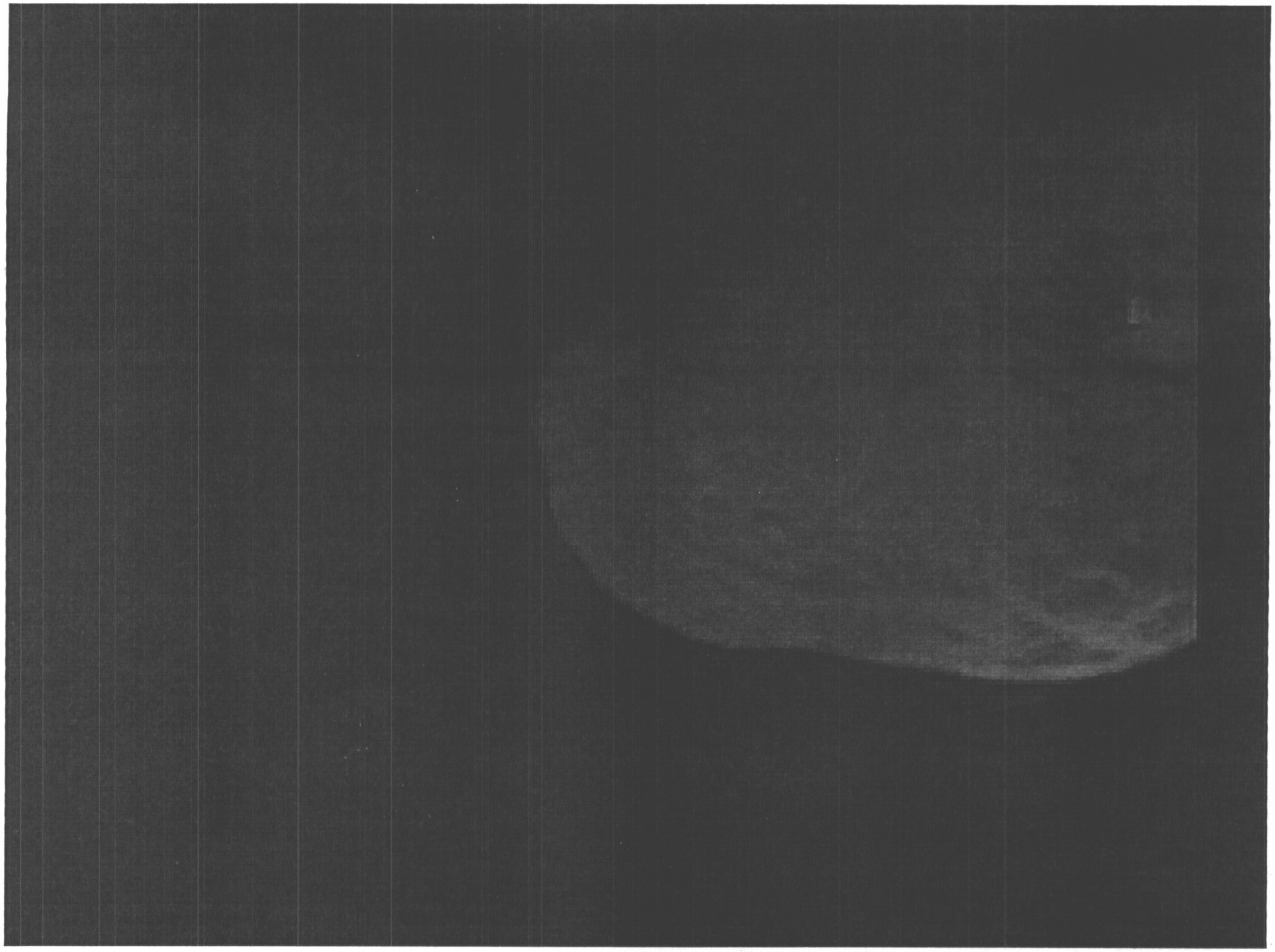
System Engineering Challenges of Future Space Missions

