III. Solar Sail Flight System Technology

Session Facilitator:
Gregory P. Garbe

Outline

- Executive Summary
- Solar Sail Capabilities to be Validated by ST9
- Solar Sail TCA/Mission-Level Validation Objectives for ST-9

Executive Summary

- **Workshop Addresses Following Technology Areas**
  - Sail system design metrics & scaling
  - Controlled sail deployment in an orbital/space environment
  - In-space characteristics of the deployed sail and structure
  - Sail system design metrics & scaling
  - Controlled sail deployment in an orbital/space environment
  - In-space characteristics of the deployed sail and structure
  - Sailcraft attitude control
  - System propulsion performance
  - Design approach and processes
- **Sessions Topics**
  - Future space science mission needs
  - Desired workshop products
  - Technology splinter session discussions
  - Needs/potential capabilities assessments
- **Splinter Session Topics**
  - Modeling and Simulation of Deployed Solar Sails
  - Solar Sail Material Qualities and Environmental Characteristics
  - Pointing, Control, and Navigation Technology for Solar Sails
  - Solar-Sail Packaging Deployment, and Structure Technologies

Executive Summary (continued)

- **Key Observations and Recommendations**
  - **Need the corroboration between quantitative models and ground testing for all major subsystem**
  - **Scale of validation flight needs to be no smaller then 1/3 of future science mission**
  - **Two most important Solar Sail Figure of Merits are:**
    1. Root Sail Area (L_{RSA}):
       - Square root of sail's reflective area
    2. Sail system areal density (σ_S):
       - Mass sail system (e.g., membrane, trusses, GNC, Diagnostics, etc.) divided by reflective area

- **Recommendations for ST-9 Flight Experiment**
  - **Need comprehensive diagnostic package that quantitatively measures the system performance and interaction with its environment**
  - **L_{RSA} should be minimum of 50 m**

Solar Sail Capabilities to be Validated by ST9 (1 of 2)

Required Capability	Now	OSS Ultimate	Mission Mid-Term	ST9	Current TRL	TRL 5 Test Requirement
Sail System Design						
• Structural Models	Generic	Specific	Specific	Prototype	4	
Gossamer booms [Loads/forces, Shape, Dynamics (freq.), Thermal]		w/in 2% of gnd tests	w/in 5% of gnd tests	w/in 10 % gnd tests		Ground Test data from ISP
• Materials Models	Generic	Specific	Specific	Prototype	4	
Large, thin-film membranes [Loads/forces, Shape, Optical (a/e), Thermal]		w/in 2% of gnd tests	w/in 5% of gnd tests	w/in 10 % gnd tests		Ground Test data from ISP
• Packaging and Deployment Models	Generic	Specific	Specific	Prototype	4	
Packaging [Pack factor]		w/in 2 %	w/in 5 %	w/in 10 %		Ground Test data from ISP
Deployment [Force Prediction]		w/in 2 %	w/in 5 %	w/in 10 %		Ground Test data from ISP
• Attitude Control Models	Generic	Specific	Specific	Prototype	4	
Control authority [Prediction]		w/in 2 %	w/in 5 %	w/in 10 %		Simulation data from ISP
Force/disturbance models [Gravitational, drag, CSI]		w/in 2 %	w/in 5 %	w/in 10 %		Simulation data from ISP
• Mission Design Models/Tools	Generic	Specific	Specific	Prototype	4	
Trajectory modeling [Thrust magnitude, Thrust vector steering]		w/in 2 %	w/in 5 %	w/in 10 %		Simulation data from ISP
Thrust vector direction prediction		w/in 0.1 deg	w/in 0.2 deg	w/in 0.5 deg		Simulation data from ISP
Trajectory prediction (position and velocity)		1 km 10 mm/s	1 km 10 mm/s	1 km 10 mm/s		Simulation data from ISP

Solar Sail Capabilities to be Validated by ST9 (2 of 2)

Required Capability	Now	OSS Ultimate	Mission Mid-Term	ST9	Current TRL	TRL 5 Test Requirement
Sail System Fabrication and Packaging						
• Sail System Characteristics						
Membrane						
o Reflective Area	< 500 m^2	22,500 m^2	> 6900 m^2	> 2250 m^2	4	1st Gen processes from ISP
o Reflectivity		> 90 %	> 80 %	> 70 %		Ground Test data from ISP
o Absorptivity (front)		< 5 %	< 9 %	< 10 %		Ground Test data from ISP
o Emissivity (front)		< 3 %	< 3 %	< 5 %		Ground Test data from ISP
o Emissivity (back)		> 80 %	> 80 %	> 30 %		Ground Test data from ISP
o Strength		> 100 psi	> 100 psi	> 100 psi		Ground Test data from ISP
o Conductivity		> 10^{-12} mohs/m^2	> 10^{-12} mohs/m^2	> 10^{-12} mohs/m^2		Ground Test data from ISP
System Areal density	> 20 g/m^2	< 5 g/m^2	< 15 g/m^2	< 18 g/m^2	4	Ground Test data from ISP
Packaged Volume	> 0.5 m^3	< 5.0 m^3	< 1.0 m^3	< 2.25 m^3		Ground Test data from ISP
Flight Measured Characteristics						1st Gen package from ISP
Boom [Loads, Shape, Dynamics, Thermal]		w/in 2% of model/test	w/in 5% of model/test	w/in 10% model/test		
Sail [Areal density, Loads, Dynamics, Thermal]		w/in 2% of model/test	w/in 5% of model/test	w/in 10% model/test		
Environment [Contamination, Degradation, Interaction]		w/in 2% of model/test	w/in 5% of model/test	w/in 10% model/test		
System [Areal Density, Stability, Maneuverability]		w/in 2% of model/test	w/in 5% of model/test	w/in 10% model/test		

Solar Sail Technology & Mission Implementation Roadmap

NOAA/USAF MISSIONS
Enabled by Solar Sail Propulsion

- Geostorm 1 (0.98 AU)
- Pole Sitter 1 (210 R_E X 485 R_E)

- Geostorm 2 (0.945 AU)
- Pole Sitter 2 (140 R_E X 323 R_E)

[redacted]

In-Space Propulsion Program

- 1 Au GNC HWiL
- 1Au Architecture
- Lightweight Bus

Cycle 3

- .25 Au GNC HWiL
- .25 Au Architecture

Cy

- High Fidelity Models
- Diagnostic System
- 1 Au Env. Testing

Nano Diagnostic System
0.25 Au Ground Demo

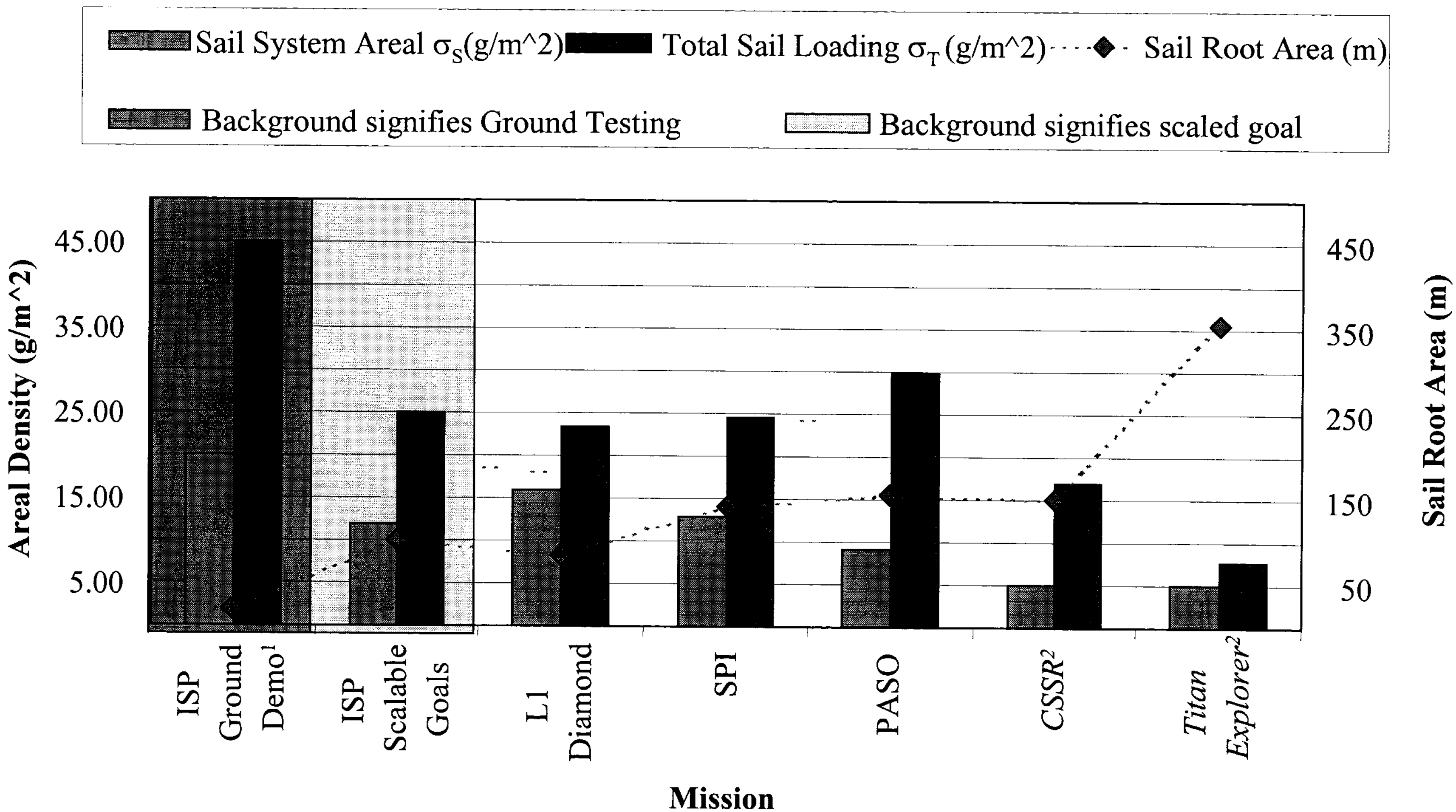
- AEC Able Ground Demo
- L'Garde Ground Demo
- JPL Integrated s/w Toolkit

0.25 Au GNC Software Development
0.25 Au Subsystem Development

NASA Technology Development

NMP Gossamer	2003: 1 AU Tech Development	2005: 1 Au Mission Validation	2007: 1 AU Science Missions	2009: .25 AU Tech Development	2011: .25 Au Mission Validation	2013: .25 AU Science Missions (2015)	
10 (radius)	10 – 25	40 – 80	80 – 150	10 – 25	70 – 125	150 – 375	***Sail Root Area (m)***
20	12 – 19	10 – 16	7 – 12	7 – 10	5 – 10	4 – 9	***System Areal Density(g/m^2)***
N/A	1	1	1	0.25	0.25	0.25	***Sail Class (Au)***
N/A	N/A	GTO, GEO	Near Earth	N/A	Inner Solar System	Near Sun	***Flight Path***

Solar Sail Figures of Merit required capabilities for Science Missions



Notes: 1) ISP Ground Demo σ_T assumes non-sail system mass of 10 kg

2) Solar Sail Propulsion is being studied to determine its viability to SSE Missions

