Formation Flying: A New Architecture
for
Future Missions

Deep Space Communication and Navigation System (DESCANSO)

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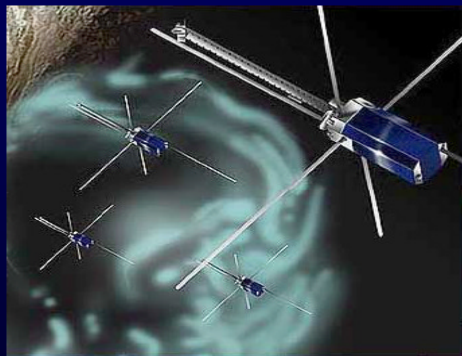
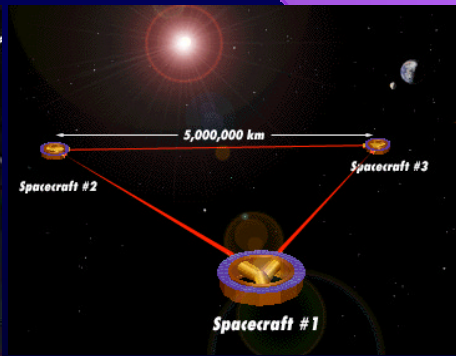
Agenda

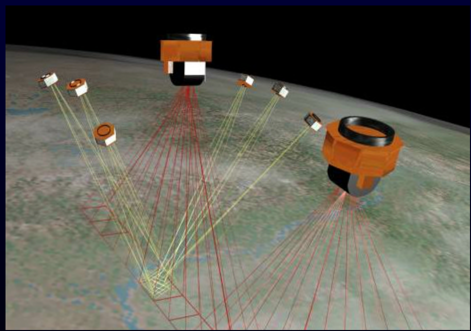
- **Overview of formation flying**
- **G&C differences between single and multiple spacecraft**
- **Key technologies for precision formation flying**
  - Methodologies and architectures
  - Components
  - Testbeds
- **Formation flying planned demonstrations**
- **JPL’s core capabilities in formation flying**
- **Imaging a light source simulation demo**
- **Summary**

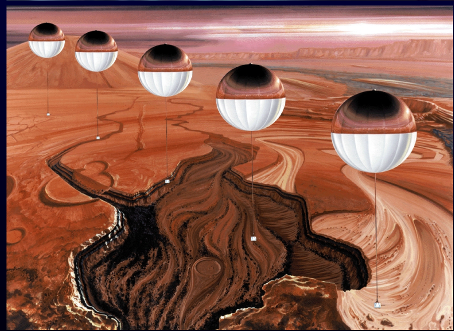
Formation Flying Spacecraft

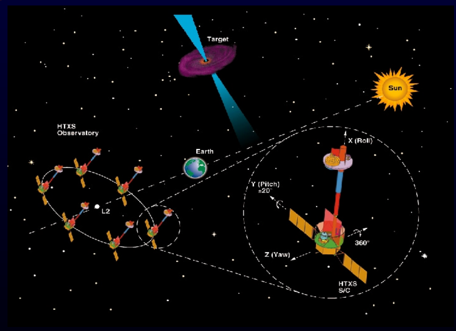
A Set of Spatially Distributed Spacecraft Flying in Formation with the Capability of Interacting and Collaborating with One-another, and Work as a Single Collective Unit, Exhibiting a System-wide Capability to Accomplish Shared Objectives











Future Distributed Mission Concepts

Partial List of Science Investigations Enabled by Distributed Spacecraft Systems:

- Planet finding and imaging
- Resolving the cosmic structure
- 3-D mapping for planetary explorers
- Time-varying gravity field measurements
- Gravity wave detection
- In situ magnetosphere and radiation
- Electrodynamics environment of near-Earth space
- Earth radioactive forcing
- Soil moisture and ocean salinity
- Atmospheric chemistry
- Global precipitation
- Coordinated observing for land imaging
- Vegetation recovery
- Space weather

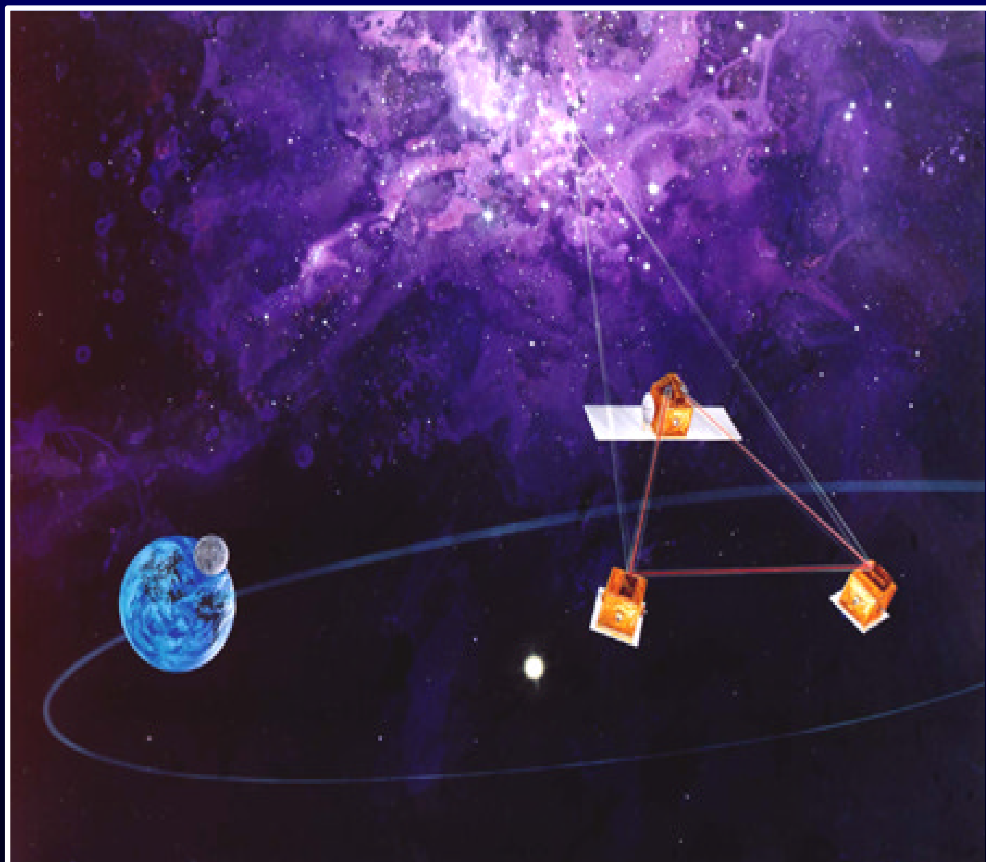
Planned Distributed S/C Missions

PROJECTED LAUNCH YEAR	MISSION NAME	MISSION TYPE
'00	New Millennium Program (NMP) Earth Observing-1	Earth Science
'01	Gravity Recovery and Climate Recovery (GRACE)	Earth Science
'03	University Nanosats/Air Force Research Laboratory Nanosat 1	Tech. Demo
'03	University Nanosats/Air Force Research Laboratory Nanosat 2	Tech. Demo
'03	NMP ST-5 Nanosat Constellation Trailblazer	Space Science
'04	Techsat-21/AFRL	Tech. Demo
'04	Auroral Multiscale Mission (AMM)/APL	Space Science/SEC
'04	Picasso-Cena (w/ Aqua)	Earth Science
'05	Magnetospheric Multiscale (MMS)	Space Science/SEC
'07	Global Precipitation Mission (EOS-9)	Earth Science
'07	Geospace Electrodynamic Connections (GEC)	Space Science/SEC

Planned FF Missions *- cont'd*

PROJECTED LAUNCH YEAR	MISSION NAME	MISSION TYPE
'08	Constellation-X	Space Science/SEC
'08	Magnetospheric Constellation (DRACO)	Space Science/SEC
'08	Laser Interferometric Space Antenna (LISA)	Space Science/SEC
'09	DARWIN Space Infrared Interferometer/European Space Agency	Space Science
'10	Leonardo (GSFC)	Earth Science
'15	Terrestrial Planet Finder (TPF)	Space Science
'25	Stellar Imager (SI)	Space Science/ASO
05+	Living with a Star (LWS)	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