Dr. T. Tupper Hyde, NASA GSFC

INCOSE Symposium,
Academic Forum

Rochester, NY
July 11, 2005

Deep Impact, 4 July 2005



Outline

- Future Space Missions
  - Exploration
  - Science
  - Communication
  - Earth Observing /Intelligence
- Trends
  - Increasing scope and complexity
  - Increasing autonomy
  - Increasing multi-partner missions
  - Increasing model based verification
- Developing System Engineers
  - Academic
  - Career Path

A little about me

- NASA
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- Applied Engineering and Technology Directorate (AETD)
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  - Maria So, Mission Systems Enginering Branch Head, maria.m.so@nasa.gov

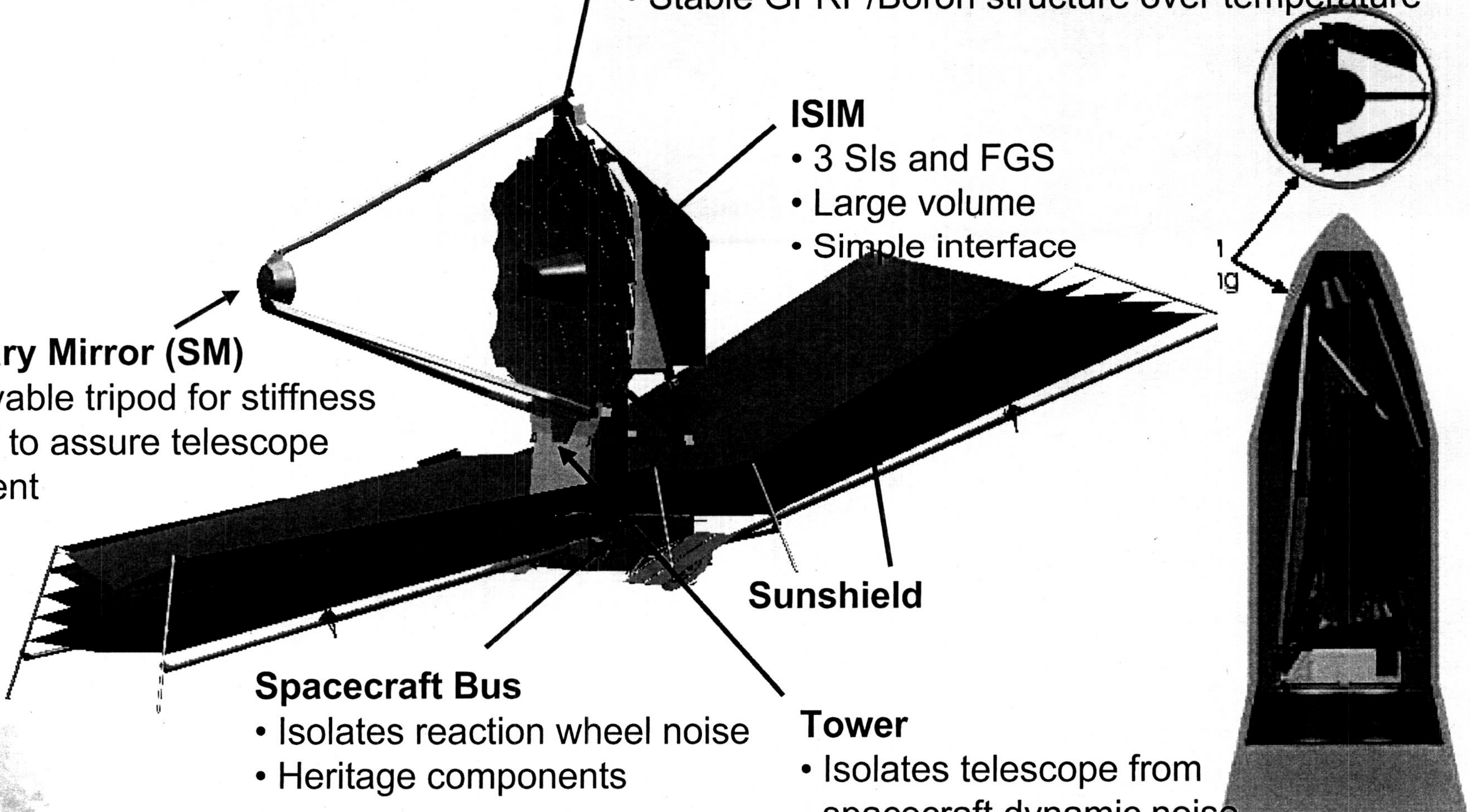
- Tupper Hyde, tupper.hyde@nasa.gov
  - Senior Engineer, GN&C background
  - James Webb Space Telescope
  - Laser Interferometer Space Antenna