Solar Sail TCA/Mission-Level Validation Objectives for ST-9

Sail Validation Objectives

1. Validate sail system design metrics & scaling
2. Validate controlled sail deployment in an orbital/space environment
3. Validate in-space characteristics of the deployed sail and structure
4. Validate sailcraft attitude control
5. Validate system propulsion performance
6. Validate design approach and processes

Objective 1. Validate Sail System Design Metrics and Scaling

Splinter Session A4
Solar Sail Packaging, Deployment, and Structure Technologies

Flight Test	Figure of Merit
Scaled Areal Density	Full Scale (22500 m^2) $\sigma_s = 10 g/m^2$
Predict and Measure Characteristic Acceleration	Function of solar angle, A_c = ?? mm/s^2 +/- 5 %
Scale Model On-Orbit	~ 1/3 Length of Full Scale (~ 1/10 full scale area)

Ground Test	Figure of Merit
Scaled Areal Density	Full Scale (22500 m^2) $\sigma_s = 10 g/m^2$
Scalable Packaging	Package approach scalable to 22500 m^2

Model & Tools	Figure of Merit
Scaled Areal Density	Full Scale (22500 m^2) $\sigma_s = 10 g/m^2$
Scalable Packaging	Package approach scalable to 22500 m^2

Objective 2. Validate Controlled Sail Deployment in an Orbital/Space Environment

Splinter Session A4
Solar Sail Packaging, Deployment, and Structure Technologies

Flight Test	Figure of Merit
Controlled Deployment (Validates Packaging) Video of Position vs. Time of Booms and Membrane	(Deploys in 30° half cone) ~ 2 hour deployment

Ground Test	Figure of Merit
Gravity Assisted Deployment Vibration and Ascent Venting test of Packaged Sail	Scale Model, and Full Scale Components

Model & Tools	Figure of Merit
Simulate Controlled Deployment	(Deploys in 30° half cone)

Objective 3. Validate In-Space Characteristics of the Deployed Sail and Structure

Splinter Session A2
Solar Sail Material Qualities and Environmental Characteristics

Flight Test	Figure of Merit
Material Properties Measurements	α/ε, conductivity, surface potential, tensile strength, etc.
Contamination Monitor	Contamination/outgassing rates
Plasma Environment Sensors (Electron/Proton)	Density, energy, composition, bulk velocity: Plasmasheath, Plasma Wake: Debye Length, density, etc.
Electrostatic Discharge Monitor	Arc Characteristics/location; Radiated and Conducted Emissions
Radiation Environment Sensors	TID for greater than 500 Å; Size, weight, sensitivity
Magnetic Field Detector	$\leq$0.1 nT
Electric Field Detector(?)	$\leq$0.1 mV Size, weight, sensitivity, frequency

Objective 3. Validate In-Space Characteristics of the Deployed Sail and Structure

Splinter Session A4
Solar Sail Packaging, Deployment, and Structure Technologies

Flight Test	Figure of Merit
Structural Stability	Stiffness (Freq., Loads, Shape, Thermal after Rigidization)
Sail Shape	Billow Magnitude TBD, Stress and Package Wrinkles, Function of solar angle

Ground Test	Figure of Merit

Model & Tools	Figure of Merit
Predict Structural Stability	Stiffness (Freq.), Loads, Shape, Thermal
Predict Sail Shape	Billow Magnitude TBD, Stress and Package Wrinkles, Function of solar angle

Objective 4. Validate Sailcraft Attitude Control

Splinter Session A4
Solar Sail Packaging, Deployment, and Structure Technologies

Flight Test	Figure of Merit
Measure Control Actuator Authority	Angular Acceleration

Ground Test	Figure of Merit
ACS Mechanism Tests	Angle and Rate

Model & Tools	Figure of Merit
Predict Control Actuator Authority	Angular Acceleration

Objective 5. Validate System Propulsion Performance

Splinter Session A1-S2
Modeling and Simulation of Deployed Solar Sails

Model & Tools	**Figure of Merit**
Improved computational tools suitable for modeling membrane:	Analytical predictions within TBD% of flight measurements
- Wrinkling (surface topology and effects on optical performance)	Computationally efficiency
- Tension fields	
- Damage mechanics	
- Thermal strain effects	
- Dynamics	

Objective 5. Validate System Propulsion Performance

Splinter Session A4

Solar Sail Packaging, Deployment, and Structure Technologies

Flight Test	Figure of Merit
Measure Characteristic Acceleration Measure Sail Shape as a Function of Solar Angle	Function of solar angle, A_c = ?? mm/s^2 +/- 5 % Resolution TBD

Ground Test	Figure of Merit

Model & Tools	Figure of Merit
Predict Characteristic Acceleration Predict Sail Shape as a Function of Solar Angle	Function of solar angle, A_c = ?? mm/s^2 +/- 5 %

Objective 6. Validate Design Approach and Processes

Splinter Session A1-S1
Modeling and Simulation of Deployed Solar Sails

Model & Tools	Figure of Merit
Improved computational tools suitable for modeling:	Analytical predictions within TBD% of flight measurements
- Long, slender booms	Computationally efficiency
- Geometric and material nonlinearities	
- Imperfection sensitivity	
- Stability/buckling - Damage modeling - Fatigue - Root interface/joint modeling - Sensitivity analysis	

Splinter Session A1-S2
Modeling and Simulation of Deployed Solar Sails

Model & Tools	Figure of Merit
Improved computational tools suitable for modeling membrane: - Wrinkling (surface topology and effects on optical performance) - Tension fields - Damage mechanics - Thermal strain effects - Dynamics	Analytical predictions within TBD% of flight measurements Computationally efficiency

Objective 6. Validate Design Approach and Processes

Splinter Session A1-S3
Modeling and Simulation of Deployed Solar Sails

Model & Tools	Figure of Merit
Improved computational tools for modeling system performance, including: - Structural model interaction with control system (CP/CM, model reduction, …) - Thermal-structural interactions (Gradients, shock) - Boom/membrane interfaces (stiffness discontinuities, …)	Analytical predictions within TBD% of flight measurements Computationally efficiency

Splinter Session A1-S4
Modeling and Simulation of Deployed Solar Sails

Model & Tools	Figure of Merit
Improved computational tools for predicting sail temperatures: - Sensitivity to variations in optical properties - Further inputs from thermal discipline required for large thin-film membranes	Analytical predictions within TBD% of flight measurements Computationally efficiency

Objective 6. Validate Design Approach and Processes

Splinter Session A4
Solar Sail Packaging, Deployment, and Structure Technologies

Flight Test	Figure of Merit

Ground Test	Figure of Merit
Scaled Areal Density	Full Scale (22500 m^2) $\sigma_s = 10 g/m^2$
Scalable Packaging	Package approach scalable to 22500 m^2
Large Scale Seaming/Handling	
Repeatable Processing of Films	Coating, Thickness
Measure Material Grounding (Electrical)	
Adhesive Sticking	
Strength Margins on Booms	Safety factor of 4 ?

Model & Tools	Figure of Merit
Scaled Areal Density	Full Scale (22500 m^2) $\sigma_s = 10 g/m^2$
Scalable Packaging	Package approach scalable to 22500 m^2
Large Scale Seaming/Handling	
Repeatable Processing of Films	Coating, Thickness

Objective 6. Validate Design Approach and Processes

Splinter Session A2
Solar Sail Material Qualities and Environmental Characteristics

Ground Test	**Figure of Merit**
Physical Properties	Areal Mass= $\leq$ 10 g/m^2
Optical Properties	Reflectivity= Specular 83%; Diffuse 8%; α/ε Ratio= absorbtivity 9% Front Side Emmisivity = 3%; Back Emmisivity= 28-30% Chromium Maximum operating temperature 680°K
Mechanical Properties	>100 psi at end of life tensile strength (g/m^2) δCTE (TBD)
Charging Properties	Conductivity=$\geq 10^{-12}$ mhos/sq

Objective 6. Validate Design Approach and Processes

Splinter Session A2
Solar Sail Material Qualities and Environmental Characteristics

Model & Tools	Figure of Merit
Solar Wind Plasmas/Fields	Solar Wind density, composition, velocity, magnetic field specifications
Geosynchronous	Trapped Radiation Environment, Charging Plasma
Solar Energetic Proton Events	SPE total ionizing dose specification
Micrometeoroid Environment	Impact rate, damage criteria specifications
Solar EUV/UV Environment	Solar EUV/UV fluence vs wavelength specification

Model & Tools	Figure of Merit
Effects of Environment on Deployment	Shelf Life and Blocking (Stiction)
Radiation Effects on Sail Performance including EUV/UV on Sail Performance	Radiation deposition in Sail Film; Property Changes from Dose
Surface Charging Modeling	Surface Potentials on Sail Surfaces
Plasma Interactions Modeling	Plasmasheath/Wake 3-D Model

IV. Formation Flying Technology

Session Facilitator:

Jesse A. Leitner

Outline

- Executive Summary
- Formation Flying Capabilities to be Validated by ST-9
- Overview and Introduction
  - What is Formation Flying?
  - Scope of the ST-9 Formation Flying Technology Capabilities Area
- Science Mission Capabilities Roadmap and Timeline
- Technology Capabilities Roadmap
- Figure Of Merit (FOM) Definitions
- State Of The Art
- Acronym List

Executive Summary

- **Workshop Addresses Following Technology Areas**
  - "Precision Formation Flying" (PFF): The frequency and tightness of formation control (not just navigation)
  - Continuous process of maintaining or tracking a desired geometric configuration
- **Sessions Topics**
  - Future space science mission needs
  - Desired workshop products
  - Technology splinter session discussions
  - Needs/potential capabilities assessments
- **Splinter Session Topics**
  - Relative Navigation, Relative Attitude, and metrology sensors and algorithms: the engineering measurements of formation flying
  - Formation Control algorithms and actuators: the logic and actuation hardware to calculate and produce forces needed for formation flying
  - Intersatellite Communications, timing, time transfer: systems to share data between the spacecraft, synchronize spacecraft, and disseminate commands
  - Modeling, Simulation, and Mission Design Tools: tools and methodologies needed to verify performance on the ground
  - Autonomous Constellation Management and Control: the high level control layer for multi-spacecraft operations

Executive Summary (continued)

- **Key Observations and Recommendations**
  - The big challenge will be to craft a mission concept which is affordable and technology-centered, and has enough elements with sufficiently high performance to truly alleviate the future risks of upcoming strategic Space Science missions.
  - This team must find the right mix of proving relevance, reducing risk, and controlling cost.
  - For example, a scientific or instrument-centered demonstration - i.e., an interferometry or imaging demonstration, while providing the ultimate validation if successful, may have the tendency to break the bank.