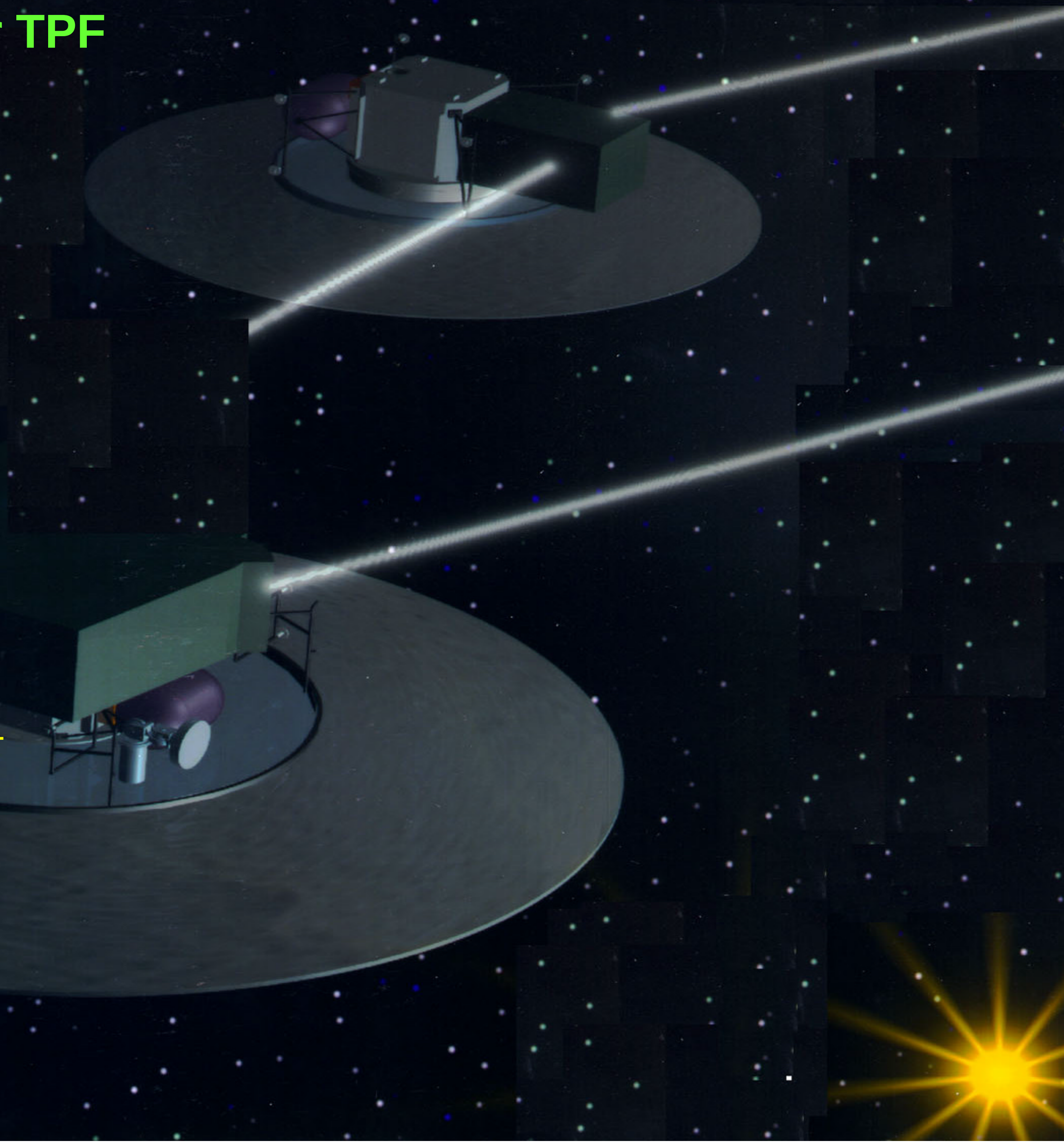
ST-3



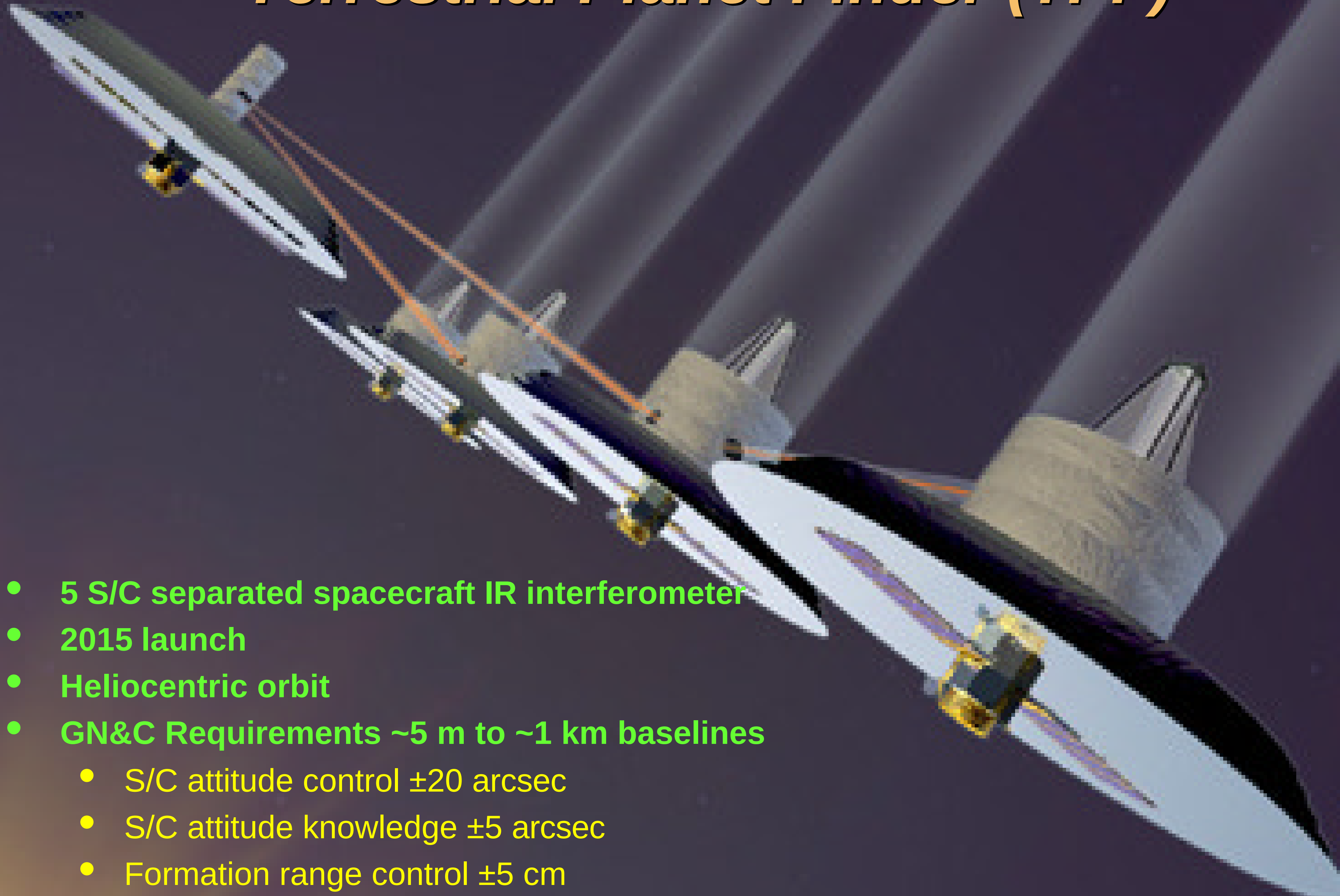
- **Precision Formation of Multiple Spacecraft Form a Single Virtual Science Instrument**
- **Increased Performance, Accuracy and Reliability**
  - Interferometric Imaging Without Large Truss
  - Distributed Computing via Interspacecraft Communication
  - No Single Point Failures
  - Autonomous Formation Keeping, Alignment and Reconfiguration

Starlight

- **Two (2) S/C mission**
- **Technology demonstration for TPF**
  - Formation flying
  - Separated S/C optical interferometry
- **March 2006 launch**
  - Delta II 7325
- **Heliocentric orbit**
- **6 month mission**
- **GN&C Requirements**
  - 50 to 1010 m baselines
  - S/C attitude control ±1 arcmin
  - S/C attitude knowledge ±10 arcsec
  - S/C translational velocity control ±0.1 mm/sec
  - Formation range control ±3 cm
  - Formation bearing control
    - Acquisition ±0.7 arcmin
    - Observation ±6.7 arcsec

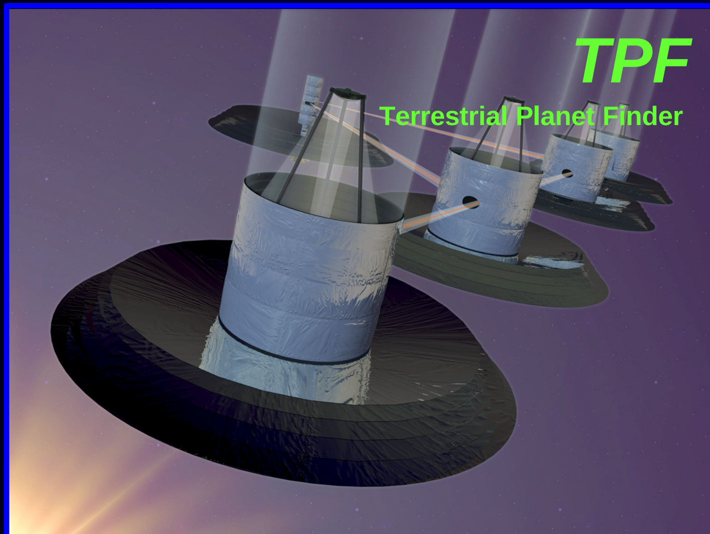


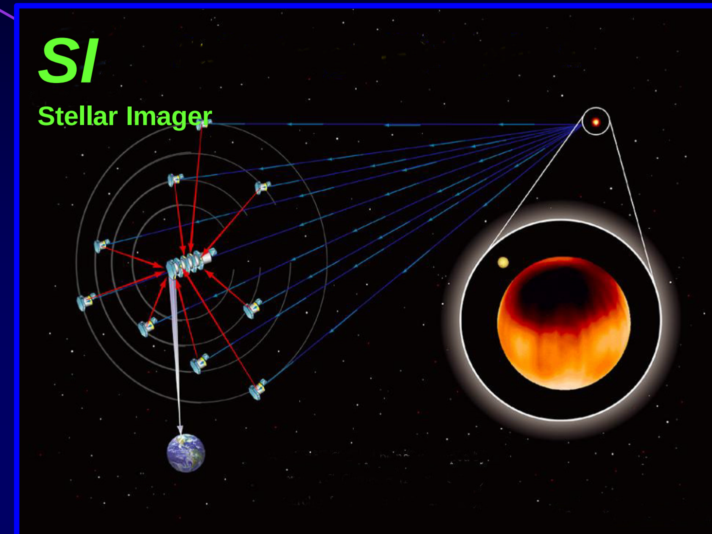
Terrestrial Planet Finder (TPF)

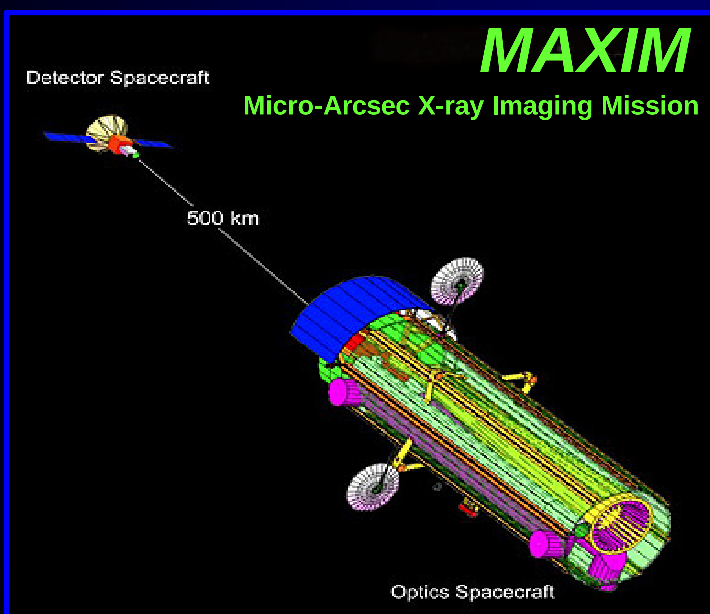


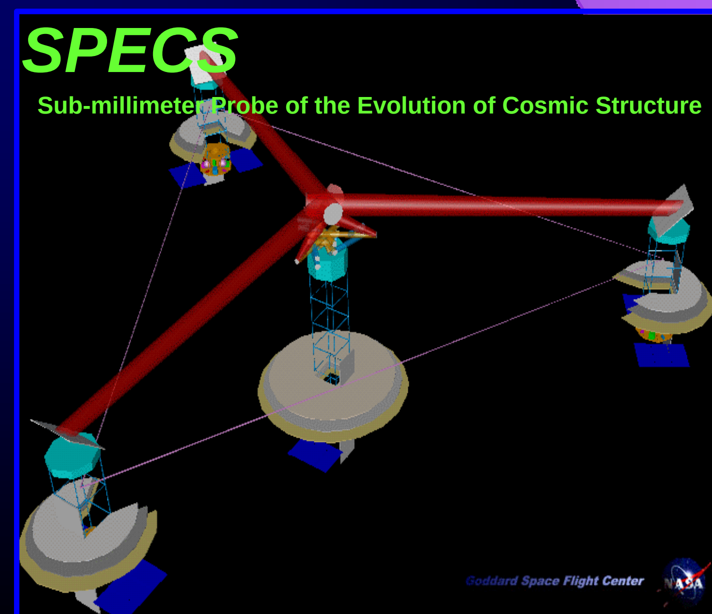
- **5 S/C separated spacecraft IR interferometer**
- **2015 launch**
- **Heliocentric orbit**
- **GN&C Requirements ~5 m to ~1 km baselines**
  - S/C attitude control ±20 arcsec
  - S/C attitude knowledge ±5 arcsec
  - Formation range control ±5 cm
  - Formation bearing control ±5 arcmin

Other FF Missions



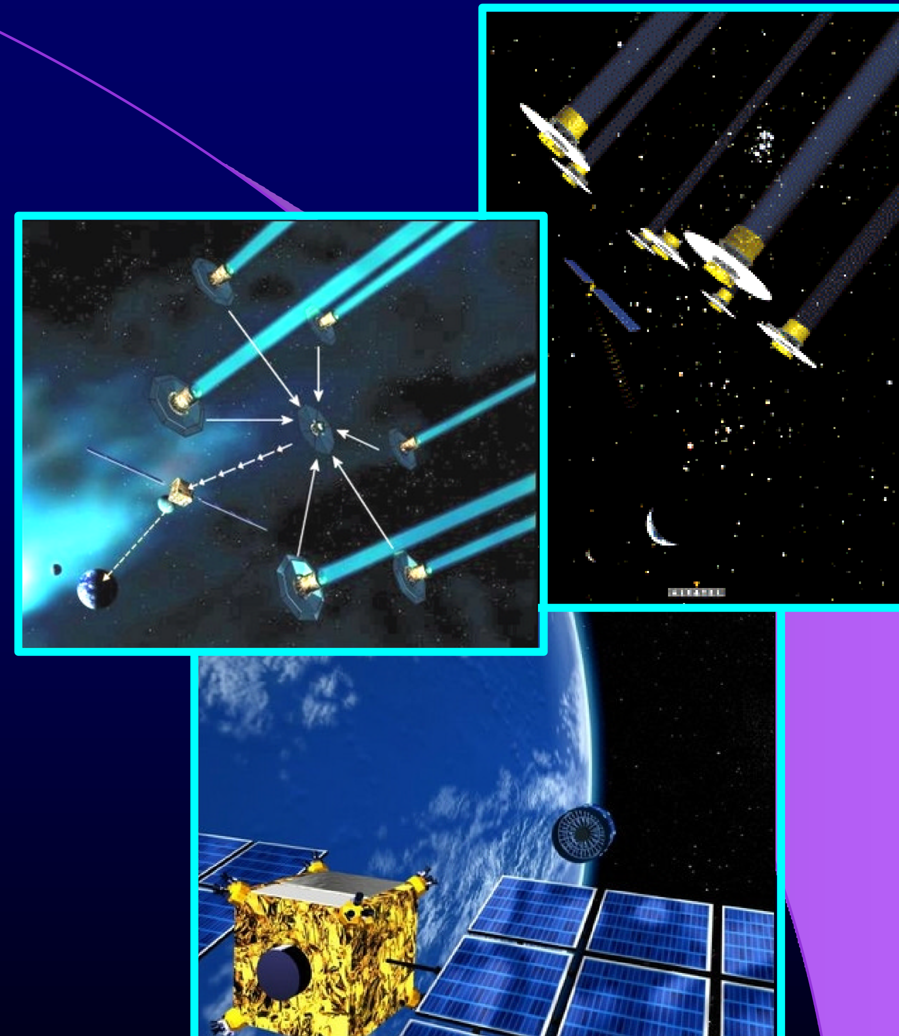






Other Missions

- **ESA**
  - DARWIN
  - XEUS
- **DOD**
- **Academia**
  - Stanford
  - MIT
  - Michigan
  - UCLA
  - UCSB
  - BYU
  - U of Washington
  - Others



XEUS (2007): x-ray telescope with mirror s/c 50 m ahead of detector s/c, control to mm, in earth orbit

G&C Differences from Single S/C

- **Hybrid Architecture**
  - Formation representations, commanding, centralized/decentralized
  - Distributed/hierarchical estimation and control
  - Highly coupled attitude and translation degrees of freedom
  - Commanding/coordinating 6 dof for all S/C in the formation
- **Separated platforms and processors which brings about the possibility of shared responsibilities**
  - Distributed information, computation, and inter-spacecraft communication
  - Shared functions/measurements
  - Time-tagging uncertainties, and delays
  - Processing asynchronous measurements & estimation
  - Additional data type fusion
  - FF sensor (relative attitude and relative position measurement sensors)

G&C Differences from Single S/C - cont'd

- **Distributed guidance and control**
  - Optimal allocation of control authority for 6dof maneuvering
  - Local path planning capability on each S/C, or by a central authority or a hybrid approach
  - Integrated relative position & inertial attitude estimation
- **Planning of coordinated relative motions**
  - Relative motions planning to balance consumption of fuel among all S/C
  - Path planning to avoid collisions
  - Path planning to avoid glint/contamination from neighboring plumes

