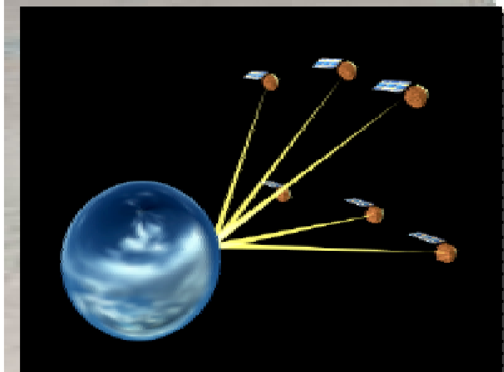
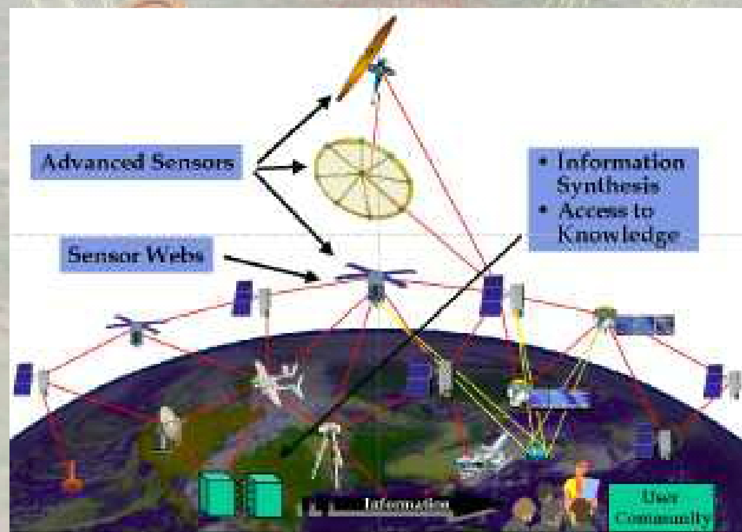
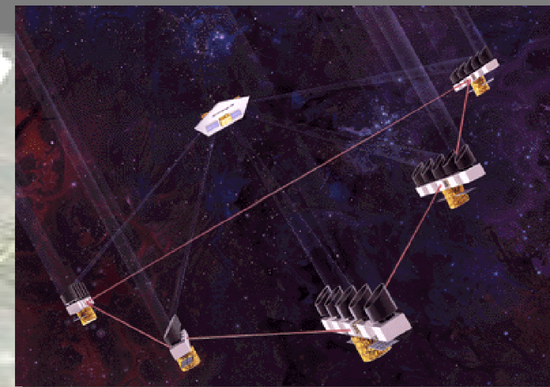
Distributed Space Systems- Revolutionizing Earth & Space Science



Co-observation



Coincidental Observations



Interferometry

Multi-point observation

Tethered Interferometry

A new era of space exploration will be enabled by cooperating spacecraft

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Distributed Spacecraft Missions

Projected Launch Year	Mission Name	Mission Type
00	New Millennium Program (NMP) Earth Observing-1 (2)	Earth Science
01	Gravity Recovery and Climate Recovery (GRACE) (2)	Earth Science
03	University Nanosats (AFRL/GSFC) ORION nanosat mission (2)	Technology Demonstrator
03	University Nanosats (AFRL) 3 Corner Sat misson (3)	Technology Demonstrator
03	University Nanosats (AFRL/GSFC) ION-F mission (3)	Technology Demonstrator
03	Synchronized Position Hold Engage & Reorient Experimental Satellites	Technology Demonstrator
03	NMP ST-5 Nanosat Constellation Trailblazer (3)	Space Science
04	Techsat-21/AFRL (3)	Technology Demo
04	Auroral Multiscale Mission (AMM)/APL	Space Science/SEC
04	ESSP-3-Cena (w/ Aqua) (2)	Earth Science
05	Starlight (ST-3) (2)** (ground-based only at the moment)	Space Science/ASO
05	Magnetospheric Multiscale (MMS) (4)	Space Science/SEC
06	MAGnetic Imaging Constellation (MAGIC) (7, string of pearls)	Space Science
06	COACH (2-3)	Earth Science
07	Global Precipitation Mission (EOS-9)	Earth Science
07	Geospace Electrodynamic Connections (GEC)	Space Science/SEC
08	Constellation-X (4)	Space Science/SEU
08	Magnetospheric Constellation (DRACO) (50-100)	Space Science/SEC
08	Laser Interferometer Space Antenna (LISA) (3)	Space Science/SEU
09	DARWIN Space Infrared Interferometer/European Space Agency	Space Science
10	Leonardo (GSFC) (4-8)	Earth Science
15	Stellar Imager (SI) (10-30)	Space Science/ASO
	Astronomical Low Frequency Array (ALFA)/Explorers	Space Science
12	MAXIM Pathfinder (2-3)	Space Science/SEU
05+	Living with a Star (LWS) (many)	Space Science
05+	Soil Moisture and Ocean Salinity Observing Mission (EX-4)	Earth Science
05+	Time-Dependent Gravity Field Mapping Mission (EX-5)	Earth Science
05+	Vegetation Recovery Mission (EX-6)	Earth Science
05+	Cold Land Processes Research Mission (EX-7)	Earth Science
05+	Hercules	Space Science/SEC
05+	Orion Constellation Mission	Space Science/SEC
15	Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) (3)	Space Science/SEU
20+	Planet Imager (PI)	Space Science/ASO
20	MAXIM X-ray Interferometry Mission (34)	Space Science/SEU
15+	Solar Flotilla, IHC, OHRM, OHRI, ITM, IMC, DSB Con	Space Science/SEC
15+	NASA Goddard Space Flight Center Earth Sciences Vision	Earth Science
15+	NASA Institute of Advanced Concepts/Very Large Optics for the Study of Extrasolar Terrestrial Planets	Space Science

DSS Top-Level Glossary

DSS Tiger Team Scope- **the space & ground systems and technologies that enable the formulation, development, and execution of missions which permit 1) coordinated observations from different perspectives, 2) spatially distributed instruments making time synchronous observations 3) multiple spacecraft to operate as a single instrument**

KEY TERMS-

Distributed Space Systems (DSS)- **an end-to-end system including two or more space vehicles and a cooperative infrastructure for science measurement data acquisition, processing, analysis and distribution (other issues: power, storage, thermal, …)**

Constellation-**a collection of space vehicles that constitutes the space element of a DSS.**

Constellation Management-**the management and the operations of the space and ground segments of a DSS**

Cluster- **a functional grouping of spacecraft, formations, or virtual platforms, possibly an element of a larger constellation.**

Coordinated Pointing- **the maintenance or re-orientation of two or more space vehicles to a common point or set of points at the same time or at a desired time separation.**

Fleet- **a generic term for collection of spacecraft with a high-level complementary goal**

Formation- **multiple spacecraft with a desired position and/or orientation relative to each other or to a common target.**

Formation Flying- **the maintenance of a relative separation, orientation or position between or among spacecraft**

Sensor Web- **a system of intra-communicating spatially distributed sensor pods or crafts that may be deployed to monitor environments. The elements of the sensor web may be ground-based, aerial, or space-based components.**

Virtual Aperture- **an effective aperture generated by a cluster (or several clusters) of physically independent elements**

Virtual Platform- **a spatially distributed network of individual vehicles, or assets collaborating as a single functional unit, and exhibiting a common system-wide capability to accomplish a shared objective**

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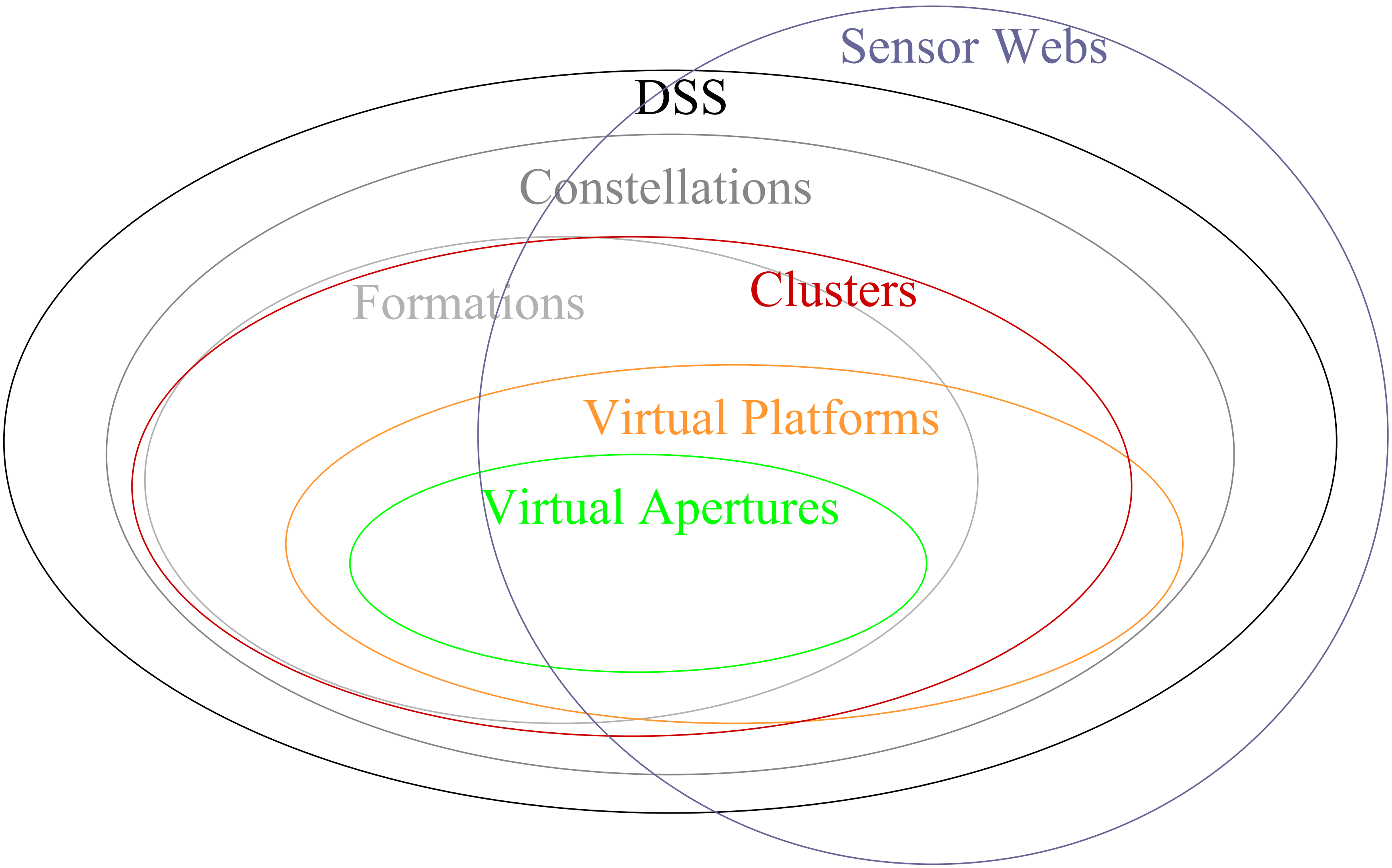
DSS Venn Diagram



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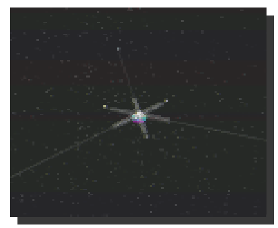
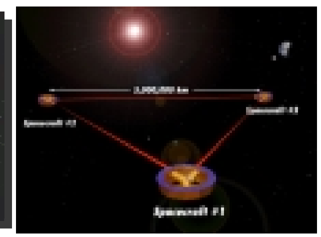
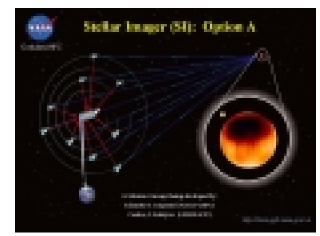
The Large Aperture Sensing Spectrum

What's best, connected or freeflying?

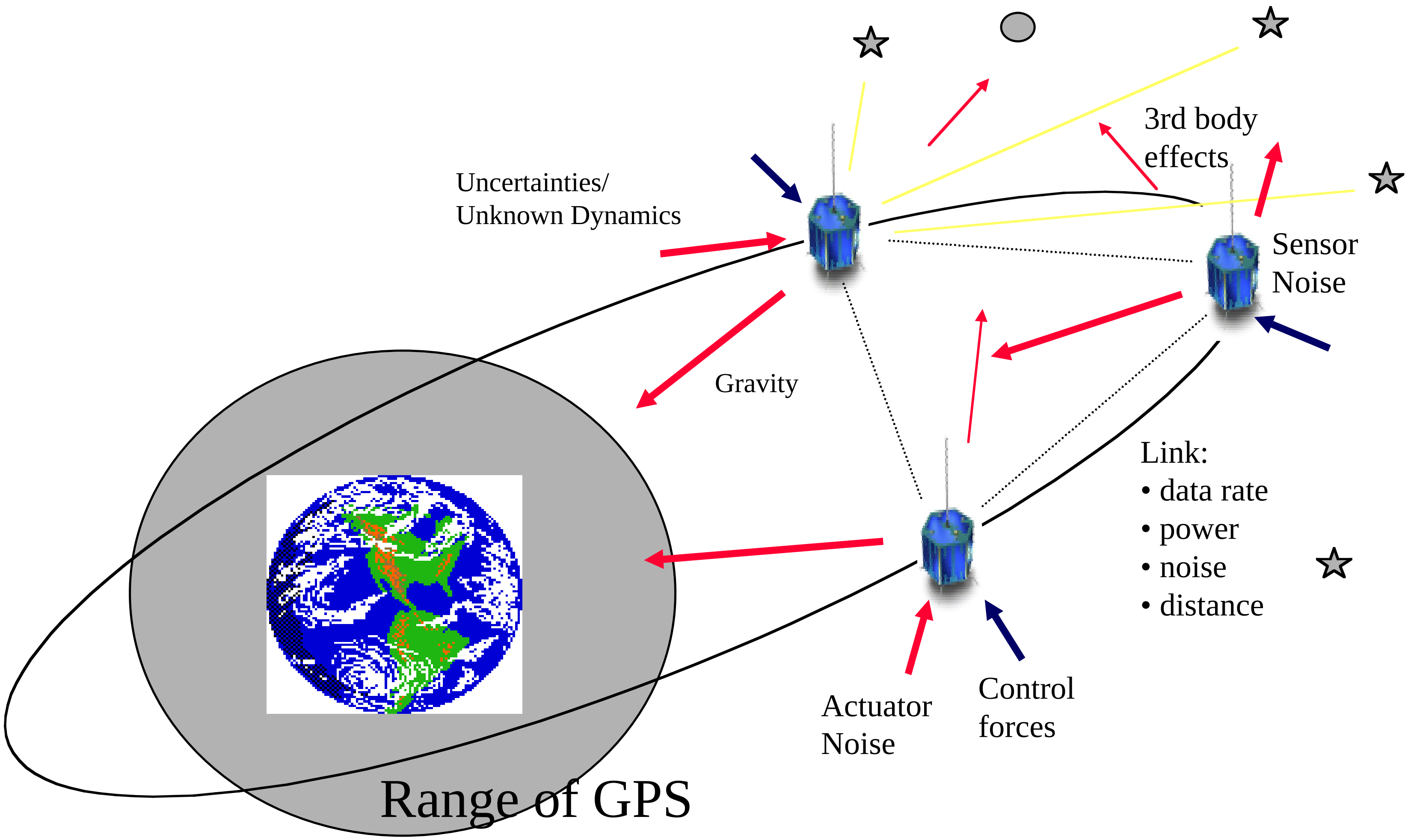
Extremely Challenging Dynamics!