- **Recommendations for ST-9 Flight Experiment**
  - Importance of exercising system elements in an integrated manner
  - Demonstrate mature component technologies in an integrated package
  - Allocate virtually all risk into the system-level aspects instead of component-level

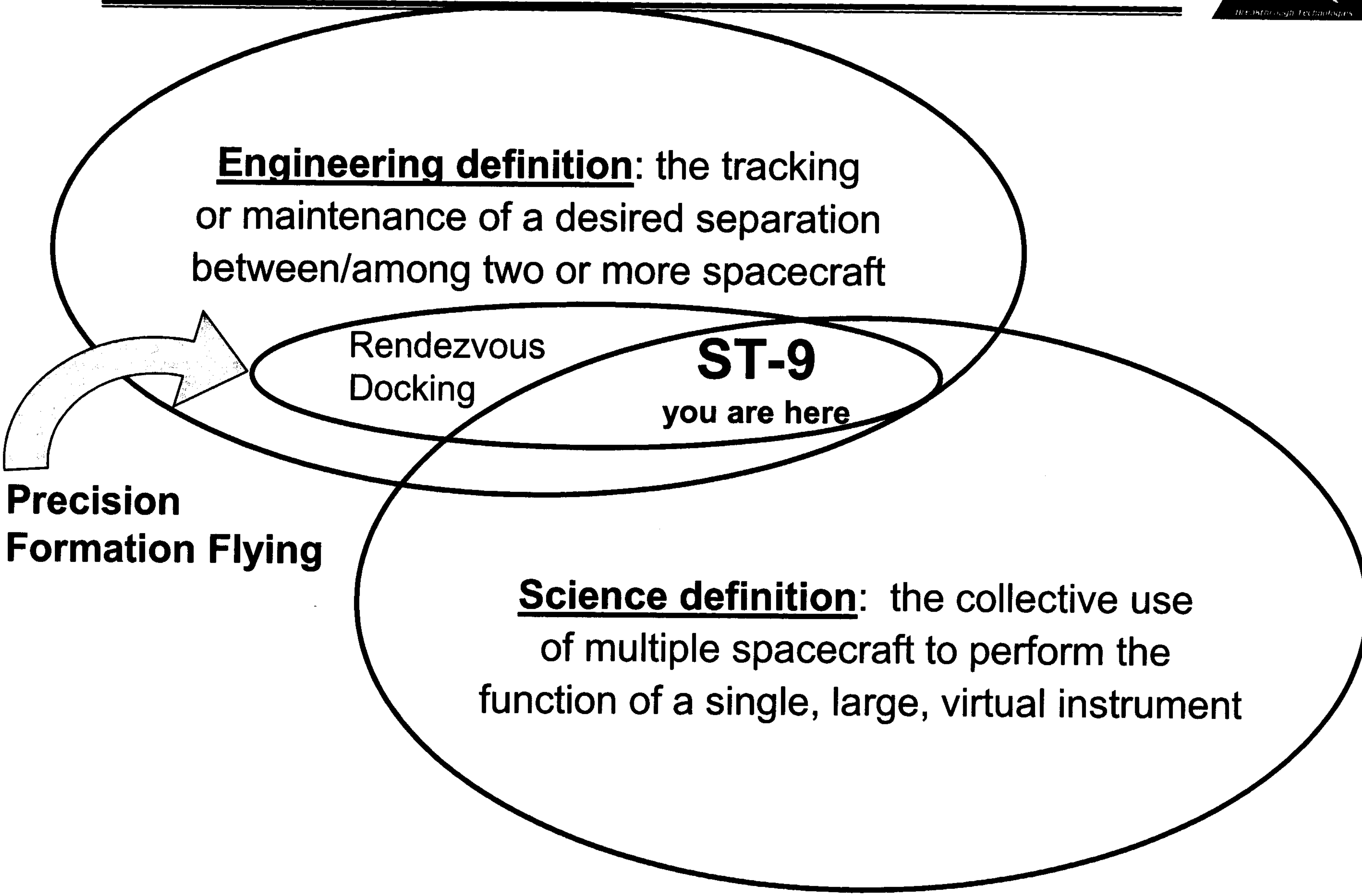
Formation Flying Capabilities to be Validated by ST9

	Figure of Merit				
Required Capability	Now	ST9	SSE Ultimate	Current TRL	TRL 5 Test Requirement
Number of Satellites	N/A	3 desired 2 minimum	>30	For constellation s, 9 For formations, 6	Distributed simulation environment
Measure relative position	2 cm postproc	< 2 cm on-board, real-time	< 1 nm on-board	2 cm: 6 < cm: 4	RF or optical channel simulator with high fidelity dynamic simulator and real-time estimation
Measure relative bearing angles	N/A	1 am	1 mas	4	HW prototype integrated into high fidelity simulation, with real-time estimation
Control relative position	N/A	10 cm	3 nm	4	RF or optical channel simulator with high fidelity dynamic simulator and real-time estimation and control loops wrapped around.
Control relative bearing angles	N/A	5 am	10 mas	2	HW prototype integrated into high fidelity simulation, with real-time estimation and control loops wrapped around
Formation line-of-sight Control	N/A	Probably a stretch to consider	100 nas	1	Interferometric verification
Inter-S/C Communication Rate	300 Mbps TDRSS	10-1,000 Kbps < 20 W, 20 kg	3-10 Mbps	6	Testing of low power lightweight device through RF or optical channel simulator
Range	1 km	100m - 1km	1-500 km	N/A	Channel simulator
Formation Commanding	Ground	On-Board	On-Board	4	Distributed simulation
Autonomous collision avoidance	N	Y	Y	4	High-fidelity simulation
Precision of time synchronization	3 ns GPS	< 1 µs	1 ps	9	Time transfer simulator with GPS or other accurate clock

Overview and Introduction

- **Precision Formation Flying System Technology is critical for a broad range of future NASA Space Science missions**
  - TPF (ASO)
  - MAXIM, MAXIM PF (SEU)
  - Stellar Imager (SEC)
  - LF, PI, SPECS, ...
- **The "precision" qualifier carves out a somewhat well-defined niche in the formation flying field with the following characteristics**
  - Continuous and robust, possibly high bandwidth intersatellite communications
  - On-board relative navigation/bearing at high data rate with high-precision through the communication links
  - Oontinuous formation control at high bandwidth and high-precision through the communication links
  - Highly-optimized formation/mission design and analysis
  - Integrated hardware-in-the-loop, high-fidelity simulations
  - Autonomous and robust closed-loop on-board control during science gathering

What is Formation Flying?



Scope of the ST-9 FF TCA

- **In the context of ST-9, we will focus on the problem of "Precision formation flying"**
  - Precision, in this case, refers to a continuous process of maintaining or tracking a desired geometric configuration
  - Collectively, it is the frequency and tightness of formation control (not just navigation)
- **Since the focus is on demonstrating technologies critical to future NASA Space Science Enterprise missions, the orbits of primary interest: are HEO, libration points, heliocentric, deep space**

Science Mission Capabilities Roadmap and Timeline

Capability

loose formations
MMS

sub-micron rel pos estim.
cm s/c pos control, 5 s/c
TPF

micron rel nav
micron s/c pos control, 8 s/c
MAXIM

nm rel nav
nm control, 30 s/c
SI

<nm rel nav
nm control, 30+ s/c
PI, LF

Magnetospheric	Detect/ID planets	Black hole phenomena	Asteroseismology	Imaging Planets
2009	2015	2017	2020	2025

Technology Capabilities Roadmap

Capability	2009		2015		2017	2020	2025
Autonomous operations			5 s/c		8 s/c	30 s/c	
Intersatellite Comm	100 kbps				1 Mbps		
S/C Formation Control	100m		2 cm	10 μm		3 nm	
Rel Position Estimation	10m	10 cm	3 nm			0.5 nm	

Figure Of Merit (FOM) Definitions

- **Relative position estimate: the estimated value of relative position between spacecraft**
- **S/C Formation Control: the controlled separation between selected references points between two spacecraft.**
- **Intersatellite communications bandwidth: the number of bits of data passed from one spacecraft to another.**
- **Formation geometric dimension: the number of dimensions in free-space spanned by the desired formation**

State Of The Art

- Relative position estimate: 1 micron range change, 2 cm ranging (post-processed)
- Formation control: kms (EO-1/LS-7)
- Intersatellite comm data rate: 300 Mbps (large EIRP) TDRSS
- Formation geometric dimension: 1 (rendezvous docking)
- Number of s/c managed collectively: ~50 (from the ground)

Acronym List

MMS	Magnetospheric Multi-Scale Mission (SEC)
TPF	Terrestrial Planet Finder Mission (ASO)
MAXIM	Miscro Arcsecond X-Ray Imaging Mission (SEU)
SI	Stellar Imager Mission (SEC)
PI	Planet Imager Mission (ASO)
LF	Life Finder Mission (ASO)

V. System Technology for Large Space Telescopes

Session Chair:

Juan A. Roman

Outline

- Executive Summary
- Large Telescope Capabilities to be Validated by ST9
- Overview and Introduction
- Ultimate Capabilities
- Science Mission Capabilities Time Line
- Goal of Splinter Sessions

Executive Summary

- Workshop Addresses Following Technology Areas
  - Issues of large (10-25m), cryogenic (4K), low mass telescope systems.
- Sessions Topics
  - Future space science mission needs
  - Desired workshop products
  - Technology splinter session discussions
  - Needs/potential capabilities assessments
- Splinter Session Topics
  - Large Telescope System Simulation and Modeling
  - Materials, Structures, Actuators, and Controls for Fabrication, Packaging and Deployment of Large Telescope Systems
  - Optical Correction and Active Figure Control for Large Aperture Telescopes
  - Thermal Control at Cryogenic Temperatures for Large Aperture Telescopes
  - Structure and Control Dynamics of Large Telescope Systems

Executive Summary (continued)

- **Key Observations and Recommendations**
  - **ST-9 can accelerate development of needed technology before they are mature enough to be applied in a strategic scientific mission.**

- **Recommendations for ST-9 Flight Experiment**
  - **Applicable to a Far-Infrared (20 - 600μm) mission with 10 – 25m telescope at 4 K**
  - **ST-9 can validate several of the following critical technologies**
    - Deployable low areal density aperture scalable to diameter >10m
    - Passive cooling (with sunshields / radiators) to ~20 K
    - Active cooling of large structures from ~20 K to ~4 K
    - Integrated system modeling of end-to-end performance
    - Pointing stability consistent with telescope design
    - Wavefront sensing and control
  - **Orbit traceable to target mission (e.g., L2), however:**
    - Will tolerate thermal and dynamical differences necessitated by other orbits (e.g., LEO, GTO)
    - Will tolerate contamination and radiation differences

Large Telescope Capabilities to be Validated by ST9

Required Capability*	Figure of Merit: Now	Figure of Merit: ST9	Figure of Merit: SSE Ultimate	Current TRL
Deployable large aperture—areal density	$15 kg/m^2$	Scaleable to SSE requirement for diameter	$<5\ kg/m^2$	4
Deployable Large Aperture—Diameter	6m segmented	Scalable diameter; segmented or membrane	10-25m	4
Wave-front sensing and control, Figure control $\leq \lambda/20$, static and dynamic	$\lambda/15$ rms over 36 segments with 4 dof/segment	Any demonstrated wavefront quality	$\lambda/1000$ (vis-coronagraph) $\lambda/20$ rms full aperture	4
Passive Cooling on telescope shield	40K outer	Scalability to SSE goal temperature	10 W @ 40 K 15K desired	4
Active Cooling on telescope sunshade and on components	250mW at 18K 1-2mW at 1K	Scalability to SSE goal temperature	1 W @ 15 K; 100 mW @ 4 K	4
Thermal Transport systems	Capillary pump loops, 100K-20K LN2 at 70-100K Ne at 35K H2 at 20-30K; 5W over 2.5 m distance with 2-3 W/K	Scalability to SSE goal temperature	15k→4k, 1W at 15K with 5 W/K, 100mW at 4K with 1 W/K	4
Integrated Modeling	10^4 nodes mechanical, optical, or thermal	Embedded integrated optical, mechanical, and/or thermal software demonstration	10^6 embedded nodes, Integrated optical, mechanical, and thermal	3
ST9 on-orbit behavior relatable to the planned operational environment	LEO, GEO, GTO	Temperature stability on orbit	L2 or thermally stable orbit	

* These required capabilities are a critical subset; other important capabilities may not be listed here.