Formation Flying Control Fundamentally Different from Single Spacecraft Control

Differences Between Deep Space and Earth Orbiting Formation Flying

- **Deep Space**
  - High level of accuracy requirements
    - Precision control of relative inter-spacecraft positions (centimeter & better) and attitude alignment (arc-minute & better), precision synchronized motions and bearing angle accuracy
  - Absolute position determination & control of each spacecraft in inertial space not important
  - Real time, autonomous capabilities for all deep space formations
- **Earth Orbiting**
  - Meter class control
  - Large number of spacecraft
  - Absolute position determination & control of each spacecraft wrt. Earth
  - Can be non-realtime, ground in the loop formations
  - Re-configurable formations, high fidelity environmental modeling (gravity, drag), orbital dynamics, fuel optimal station keeping
  - Use of existing sensor network infrastructure (GPS)

Technology Challenges

- **Formation control**
  - Hi precision sensors
  - Synchronous reconfiguration/reorientation
  - Decentralized/centralized distributed control and estimation
  - Precision relative position and inertial attitude control for interferometry
- **Extremely high precision/low noise thrusters, wheels, etc.**
- **Communication, cross-links, downlinks**
- **High speed distributed computing, data management & autonomy**
  - Collaborative behavior
  - Autonomous fault detection/recovery
  - Coordinated instruments and science planning/processing
  - Efficient numerical integrators which handle large scale variations in states (relative position and attitude)
- **High fidelity modeling and distributed real-time simulation**
- **HW Testbeds**
  - Ground testing of 6dof

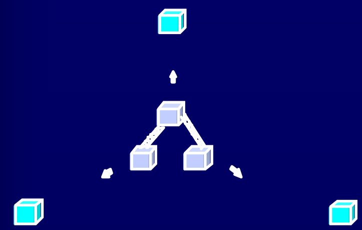
Formation G&C - Key Technologies

Key FF Tech. \ Missions	StarLight/ TPF	MAXIM Pathfinder	SI	SPECS
Architecture				
Master/Slave	Y	-	-	-
Scaleable	-	Y	-	-
Fault Tolerant	Y	Y	Y	Y
Relative Sensor	RF+MET	-	RF+Laser+MET	-
Relative Range/Bearing	Y	Y	Y	-
Estimation				
Data Fusion (multi-rate/res.)	Y	Y	Y	Y
Calibration	Y	Y	Y	Y
Guidance				
Path Planning – 6DOF	Y	Y	Y	Y
On-the-Observation	Y	Y	Y	Y
Collision Avoidance	Y	Y	Y	Y
Lost-in-space Acquisition	Y	Y	Y	Y
Control (Relative+Inertial)				
Hierarchical/Distributed	Y	Y	-	-
Coordinated	Y	-	-	-

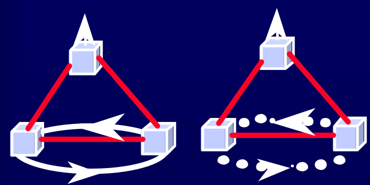
Y = Applicable **- = Insufficient Information**

Formation Flying G&C Algorithms

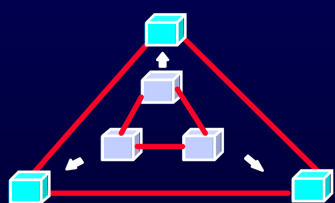
Unique Capabilities



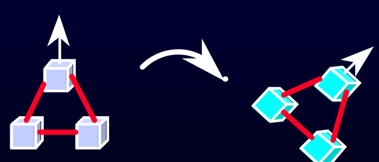
Formation Initialization



Formation Observation Slew



Formation Resizing



Formation Retargeting Slew

- Precision alignment (mm-cm, arcsec- arcmin), synchronized motions, and autonomous reconfigurations of spacecraft.
  - formation acquisition,initialization & maintenance, station keeping
  - formation maneuver planning and execution
  - fault detection and recovery

- Underlying Technologies:
  - Autonomous guidance and control algorithms, software, and testbeds
  - Scalable FF control architectures
  - Formation estimation algorithms
  - Testbed Demonstration of precision translation and synchronized rotations
  - Precision formation controls optimized for time and/or fuel
  - Data fusion of high number of formation sensors across many spacecraft
  - Algorithms for optimal u-v plane mapping of science target
  - Optimal Path planning
  - Collision avoidance

Guidance & Control Approach

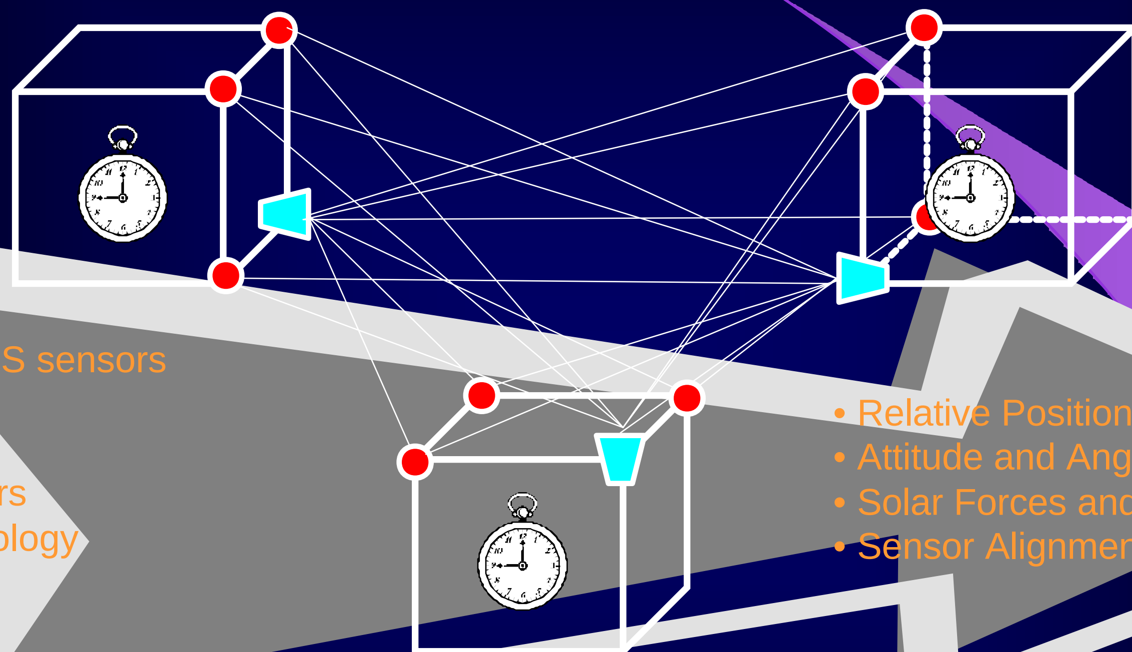
- **Rule-based estimation and controls for the coordination and control**
- **Why rule based? The control rules are determined by the occurrence and time duration of certain discrete-event sequences.**
  - Main advantages:
    - Handles complexity, modeling uncertainties with robustness.
    - Control rules can be developed using sensor data directly without extensive processing and system dynamic models.
    - Control laws are in the form of logical statements that can be easily programmed.
- **Multi-mode controllers for acquisition, alignment, and synchronized motions.**
- **Computationally efficient and robust algorithms for formation estimation.**
  - Centralized vs. decentralized architectures, rule-based estimators to avoid computational complexities (e.g. on-board solution to Riccati equation for Kalman filtering)

Guidance & Control approach *(Cont'd)*

- **Graph-theory-based formation representations for estimation and control.**
  - Can conveniently describe information flow or availability of information at at a given incidence.
  - Graph will describe flow of inter-spacecraft communication
  - Estimation graph will describe availability of state information
- **Testbeds to validate distributed sensing, estimation, communication, and control system experimentally.**
- **Investigate new potential formation control problems in end-to-end high-fidelity simulations and laboratory experiments.**

Formation Estimation

Unique Capability



- Formation/GPS sensors
- Star Tracker
- Gyro
- Accelerometers
- Inter-s/c Metrology

- Relative Position, bearing and Velocities
- Attitude and Angular Rate
- Solar Forces and Torques
- Sensor Alignments and Biases

- Order n^2 state estimation problem
- Centralized/decentralized
- Asynchronized data type
- Integrated position/attitude estimation
- Relative state (range/bearing, attitude) estimates are highly coupled

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Formation Flying Simulation
Unique Capabilities

- **Challenging formation-pointing/path-length control requirements**
  - High-precision simulations
  - Large dynamic-range of spatial scales - many km's to sub-micron
- **Coupled dynamical systems for pointing, pathlength & vibration control**
  - spacecraft; siderostats, fast steering mirrors, flexible collectors, optical delay line, voice-coil, piezo-actuator, active vibration isolators.
  - Many modes and degrees-of-freedom
  - Distributed simulation
- **Wide dynamic range - natural frequencies - 0.1 hz to > 2 khz**
  - Mixed time steps numerical integration and special integration algorithms needed
- **Control system loop closures across multiple spacecraft**
  - Complicates partitioning of simulations (e.g. Mapping onto different cpu's)
- **Simplified/abstracted simulation modeling for analysis & design**
  - Kinematics and/or noise disturbance approximations to individual subsystems
  - Reduced order modeling & simulation
- **Distributed clocks & channel delays across multiple spacecrafts**
- **Real-time performance to support hardware/system-in-the-loop tests**

TPF Spacecraft Systems Simulation

Path Length Control

Fringe Position (1 KHz) → **COPHASING SYSTEM**
Laser Metrology (3-5 KHz) →
Accelerometer (3-5 KHz) →

COPHASING SYSTEM

Optical Delay Line (ODL)

- Translation Cart (~10cm, 1 mm, 0.1 Hz)
- Voice Coil (~1 cm, 1 mm, 10-20 Hz)
- Piezo Stack (~1 µm, 5 nm, ~1 KHz)

Autonomous Formation Flying (AFF) Positions (50 Hz) → **SPACECRAFT SYSTEM**

SPACECRAFT SYSTEM

Station Keeping

- Thrusters (~5 km, 1 cm, 1 Hz)

Pointing Control

Star-field centroid dist. (~few 100 Hz) →

COPHASING SYSTEM

Fast Steering Mirror (FSM)

- 2-axis flex-pivoted tip/tilt (10 arc-sec, 2 milli-arc-sec, 200 Hz)

Fine Guidance Sensor (~200 Hz) →

SIDEROSTAT SYSTEM

Alignment Struts

- Cryo Actuators (~30deg, 1 arc-sec, 50 Hz)

Gyro (few 10 Hz) →
Star Tracker (2 Hz) →

SPACECRAFT SYSTEM

Spacecraft Attitude

- Reaction Wheels (15 arc-sec, 1arc-sec, ~10 Hz)

Autonomous Formation Flying (AFF) Attitude (50 Hz) →

FORMATION SYSTEM

Relative Attitude (Bearing)

- Reaction Wheel (360 dg, 2-4 arc-min, ~25 Hz)

Vibration Control

Mode Velocity (100 - KHz) →

ISOLATION SYSTEM

Reaction Wheel & Optical Subsystem Isolation

- Hexapod with Active Damping (~mm, < 1 mm, ~5 KHz)

- **Multiple Spacecraft**
- **Rigid & Flex Dynamics**
- **Instrument Dynamics**

Input Data Annotated with representative **Sample Rates**
System Data Annotated with representative **Control Ranges, Control Accuracy/Jitter, Closed-Loop Bandwidths**

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Formation Actuation Technologies

Formation Flying Needs:

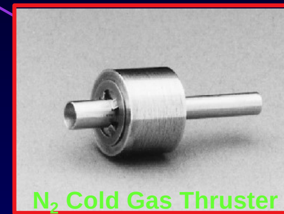
Coarse actuation for gross retargeting and formation reconfiguration, and
Precision actuation for stable and accurate pointing for science observations

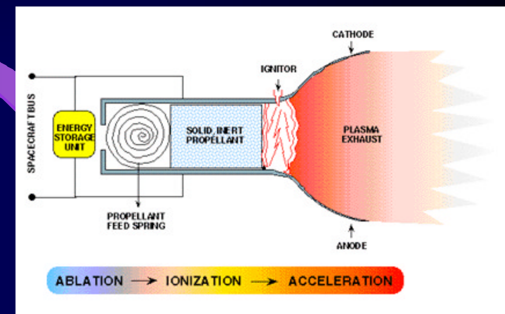
- Reaction wheels can do both coarse & fine stage actuation, however:
  - Wide-band harmonic disturbances compromise on-board science
  - Controls only attitude degrees of freedom
- Coarse actuation technologies are relatively well developed, however:
  - Contamination of optical surfaces on science missions
  - Relatively low specific impulse (Isp)

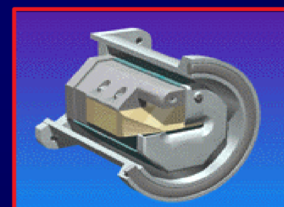
More development needed in non-contaminating Precision Actuation Technologies