Hubble	NGST	UltraLITE	SPECS	LISA	Stellar Imager
					
Monolithic	Deployable Filled	Deployable Sparse	Tethered Formations	Hybrid Formations	Freeflyer Formations

Rigidity
Large and heavy
Absolute Resolution Constraint
Near perfect large-scale manufacturing required

Controllability
Sensing extremely challenging
"Unconstrained Resolution"
Manufacturing requirements on smaller optics

DSS Systems Engineering Example



DSS Systems Engineering - Example Requirements flowdown

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Science Requirements
Area Coverage   Timeliness   Resolution   min. SNR   Wavelength(s)   "image" dynamic range   target set

Mission Requirements
S/C   S/C formation/orbit design   aperture size   aperture fill factor   aperture config.   relative navigation
formation control   Science OBP   Amount of Data Downlink   Amt Data Crosslink   autonomy/automation

On-board Engineering and Technology Requirements, level 1
Spacecraft/sub-aperture sizing   CommBW and data rate   relative navigation   formation sensors

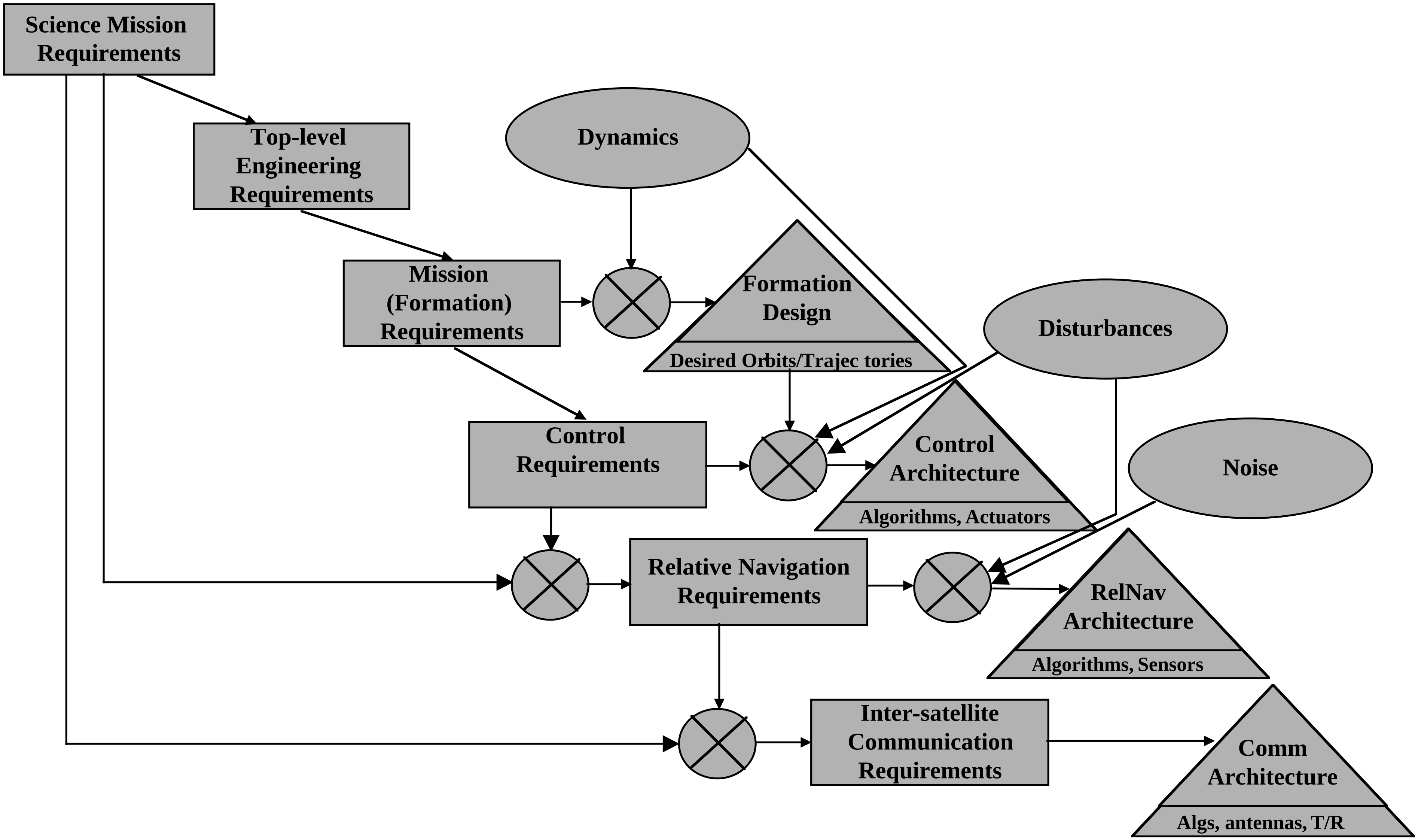
On-board Engineering and Technology Requirements, level 2
I/S comm system (including frequencies)   GN&C system   engineering OBP

On-board Engineering and Technology Requirements
power   thermal   mass

Launch Requirements
LVs   LV fairing size(s)   dispensation system   initialization   #stages   insertion points

Ground System Requirements
DL/UL locations/antenna sizes   manning   security   processing   tools for data fusion/coregistration

Formation Flying Systems Engineering



DSS Missions and Demonstrations

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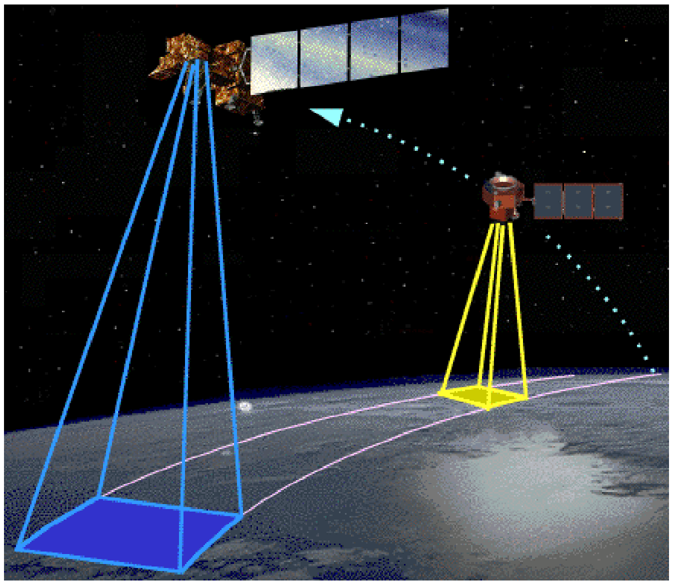
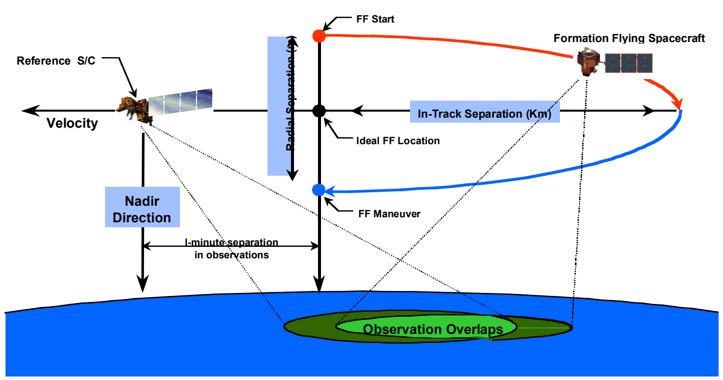
NMP EO-1 Enhanced Formation Flying (EFF) Experiment





Level - I:

Demonstrate the Capability to Fly Over the Same Ground Track As LandSat-7 Within 3 Km at a Nodal Separation Interval of Nominally One Minute During Which Time an Image Is Collected.

Level-II:

EFF- **Shall Provide the Autonomous Capability of Flying Over the Same Groundtrack of Another S/C at Fixed Separation Times.**

Autonomy - **Shall Provide On-Board Autonomous Relative Navigation and Formation Flying Control for EO-1 and LandSat-7.**

AutoCon Flight Control System - **Shall Provide Autonomous Formation Flying Control Via AutoCon (to provide future reusability).**

Ground Track - **EO-1 Shall Fly the Same Ground Track As LandSat-7.**

Separation - **EO-1 Shall Remain Within a 1-Minute In-Track Separation from LandSat-7.**

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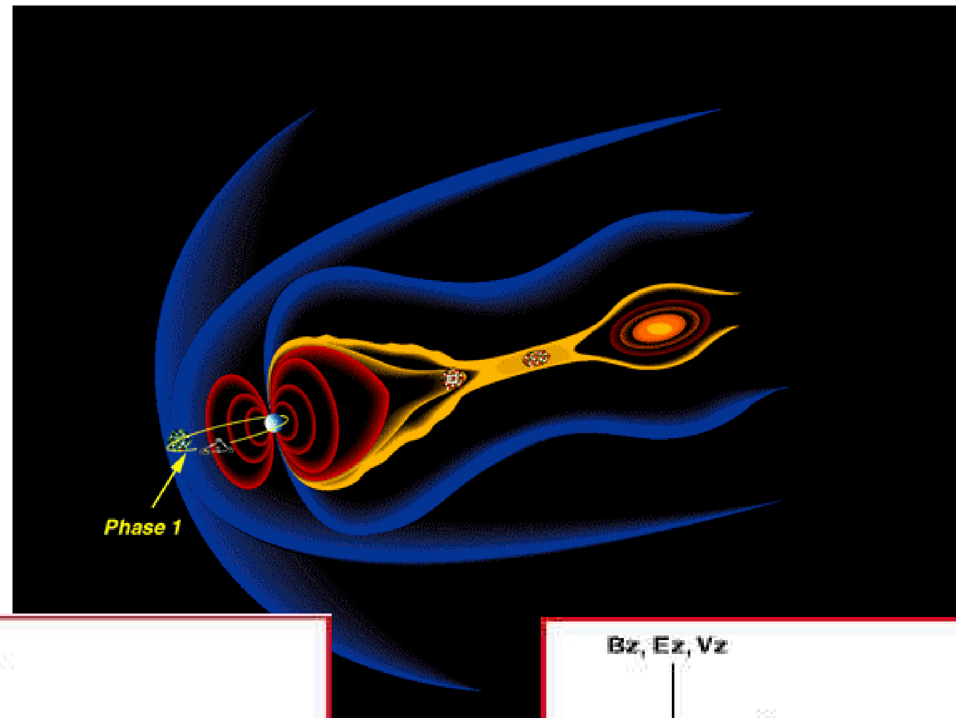
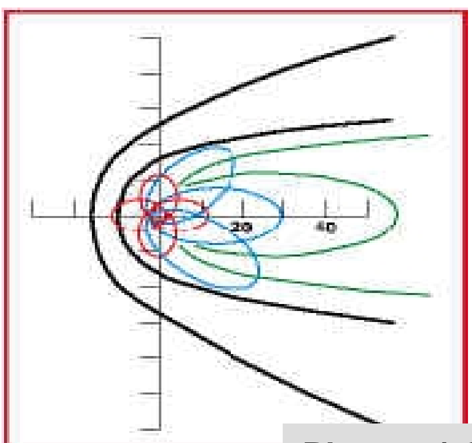
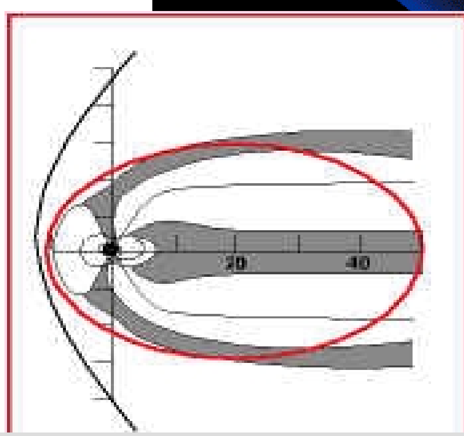
Magnetospheric Multi-scale

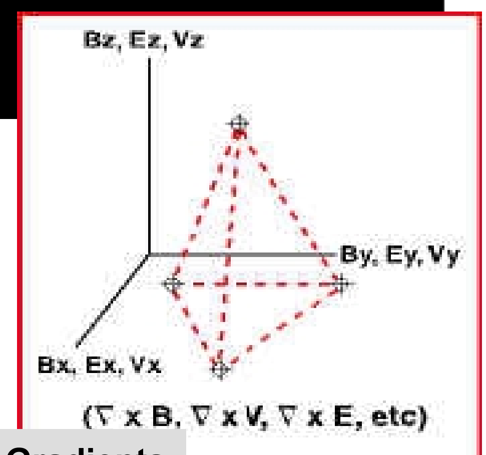
How do small-scale processes control large-scale phenomenology, such as magnetotail dynamics, plasma entry into the magnetosphere, and substorm initiation?