JWST Components

Optical Telescope Element (OTE)
- Beryllium (Be) or ULE optics
- Performance verified on the ground

Primary Mirror (PM) – 6.5 meter
- 18 (1+ m) hex segments simplify mfg and design
- Deployable chord fold for thermal uniformity
- Stable GFRP/Boron structure over temperature

ISIM
- 3 SIs and FGS
- Large volume
- Simple interface



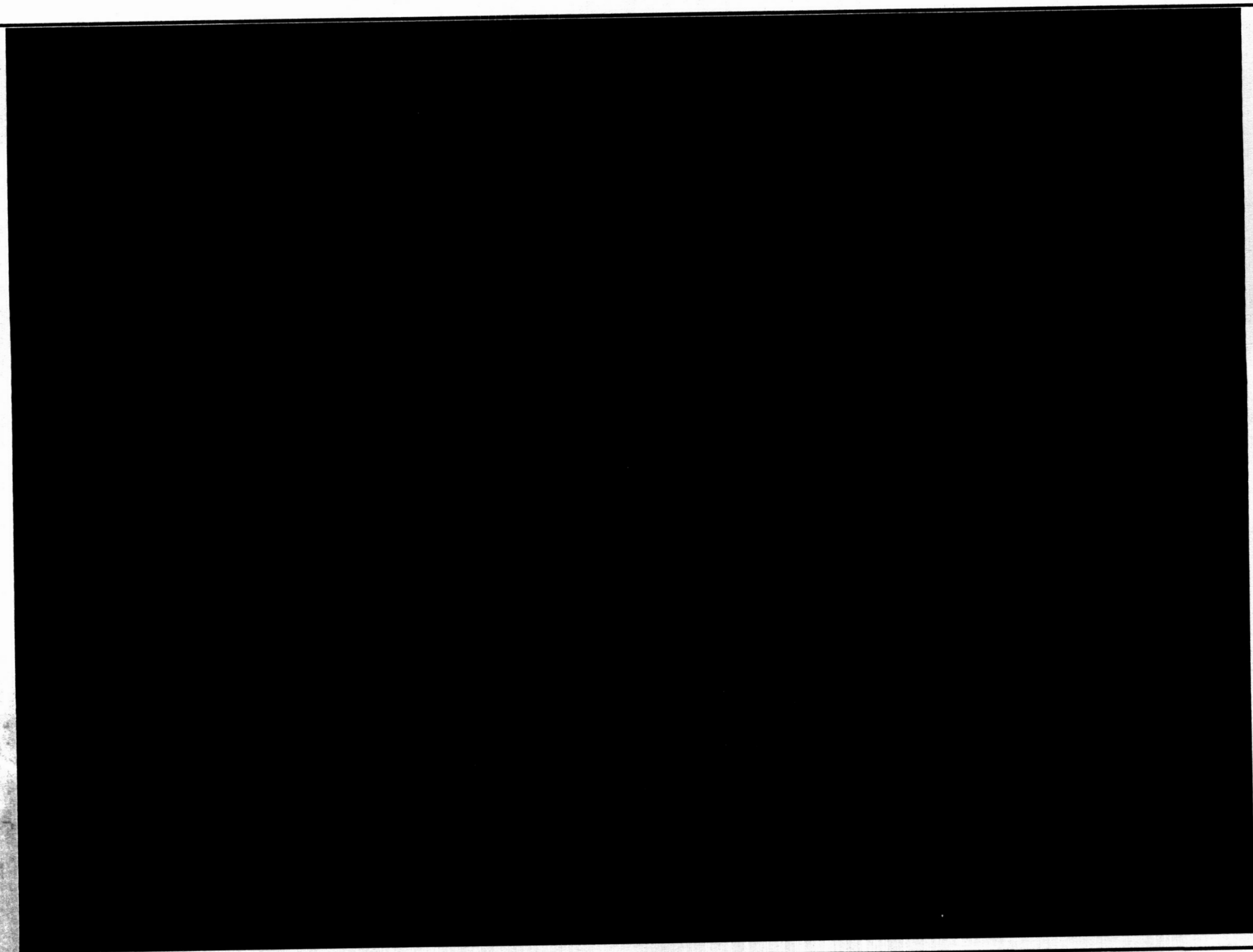
Secondary Mirror (SM)
- Deployable tripod for stiffness
- 6 DOF to assure telescope alignment