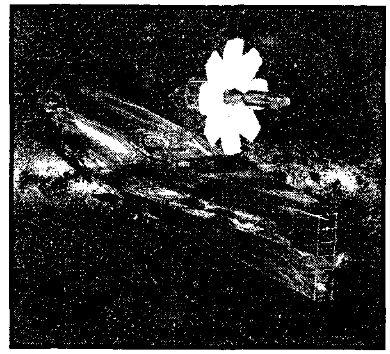
Large Space Telescopes

Motivation for a Large Cryogenic Space Telescope

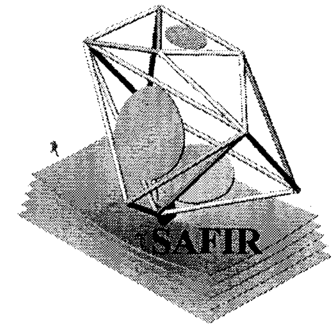
- A key element of the SSE mission series is a large space telescope, 10-meter diameter, cryogenically cooled to 4 K and optimized for wavelengths between 40 μm and 1 mm.
- The combination of aperture diameter and telescope temperature will provide a raw sensitivity improvement of more than a factor of 1000 over presently-planned missions,therefore, capable of conducting groundbreaking research.
- In consideration of its enormous scientific potential, such a mission was recommended by the National Academy of Sciences Astronomy Decadal Committee as "the next step in exploring this important part of the spectrum."

State of the Art

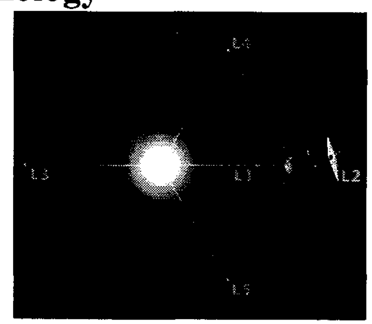
- The JWST is consider to be the departing point for future missions.



Concept based on JWST technology



Concept based on large stretched membranes



L2, sun-synch, etc., provide stable thermal environments

Enabling Capabilities

- Very lightweight mirrors
- High dynamic wavefront sensing and control
- Active and passive cooling below 10 K
- Validation of end-to-end models in relevant environment

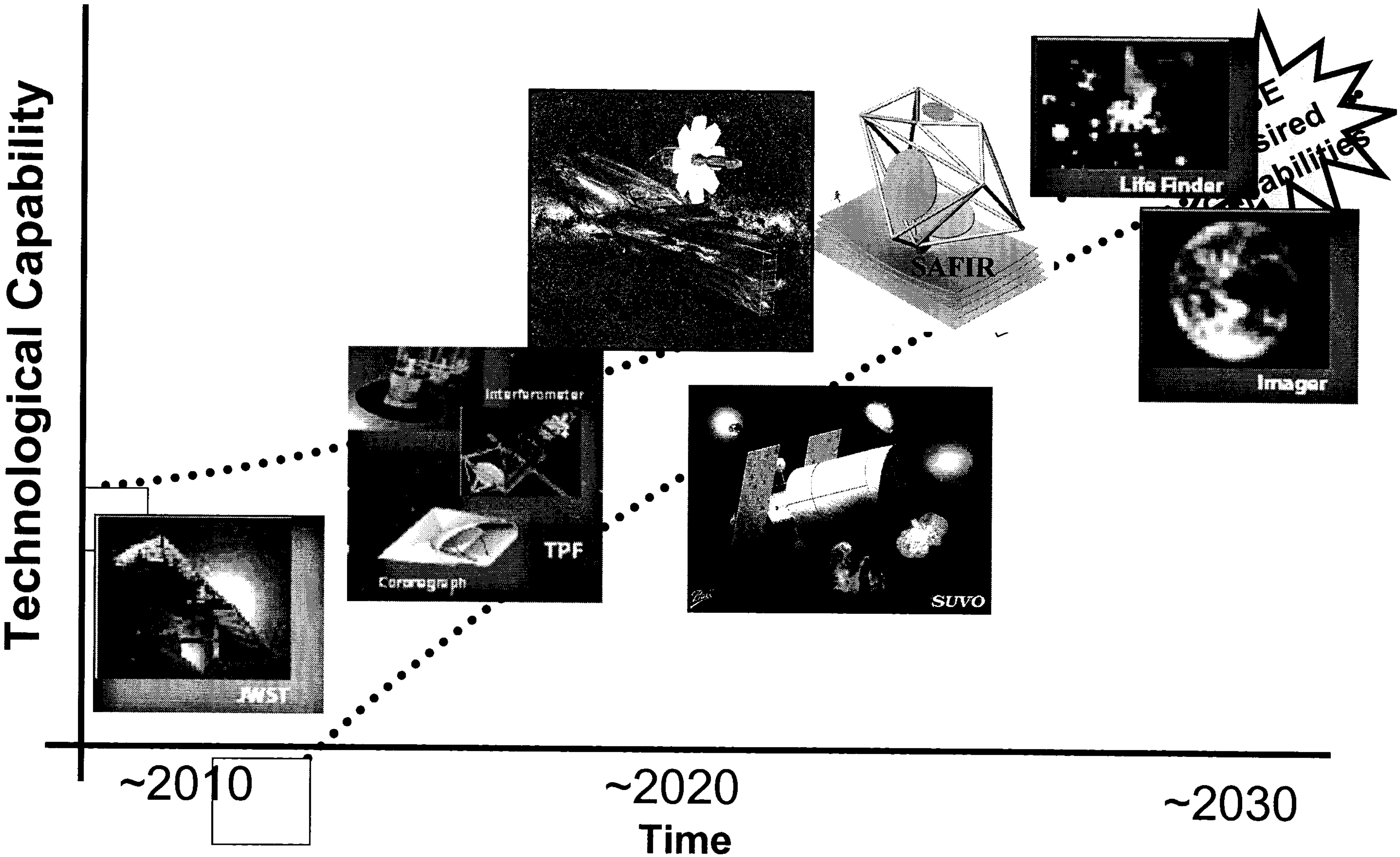
Overview and Introduction
ST-9

- Critical stepping stone toward making possible future Large Space Telescopes.
- Will enable the next breakthrough in technology capabilities that requires in-space system validation.
- Development of needed technology capabilities can easily take a decade or more before they are mature enough to be applied in a strategic scientific mission.
  - ST-9 can accelerate this process
- The focus is on system "validation" to address the gaining of understandings that are useable beyond the confines of the specific hardware, e.g., scaling based on correlations with analytical models.

"Ultimate Capabilities"

- **Some of these capabilities are:**
  - Building of deployable large, low areal density mirrors and their associated structural components for operation at ambient and cryogenic temperatures.
  - Wavefront control with active control of optical elements and micro-dynamic and thermal structural effects to surpass diffraction-limited performance.
  - Providing active and passive cooling for full-aperture, all-optics cooling to ~4K and other technologies for achieving a similar reduction in thermal system noise for infrared space telescope systems.
  - Robust end-to-end modeling of telescope system and validation of system model.

Science Mission Capabilities Time Line



Areal Density Figure of Merit

Areal Density = Mass per unit area (Kg/ m^2). It includes mirror, actuators, cables and backing structure of optical system.

<1Kg/ m^2, <\$500K/m^2 <4 K, 10 – 25 m dia. with high packing density (fit in EELV)

ST-9:
~5Kg/ m^2, <\$1M/m^2,
<10K, diffraction limited at 20 - 40um

AMSD: 15Kg/ m^2,
\$5M/m^2, 30-50K,
50nmRMS

Goal of Splinter Sessions

- Identify and refine the capabilities needed for future Large Space Telescopes missions under consideration by the Space Science Enterprise.
- Define validation requirements for each of the technology capabilities in a quantitative manner and at a realizable level of technology maturity to support a 2008 launch date.
- Opportunity to obtain inputs from the broadest possible base – industry, academia, government.

Acronyms

- ST – Space Technology
- EELV – Evolved Expendable Launch Vehicle
- L2 – Libration Point 2
- LEO – Low Earth Orbit
- GTO – Geostationary Transfer Orbit
- JWST – James Webb Space Telescope
- TPF – Terrestrial Planet Finder
- SAFIR – Single Aperture Far IR telescope “sapphire”
- SSE - Space Science Enterprise
- SUVO – Space Ultraviolet Observatory
- AMSD – Advanced Mirror System Demonstrator

VI. Descent and Terminal Guidance for Pinpoint Landing and Hazard Avoidance

Session Chair:

Dr. Sam W. Thurman

Executive Summary

- **Workshop Addressed Following Technology Areas**
  - **"Pinpoint" Landing**
  - **Hazard Detection and Avoidance**
- **Sessions Topics and Activities**
  - **Future space science mission needs**
  - **Desired workshop products**
  - **Technology splinter session discussions**
  - **Needs/potential capabilities assessments**
- **Splinter Session Topics**
  - **Guidance, Navigation and Control (GN&C) Systems**
    - Modeling and Simulation
    - Sensors/Algorithms for Guidance and Navigation
    - Aerodynamic/Propulsive Maneuvering System Options
  - **Terrain Sensing and Hazard Recognition Systems**
    - Terrain Sensors and Hazard Detection/Recognition Algorithms
    - Architectural Options for GN&C Systems with Terrain Sensors
- **Key Splinter Session Observations and Recommendations**
  - **Target body environment characteristics driving descent/landing system design tend to group into airless bodies and those with atmospheres**
  - **Mars environment viewed as stressing case in many important aspects**
    - Presence of atmosphere allows/requires use of aerodynamic deceleration systems
    - Low atmospheric density effectively also requires propulsive maneuvering systems to accomplish targeted landing with hazard avoidance capability

Executive Summary (continued)

- **Recommendations for ST-9 Flight Experiment**
  - **Important to exercise system elements in an integrated manner**
    - Onboard navigation incorporating both inertial and terrain sensing capability
    - Hazard recognition, safe target landing site selection, and aerodynamic/propulsive steering using navigation data
  - **Terrestrial sub-orbital (via sounding rocket boost) or descent-from-orbit flight test mission recommended**
    - Lander Test Vehicle with Following Capabilities
      - Onboard Navigation
        - » Inertial sensors and prototype terrain sensor(s)
        - » Navigation algorithms and computations for inertial/terrain sensor data fusion
        - » Hazard recognition and safe landing site selection algorithms and computations
      - Onboard Guidance & Control
        - » Targeted parachute descent using "smart" parachute deployment logic
        - » Consider propulsive terminal descent to soft landing (if it fits cost target)
  - **Rationale**
    - Enables operation of integrated GN&C system in flight-like manner
    - Dynamical scaling can be used to create flight dynamics environment representative of many different "smart" landing mission environments
    - Near-Earth environment offers low-cost multiple test flight opportunities and ability to acquire many detailed measurements for model correlation and validation
  - **This approach would validate a GN&C system architecture capable of scaling to meet most projected future mission needs over next 10-15 years**