- 4 identical spacecraft in a variably spaced tetrahedron (1 km to several *earth radii*)
- 4 orbit phases, orbit adjust
- 2 year in-orbit (minimum) mission life
- Interspacecraft ranging and communication
- Advanced instrumentation, integrated payload
- Attitude knowledge < 0.1°, spin rate 20 rpm







Phases 1-3, Equatorial - Phase 4, Polar - Determination of Spatial Gradients

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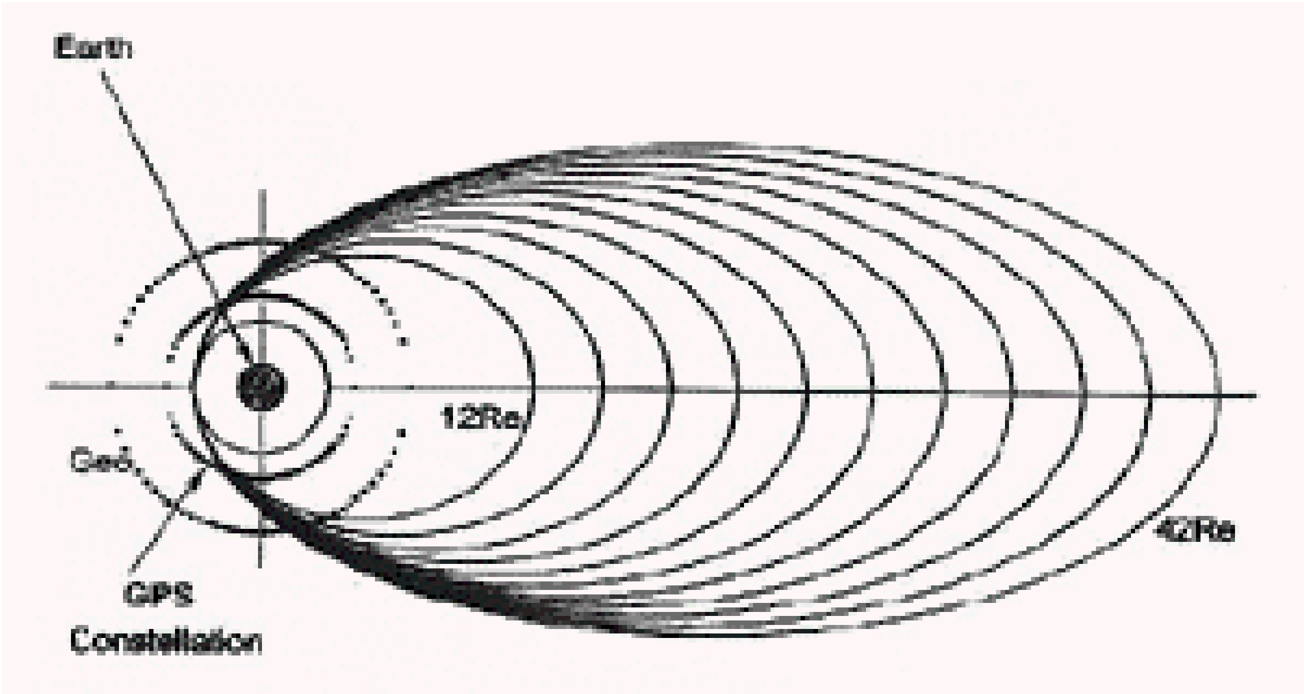
DRACO - Magnetospheric Constellation

Fundamental measurements: magnetic field, plasma flow field, and energetic particle acceleration



- **50-100 nanosatellites - "weather observatories"**
- **Orbits have 3Re perigee with varying apogees from 12Re to 42Re.**
- **Nanosats communicate with ground during perigee region.**

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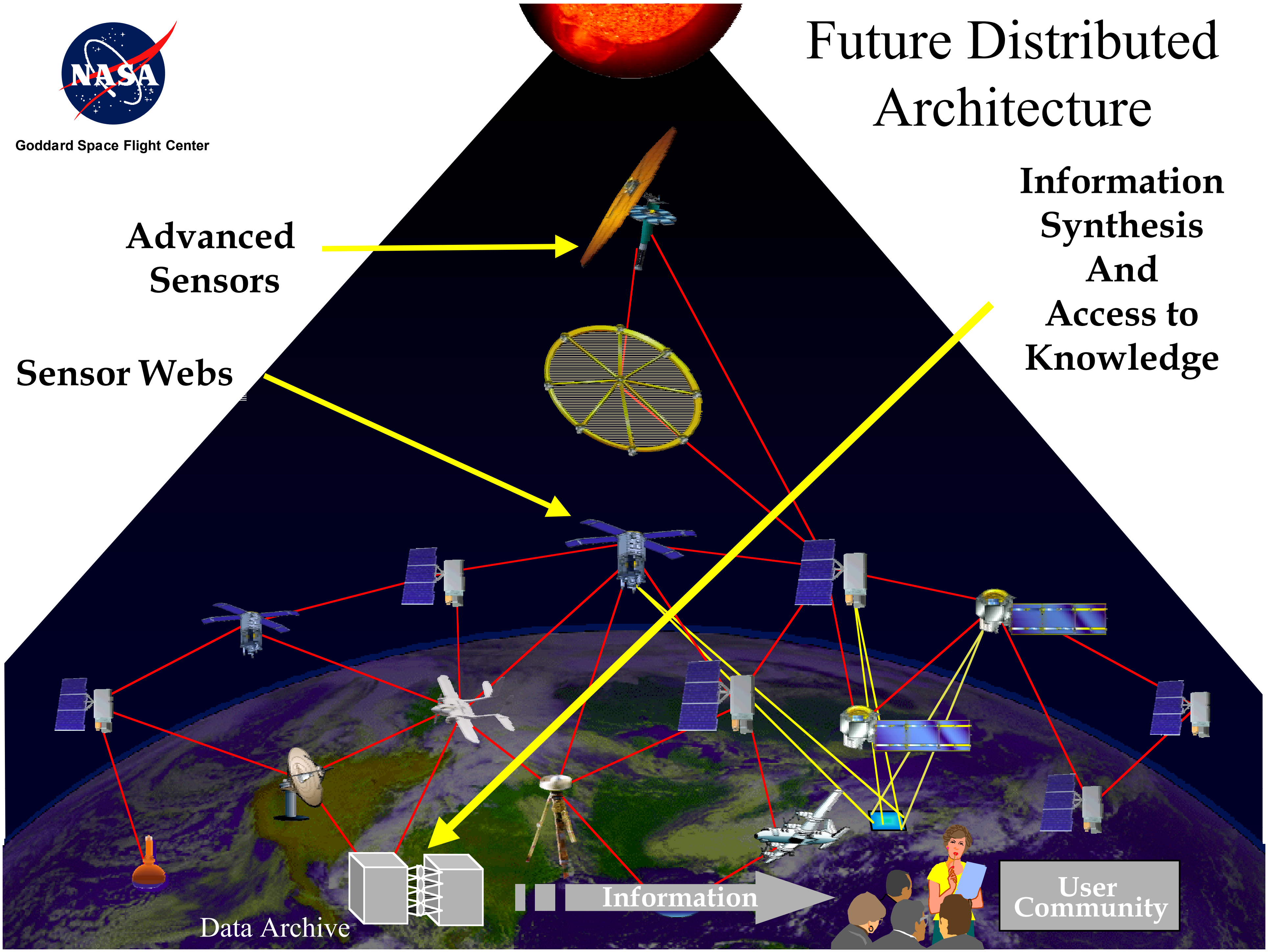
Future Distributed Architecture



Precision Formation Flying Missions and Mission Concepts

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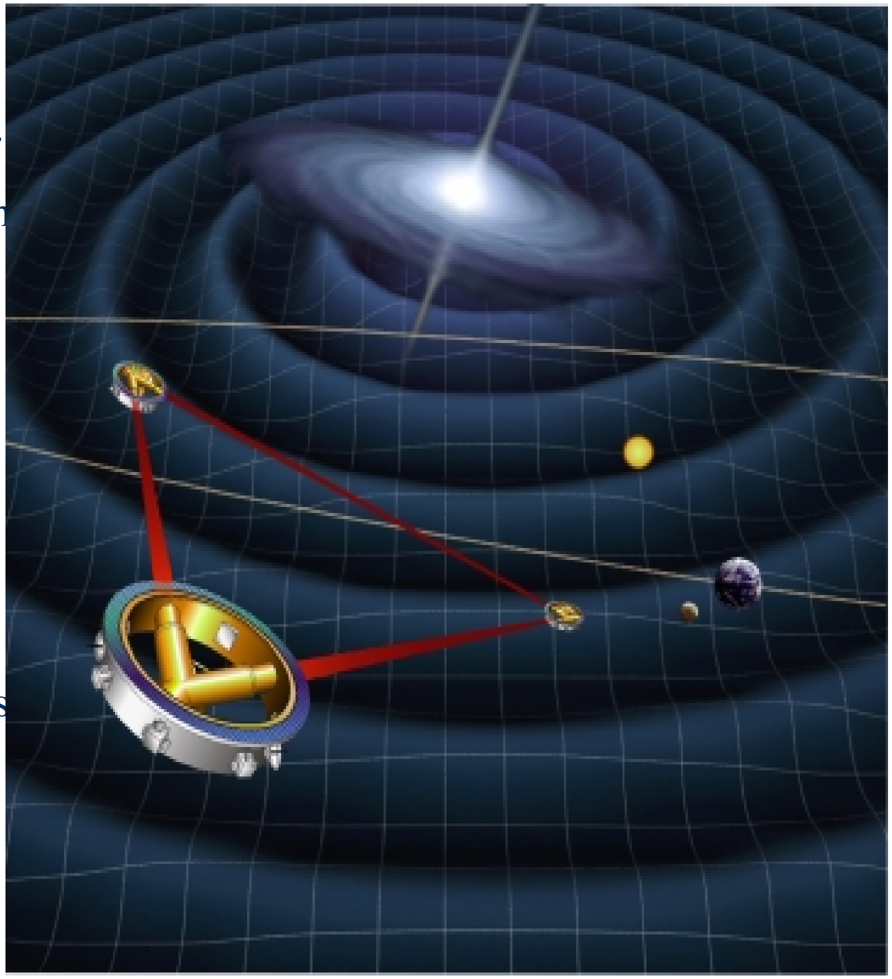
Laser Interferometer Space Antenna (LISA)

Mission:

- 3 spacecraft separated by 5,000,000 km form a three-arm 'Michelson Interferometer' to observe gravitational waves in a 10^{-4} to 10^{-1} Hz bandwidth

Approach:

- Each spacecraft payload includes two freely falling proof masses which serve as arm "end mirror" optical references
- Test masses must be free of non-gravitational forces (geodesically pure)
- Gravitational waves cause change in optical path in one arm of interferometer relative to other arm
- Distance changes measured with picometer precision to detect gravitational wave strains down to 10^{-23}
- Disturbance Reduction System (DRS) uses proof mass displacement sensor outputs to drive low-noise micro-Newton thrusters for 'drag-free' system operation



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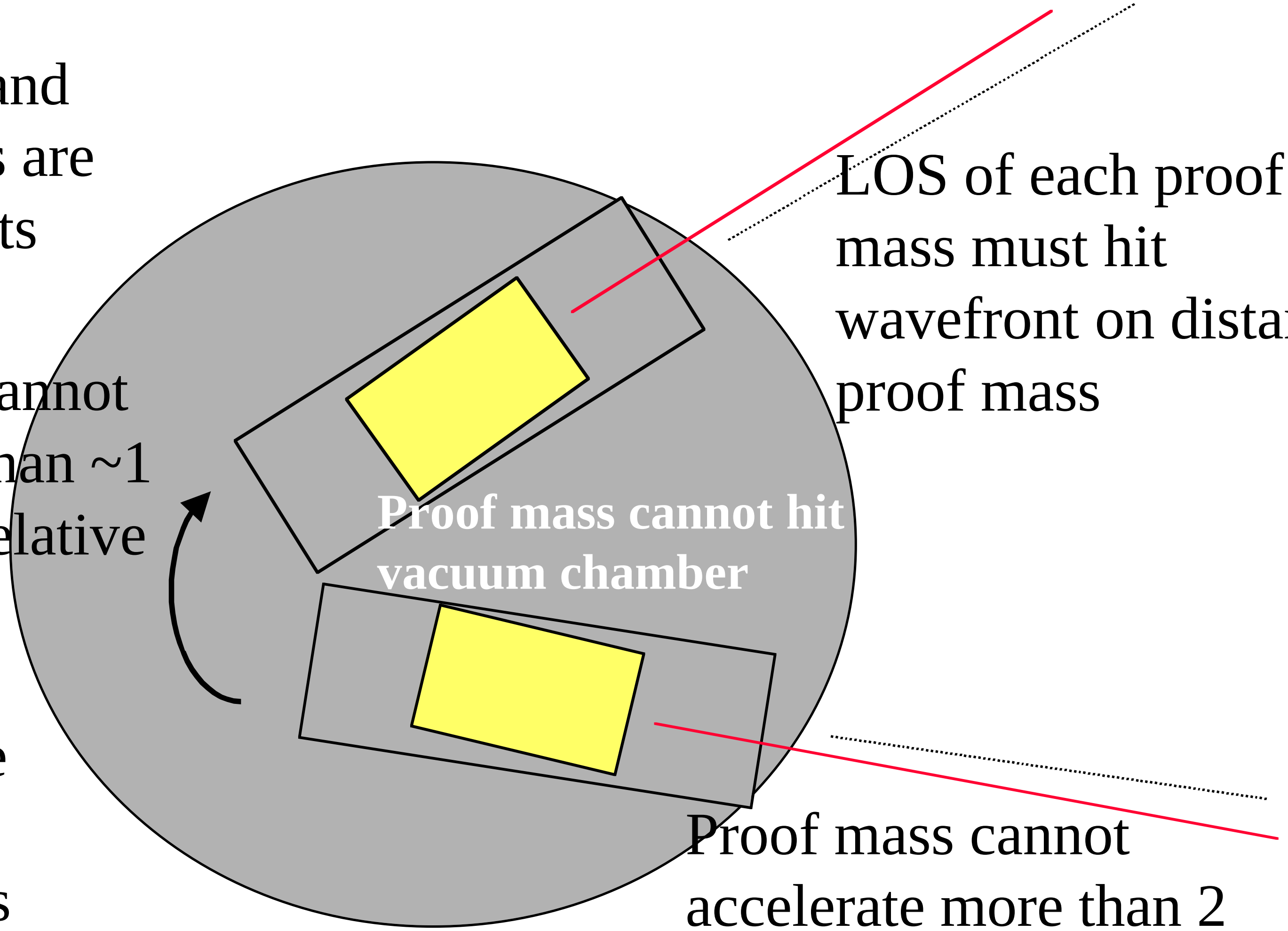
Requirements in the small-scale LISA formation

The spacecraft and each proof mass are in different orbits

Proof mass cannot move more than ~1 nm/Hz^0.5 relative to chamber



LOS of each proof mass must hit wavefront on distant proof mass

No control can be applied in measurement axis within the MBW.

Proof mass cannot accelerate more than 2 femto-m/s^2/Hz^0.5

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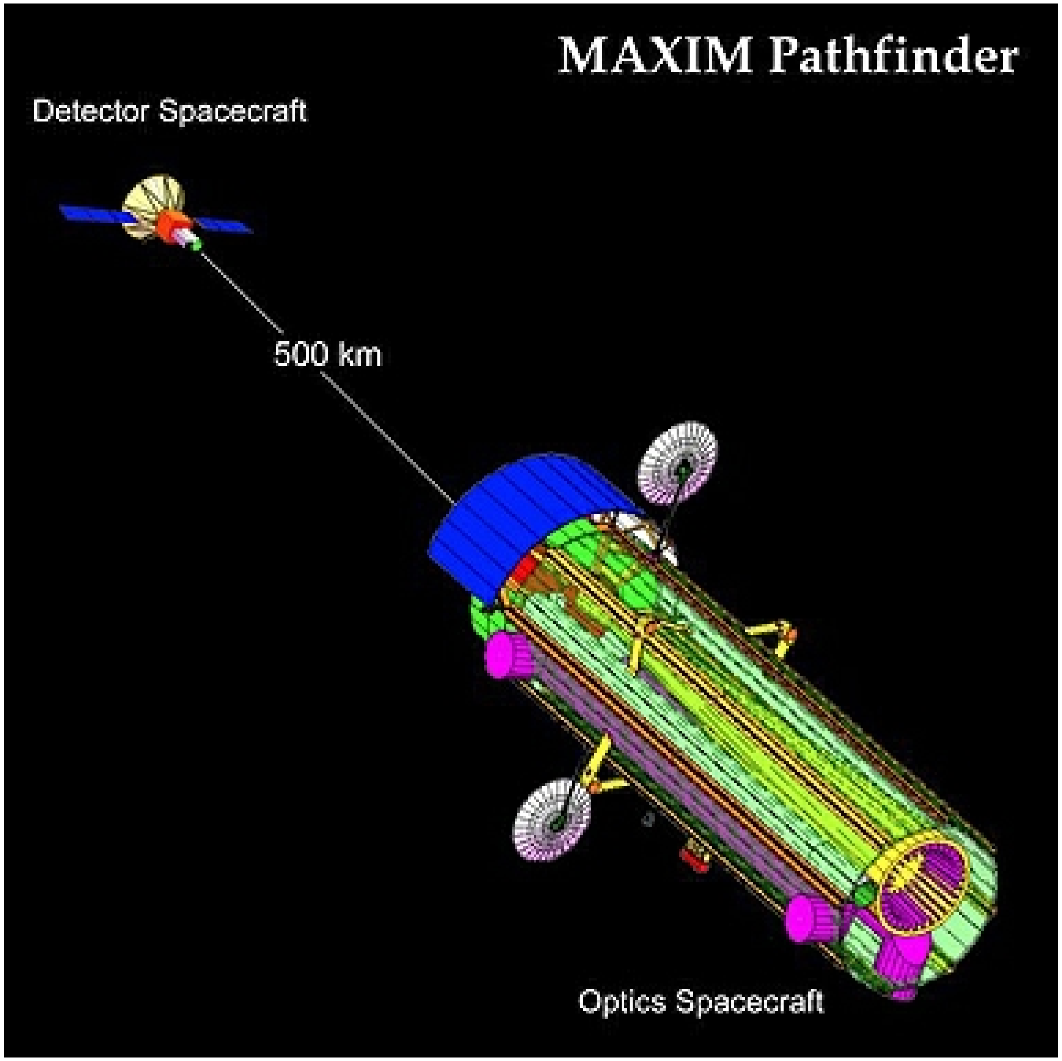
MAXIM Pathfinder

•Demonstrate the feasibility in space of X-ray interferometry for astronomical applications.