Sunshield

Spacecraft Bus
- Isolates reaction wheel noise
- Heritage components

Tower
- Isolates telescope from spacecraft dynamic noise

JWST Deploys



Spaceflight Projects . . .

Space Missions:

- Are often large, complex, and expensive
- Have to work first time, remote
- Require teams of scientists, engineers, and managers
- Are often spread over many organizational groupings

An Assessment (2004) by SJ Kapurch

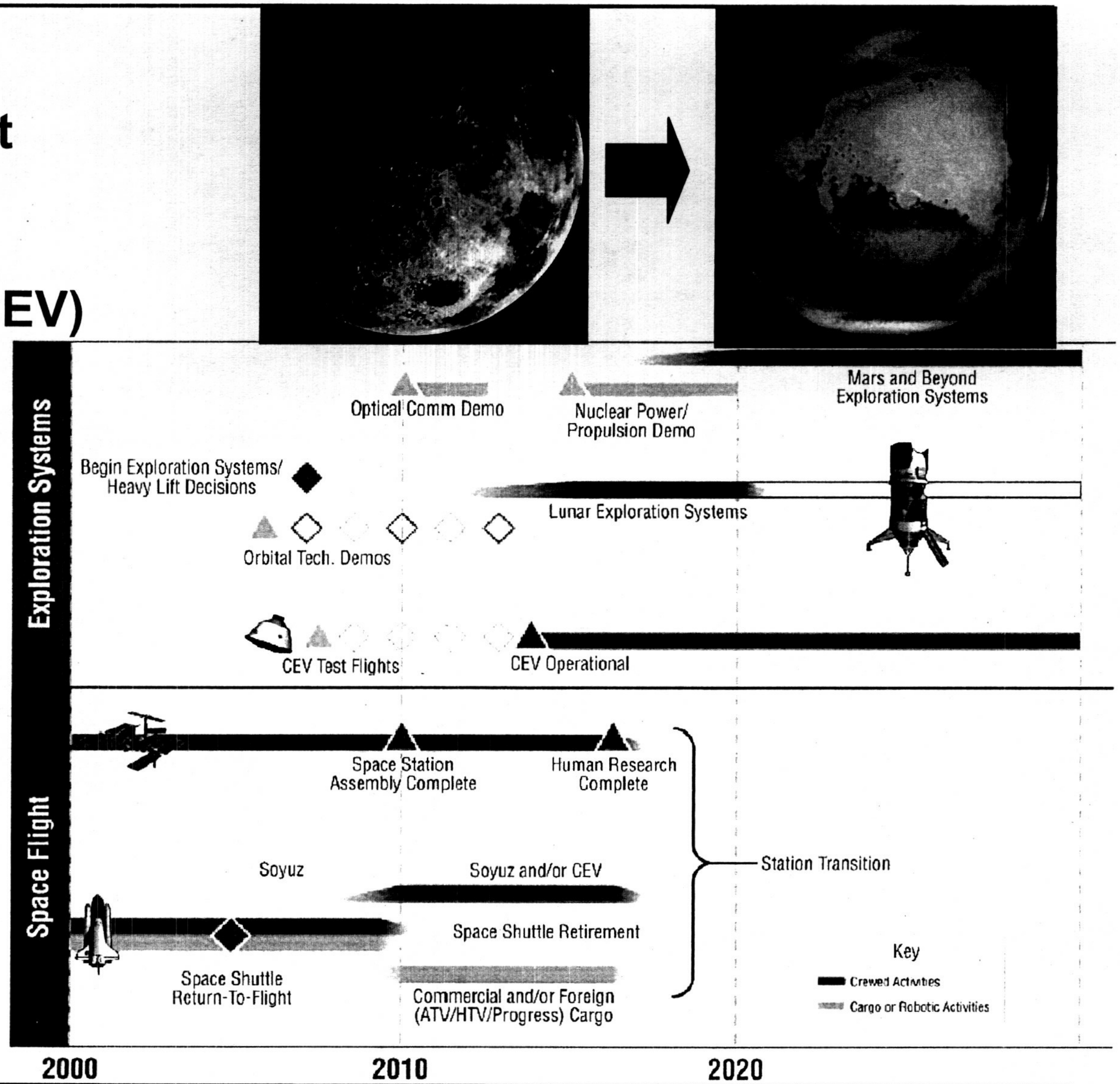
- Systems engineering issues in programs have contributed to failures, schedule delays, and cost overruns.
- Systems issues have resulted in findings in several reports.
- The exponential growth in technical complexity, and resulting potential technical risk is expected to continue, challenging our ability to engineer systems effectively.