Descent/Terminal Guidance Capabilities to be Validated by ST9

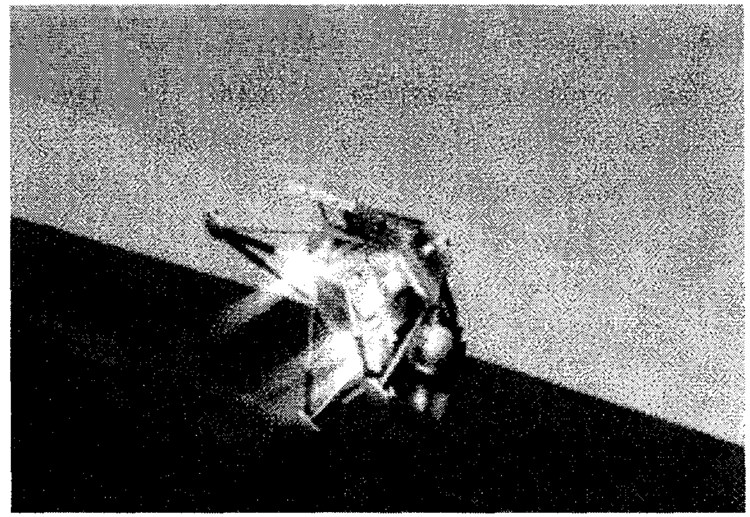
	Figure of Merit				
Required Capability	Now	ST9	SSE Ultimate	Current TRL	TRL 5 Test Requirement
Landing Accuracy (body w/ atmos., km)	100-300	3-6 km	<100 m	3	Sub-scale "smart" para deploy test
Landing Accuracy (airless body, km)	1-10	0.1-1.0 km		4	Real-time sim w/ terrain sensing
Horizontal maneuvering capability	limited	100-200 m,	3-5 km	5	N/A
Hazard detection - rocks	none	Rocks > 0.75 m	any	3-4	Terrain sensor field testing (e.g. helicopter, rocket sled)
Hazard detection - slopes	none	Slopes > 20 deg	any		
On-board navigation accuracy	0.2-20 km	10-100 m	1-10 m	4	Integrated nav system field testing (e.g. helicopter, rocket sled)

Overview and Introduction

- **Future Space Science Mission Needs**
  - **Variety of desired missions for planetary surface exploration**
    - Lunar and Mars exploration and sample return
    - Comet and asteroid sample return
    - Europa lander
    - Venus and Titan exploration
  - **Many scientific objectives benefit/enabled by new engineering capabilities for delivery of scientific payloads to planetary surfaces**
    - "Pinpoint" Landing
    - Hazard Detection and Avoidance
- **Workshop Conducted with Following Objectives**
  - **Identify potential mission needs and requirements via diverse group of engineering experts from government, industry, academia**
  - **Survey component/subsystem technologies for meeting these needs**
    - Functionality and performance
    - Technology maturity, test/validation requirements and approaches
    - Modeling and scaling of test/validation results to different mission environments
  - **Synthesize survey results to map and prioritize technology candidates versus mission needs**
  - **Formulate recommendations for ST-9 Flight Experiment scope and content to be considered during subsequent Pre-Phase A and Phase A study effort**

"Smart" Landing Overview

- **"Smart" Landing Technologies**
  - **Pinpoint Landing**
  - **Hazard Detection & Avoidance**
- **Science Mission Benefits**
  - **Ability to reach landing sites which may lie in areas containing hazardous terrain features**
    - Escarpments
    - Craters
    - Slopes and rocks
  - **Ability to land accurately at select landing sites of high science value**
    - Small terrain types/features or isolated locations (e.g., safe target site within larger region of hazardous terrain)
- **State of the Art**
  - **No existing system-level capability**
  - **Some previous examples of propulsive maneuvering in Apollo/Viking era**
    - Apollo Lunar Module descent/landing
    - Surveyor and Viking Landers
  - **Some recent terrestrial examples of terrain sensing in "smart" weapons**



- **Technical Approach**
  - **Onboard Navigation**
    - Accurately determine current and predicted lander flight path
  - **Terrain Sensing**
    - Sense terrain characteristics and recognize hazardous features
    - Identify safe landing site that can be reached given lander's maneuverability
  - **Onboard Guidance**
    - Provide maneuvering capability (aerodynamic or propulsive) to steer lander to touchdown at desired safe landing site

Science Capabilities Roadmap

Potential Mission Timeline

- 2009/10
  - Mars Science Laboratory
  - Lunar South Pole/Aitken Basin Sample Return
- 2012/13
  - Comet/Asteroid Surface Sample Return
  - Venus In-Situ Explorer
- 2014/15
  - Mars Sample Return
- 2020 +
  - Europa Lander
  - Titan Explorer
  - Mars and Lunar Robotic Outposts
  - Human Exploration Missions

"Smart" Landing Capability Needs

- 2009/10
  - Landing accuracy <6 km (Mars), 0.1-1 km (Moon)
  - 100 m maneuvering to avoid hazardous slopes/rocks
- 2012/13
  - Landing accuracy <0.1 km (small body), 10-100 km (Venus)
  - 100-200 m maneuvering to avoid small body terrain hazards
- 2014/15
  - Landing accuracy 1-3 km
  - 100-300 m maneuvering to avoid all hazardous terrain features
- 2020+
  - Landing accuracy < 0.1 km (airless bodies and Mars), 10-100 km (Titan)
  - 100-500+ m maneuverability to avoid all hazardous terrain (airless bodies, Mars)

Technology Capabilities Roadmap

- **Current Generation (today)**
  - **Landing Accuracy**
    - Bodies with Atmosphere: 100-300 km
    - Airless Bodies: 1-10 km
  - **Hazard Detection and Avoidance**
    - none
- **Next Generation (incorporating results from ST-9)**
  - **Landing Accuracy**
    - Bodies with Atmosphere: 3-6 km
    - Airless Bodies: 0.1-1 km
  - **Hazard Detection and Avoidance**
    - detecting 99% of rocks > 0.75 m; detect > 20° slopes
    - 100-200 m divert capability
- **Future Generation Goals (beyond ST9)**
  - **Landing Accuracy**
    - Bodies with Atmosphere: < 100 m
    - Airless Bodies: < 10 m
  - **Hazard Detection and Avoidance**
    - detecting 99% of rocks > 0.2 m; detect / analyze terrain features at and near landing site (including non-geometric hazards)
    - 0.5-5.0 km divert capability

Figure Of Merit (FOM) Definitions

- **Pinpoint Landing**
  - **Delivery Accuracy**
    - Miss distance between target landing site and actual landing location
- **Hazard Detection and Avoidance**
  - **Hazard detection/recognition**
    - Detection and recognition of geometric and non-geometric terrain hazards
      - Detection and recognition of geometric hazards such as craters, escarpments, rocks, slopes, etc.
        - » Key metrics: probability of missed detection of hazardous terrain and probability of false positive from non-hazardous terrain
      - Detection and recognition of non-geometric hazards such as terrain areas with low/insufficient bearing strength
        - » Key metric is similar to above
  - **Maneuver capability for hazard avoidance**
    - Site redesignation capability versus altitude/velocity regime during descent

VII. Aerocapture System Technology for Planetary Missions

Session Facilitator:

Michelle Munk

Presentation to NMP ST9 Workshop

Washington, D.C.

February 2003

Outline

- Executive Summary
- Aerocapture Capabilities to be Validated by ST9
- Aerocapture Overview
  - Aerocapture as an Enabling Technology
- Technology Areas to be Addressed by ST9
  - Experiment Requirements
- Science Capabilities Roadmap
  - Aerocapture Mission Summary
- Technology Roadmap
- State of the Art
- Figures of Merit Definitions

Executive Summary

- **The Splinter Sessions Focused on the Following Technology Areas**
  - **System and Performance Modeling**
  - **Aerodynamics and Aerothermodynamics**
  - **Thermal Protection Systems/Structure**
  - **Guidance, Navigation, and Control (GN&C)**

- **Session Topics**
  - **Future space science mission needs**
  - **Desired workshop products**
  - **Technology splinter session discussions**
  - **Needs/potential capabilities assessments**

Executive Summary (continued)

- **Key Observations**
  - **Aerocapture is applicable to all planetary destinations with suitable atmospheres (Venus, Earth, Mars, Jupiter, Saturn, Titan, Uranus, and Neptune)**
  - **The primary advantage of aerocapture is propellant mass savings. The net vehicle mass savings range from 20-80% depending on the destination and can manifest themselves in terms of smaller, cheaper launch vehicles or increased payloads.**
    - Preliminary results indicate that some missions (e.g. Neptune Orbiter) cannot be done without aerocapture because they won't fit on the largest available launch vehicle (Delta IV heavy).
    - Aerocapture can also reduce trip time (by allowing higher arrival speeds than chemical capture can feasibly accommodate), and enable new missions with increased flexibility
  - **Aerocapture is a systems technology in which most of the elements already exist due to development in other aeroentry applications. The critical next step is to assemble these elements into a prototype vehicle, fly it in the space environment and thereby validate the design, simulation and systems engineering tools and processes**
    - This need is very well matched to the NMP program objective that ST-9 be a systems level validation experiment
  - **ST-9 flight experiment is key to making aerocapture technology available to science missions**

Executive Summary (continued)

- **Recommendations for ST-9 Flight Experiment**
  - **ST-9 should validate the most mature and immediately useful vehicle configuration, which is the blunt body aeroshell**
    - Blunt body aeroshell systems provide robust performance for aerocapture at all "small body" destinations in the solar system (Mars, Titan, Venus, Earth)
    - The validation will be directly relevant to other aeroshell geometries (as will be needed for the gas giants) for the guidance, simulation and systems engineering disciplines
  - **The ST-9 flight validation must demonstrate a drag delta-V of 2 km/s, in order to involve all of the essential physics of the problem and serve as an acceptable validation of aerocapture**
    - Although the ST-9 cost cap precludes a "true" aerocapture flight test involving a hyperbolic to elliptic orbit change effected by atmospheric drag, this objective can be accomplished with an elliptical-to-elliptical orbit change.
  - **The ST-9 flight test should include an autonomous periapse raise maneuver after the atmospheric portion of the flight**
  - **The ST-9 vehicle should incorporate diagnostic instrumentation to the maximum extent possible under the cost cap**
    - The two priorities are to get information about the hypersonic flow field around the vehicle and to quantify the performance of the thermal protection material.
  - **The ST-9 vehicle should baseline mature TPS and structural materials to minimize risk**
    - However, it is recommended (if affordable given the cost cap) that the vehicle incorporate a test coupon of one or more new TPS materials that are candidates for future aerocapture and/or aeroentry missions at other planets. These coupons should be incorporated in such a way that their failure does not compromise the overall flight test experiment