•Provide an imaging of celestial X-ray sources with resolution of 100 micro-arcseconds, 5000 times better than the Chandra observatory.



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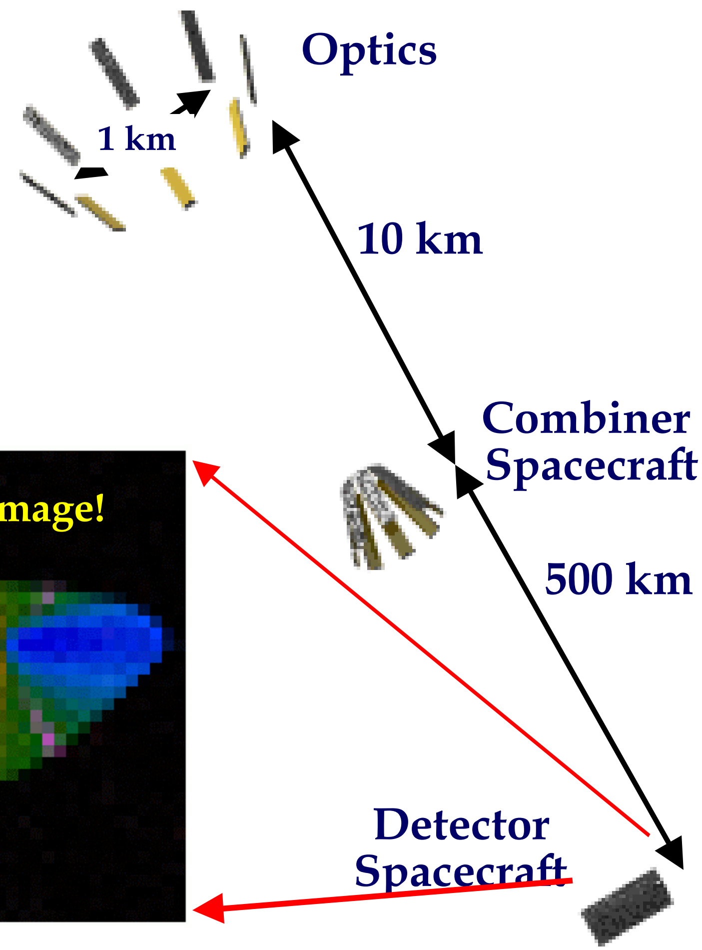
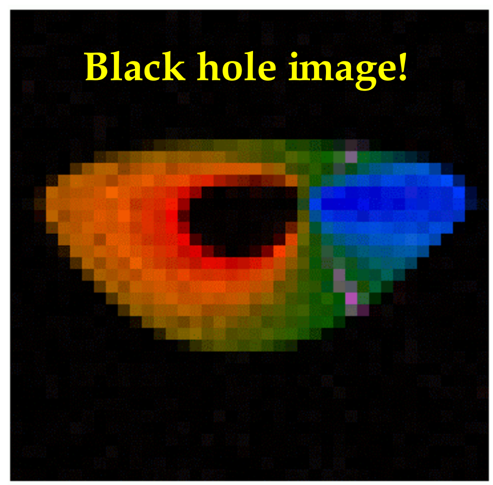
The Black Hole Imager: Micro Arcsecond X-ray Imaging Mission (MAXIM) Observatory Concept

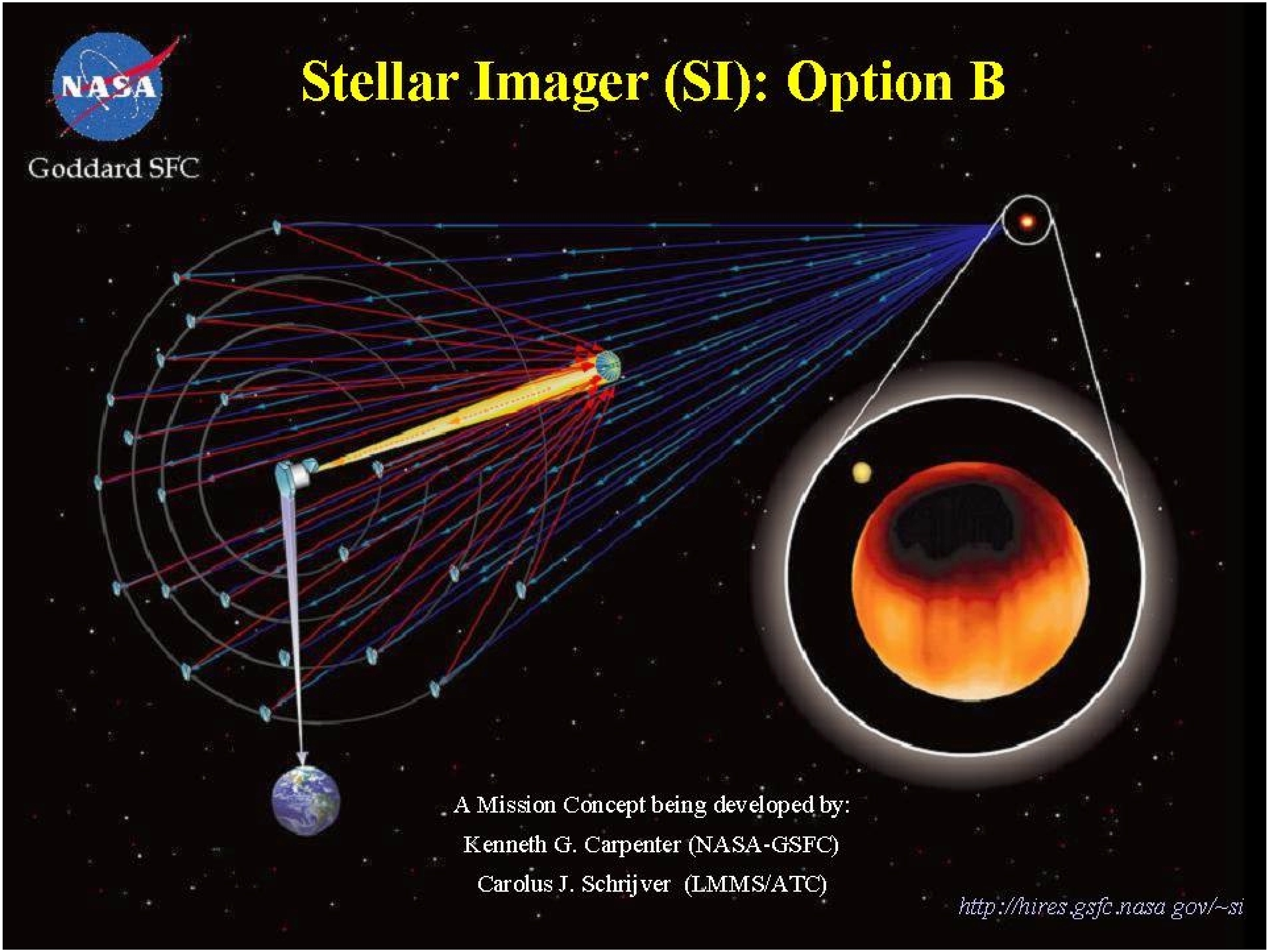
32 optics (300 × 10 cm) held in phase with 600 m baseline to give 0.3 micro arc-sec

34 Formation Flying Spacecraft

System is adjustable on orbit to achieve larger baselines







Goddard SFC
Stellar Imager (SI): Option B
A Mission Concept being developed by:
Kenneth G. Carpenter (NASA-GSFC)
Carolus J. Schrijver (LMMS/ATC)
http://hires.gsfc.nasa.gov/~si

DSS Technology

DSS Technology Challenges

- Centimeter to nanometer control over S/C separations ranging from meters to 1000s of kilometers
- Precise and coordinated spacecraft pointing to sub-arc seconds
- Coordinated (simultaneous) Orbit/Attitude control of multiple spacecraft
- Tethered formation control
- Autonomous fleet reconfiguration, replenishment, upgrade, and repair
- Initialization of multi-spacecraft fleets: collision avoidance
- Autonomous ground operations for formations and constellations; extreme challenge is a mission consisting of 100's to 1000's of satellites
- Multiple spacecraft deployment systems : deployerships and release mechanisms
- Data management: Mb-Gb/sec of data in space-to-space communications networks
- Inter-spacecraft communications for fleet control
- Cross-calibration, data management/processing of distributed instruments
- Mass production and I&T of low-cost Microsat and Nanosat vehicles
- Modeling, simulation and testbed infrastructure

Dominant Technology Drivers for NASA DSS Missions

- **Cost!**
  - *MMS - need low-cost means of long range relative nav*
  - *Drives the need to push GPS to its limits*
- Span of coverage
  - *DRACO, MMS - Must cover large spatial region time-synchronously*
- Extremely low noise characteristics (high sensitivity of payload)
  - *LISA - Measurement would be lost in the most minimal gravitational or seismic disturbances*
- Long mission duration
  - *SI - Must last through entire solar cycle*
- "Awkward" Science Sensors
  - *MAGnetic Imaging Constellation - Each craft has 4 500 meter antennae*
- High required angular and spatial resolution
  - *SI, MAXIM - milli-micro arcsecond line-of-sight requirements*

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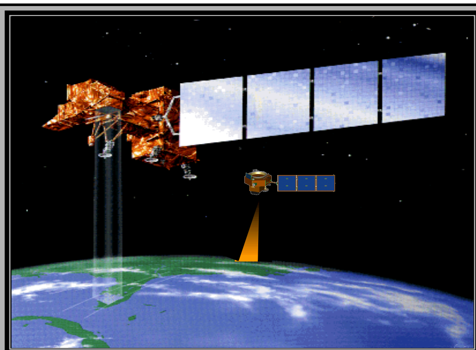
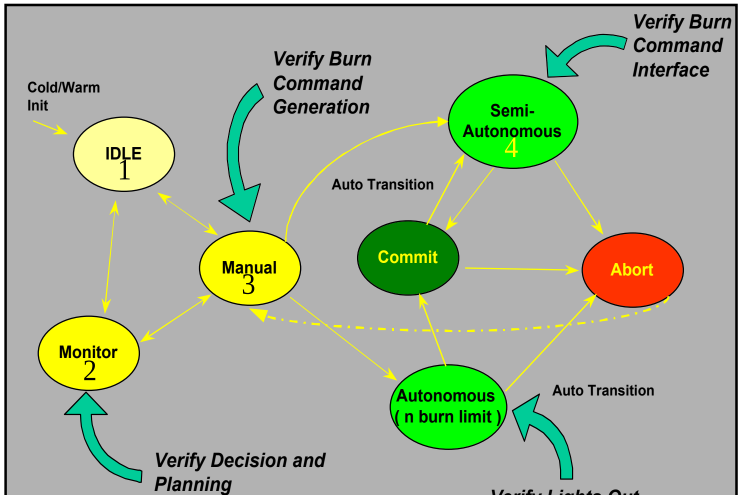
DSS Technology Development Areas



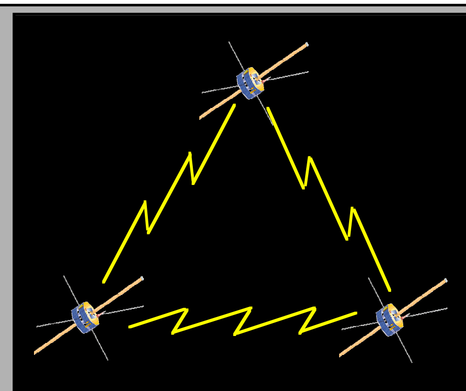
Formation Sensing and Control

Sensing, actuation, and algorithms required to maintain and/or understand vehicle position or orientation



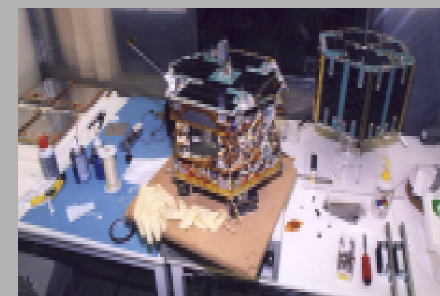
Constellation Management and Mission Operations

High-level control strategies to enable collaborative multi-spacecraft campaigns



Intersatellite Communications

Hardware, software, and advanced coding and compression algorithms to satisfy unique DSS communications needs

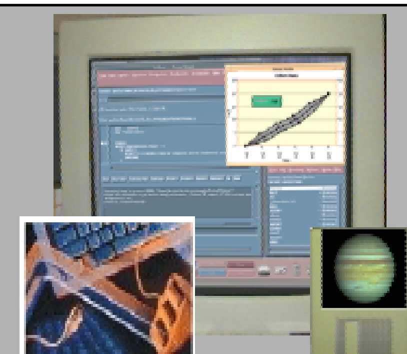


Miniaturized Spacecraft Technology

Approaches to reducing spacecraft bus infrastructure requirements in the areas of cost,mass, volume, and power