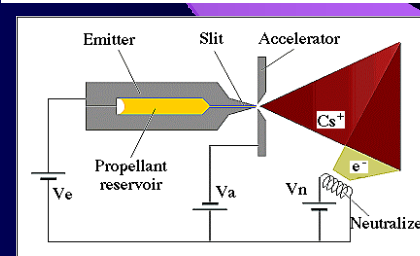
Spacecraft Actuation Technologies

- **Cold gas (N_2) thrusters**
  - As small as 4.5 mN, <u>non-contaminating</u>
  - ST3 requires >50 mN due to solar press. and torques
  - Low I_{sp} (60 sec)
- **Pulse Plasma Thrusters (PPT)**
  - 700 µN per pulse, up to 6 Hz
  - Intermediate I_{sp} (typ. 500 - 1,500 sec)
  - High power
  - Contamination concerns
- **Field Electric Emission Propulsion (FEEP)**
  - 1 µN to 2 mN thrust
  - Very high I_{sp} (6000- 9000 sec)
  - High power (approx. 60W/mN)
  - Contamination concerns
- **Colloidal thrusters**
  - 1 µN to 100 µN thrust (ST7 Technology)
  - Historical tests performed at thrusts up to 1.3 mN
  - Intermediate Isp (500 - 1000 sec)
  - Low power (about 10W/mN)
  - Contamination and propellant irradiation concerns
- **Miniature Ion Thrusters**
  - 0.5 - 3 mN for 3-cm dia. engine
  - Scalable to larger thrusts for larger size thrusters
  - 3000 sec Isp
  - Approx. 30W/mN specific power
  - Xenon gas propellant: benign, <u>non-contaminating</u>, central tank feeding multiple thruster clusters


N_2 Cold Gas Thruster





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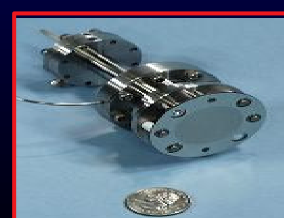

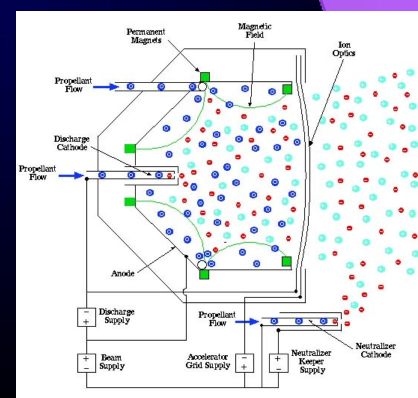

Spacecraft Actuation Technologies

Comparison

Thruster Type	Cold Gas	PPT	FEEP (Indium)	FEEP (Cesium)	Colloid	Miniature Ion
Thrust (mN)	4.5 - 4,500	0.002 - 0.7	0.001 - 0.5	0.001 - 1.4	0.001 - 0.1	0.5 - 3
Isp (sec)	60 (N_2)	500 - 1500	6,000 - 9,000	6,000 -9,000	500 - 1,500	3000 (typ.)
Ibit (Ns)	10^{-4}	10^{-4} - 10^{-6}	10^{-8} (est.)	10^{-8} (est.)	10^{-8} (est.)	TBD
Specific Power (W/mN)	N/A	70 - 100	60	60	10	30
Propellant	Typ. N_2	Teflon	Indium	Cesium	Glycerol, Ionic Liquids, Formamide	Typ. Xenon
Contamination Concerns	No	Yes	Yes	Yes	Yes	No
Comments	Central Tank Large required propellant volume	Modular Fuel Bar, Pulsed Operation Only	Modular Tank Design, Capillary Feed	Modular Tank Design, Capillary Feed	Modular Tank Design, Capillary Feed	Central Tank scalable to significantly higher thrusts for larger engines supercritical (compact) propellant storage

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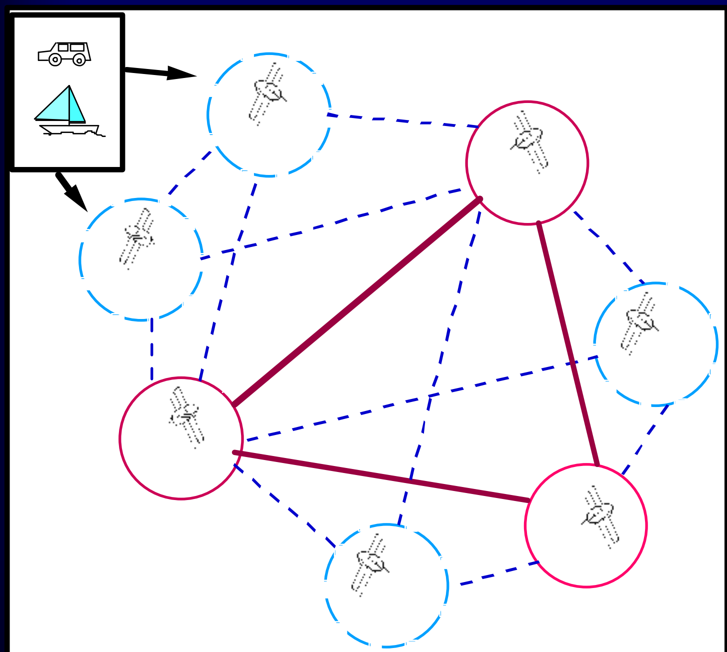
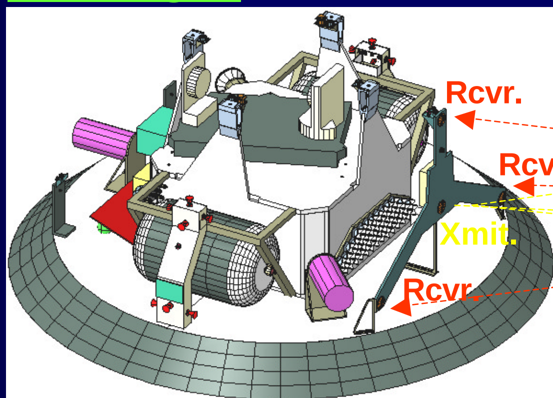
Autonomous Formation Flying (AFF) Sensor



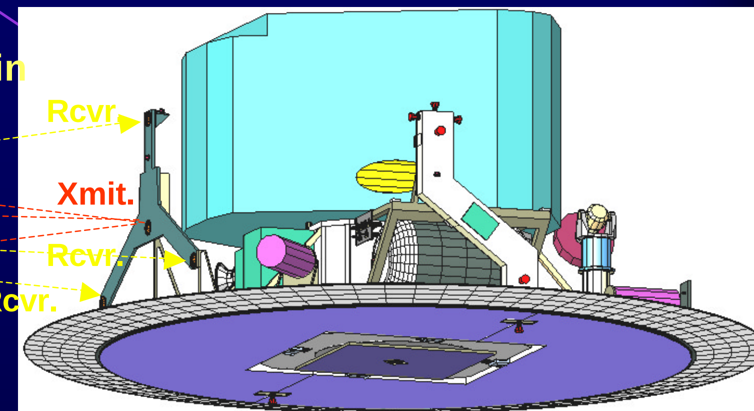
- **Autonomous Formation Flying GN&C Sensor (AFF)**
  - Similar to a GPS ADS but with 6 receive antennas and 2 transmit antennas
    - 4pi steradian coverage (FOV)
  - Provide relative measurements: bearing, bearing rates, range, range rate and time
  - Ideal for multiple spacecraft in Earth orbit and deep space
    - Formations and constellations
    - Rendezvous and docking
    - Self contain system, does not require NAVSTAR GPS satellites' signals
      - But can accommodate if necessary
  - High performance relative measurements
    - ±1 cm ranging, ±1 mm/sec velocity, ±1 arcminute attitude
    - 1m to ~10km operational range as designed

Formation Sensing Technologies

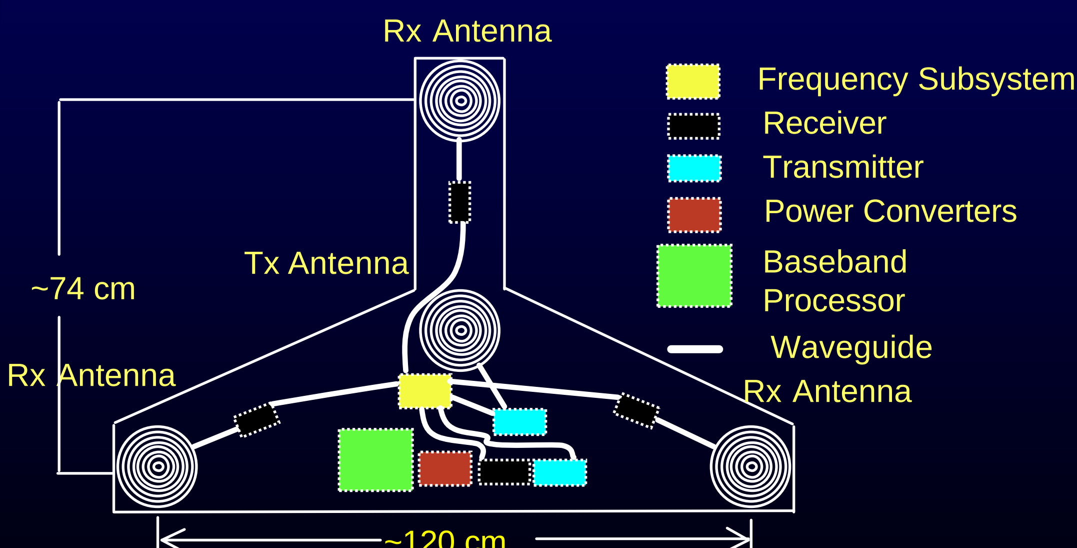
StarLight

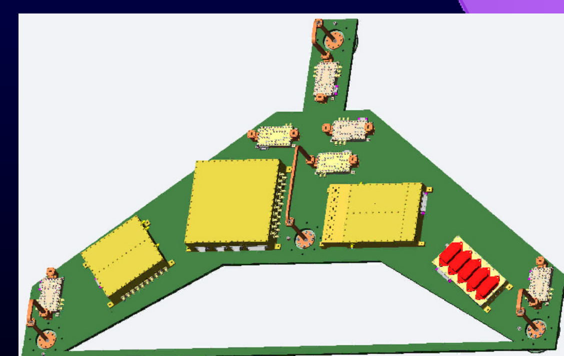


Operating Range = 30-1000 m
Range accuracy = 2 cm
Bearing accuracy = 1 arc-min
FOV (half-cone) = 70 deg



Comm. Channel = 1 kbit/s
RF Freq. = 30 Ghz



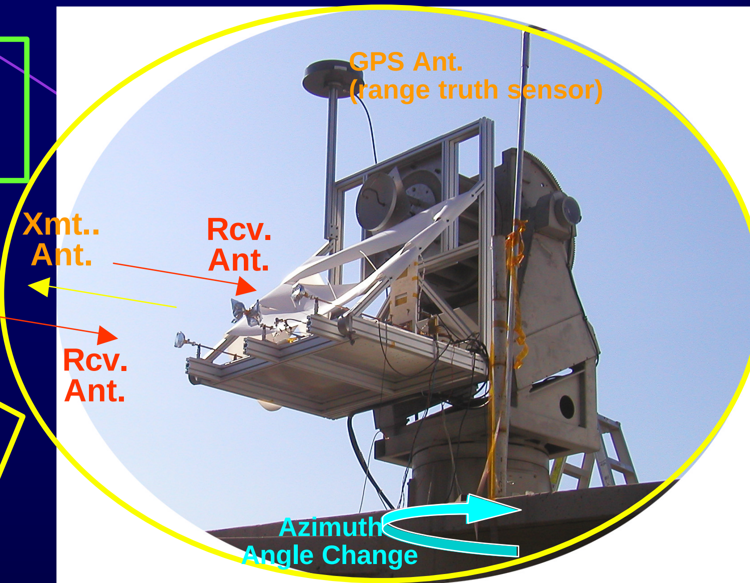


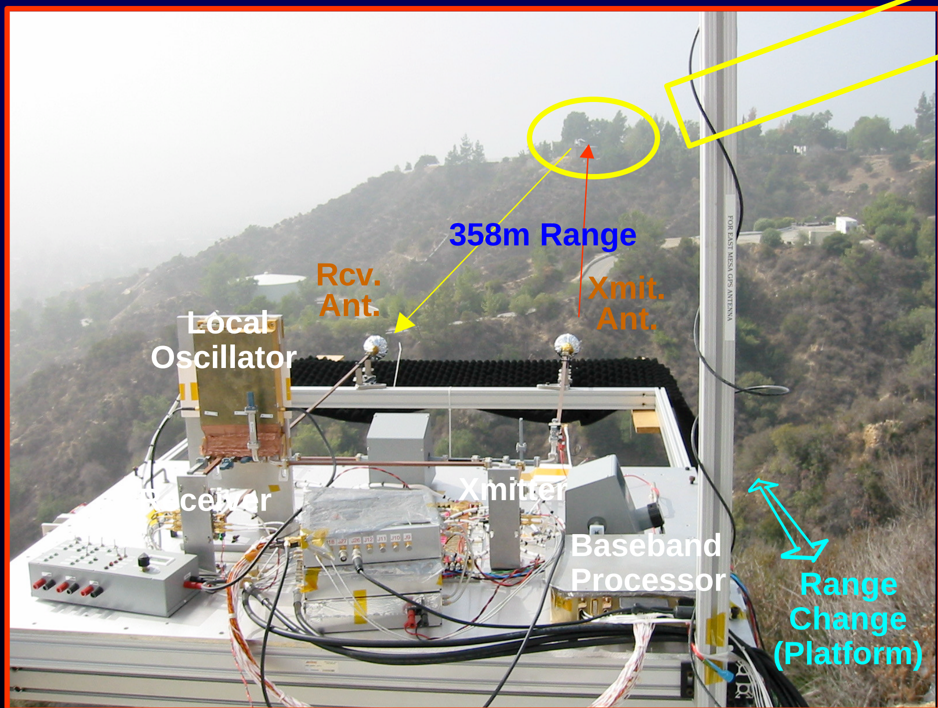
Electronics mounted on back of mounting plate

Autonomous Formation Flying (AFF) Sensor

Formation Sensing Technologies - *cont'd*

Autonomous Formation Flying (AFF) Sensor Field-Test Setup (2002)