Aerocapture Capabilities to be Validated by ST9

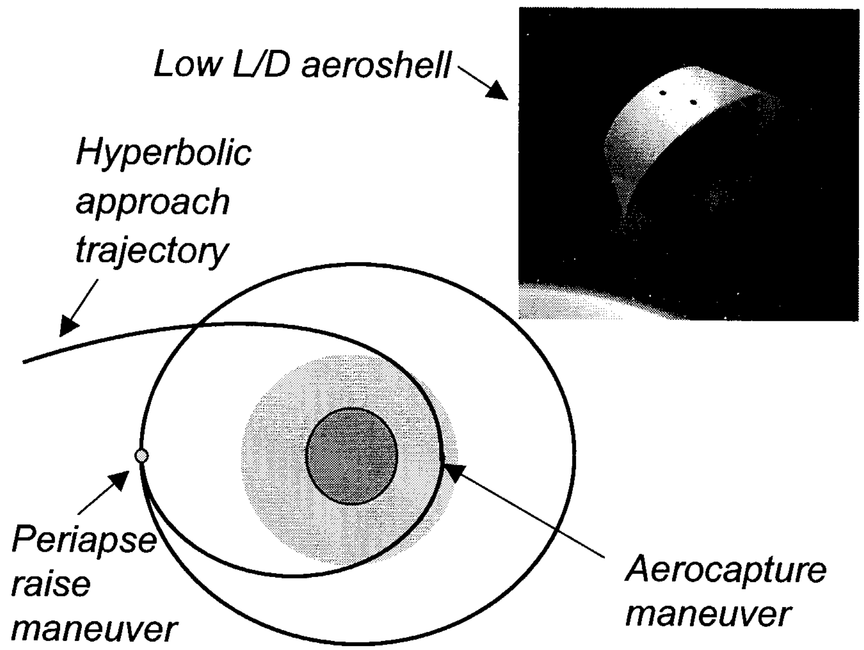
	Figures of Merit				
Required Capability	**Now**	**ST9**	**SSE Ultimate**	**Current TRL**	**TRL 5 Test Requirement**
Aftbody aeroheating uncertainty (%)	200	100	100	N/A	N/A
Aero/RCS interaction uncertainty (%)	300	100	100	N/A	N/A
Aerocapture GN&C validated	Validated by simulation	Validated by flight	Provided by ST9	5	7
GN&C validation (# of segments flight validated)	2	3 Mission critical exit phase validated	3 Provided by ST9	N/A	N/A
Atmospheric flight simulation validation for aerocapture	Monte Carlo trajectories predicted for range of environments, uncertainties	Trajectory reconstruction validates predicted trajectory, flight environment, uncertainty	Provided by ST9	5	7
Vehicle captured into required orbit, aeromaneuvering effort indicator within 3-Sigma range predicted	Success predicted by simulation, 3-sigma aeromaneuvering effort indicator predicted through Monte Carlo	Success validated by flight, aeromaneuvering effort indicator within 3-sigma range predicted	Provided by ST9	5	7
Vehicle completed autonomous periapsis raise maneuver, Delta V for periapsis raise within 3-Sigma range predicted	Success predicted by simulation, 3-sigma Delta V predicted through Monte Carlo	Success validated by flight, Delta V within 3-Sigma range predicted	Provided by ST9	5	7
Aerocapture spacecraft/aeroshell integration validated	Success predicted by design methods	Success, design methods validated by flight	Provided by ST9 and design work for SSE	5	6

Aerocapture Overview

What is it?
- Aerocapture is an orbit insertion flight maneuver executed upon arrival at a planet.
- Spacecraft flies through the atmosphere and uses drag to effect multi-km/s deceleration in one pass
- Requires minimal propellant for attitude control and a post-aerocapture periapse raise maneuver.

Benefits
- Significant reduction in propellant load; arrival mass can be reduced by 20-80% for the same payload mass depending on the mission
- Achieves the required orbit faster than with aerobraking or SEP alternatives (hours vs weeks/months)
- Can result in reduced flight times since arrival speeds can be higher than for propulsive capture

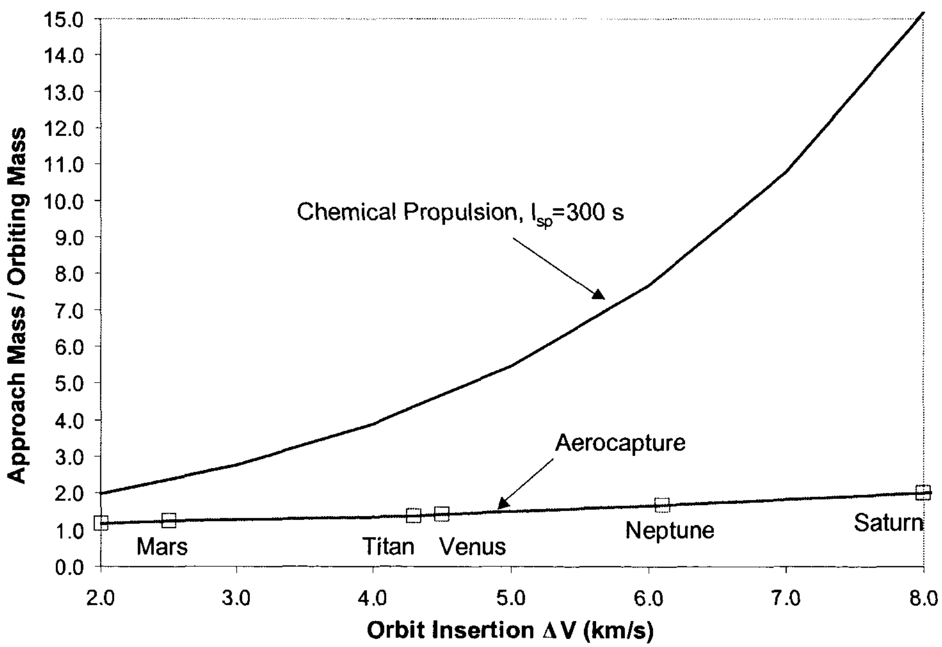
State of the Art
- Never been attempted before
- Considerable relevant experience from past aeroentry and aerobraking missions
- Sufficient technical maturity exists for a flight test experiment



Primary Technical Approach
- Spacecraft carried inside a protective aeroshell
- Aeroshell provides both thermal protection and aerodynamic surface functionality
- Aeroshell cutouts and feedthroughs enable full spacecraft functionality during cruise
- Automatic guided flight through atmosphere using specialized algorithms/software
- Aeroshell jettisoned after capture

Aerocapture is an Enabling Technology

- **Aerocapture can save so much propellant mass that it enables missions that cannot otherwise be done**
  - **Propulsive orbit insertion obeys the rocket equation: $M_{fuel} \sim \exp(\Delta V)$**
  - **Aerocapture mass is predicted to scale almost linearly: $M_{AC} \sim \Delta V$**



	Approximate Maximu Launch Capability		Required Missio Delivered Mass	
	Launch Vehi and C3	Max. Delivere Mass (k	Propulsiv Orbit Insertion (kg)	Aero-captur (kg)
Mars Sample Return ('03/'05 concept)	Delta IV 445 (C3=10)	3700	2000	110
Titan Explorer (orbiter only)	Delta IV 4450 SEP + VGA (C3=110)	1400	4400	90
Neptune Orbiter	Delta IV 4450 SEP + VGA (C3=140)	800	4700	80
Venus Sample Return	Atlas V 531 (C3=10)	4200	13000	400

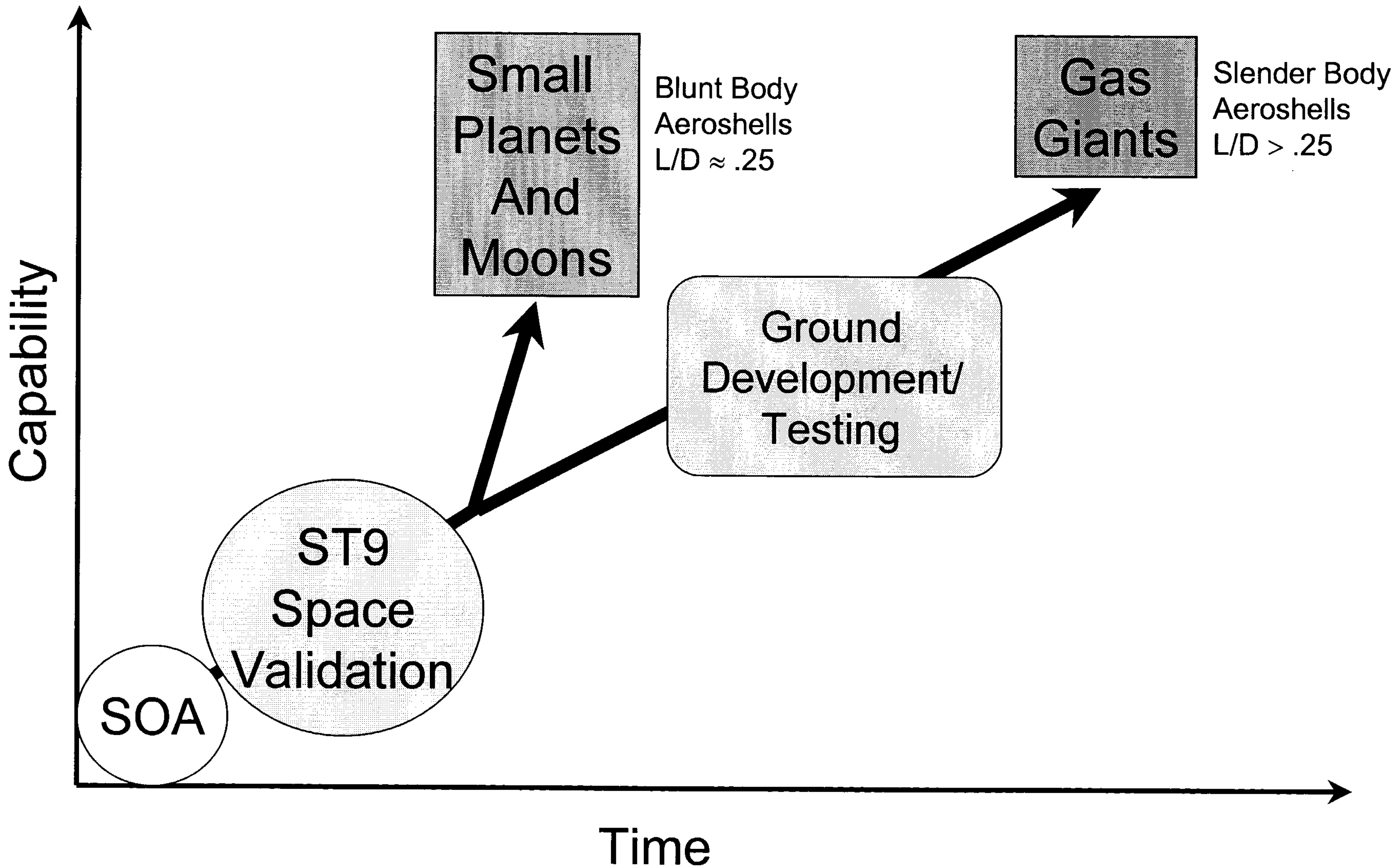
Aerocapture Technology Areas to be Addressed by ST-9

- Complete systems level test of a free-flying vehicle in order to validate the design, simulation, and systems engineering tools and processes.
- This validation will directly address flight mechanics, vehicle design, systems engineering and integration, no matter what the future planetary destination is.
- This validation will partially address aerothermodynamics and TPS, since the applicability to future missions is more limited because of the specialized needs of the different destinations.