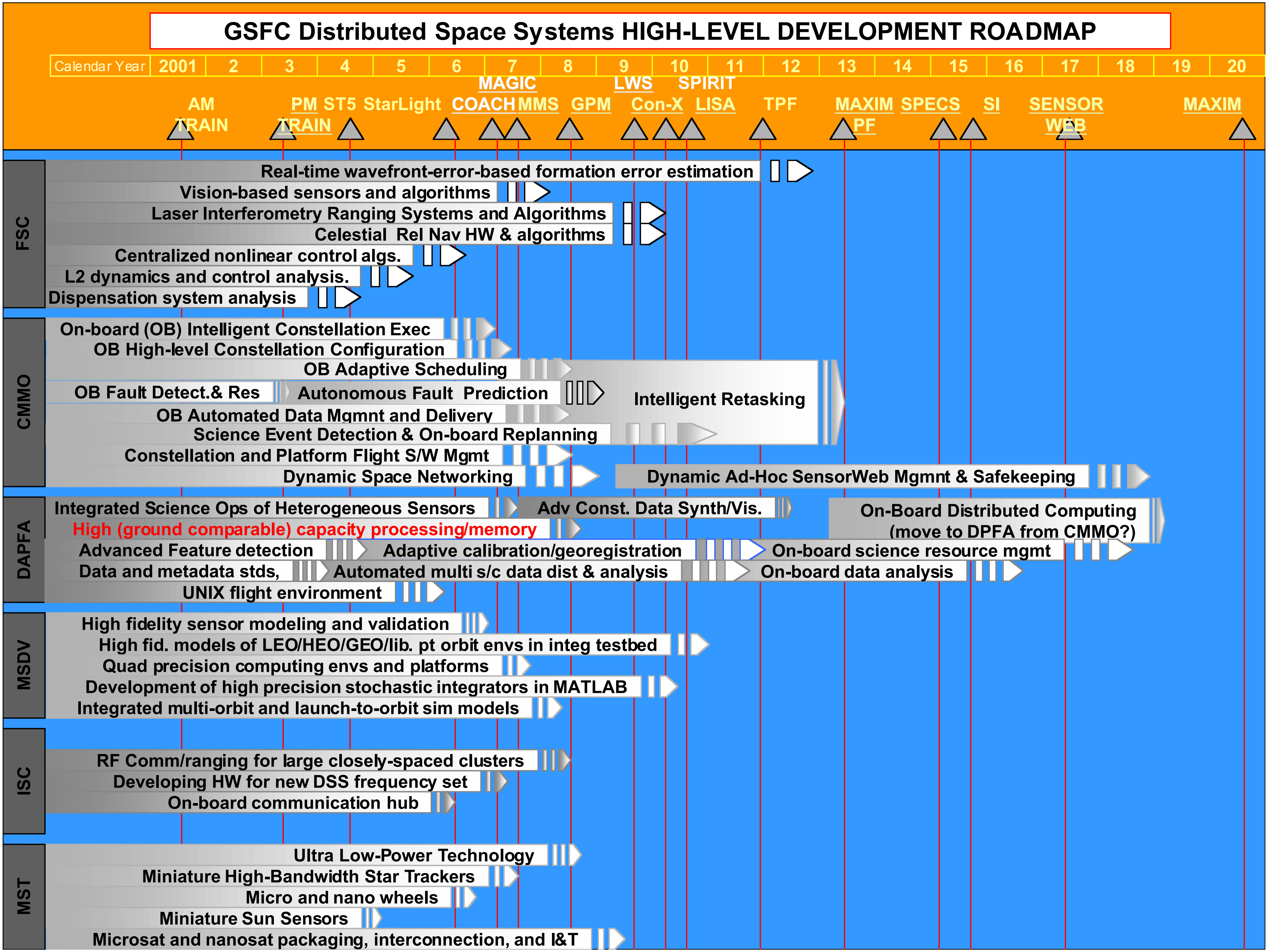
Mission Synthesis, Design, and Validation

The end-to-end DSS systems analysis



Data Acquisition, Processing, Fusion, and Analysis

Data operations of the DSS E2E system in fulfilling the scientific objectives

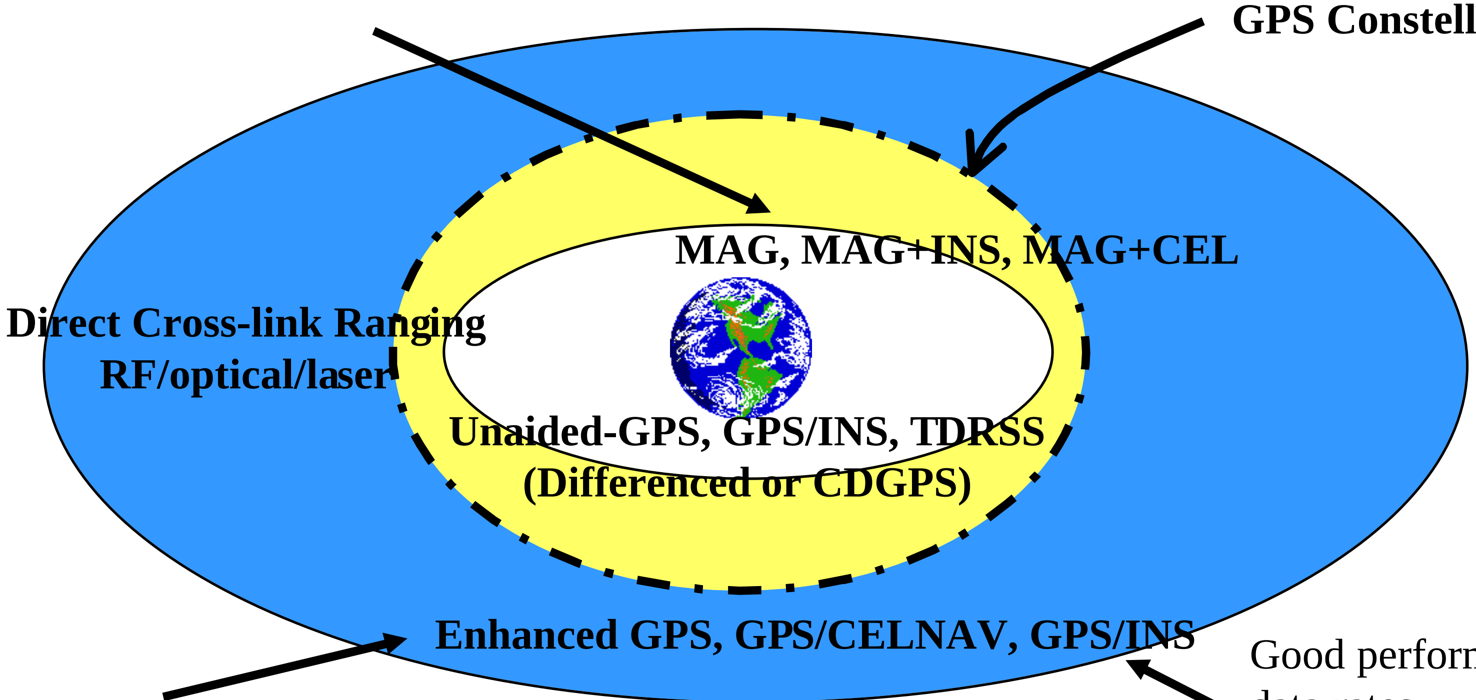


GSFC Distributed Space Systems HIGH-LEVEL DEVELOPMENT ROADMAP
Calendar Year 2001 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
AM TRAIN
PM TRAIN
ST5
StarLight
MAGIC COACH
MMS
GPM
LWS Con-X
SPIRIT LISA
TPF
MAXIM PF
SPECS
SI
SENSOR WEB
MAXIM
FSC
Real-time wavefront-error-based formation error estimation
Vision-based sensors and algorithms
Laser Interferometry Ranging Systems and Algorithms
Celestial Rel Nav HW & algorithms
Centralized nonlinear control algs.
L2 dynamics and control analysis.
Dispensation system analysis
CMMO
On-board (OB) Intelligent Constellation Exec
OB High-level Constellation Configuration
OB Adaptive Scheduling
OB Fault Detect.& Res
Autonomous Fault Prediction
Intelligent Retasking
OB Automated Data Mgmnt and Delivery
Science Event Detection & On-board Replanning
Constellation and Platform Flight S/W Mgmt
Dynamic Space Networking
Dynamic Ad-Hoc SensorWeb Mgmnt & Safekeeping
DAPFA
Integrated Science Ops of Heterogeneous Sensors
Adv Const. Data Synth/Vis.
On-Board Distributed Computing (move to DPFA from CMMO?)
High (ground comparable) capacity processing/memory
Advanced Feature detection
Adaptive calibration/georegistration
On-board science resource mgmt
Data and metadata stds,
Automated multi s/c data dist & analysis
On-board data analysis
UNIX flight environment
MSDV
High fidelity sensor modeling and validation
High fid. models of LEO/HEO/GEO/lib. pt orbit envs in integ testbed
Quad precision computing envs and platforms
Development of high precision stochastic integrators in MATLAB
Integrated multi-orbit and launch-to-orbit sim models
ISC
RF Comm/ranging for large closely-spaced clusters
Developing HW for new DSS frequency set
On-board communication hub
MST
Ultra Low-Power Technology
Miniature High-Bandwidth Star Trackers
Micro and nano wheels
Miniature Sun Sensors
Microsat and nanosat packaging, interconnection, and I&T

Relative Navigation

Low-cost approaches

GPS Constellation



Good performance at high data rates

CELNAV, WFE sensing

Enhanced receivers with integrated filter and tracking loops, weak signal acquisition and tracking capability.

Use sensors already on-board for attitude, safe-hold, etc.

Perhaps the only means of achieving “optical quality” figure errors of formations

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AMSAT Phase 3D (AO-40)

Experiment Objectives

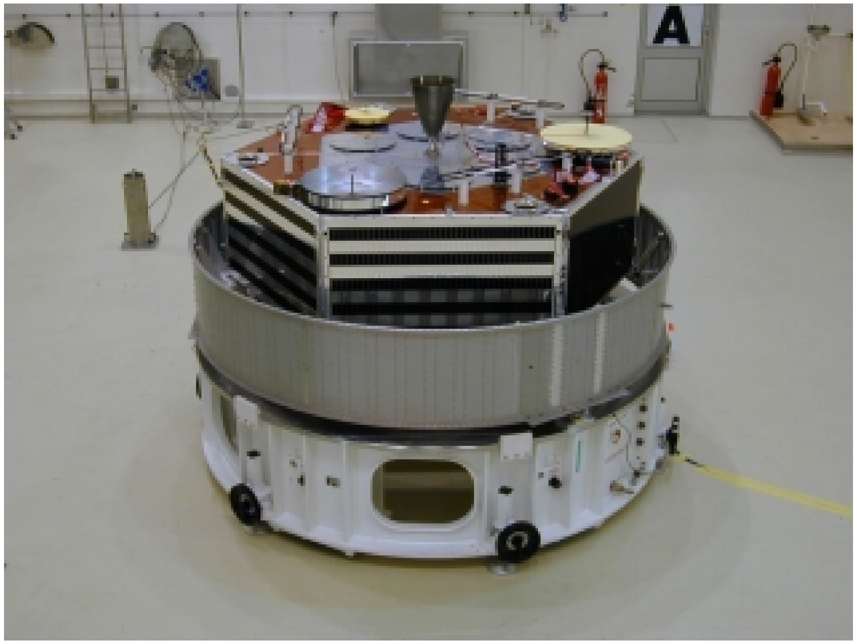
- Long term, real time attitude and orbit determination experiment
- Mapping the GPS constellation antenna patterns above the constellation
- Understanding the robustness and limitations of using GPS above the constellation

Team

AMSAT, NASA GSFC

GPS Hardware

- 2 Trimble Tans Vector Receivers
- 4 patch antennas on perigee side of spacecraft
- 4 high gain (10 dB) antennas on apogee side of spacecraft



AMSAT Phase 3D in Kourou

Launch: November 16, 2000
Vehicle: Ariane 5
Orbit: 1000 by 58,800 km, i=6

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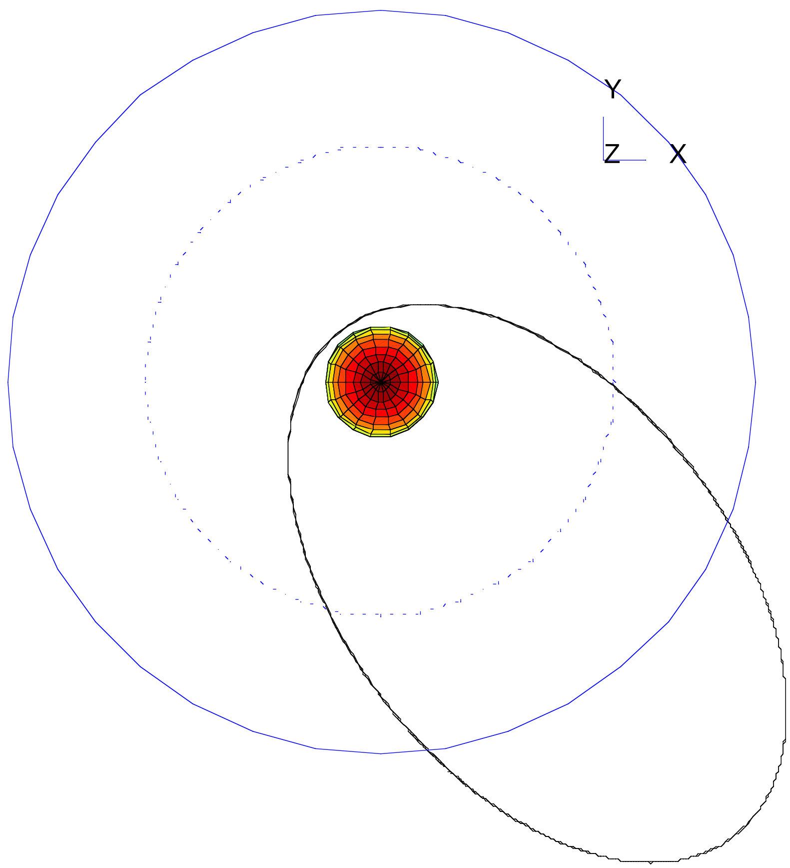
AO-40 Orbit with Geosynchronous & GPS Orbits Superimposed



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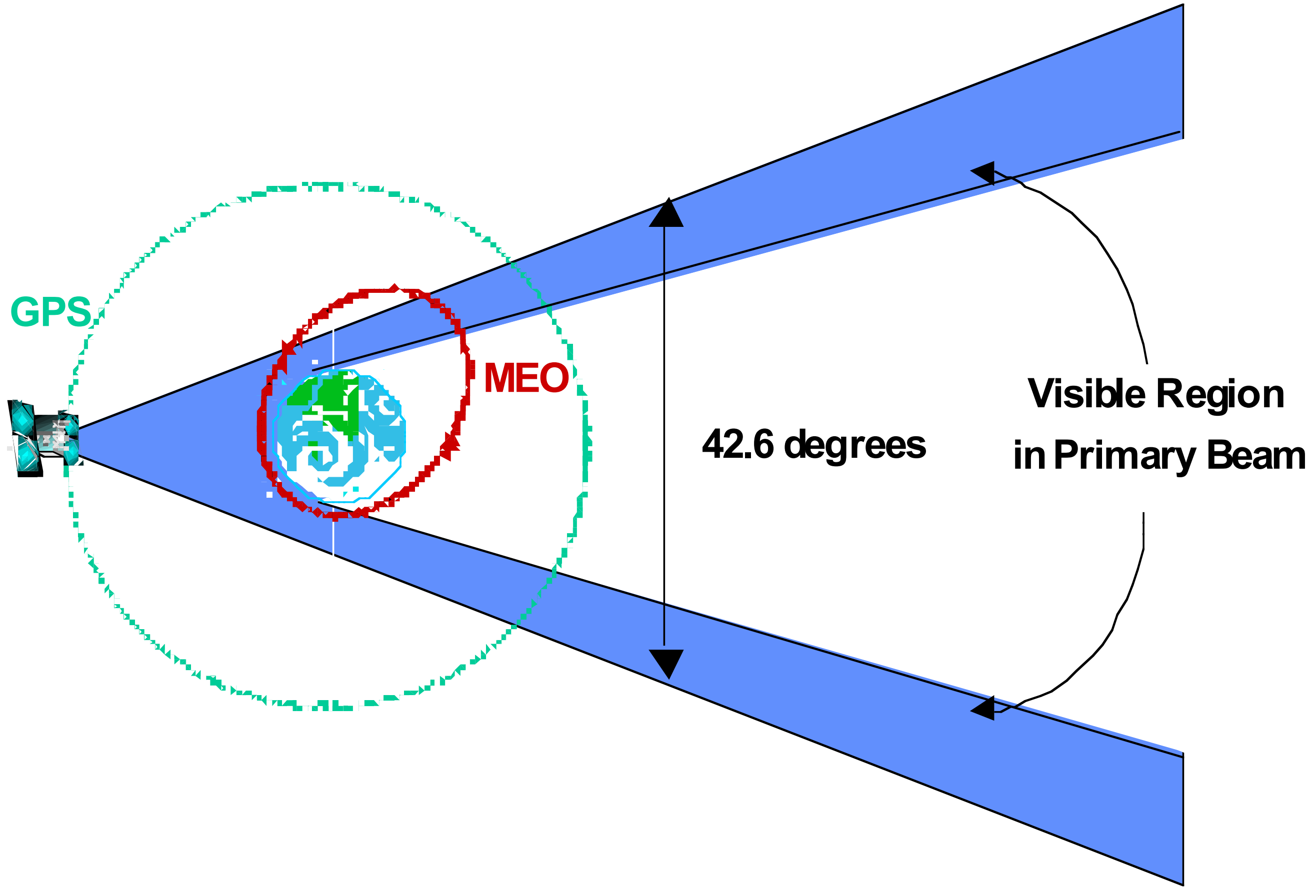
MEO Test Case