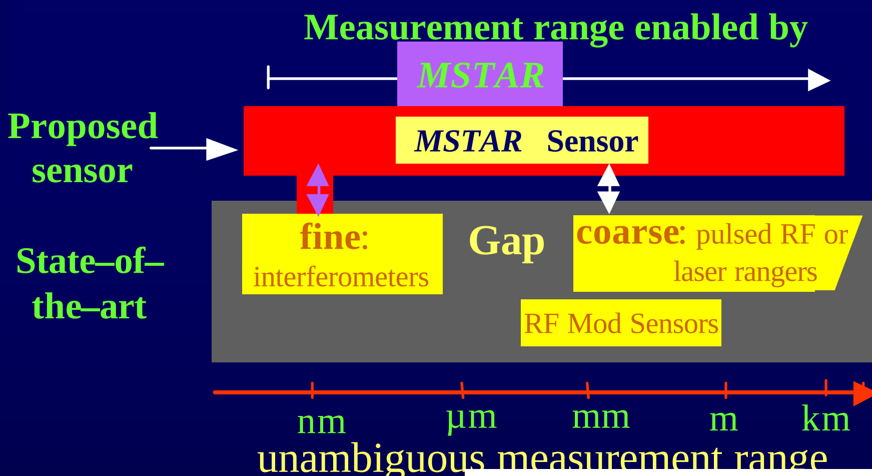


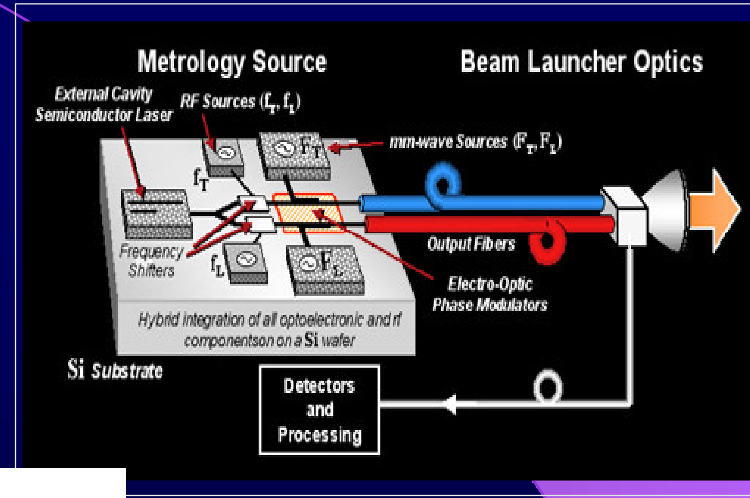
Demonstrated Performance:

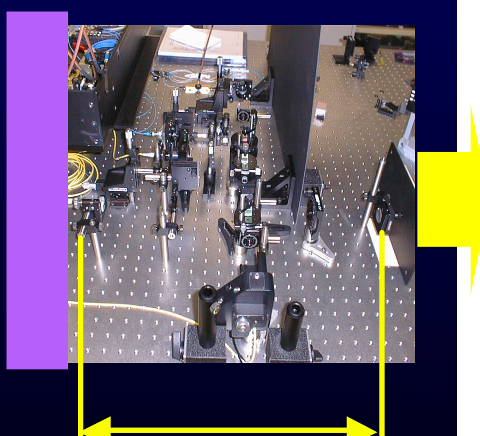
Range = 2cm

Bearing = 1 arcmin

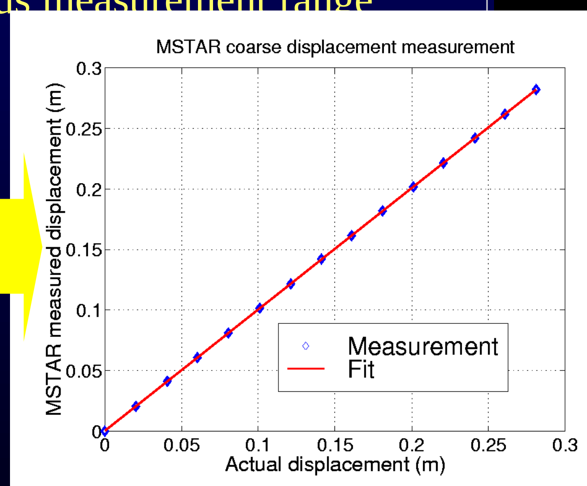
Formation Sensing Technologies - *cont'd*







Physical distance = 0.53 m



Nanometer precision, ultra-high dynamic range <u>absolute</u> range sensor.

Breadboard demonstrated in FY01

Modulation Sideband Technology for Absolute Ranging (MSTAR) Sensor

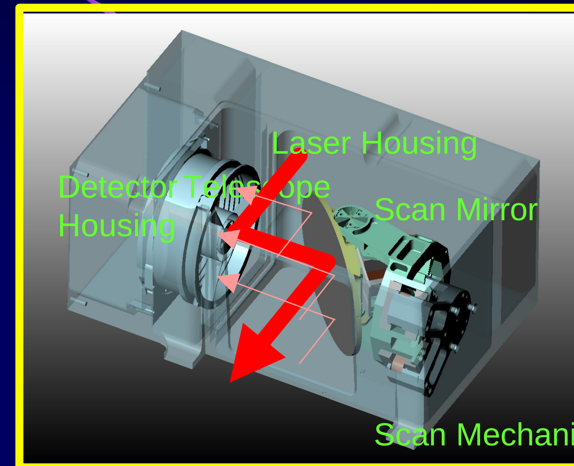
Rendezvous Sensor - LAMP

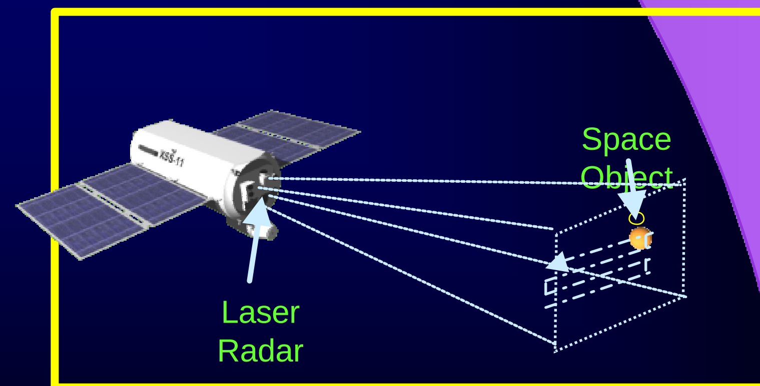
Specifications

Lightweight (< 4 kg)
Low-power (< 25 W)
Small footprint (4,000 cc total)
Operating range: 0.5m ~ 5 km
Accuracy:
- ~5m (5 – 2 km)
- ~0.25% range (2km – 10m)
- ~2.5cm (< 10 m)

10°x10° field of regard
100x100 pixel map in 1 sec

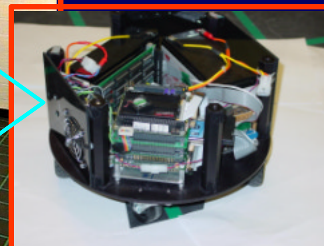
Laser Imaging Radar - LIDAR





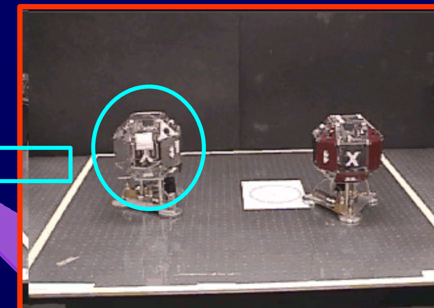
Unique, Lightweight, Low-power, High-accuracy Sensor

Formation Flying - Ground Testbeds



BYU

Multi-Agent Intelligent Coordinated Control



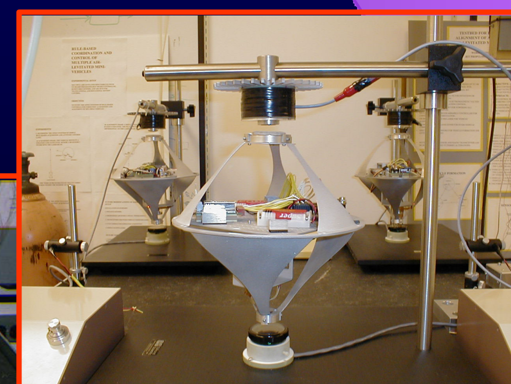
MIT

Synchronized Position Hold Engage Reorient Experimental Satellites - SPHERES

Realistic Dynamics with Air & Magnetic Levitation

FORMATION ACQUISITION & ATTITUDE ALIGNMENT TESTBED
(1998)

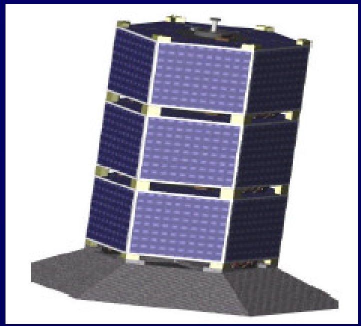
SYNCHRONIZED ROTATION TESTBED (2000)



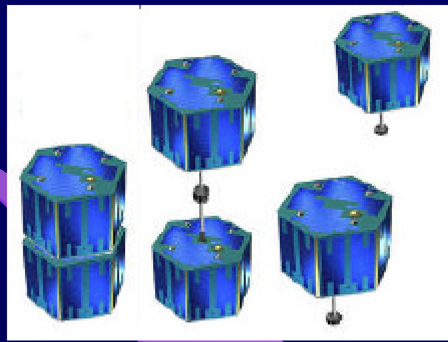
FORMATION OPTICAL ALIGNMENT TESTBED
(2002)

JPL/UCLA

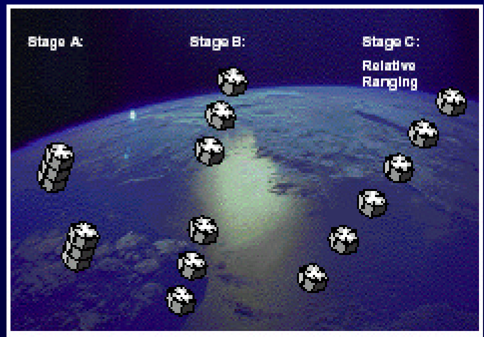
Formation Flying – Flight Testbeds



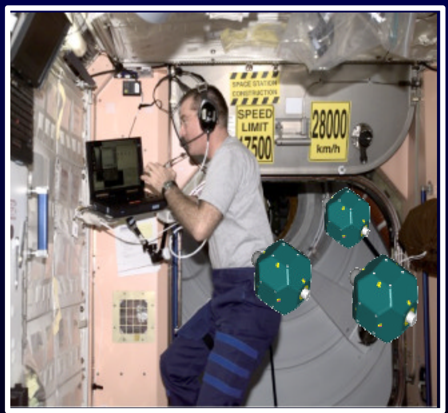
Three Corner Satellite Constellation (Stacked configuration)
Arizona State, Univ. of Colo., Boulder, New Mexico State Univ.



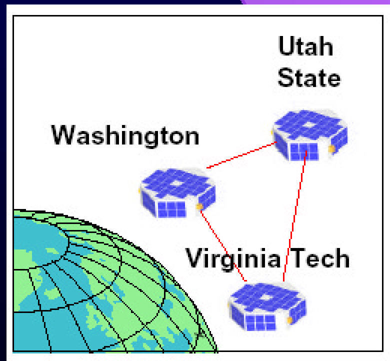
Emerald Spacecrafts
Stanford Univ., Santa Clara Univ.



ORION
GSFC/Stanford Univ.



SPHERES
MIT

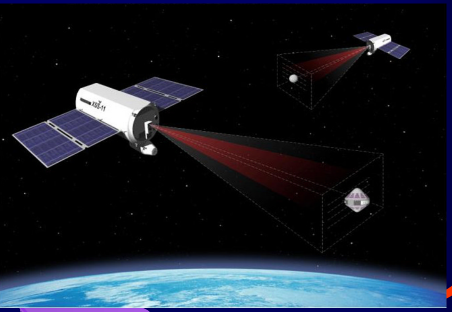


Ionospheric Formation
Utah State, Univ. of Washington, Virginia Polytechnic Institute & State Univ.

