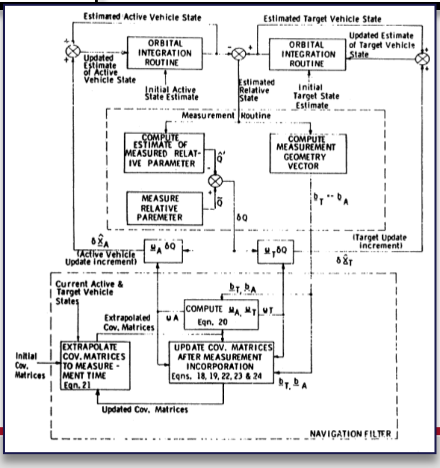
Lidar

GPS

Star Tracker

IMU

Target Ground Track



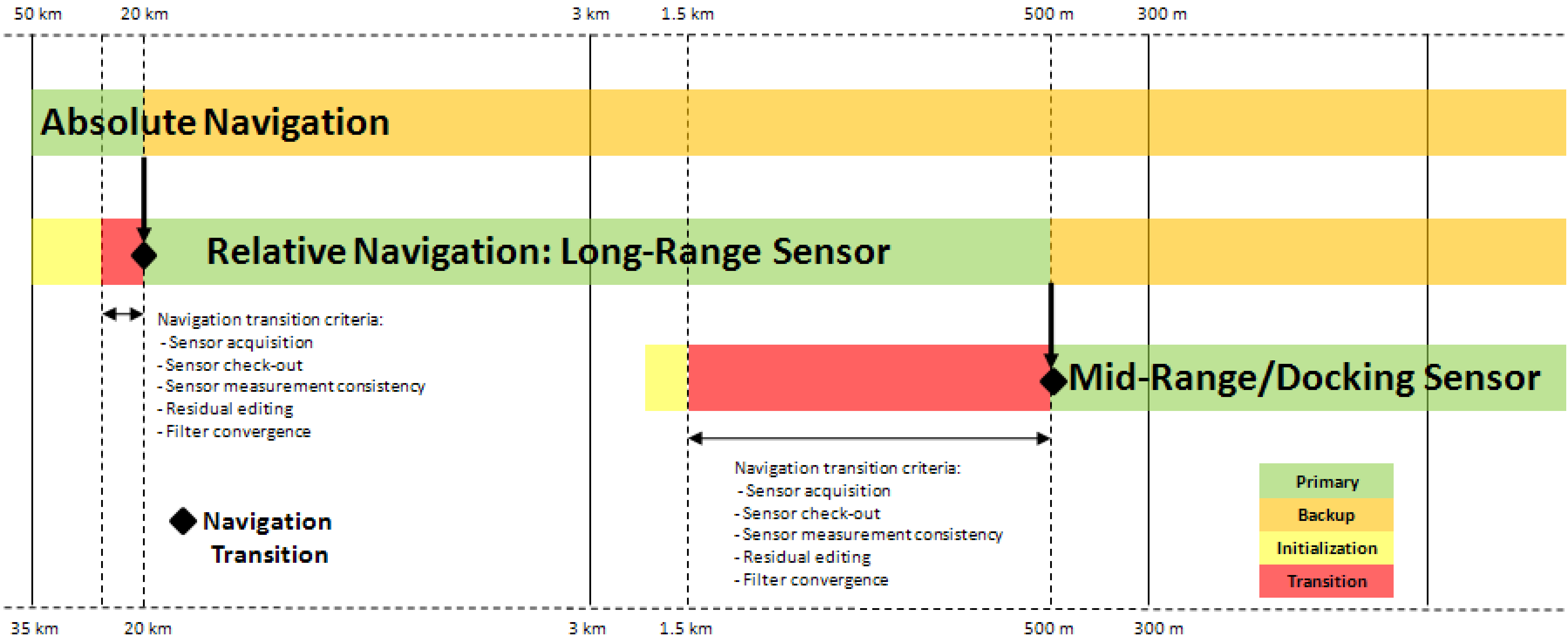
Target Inertial State

Relative State

Chaser Inertial State

Navigation Sensor Utilization & Transition

- Navigation system uses different sensor types along the trajectory
- Navigation system undergoes transition from one sensor type to another as the chaser approaches a target
- Navigation system performance is enhanced with the addition of higher accuracy sensor types



Navigation transition criteria:
- Sensor acquisition
- Sensor check-out
- Sensor measurement consistency
- Residual editing
- Filter convergence