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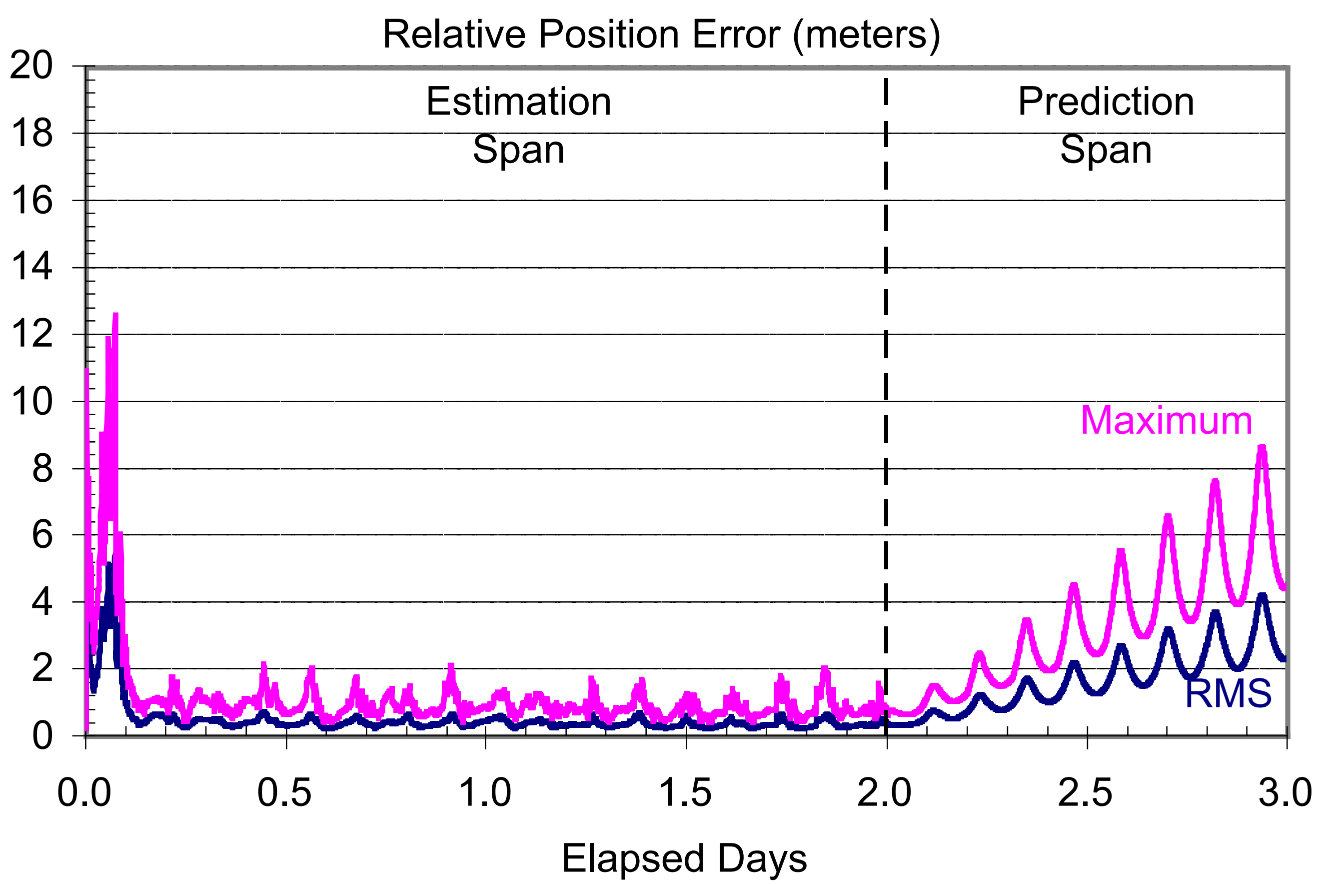
MEO Relative Position Accuracy



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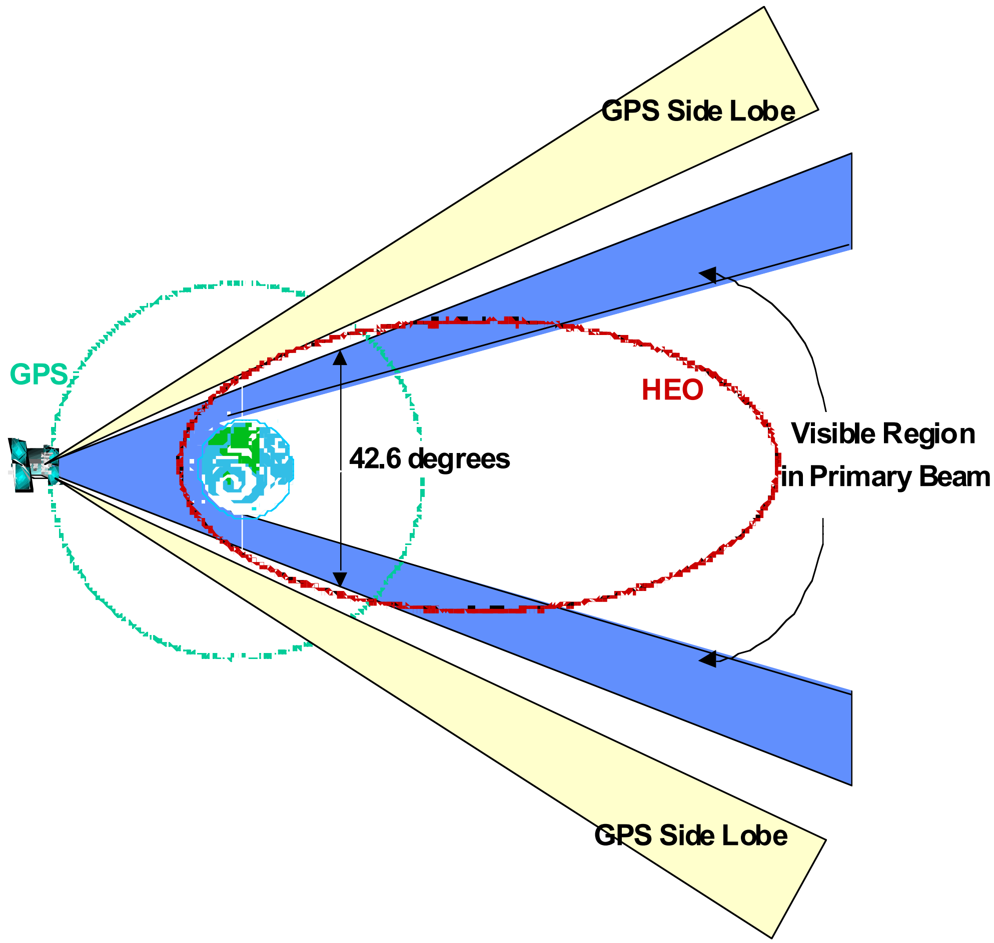
HEO Test Case



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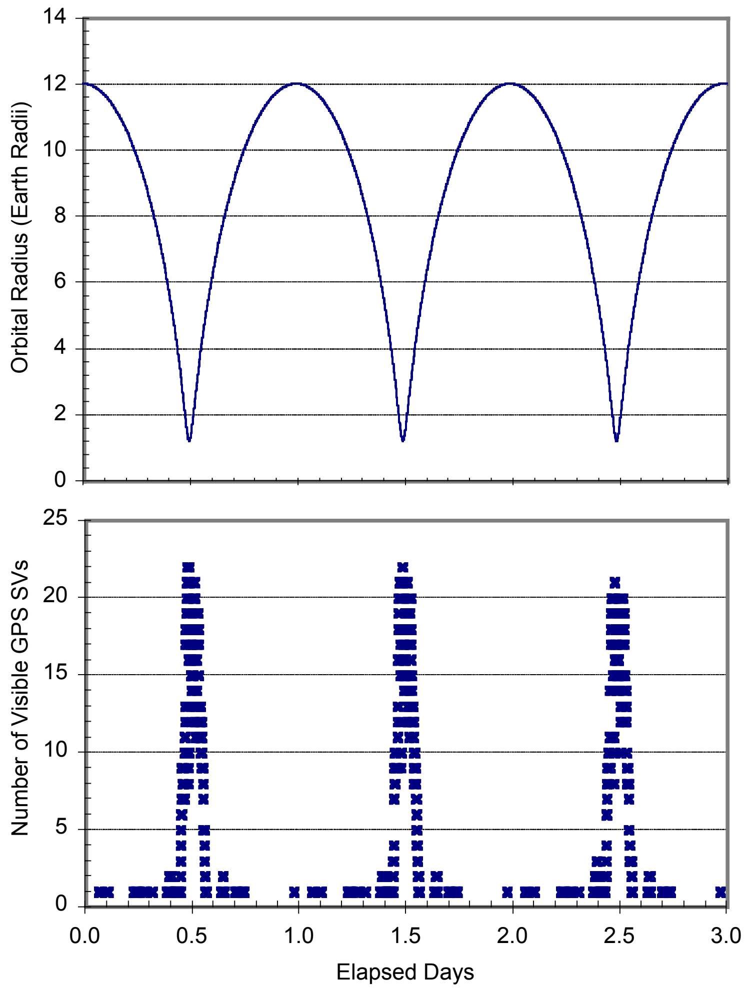
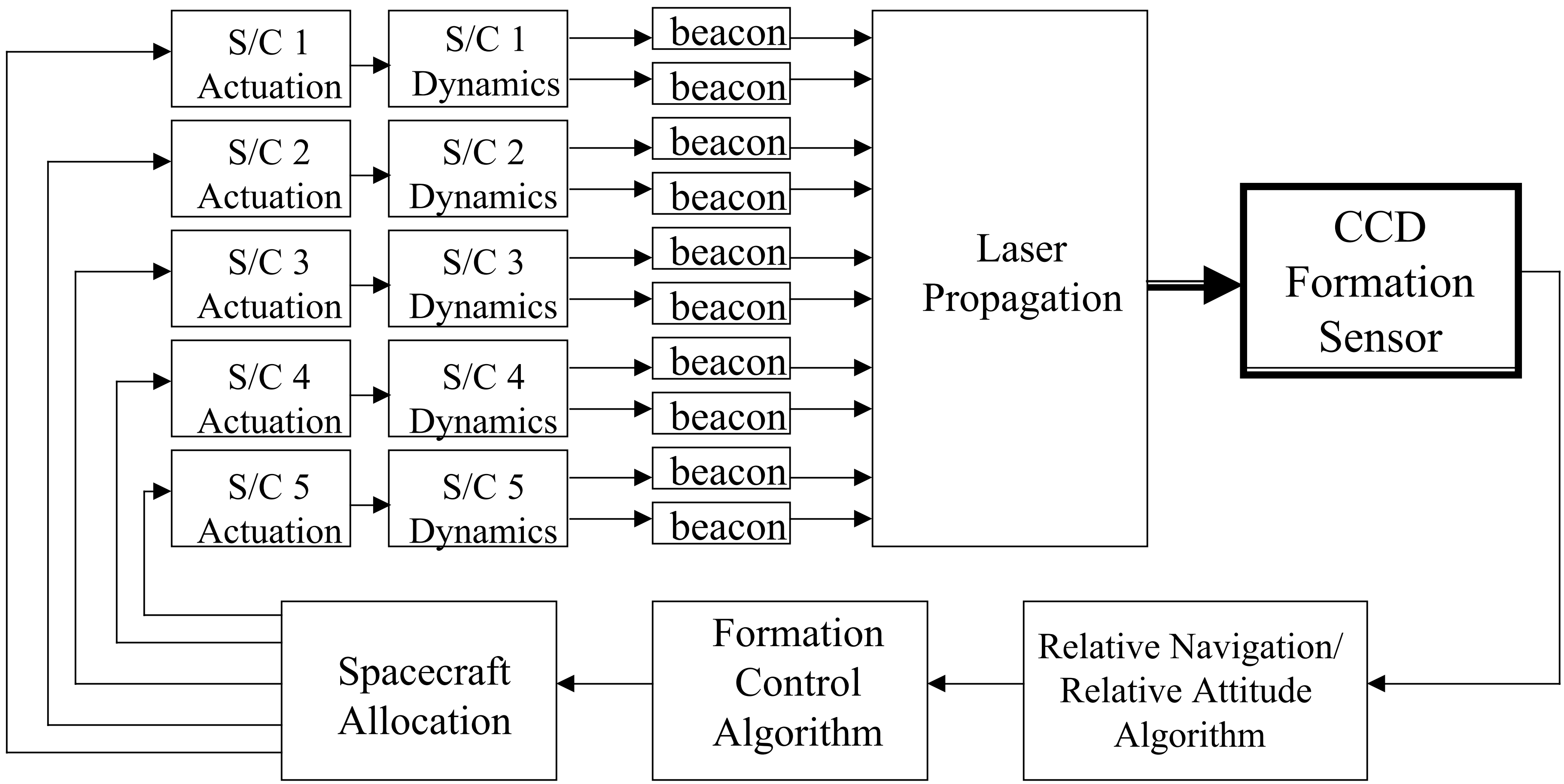
HEO GPS Visibility



Coarse Formation Alignment Block Diagram

(5 S/C example)



Wide dynamic range and fine resolution: formation modes

- **Lost-in-space/initial insertion**
- **Coarse vehicle placement**
- **Coarse vehicle orientation**

} GN&C

- **Formation initialization**
  - VISNAV/CCD/modified star tracker (25 mm lateral motions)
  - 3 color laser interferometer (10 nm distance from hub)
  - Star trackers on mirror-craft all tracking same guide star (as)
- **Capture**
  - mirrorcraft-to-mirrorcraft laser ranging required to get from 25 mm to 50 micron measurement accuracy
  - Other handoff values must be determined by ISAL analysis based partially on dynamic range of wavefront error sensing approach.
- **Calibration (backing out system parameters)**
- **Maintenance**
  - Real-time wavefront error sensing (e.g., phase diversity)
  - Mirror motion control
  - Continuous feep counterbalance on spacecraft