Formation Flying – Flight Tech Demo

ST6/XSS11 (ARX - Autonomous Rendezvous Experiment)

- NASA/AFRL
- Launch: 2004
- Operating range: 5000m-10m
- Mass: 110 kg

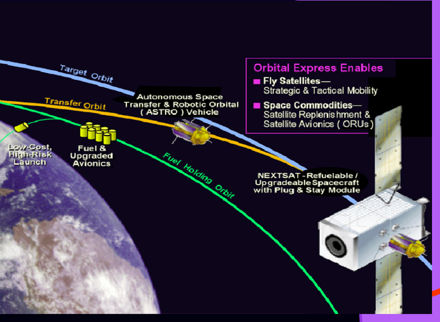


DART (Demonstration of Autonomous Rendezvous Technologies)

- NASA Space Launch Initiative
- Launch: 2004
- Mass: 350 kg
- Pegasus launch, ~15meter proximity operation, onboard Video Guidance Sensor (VGS)

Orbital Express

- NASA/DARPA
- Launch: 2005
- Mass: 300-500 kg
- Autonomous approach, docking, fuel transfer, repairs



JPL/AFRL Flight Experiment

JPL's Capabilities in Formation Flying

JPL Relevant Experience

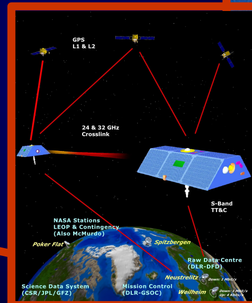
JPL has Significant FF Experience from Relevant Missions and Mission Studies

- **Formation Flying Control**
  - Formation Initialization, Multi-body control, Formation Maneuver, Formation Sensors
- **On-board Trajectory Design, Guidance and Control**
  - Autonomous Rendezvous and Path Planning
  - Target Acquisition
- **On-board Data/Image Processing**
  - Collision avoidance, Autonomous Formation Reconfiguration
- **TPF and Distributed Spacecraft Technology Programs**
  - Formation Flying Technologies
- **End-to-End Hi Fidelity system modeling/simulation**
  - Real-time HW-in-loop, Distributed

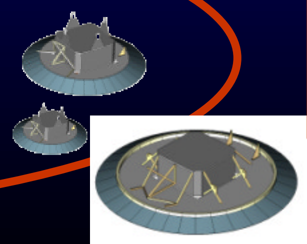
- **Relevant Missions:**
  - GRACE
  - TPF
  - ST3, StarLight
  - ST-6 Autonomous Rendezvous (ARX)
  - Mars Sample Capture
- **Relevant Mission Studies:**
  - Mars/Venus Sample Return
  - Small Body Sample Return
  - Comet Nucleus Sample Return (CNSR)

Precision Metrology Sensor

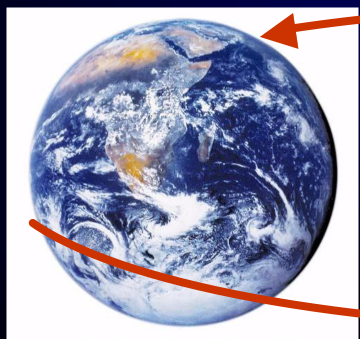
Formation Ranging



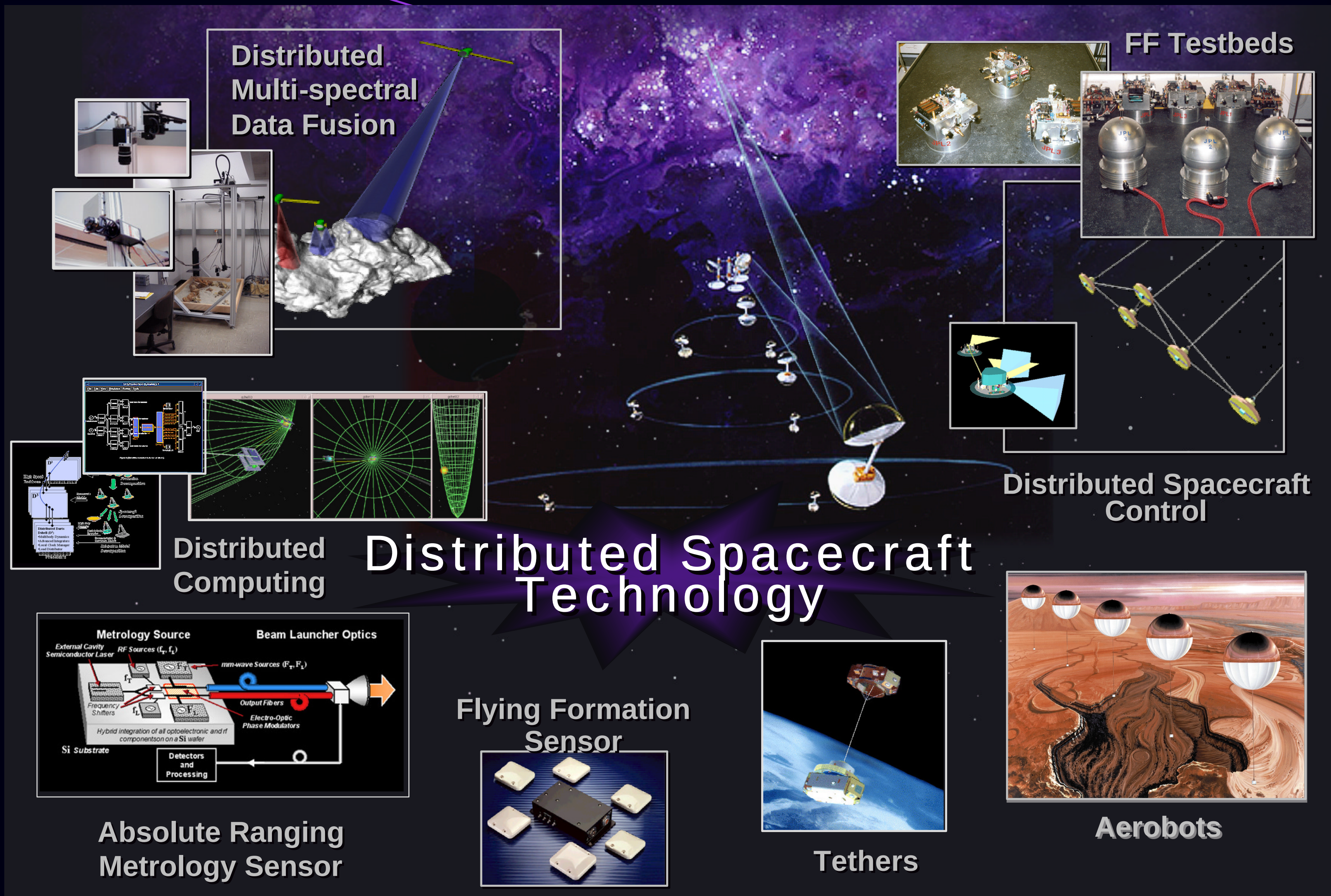
Formation Control Architecture/Algorithms



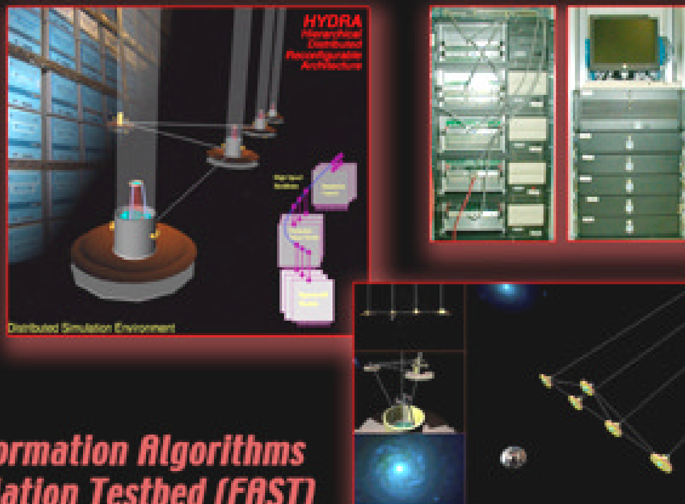
Real-time, Distributed Simulation



Precision Formation Control


Distributed Multi-spectral Data Fusion
FF Testbeds
Distributed Spacecraft Control
Distributed Computing
Distributed Spacecraft Technology
Metrology Source
Beam Launcher Optics
External Cavity Semiconductor Laser
RF Sources
mm-wave Sources
Frequency Shifters
Output Fibers
Electro-Optic Phase Modulators
Hybrid integration of all optoelectronic and rf components on a Si wafer
Si Substrate
Detectors and Processing
Absolute Ranging Metrology Sensor
Flying Formation Sensor
Tethers
Aerobots

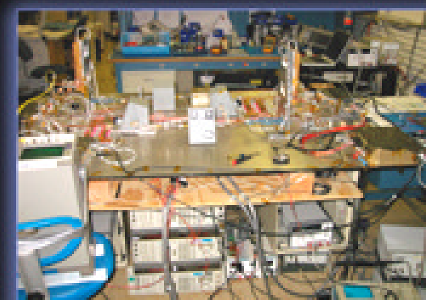
TERRESTRIAL PLANET FINDER (TPF) FORMATION FLYING TECHNOLOGY TESTBEDS



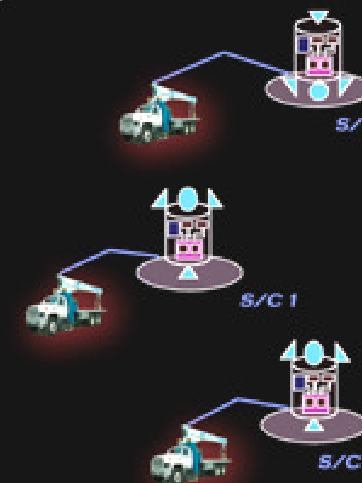
Formation Algorithms & Simulation Testbed (FAST)

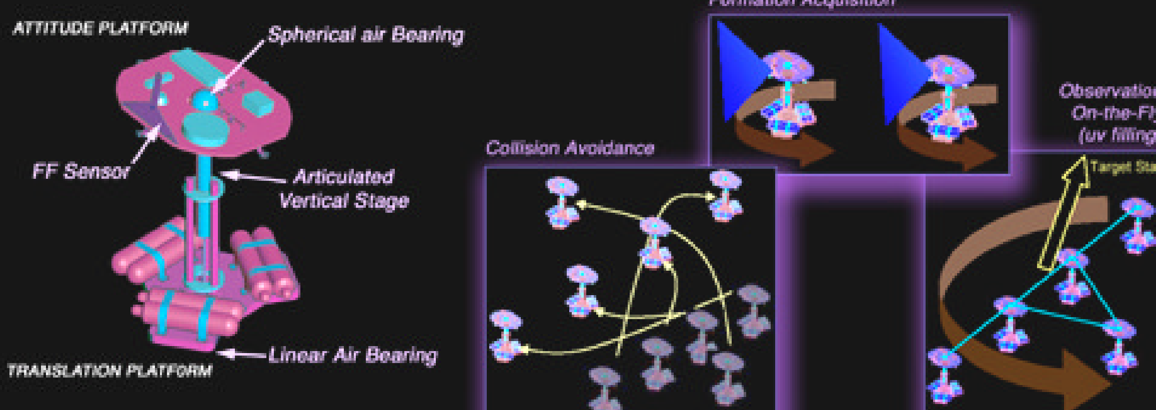
Formation Sensor Testbed (FST)

Hardware-in-the-Loop Testbed



4π-steradian Articulated Testbed



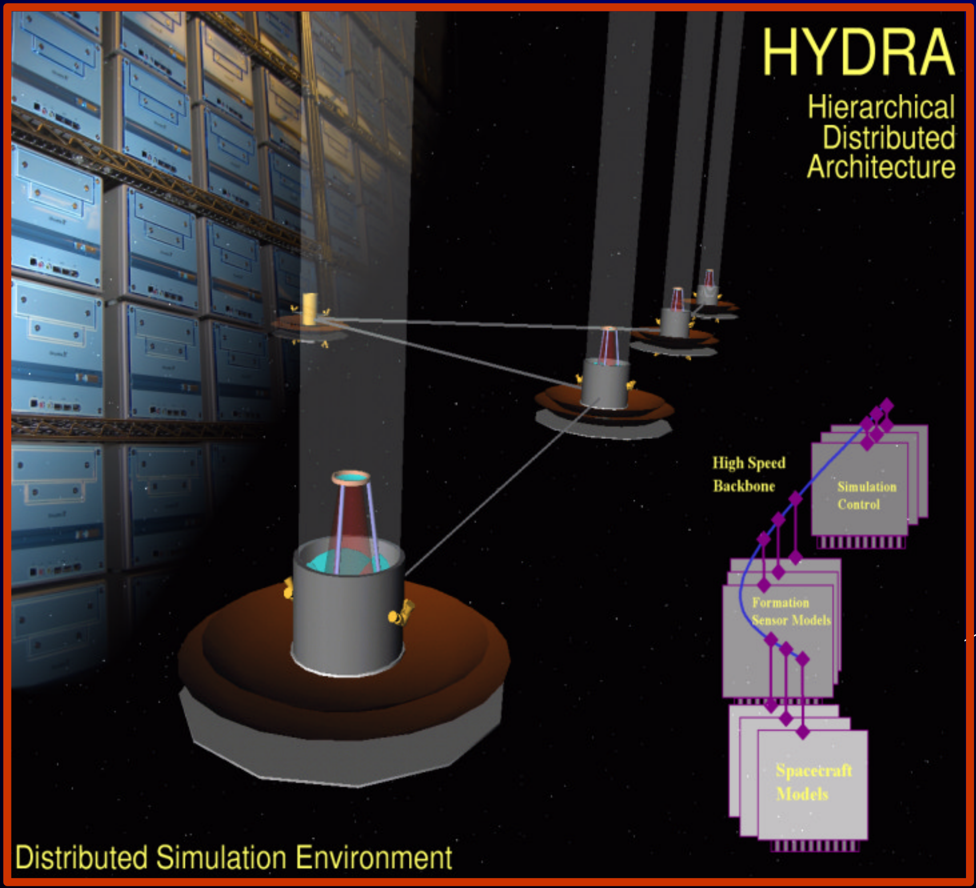


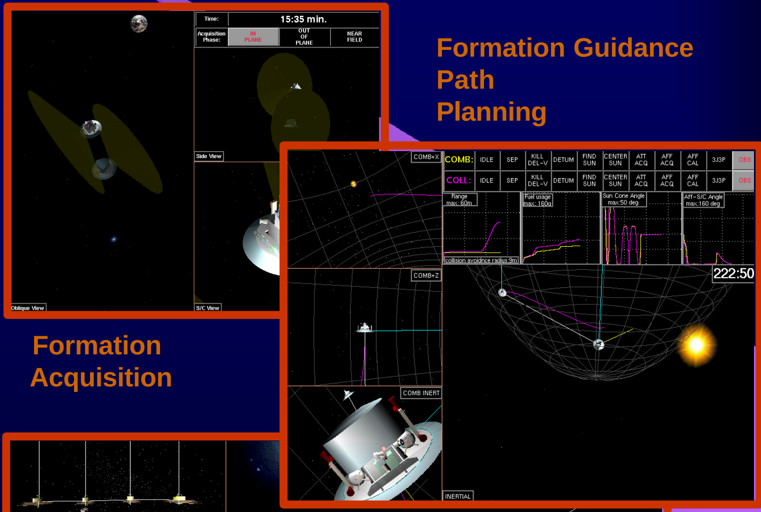
Formation Control Testbed (FCT)