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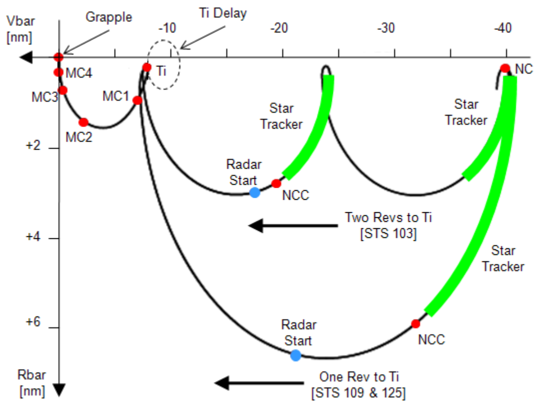
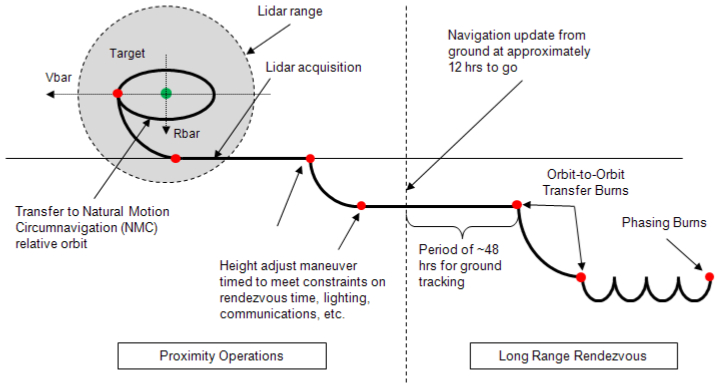
Trajectory Considerations

- Must accommodate unique tracking requirements of each sensor
  - Max range-rate, angle rate limits (e.g., lighting for optical system)
  - Sensor search volume can be minimized and acquisition time lengthened by appropriate trajectory design (e.g., co-elliptic approach)
- To accurately perform maneuvers, sufficient tracking time must be provided before performing the on-board computed maneuvers
  - Large sensor random errors require smoothing
  - Large observable biases require time to adequately estimate bias effects
- Profile should have inherent dispersion handling capability
  - robust to broad spectrum of dispersions while still maintaining integrity of desired profile characteristics with passive abort capability (desired)
  - Co-elliptic altitude difference must be large enough to maintain positive closing rate, despite dispersions, yet small enough to maximize acquisition opportunity
  - Multiple rendezvous opportunities to handle contingency cases
- Maneuver types/trigger points should be selected, where possible, that are insensitive to certain navigation errors
  - Example: Use of elevation angle to specify terminal phase initiation maneuver to maintain *standardized* closing profile to VBAR offset

Two Common Approaches To Rendezvous

- Stable orbit point on Vbar (Shuttle, Orbital Express)
  - Provides opportunity to stop on Vbar prior to rendezvous
  - Opportunity for more ground interaction
- Double Co-elliptic Approach (Apollo, XSS-11, COTS)
  - Provides easily modulated variable closing rate
  - Can be tailored to meet needs of sensors
  - Passive abort capability
  - Suitable for autonomous operation
  - Minimal input from the ground





Selection of rendezvous approach based on CONOPS, system requirements, sensors and actuators

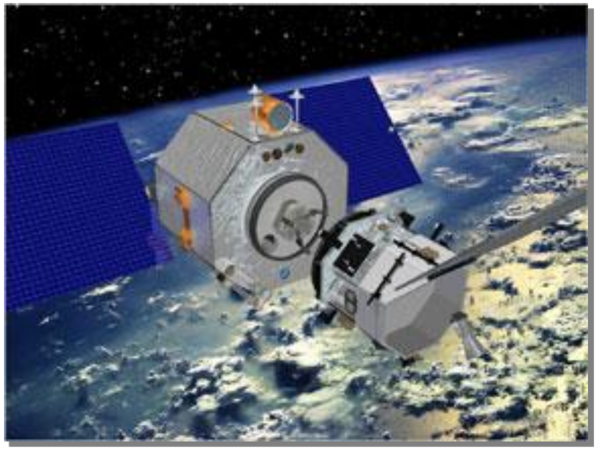
Autonomous Flight Management

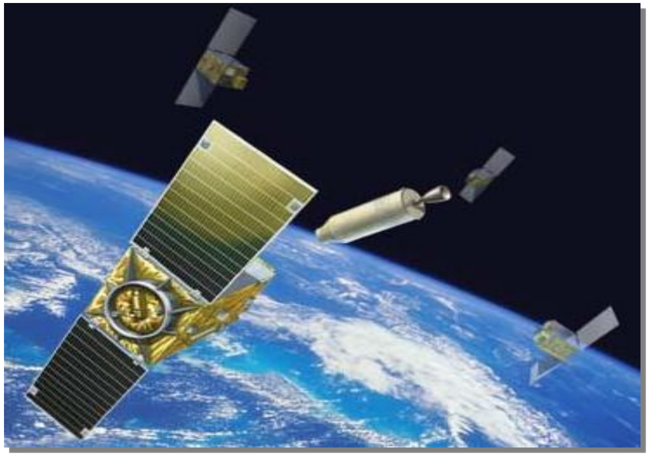
Orbital Express

- DARPA Advanced Technology Demonstration of Satellite Servicing Operations
- Draper Autonomous Flight Manager
    - On-board planner to control all spacecraft operations

XSS-11

- AFRL Proto-flight for a microsatellite to perform autonomous satellite inspection
- Draper Autonomous Flight Manager
    - On-board planner for trajectory and activity planning





Summary

- Systems engineering approach is required to develop acceptable sensor architecture that meets rendezvous and proximity operations mission requirements
- Development of autonomous operations requires an intimate knowledge of mission design, algorithms, system interfaces, requirements and the level of operator interaction
- Extensive navigation analysis should be part of the design process not just an afterthought
- Draper has supported and continues to support rendezvous flight programs past and present