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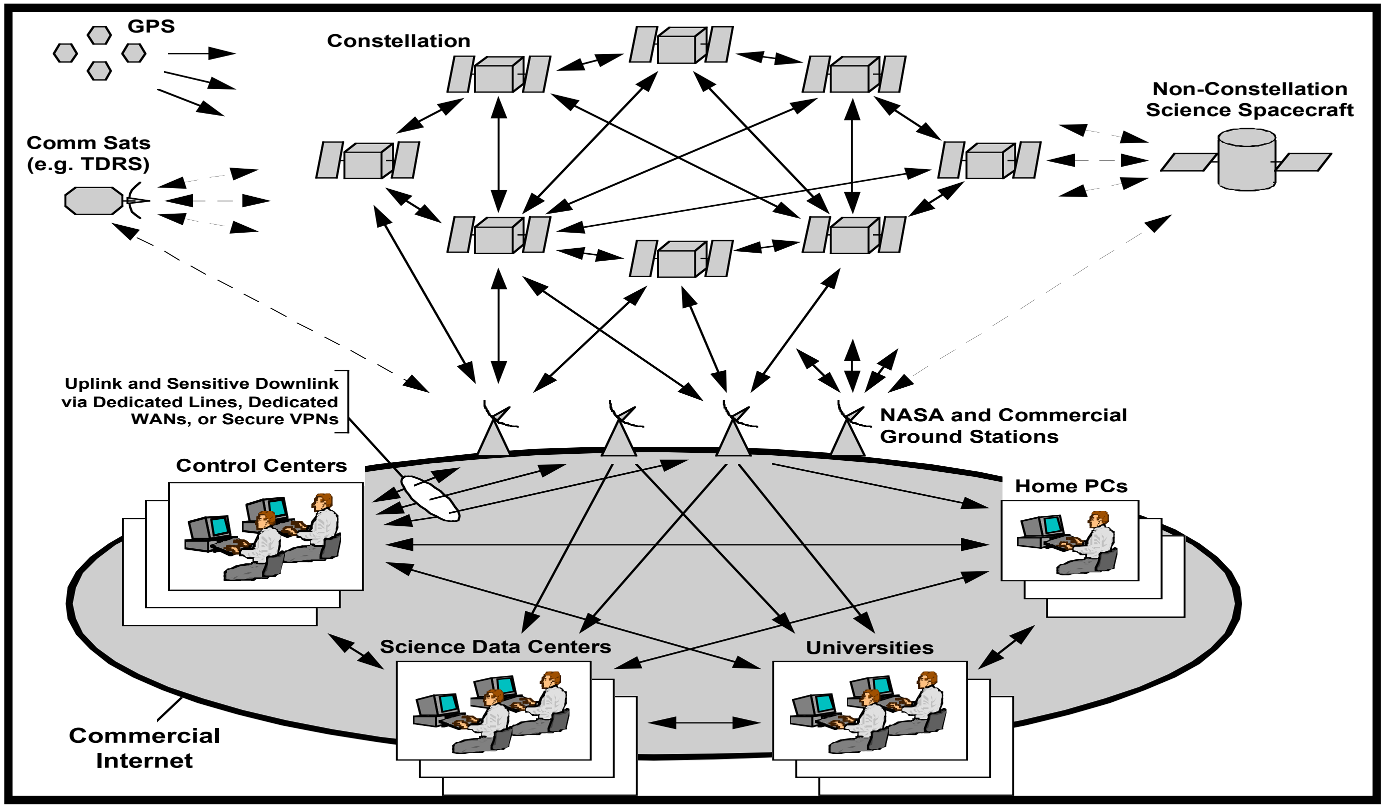
DFPA Scenario for DSS

- Distributed systems of spacecraft
- Distributed systems for ground-based processing
- Need for integrated space/ground data system
- Enormous data volumes



- Management of large constellations – command and control, flight dynamics, trending and analysis
- Collaborative planning and scheduling
- Fusion of dissimilar science data products from diverse instruments, locations

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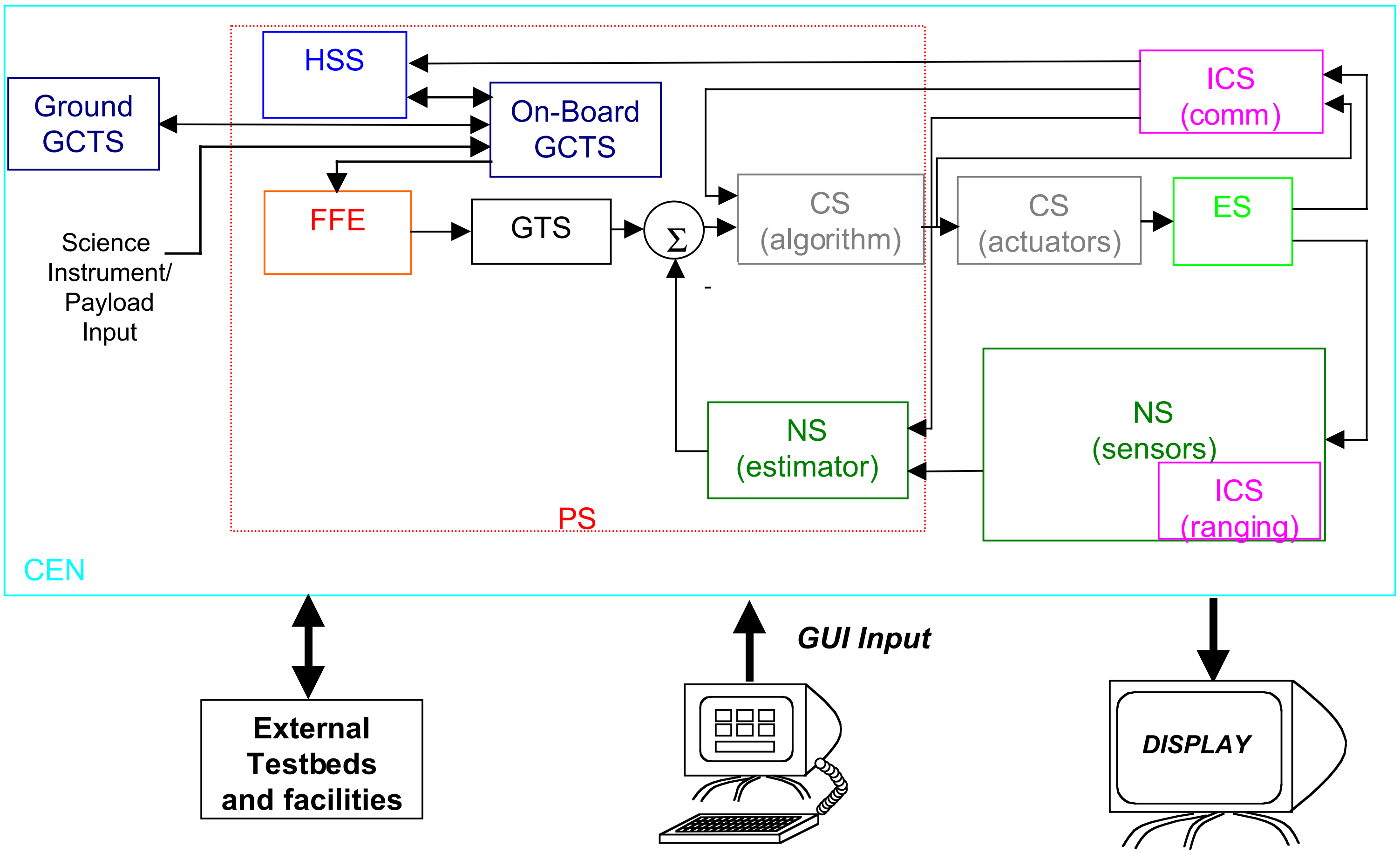
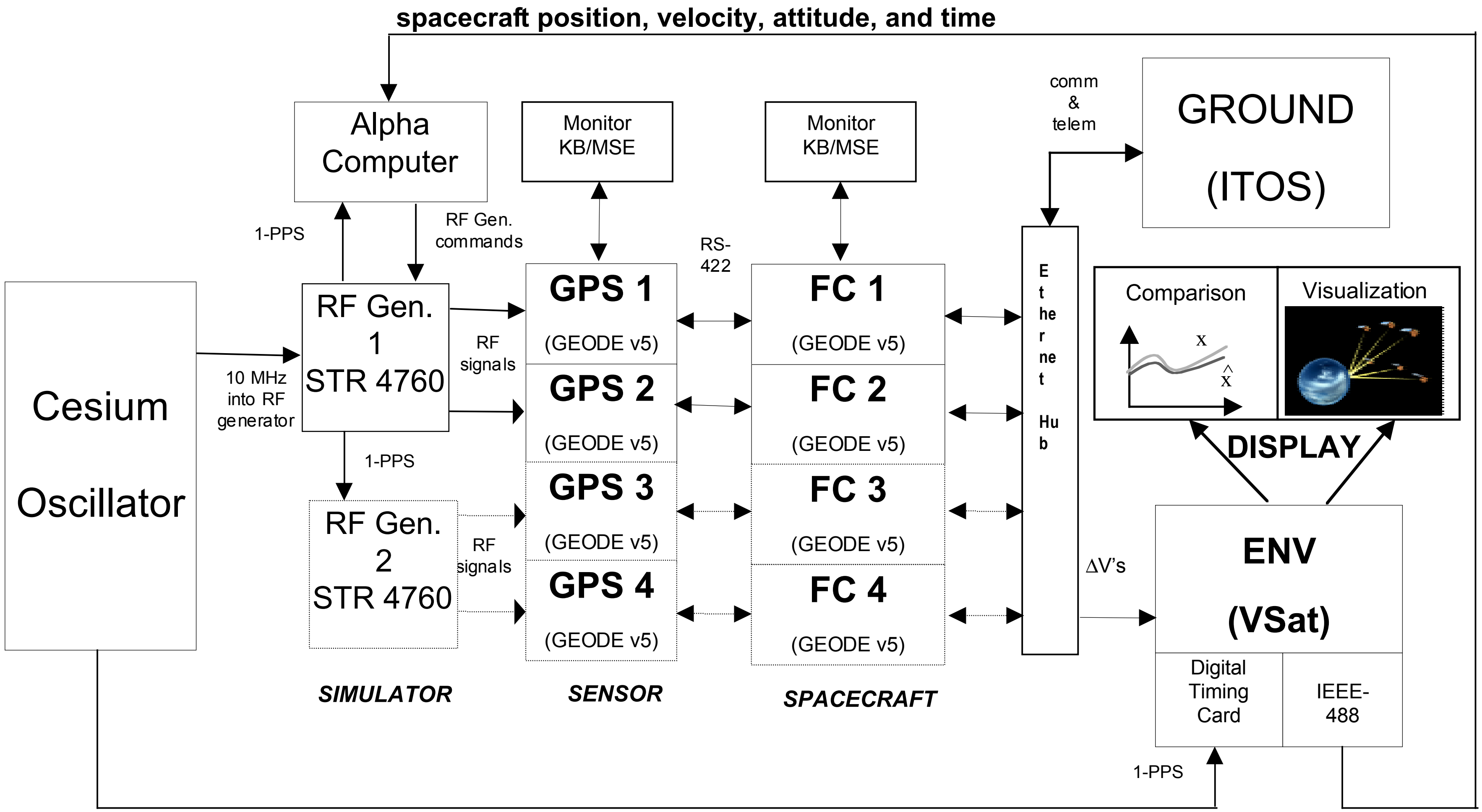
Formation Flying Testbed System Architecture



GCTS: Ground Control/Telemetry, **HSS: Health & Status**, **FFE: Formation Flying Executive**, **GTS: Guidance/Trajectory**, **CS: Vehicle Control**, **ICS: Intersatellite Comm**, **ES: Environment**, **NS: Navigation**, **PS: On-board Processing**, **CEN: Central Simulation Controller**