Experiment Requirements

- **In a single atmospheric pass, utilize bank angle modulation through an atmosphere to remove the necessary amount of delta V from the vehicle approach trajectory to achieve the target orbit.**
  - The delta V achieved during this maneuver must be on the order of 2 km/s to validate all phases of the guidance and achieve hypersonic continuum aerodynamics
- **Validate a mature and immediately useful vehicle configuration**
- **Perform an autonomous periapse raise maneuver after the atmospheric portion of the flight**
- **Utilize diagnostic instrumentation to the maximum extent possible, to acquire information about the hypersonic flow field and quantify the performance of the thermal protection material.**
  - The information obtained will be the key to model validation and technology infusion

ST-9 Feed-Forward to Science Capabilities

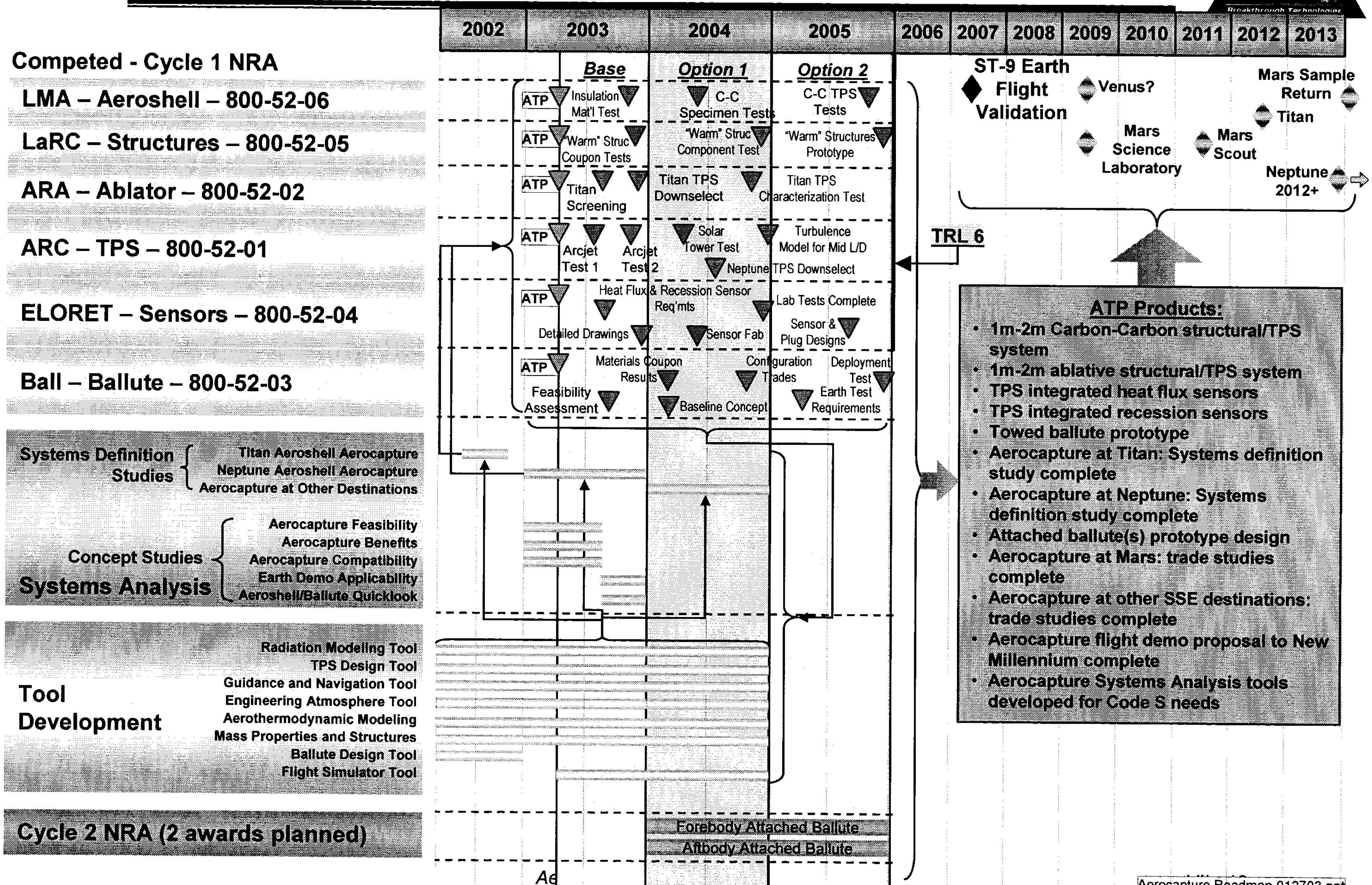


Aerocapture Mission Summary

	Mission Opportunities	Earliest Launch Opportunity	Nominal Inertial Entry Speed	Nominal Orbit Insertion Delta-V	Nominal Required L/D	Probable Aerocapture System Mass Fraction	Significant Technology Issues
Venus	Discovery or New Frontier program orbiters for remote sensing and in situ telecom relay. Long term Decadal survey goal of surface sample return.	Dis: 2007 NF: 2009 SR: 2015+	11.2	4.2	0.25	0.35	Premise of low L/D viability still to be confirmed with detailed systems analysis.
Mars	Scout and Mars Exploration program orbiters for remote sensing and in situ telecom relay. Long term program goal of surface sample return.	Sct: 2011 SR: 2014+	6.0	2.5	0.25	0.25	Requirement for backside protection not understood, will impact attainable improvements on mass fraction.
Earth	ST-9 Flight Test. Aeroassisted orbit transfer vehicles (GTO - LEO).	ST-9: 2007 AOTV: 2008	10.3	2.3	0.25	0.25	None for ST-9. AOTVs have TPS reusability and spacecraft packaging issues.
Jupiter	Discovery, New Frontiers or flagship orbiter for remote sensing or Jovian satellite tour. Decadal survey identified Jupiter polar orbiter and multiprobe mission (JPOP) as a high priority for which aerocapture may be enhancing.	Dis: 2007 NF: 2009	59.0	low cir: 17 ellip: 1-3	0.8?	0.55	No detailed system analysis to quantify required L/D. Lower mass TPS could save substantial mass.
Saturn	Saturn Ring Observer, flagship mission noted in the Decadal survey but deferred until aerocapture technology is matured.	SRO: 2012+	35.0	7.1	0.8?	0.50	No detailed system analysis to quantify required L/D. Lower mass TPS could save substantial mass.
Titan	Post-Cassini remote sensing and telecom relay orbiter (Titan Explorer), noted in Decadal survey as a high priority flagship mission. Lesser scope options may fit New Frontier program cost cap.	TE: 2012 NF: 2012	6.5	5.0	0.25	0.35	CN thermal radiation and TPS response problem being worked, will impact achievable mass fraction.
Uranus	Remote sensing orbiter, but does not appear in current Decadal priority list.	UR: 2012+	27.0	5.0	0.80	0.45	No detailed systems analysis done. However, it is likely to share Neptune issues.
Neptune	Flagship mission remote sensing orbiter and probe telecom relay rated a high priority in Decadal survey but deferred until aerocapture technology is matured.	NO: 2012+	29.0	6.0	0.80	0.45	Detailed systems analysis in progress, issues still being identified and evaluated.

Ref: Jeffrey L. Hall, Muriel Noca, JPL

Aerocapture Technology Development Roadmap



State of the Art

- **Aerocapture has never been flown in space**
- **Elements of aerocapture have been flown**
  - **Aeromaneuvering (lifting, guided and controlled) with low L/D aeroshell, lift vector modulation with low control authority**
    - Apollo, Gemini
  - **Atmospheric exit human rated for Apollo, but never flown**
  - **Russian Zond 6 spacecraft performed loft on Lunar return, to reach U.S.S.R. in 1968 (using pre-programmed bank commands)**
  - **Aeroassist demonstrated spacecraft with similar characteristics**
    - Viking – lifting, controlled, unguided Mars Entry, Descent and Landing
  - **Ballistic entries completed at**
    - Mars, Jupiter, Venus, Earth, Titan (Huygens Jan 05)
  - **Shuttle**
- **Trailing ballute never flown**
- **Russians built, launched, attempted re-entry of inflatable ballistic attached ballute**

Figure of Merit (FOM) Definitions

- Lift-to-Drag Ratio (L/D) - an aerodynamic term which quantifies the relative amounts force, perpendicular to the relative wind that constitutes an upward force (lift), and parallel and opposite the direction of motion (drag). In practical terms, this is a measure of the controllability of a vehicle. A ballistic vehicle has a lift-to-drag ratio of zero; a slender, winged vehicle has an L/D of greater than 1. For aerocapture, a vehicle with a higher L/D can maneuver through a more narrow flight corridor and compensate for greater uncertainties, but will be aerodynamically more complex than the high-heritage blunt body.

IV. Formation Flying Technology

Session Facilitator:

Jesse A. Leitner

Outline

- Executive Summary
- Formation Flying Capabilities to be Validated by ST-9
- Overview and Introduction
  - What is Formation Flying?
  - Scope of the ST-9 Formation Flying Technology Capabilities Area
- Science Mission Capabilities Roadmap and Timeline
- Technology Capabilities Roadmap
- Figure Of Merit (FOM) Definitions
- State Of The Art
- Acronym List

Executive Summary

- **Workshop Addresses Following Technology Areas**
  - "Precision Formation Flying" (PFF): The frequency and tightness of formation control (not just navigation)
  - Continuous process of maintaining or tracking a desired geometric configuration
- **Sessions Topics**
  - Future space science mission needs
  - Desired workshop products
  - Technology splinter session discussions
  - Needs/potential capabilities assessments
- **Splinter Session Topics**
  - Relative Navigation, Relative Attitude, and metrology sensors and algorithms: the engineering measurements of formation flying
  - Formation Control algorithms and actuators: the logic and actuation hardware to calculate and produce forces needed for formation flying
  - Intersatellite Communications, timing, time transfer: systems to share data between the spacecraft, synchronize spacecraft, and disseminate commands
  - Modeling, Simulation, and Mission Design Tools: tools and methodologies needed to verify performance on the ground
  - Autonomous Constellation Management and Control: the high level control layer for multi-spacecraft operations

Executive Summary (continued)

- **Key Observations and Recommendations**
  - The big challenge will be to craft a mission concept which is affordable and technology-centered, and has enough elements with sufficiently high performance to truly alleviate the future risks of upcoming strategic Space Science missions.
  - This team must find the right mix of proving relevance, reducing risk, and controlling cost.
  - For example, a scientific or instrument-centered demonstration - i.e., an interferometry or imaging demonstration, while providing the ultimate validation if successful, may have the tendency to break the bank.