MIT Spheres

JPL Modeling and Simulation Capability

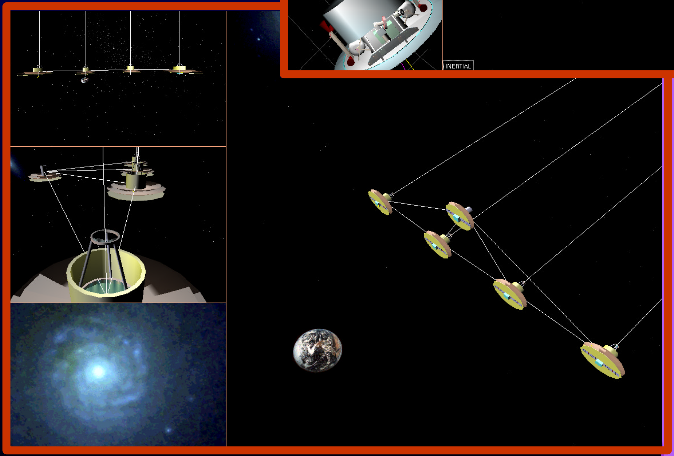
JPL has Unique Distributed, Real-time Modeling & Simulation Tools for Formation Flying





Formation Guidance Path Planning

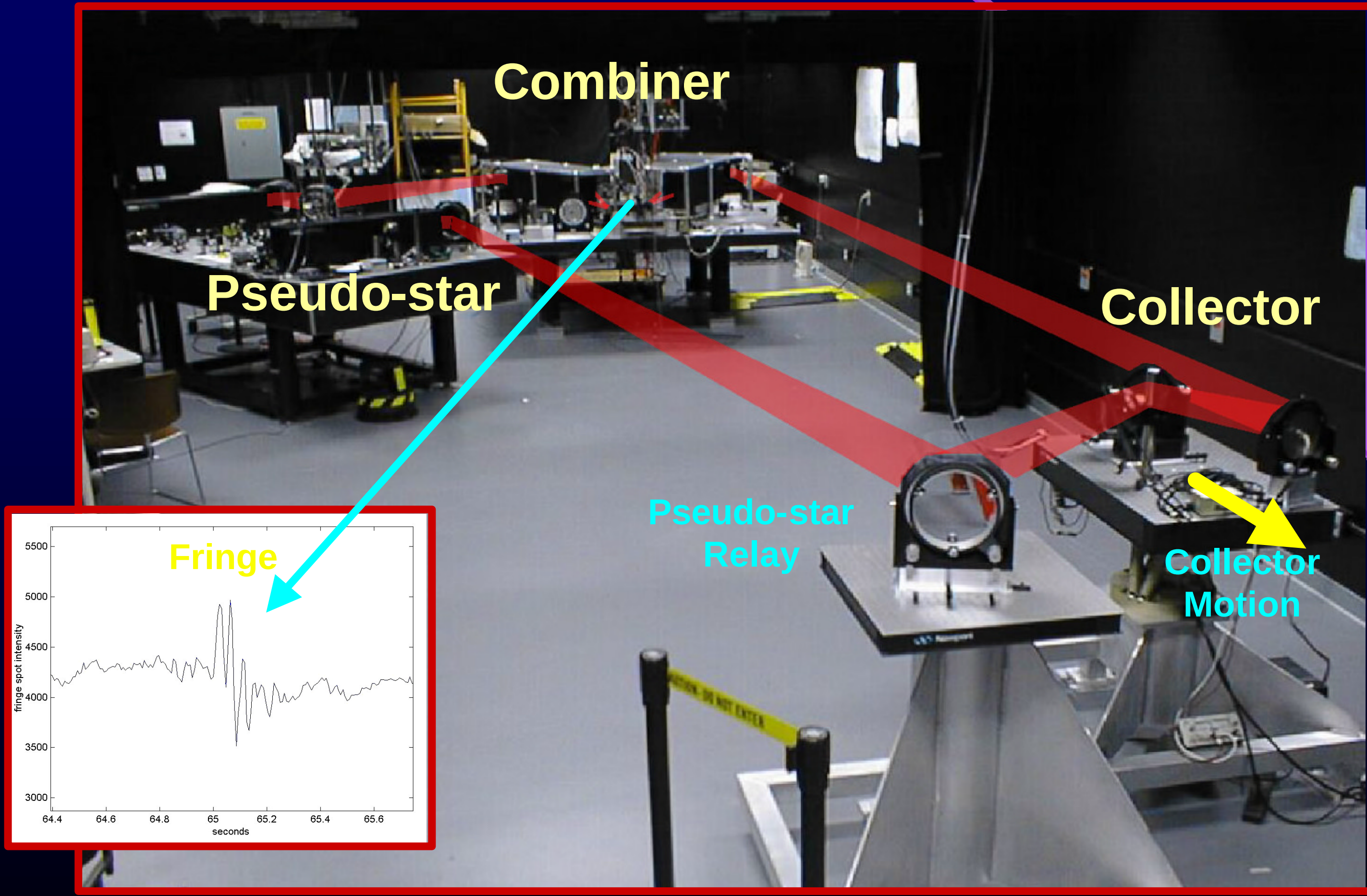
Formation Acquisition



Formation Controls Simulation

Formation Interferometer Testbed (FIT)

Fringe Acquisition and Tracking Has Been Successfully Demonstrated in the FIT Lab.

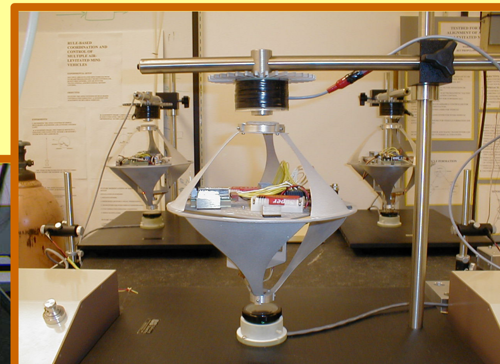


F. Y. Hadaegh – JPL

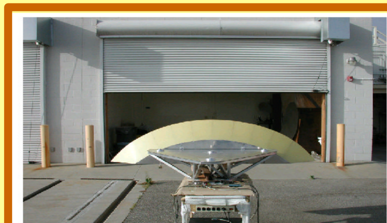
Formation Flying HW Testbeds

JPL has Optical and RF Testbeds Key to the Ground Validation of Formation Flying Metrology and Controls

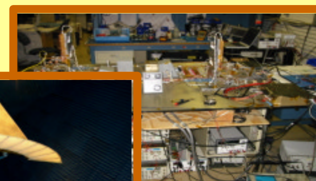
FORMATION ACQUISITION & ATTITUDE ALIGNMENT TESTBED
(1998)



FORMATION OPTICAL ALIGNMENT TESTBED
(2002)



AFF OUTDOOR ANTENNA ISOLATION TESTBED



AFF SENSOR TESTBEDS

AFF 358-METER RANGE OUTDOOR RADATED TESTBED

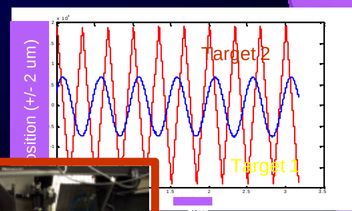
Formation Flying HW Components

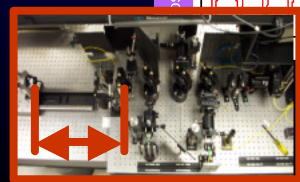
JPL Has Developed and Tested Key Formation Flying Hardware Components

- RF Range and Bearing Sensor
  - Verified functionality and performance using a fully functional brassboard of Autonomous Formation Flying Sensor (AFF)
    - Range: Max. 2 cm accuracy (directly facing)
    - Bearing angle: 1 arc-minute accuracy (directly facing)
    - Wide field of view (±70°)
    - Operational range: Nominal: 30m – 1000m
    - Recovery capability: 1 - 10 km
- Precision metrology Sensors
  - Developed and validated in laboratory:
    - **Inter-spacecraft linear metrology sensor**
      - Precision: 10 nm (1σ, change in range)
      - Validated in laboratory for range up to 600 m
    - **Angular metrology sensor**
      - Precision: 1 μm transverse offset
      - Validated in laboratory for range up to 600 m
    - **Absolute metrology sensor (MSTAR)**
      - Sub-micron absolute ranging accuracy
      - Validated in laboratory for range up to 1 m

AFF Sensor – Outdoor Testbed

Linear/Angular Metrology Sensor





MSTAR

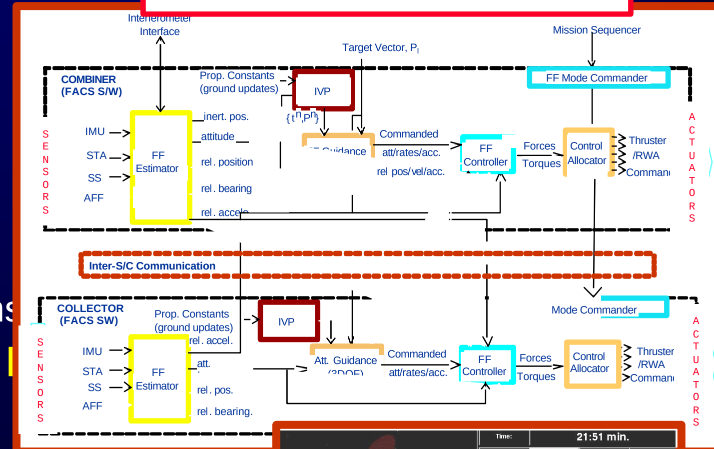
F. Y. Hadaegh – JPL

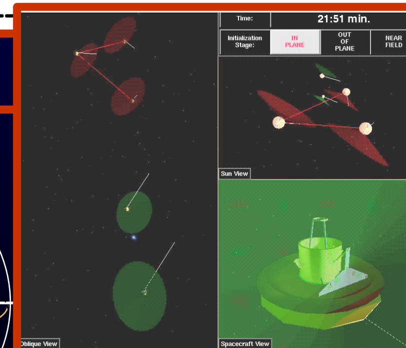
Formation Flying Algorithms and SW Components

JPL Has Developed and Tested Key Formation Flying Algorithms and Software

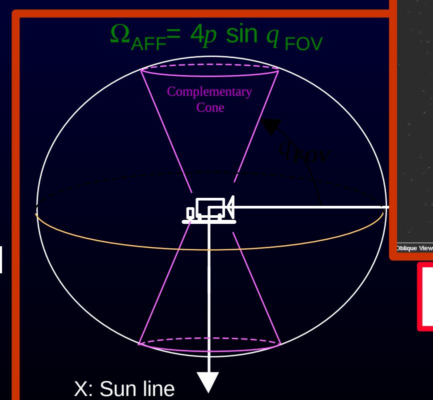
- Formation Flying Guidance and Control
  - Precision formation control
    - Relative positions controlled to 10 cm
    - Attitudes controlled to 1 mrad
  - Guaranteed Formation Initialization
    - From "Lost-in-Space" to formation
    - Using limited field-of-view, distributed formation sens
  - Optimal Formation Path Planning and Maneuver I
    - Optimal reconfiguration guidance
    - Minimum fuel/energy consumption and balancing
  - Collision Avoidance
    - Basic collision avoidance for N s/c
  - Formation Synchronized Motions
    - Interferometric Observation-on-the-Fly
    - Thruster synchronization
    - Attitudes and relative positions synchronized