Decentralized Control Full Capability



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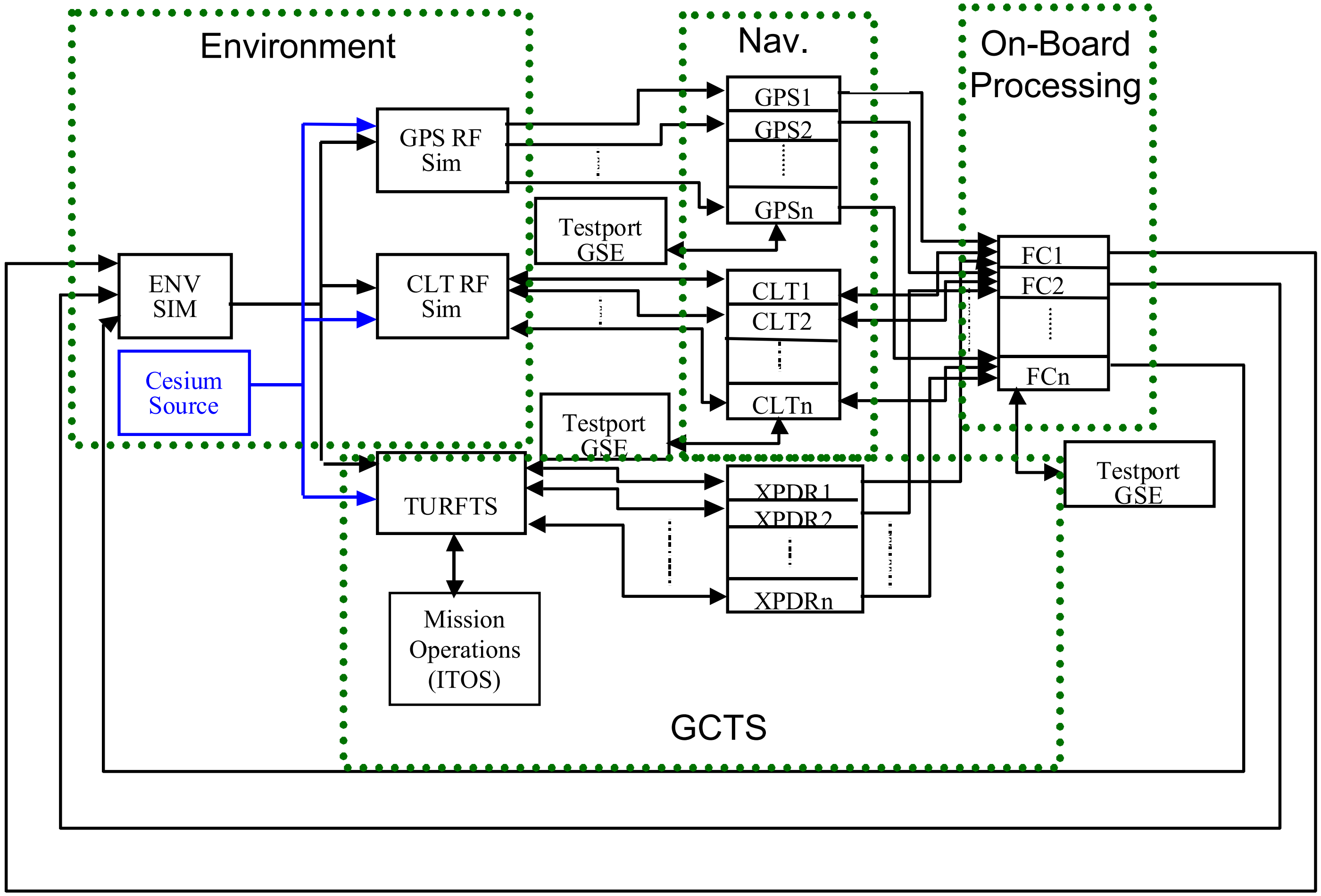
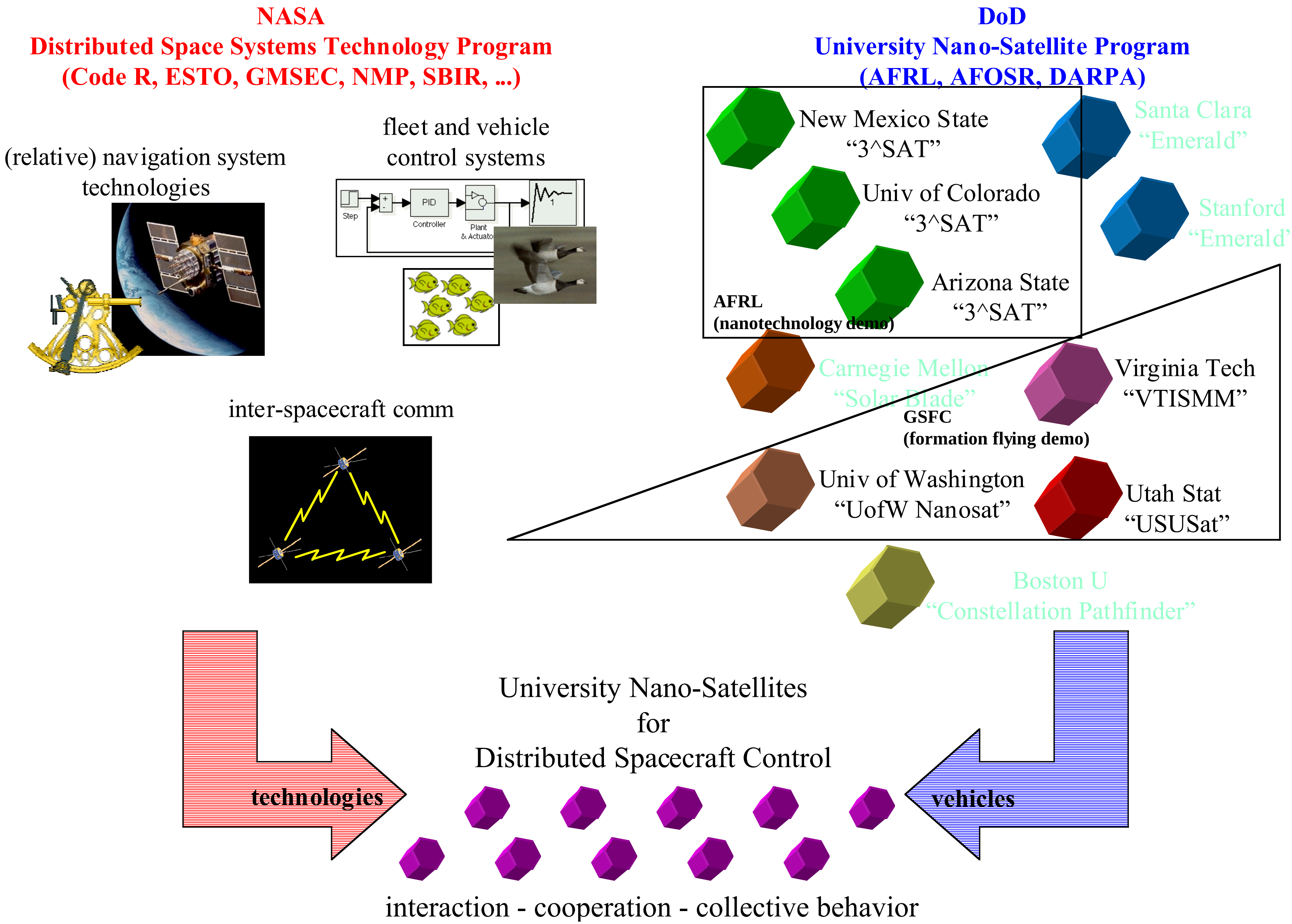
Full RF Formation Flying Simulation



NASA & the AFRL University Nanosat Program



Formation Flying Space Testbed: ORION

- Operational Characteristics
  - Mass: ~ 40 kg
  - Size: 45 cm cube
  - T_{max}: 0.2 N / thruster
  - ITB/M: 100 μm/s
  - MTL/M: 0.01 m/s^2

- GN_2 Propulsion System
  - 12 thrusters: 4x3 asymmetric
  - I_{sp} ~ 70 sec
  - ΔV_{total}: 25 m/s
  - torquer coils for detumbling
- Active station-keeping (cold gas) and 3-axis stabilization
- Advanced inter-spacecraft communication
- Relative sensing and control (carrier phase differential GPS).

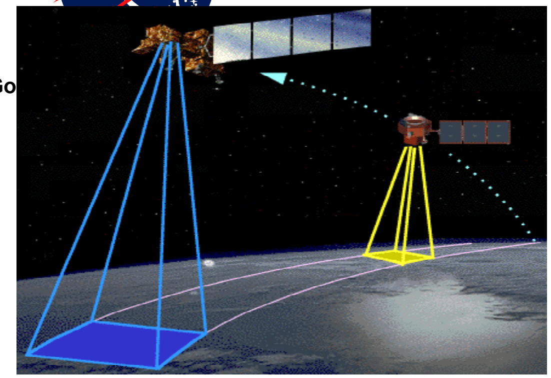
ORION2 Experiment Objectives

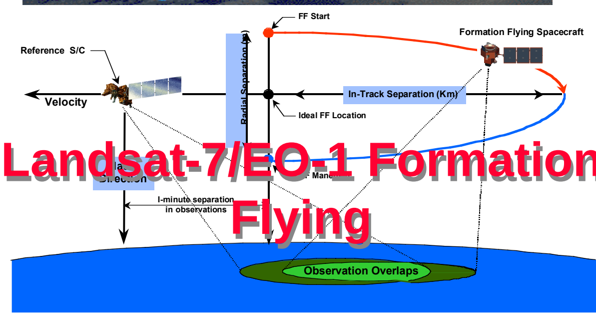
- **Provide a comprehensive on-orbit demonstration of true formation flying spacecraft**
  - Demonstrate technologies to enable a ***virtual platform***
  - GPS sensing and fleet control
  - Significant interest from both NASA & USAF
  - **Demonstrates the key technology element to be used on the TechSat-21 mission** ***(prototype of same hardware, algorithms, and software)***
- **Low-cost to NASA**
  - Micro-satellites developed using techniques from the Space Systems Development Laboratory.
- **High-risk, but**
  - Most technology developed in-house, so no major investments.

Technical Goals

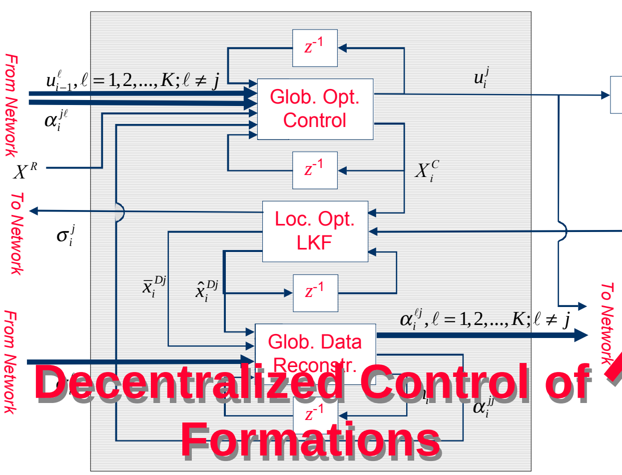
- **Demonstrate control for a cluster of micro-satellites.**
  - Real-time autonomous control software
  - Formation directed at a high-level from the ground.
- **Demonstrate GPS receiver for real-time attitude & relative navigation**
  - First on-orbit demonstration of CDGPS for precise relative navigation and control
  - Expect <<1 m (relative - radial) for determination & 5 m (relative - radial) for control.
  - Low-power, low-cost, attitude capable GPS receiver.
- **Various control architectures, real-time inter-vehicle communications link, and local ranging systems**

Integration and Infusion of DSS Technologies

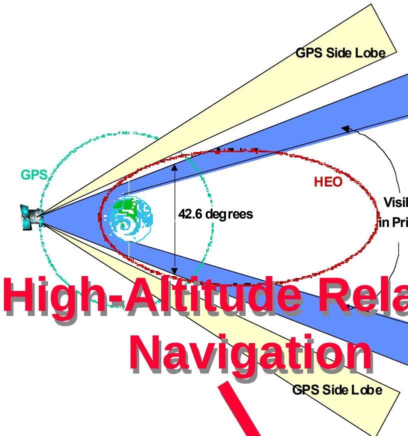




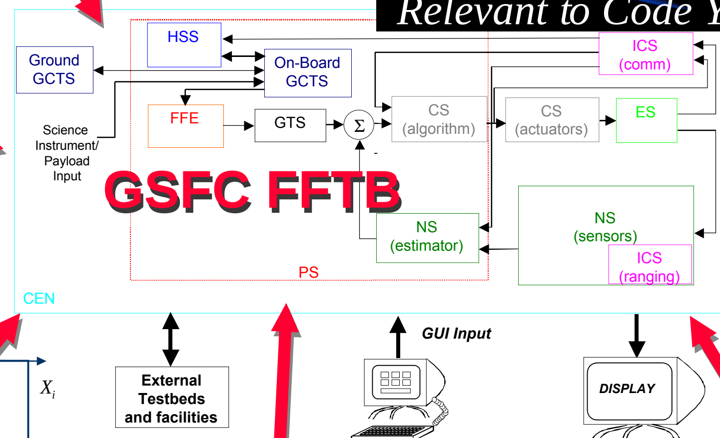
Landsat-7/EO-1 Formation Flying



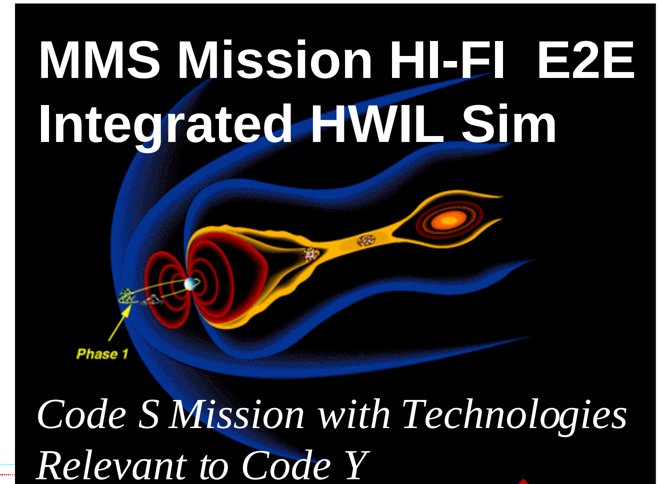
Decentralized Control of Formations



High-Altitude Relative Navigation



GSFC FFTB



- SOMO
- DDF
- Outside Partners

University NanoSats & Intersatellite Comm.

DSS- integrating and validating systems solutions to enable Enterprise multi-spacecraft missions

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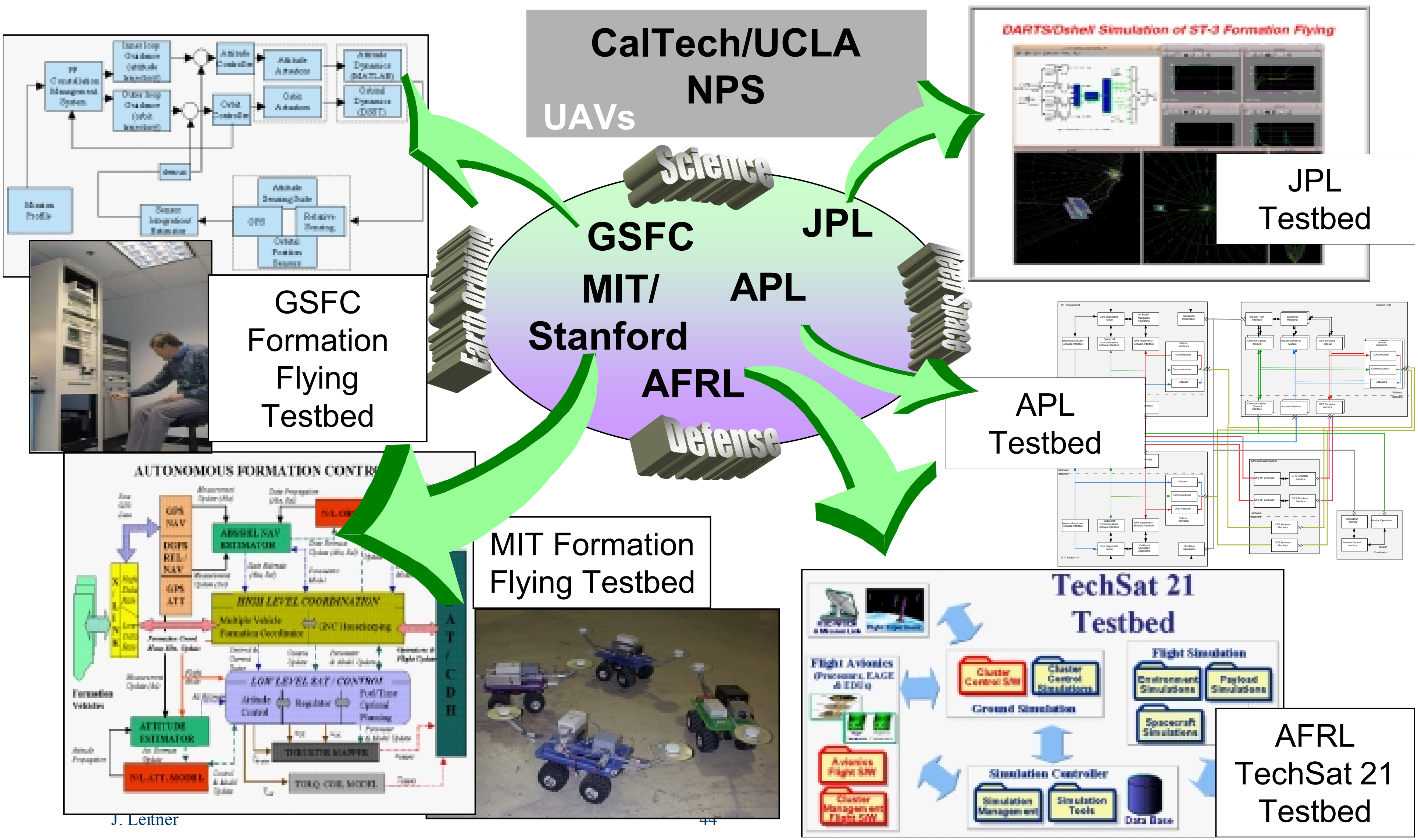
Formation Flying Testbeds



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Summary

- **The concept of DSS is opening new possibilities for science exploration from space**
- **Dozens of missions are in development or proposed to exploit DSS concepts and technologies**
- **Likewise, DSS technologies are enabling new mission concepts**
  - Tech push vs requirements pull
- **DSS cuts across all disciplines and encompasses the spacecraft, the instruments, the communication network, the ground system, and the data.**
- **DSS system development requires new processes for systems engineering and technology development**
  - Subsystems have much more significant inherent coupling
  - In many cases the science instruments and spacecraft bus components are fully integrated in the form of "sciencecraft"