- **Recommendations for ST-9 Flight Experiment**
  - Importance of exercising system elements in an integrated manner
  - Demonstrate mature component technologies in an integrated package
  - Allocate virtually all risk into the system-level aspects instead of component-level

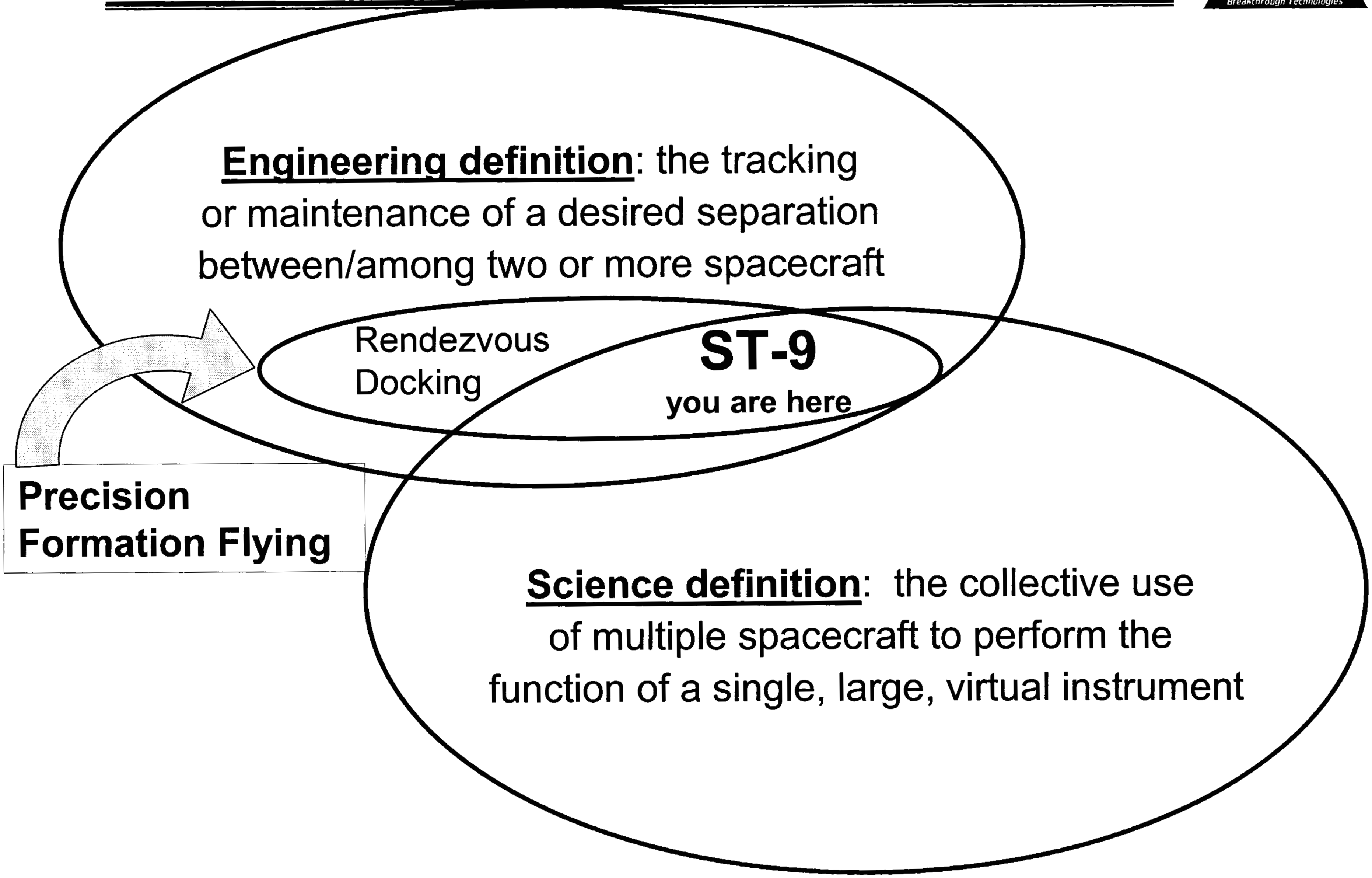
Formation Flying Capabilities to be Validated by ST9

	Figure of Merit				
Required Capability	Now	ST9	SSE Ultimate	Current TRL	TRL 5 Test Requirement
Number of Satellites	2 S/C, non-collaborative (LS-7/EO-1)	4 desired 2 minimum	>30	For constellation s, 9 For formations, 6	Distributed simulation environment
Measure relative position	2 cm postproc (over 20,000 km measurement to GPS transmitter)	< 2 cm on-board, real-time	< 1 nm on-board	2 cm: 6 < cm: 4	RF or optical channel simulator with high fidelity dynamic simulator and real-time estimation
Measure S/C-S/C bearing angles (combination of relative attitude & 3 axis position)	N/A	1 am	1 mas	4	HW prototype integrated into high fidelity simulation, with real-time estimation
Control relative position through comm. link	Rendez/Docking, < 1m short range	10 cm	3 nm	4	RF or optical channel simulator with high fidelity dynamic simulator and real-time estimation and control loops wrapped around.
Control S/C-S/C bearing angle	N/A	5 am	10 mas	2	HW prototype integrated into high fidelity simulation, with real-time estimation and control loops wrapped around
Formation line-of-sight Control	N/A	Probably a stretch to consider	100 nas	1	Interferometric verification
Inter-S/C Communication Rate	300 Mbps TDRSS	10-1,000 Kbps < 20 W, 20 kg	3-10 Mbps	6	Testing of low power lightweight device through RF or optical channel simulator
Constellation Operating Range	1 km	100m - 1km	1-500 km	N/A	Channel simulator
Formation Commanding	On-board, one spacecraft relative to other	On-Board, collaborative	On-Board, collaborativ e	4	Distributed simulation
Autonomous collision avoidance	N	Y	Y	4	High-fidelity simulation
Precision of time synchronization	3 ns GPS, on-board real-time	< 1 µs	1 ps	9	Time transfer simulator with GPS or other accurate clock

Overview and Introduction

- **Precision Formation Flying System Technology is critical for a broad range of future NASA Space Science missions**
  - TPF (ASO)
  - MAXIM, MAXIM PF (SEU)
  - Stellar Imager (SEC)
  - LF, PI, SPECS, ...
- **The "precision" qualifier carves out a somewhat well-defined niche in the formation flying field with the following characteristics**
  - Continuous and robust, possibly high bandwidth intersatellite communications
  - On-board relative navigation/bearing at high data rate with high-precision through the communication links
  - Continuous formation control at high bandwidth and high-precision through the communication links
  - Highly-optimized formation/mission design and analysis
  - Integrated hardware-in-the-loop, high-fidelity simulations
  - Autonomous and robust closed-loop on-board control during science gathering

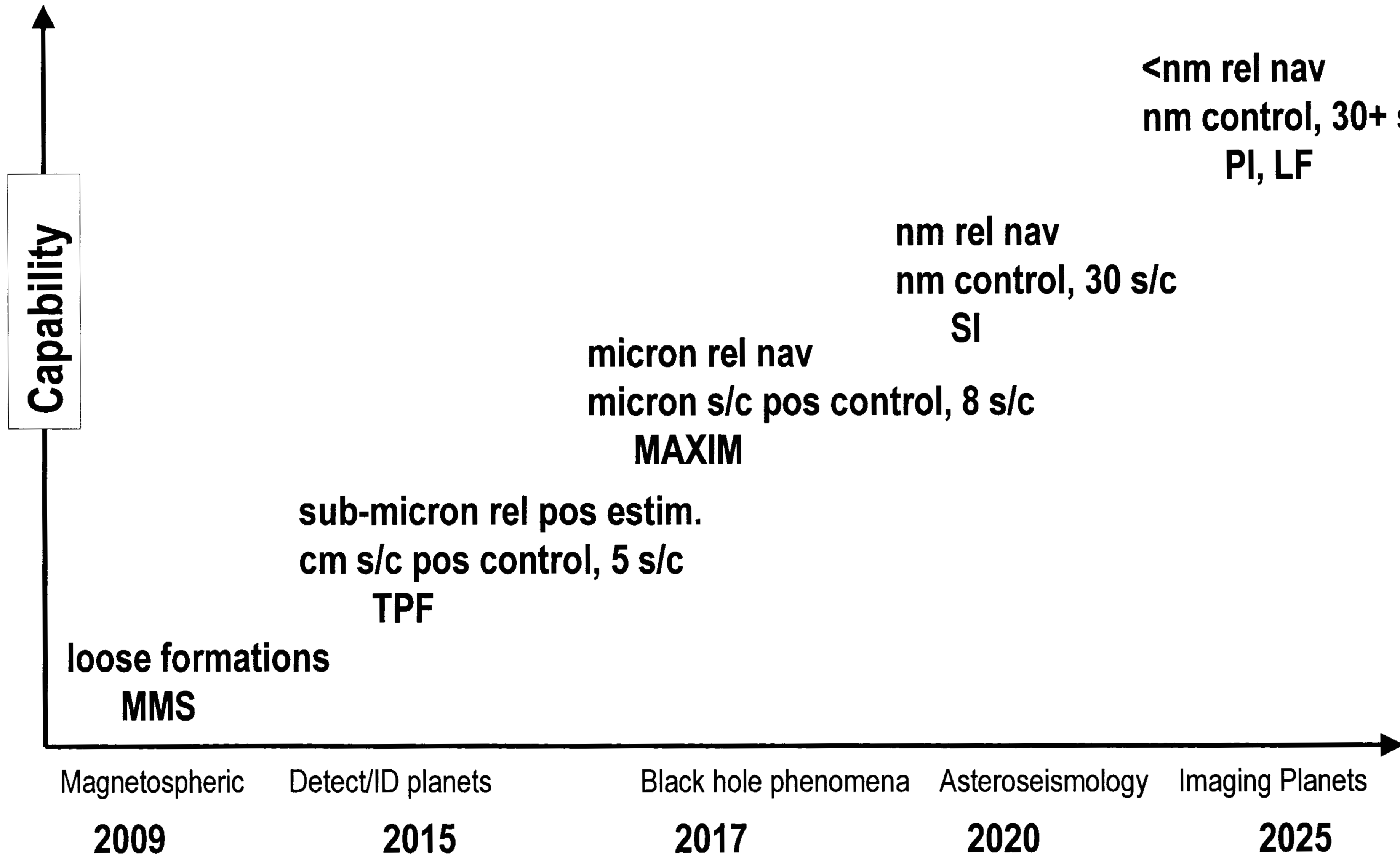
What is Formation Flying?



Scope of the ST-9 FF TCA

- **In the context of ST-9, we will focus on the problem of "Precision formation flying"**
  - Precision, in this case, refers to a continuous process of maintaining or tracking a desired geometric configuration
  - Collectively, it is the frequency and tightness of formation control (not just navigation)
- **Since the focus is on demonstrating technologies critical to future NASA Space Science Enterprise missions, the orbits of primary interest: are HEO, libration points, heliocentric, deep space**

Science Mission Capability Requirements Roadmap and Timeline



Technology Capability Requirements Roadmap*

	2009		2015		2017	2020	2025
Autonomous operations			5 s/c		8 s/c	30 s/c	
Intersatellite Comm	100 kbps				1 Mbps		
S/C Formation Control	100m		2 cm	10 μm		3 nm	
Rel Position Estimation	10m	10 cm	3 nm			0.5 nm	

*some requirements have already been achieved to TRL6 and above at the component level

Figure Of Merit (FOM) Definitions

- Relative position estimate: the estimated value of relative position between spacecraft
- S/C Formation Control: the controlled separation between selected references points between two spacecraft.
- Intersatellite communications bandwidth: the number of bits of data passed from one spacecraft to another.
- Formation geometric dimension: the number of dimensions in free-space spanned by the desired formation
- Spacecraft-to-spacecraft relative bearing: the angel composed of a combination of relative attitude and 3-dimensional position vector between spacecraft indicating the ability to maintain two spacecraft in a desired relative formation in six degrees of freedom.

State Of The Art

- Relative position estimate:
  - 1 micron range change, (relative, not absolute, range between spacecraft) GRACE in low-Earth orbit
  - 2 cm ranging, post-processed (absolute range between spacecraft), determined from spacecraft in LEO to GPS transmitter over 20,000 km distance
- Formation control: kms (EO-1/LS-7)
- Intersatellite comm data rate: 300 Mbps (large EIRP) TDRSS
- Formation geometric dimension: 1 (rendezvous docking)
- Number of s/c managed collectively: ~50 (from the ground)

Acronym List

MMS	Magnetospheric Multi-Scale Mission (SEC)
TPF	Terrestrial Planet Finder Mission (ASO)
MAXIM	Micro Arcsecond X-Ray Imaging Mission (SEU)
SI	Stellar Imager Mission (SEC)
PI	Planet Imager Mission (ASO)
LF	Life Finder Mission (ASO)