Formation Control Architecture





Formation Acquisition



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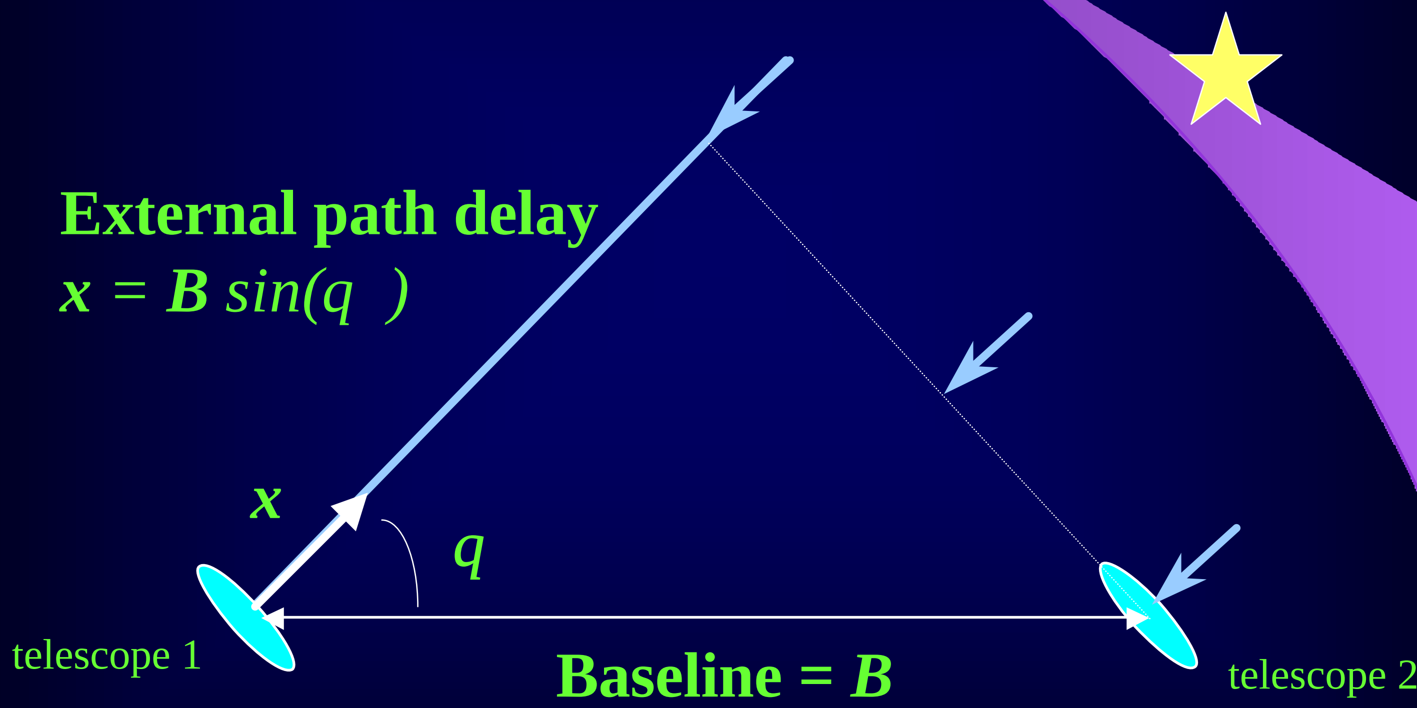
Imaging a Light Source

- **A primary application of precision formation flying is synthetic aperture imaging**
  - Using many small telescopes in tandem to give the imaging power of one very large telescope
- **A radio frequency synthetic aperture is the Very Large Array (VLA) in New Mexico**
  - Two possible versions of TPF will use the same principle but in the infrared frequency range

Astrometric Measurement

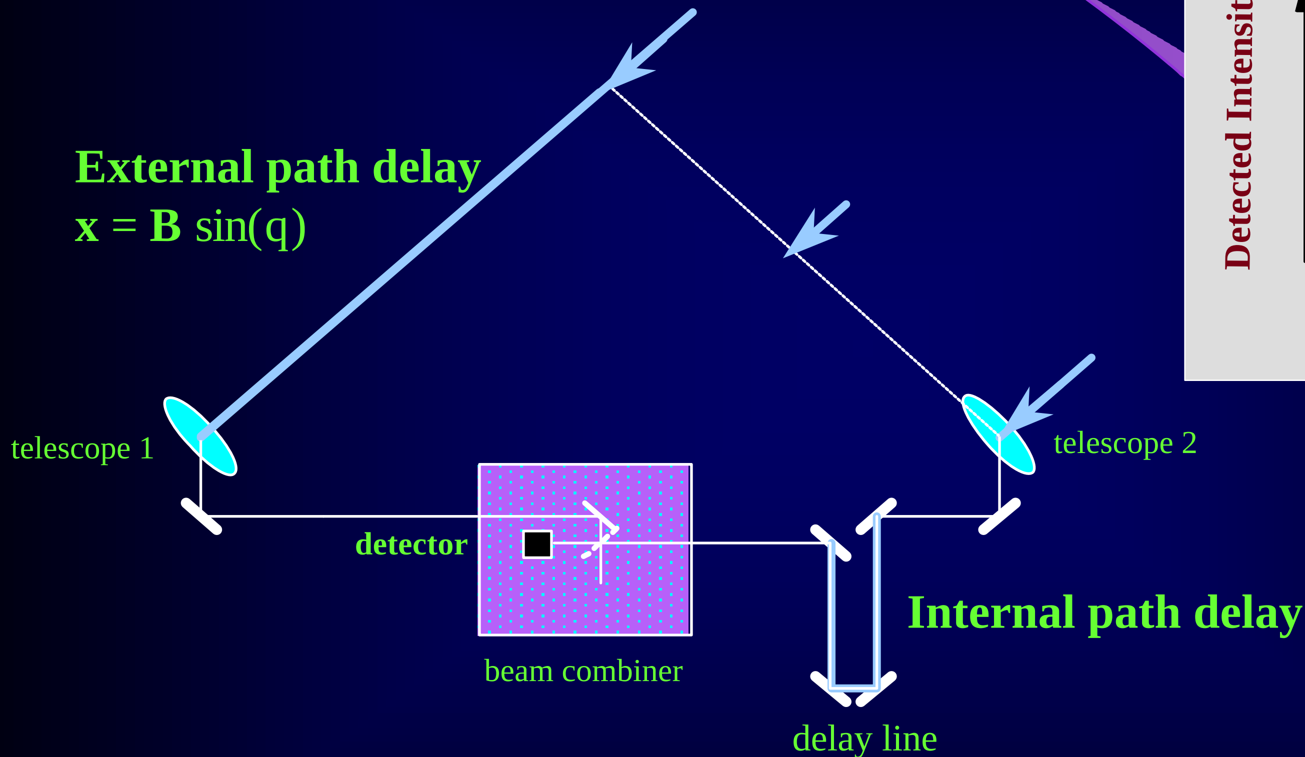
(want to know θ with high level of accuracy)

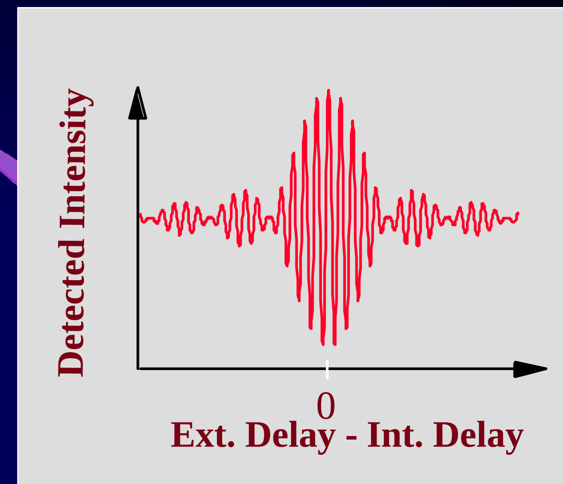


If you know B & can determine x , then we can solve for *q*

Astrometric Measurement

(want to know θ with high level of accuracy)





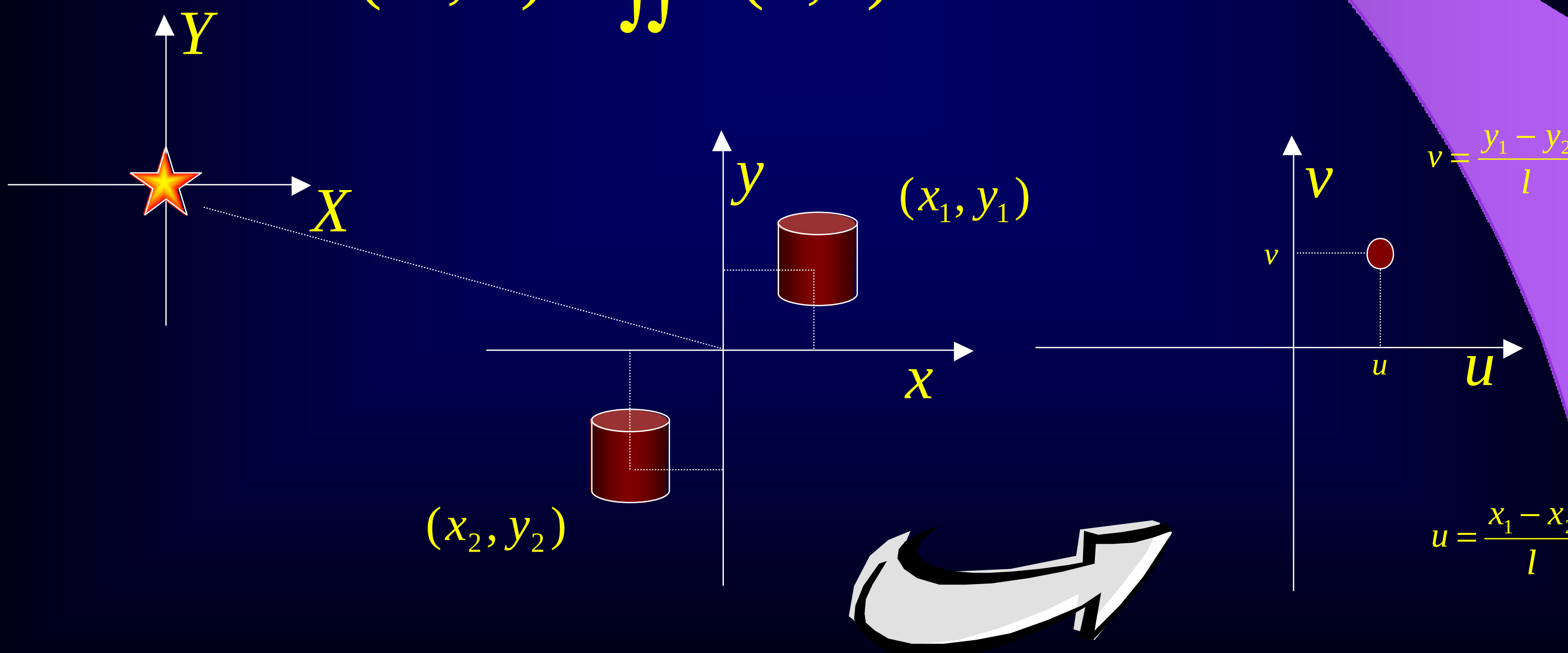
- ***The peak of the interference pattern occurs when the internal path delay equals the external path delay.***
- ***Internal metrology measures internal path delay***

Formation Flying Control

Imaging

The essential relationship used for imaging is expressed by the Cittert-Zernike formula.

$$I(X,Y) = \iint m(u,v)e^{i2p(uX+uY)}dvdu$$



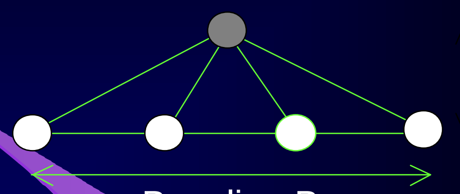
What You Will See in this Demo

- **TPF Type Formation Guidance Path Planning**
  - Autonomous Control of Formation Spacecraft
  - Autonomous Reconfiguration
  - Collision Avoidance
  - Optimal Path Planning
  - Precision Synchronized Motion

TPF FF Guidance & Control Demo

Spacecraft Description and Sequence of Events

- 600-700 kg class S/C
  - Sun shade diameter: 15 m for collectors, 12 m for combiner
  - Only collectors equipped with a telescope
- Processing @ 1 hz
- Hardware
  - Thrusters (12 on each S/C, combination of 2N, 5N thrusters – highly coupled attitude, translation)
  - AFF, 6 axis IRU, Tracker on each S/C
  - AFF FOV (80° half-cone) tailored to meet TPF configuration
- Sequence of events:



Initialization

[0 s] Stacked cluster, combiner in the middle, heliocentric, 1 AU behind earth
[10 s] Staggered, passive, timer-based, deployment (push-off springs)
[200 s] Null separation delta V and hold attitude (IRUs only – **NO AFF, Star Tracker inputs yet**)
[300 s] Go to the TPF configuration
- 80 m baseline, inertial target = [0.267, 0.535, 0.8018], collision avoidance radius = 10 m
- Duration 300 sec
- **NO AFF, Star Tracker inputs yet**

[650 s] **Enable AFF, tracker data – update formation, attitude estimates**
[750 s] Deploy cover, secondary optics

[950 s] Expand baseline to 120 m - duration = 150 sec, same inertial target, baseline orientation
[1250 s] Contract baseline to 80 m - duration = 150 sec, same inertial target, baseline orientation
[1600 s] Reconfigure - reassemble 150° away, duration = 300 sec, same inertial target (No sych. rot.)
[2100 s] Synchronized rotation - 150° arc, broken into 10 linear segments, total duration = 1500 s (IF)
- 0.1°/sec formation rotation rate

Formation Maneuvers

TPF Formation Demonstration Imaging a Light Source

Shortcut (2) to tpf_Demo.lnk

Summary

- *A New Class of Space Missions Enabled by Formation Flying (FF) Architecture*
  - TPF – Terrestrial Planet Finder, MAXIM – Micro-Arcsec X-ray Imaging Mission, SPECS – Sub-millimeter Probe of the Evolution of Cosmic Structure, SI – Stellar Imager
- *Mission Needs*
  - Precise geometrical formation and alignment, precise synchronized motions, and autonomous reconfigurations of multiple spacecraft to operate collaboratively as an instrument
- *Enabling Technologies*
  - Precision formation flying control algorithms and software
  - On-board direct formation sensing for acquisition, precise alignment & control
  - On-board inter-spacecraft communications
- *JPL Has Significant Experience/Capabilities in the Formation Flying Area*
  - Significant FF experience from relevant missions and mission studies
  - Unique distributed, real-time modeling & simulation tools for formation flying
  - Optical and RF testbeds key to the ground validation of FF metrology and controls
  - Developed and tested key formation flying hardware components
  - Developed and tested key formation flying algorithms and software
  - Mature FF technology, experienced team, and the testbed facilities for a FF flight
  - demonstration