A disclaimer:

- Missions and dates shown in this presentation are from information available as of March 2005, and, as always, are under review…

Exploration

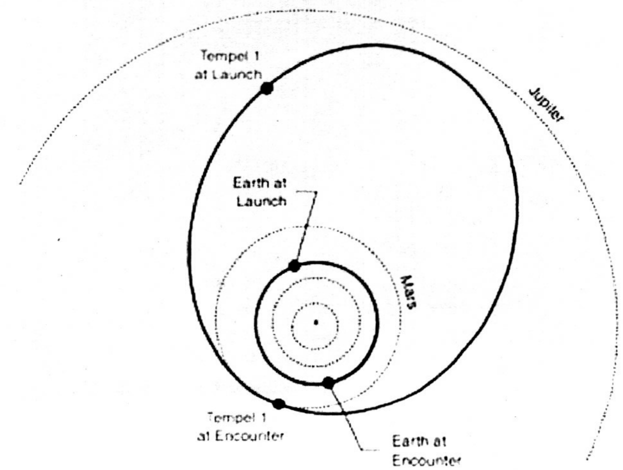
- Manned…
  - Return Shuttle to flight
  - Finish Station
  - Demonstrate Crew Exploration Vehicle (CEV)
  - Retire Shuttle, 2010
  - To Moon, 2015-2020
  - And on to Mars
    - Surface systems:
      - in-situ resource utilization (ISRU)
      - power
      - life support
      - transport
      - construction

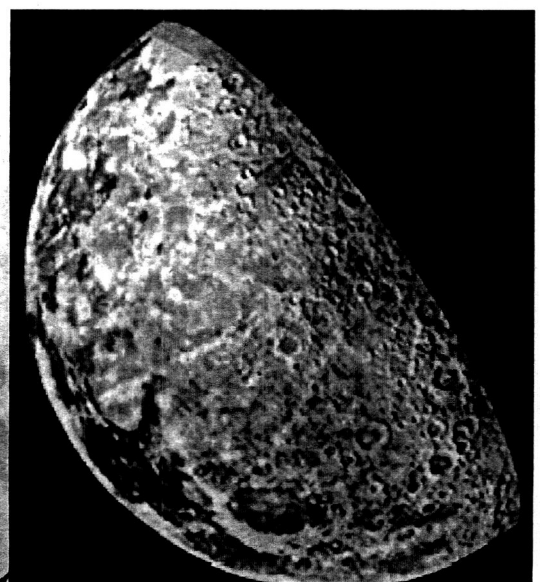


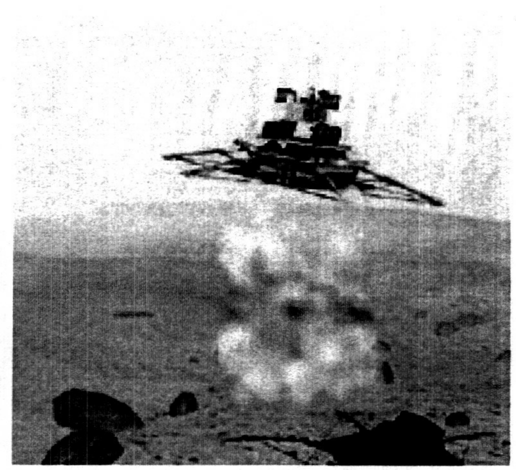
Science: Solar System

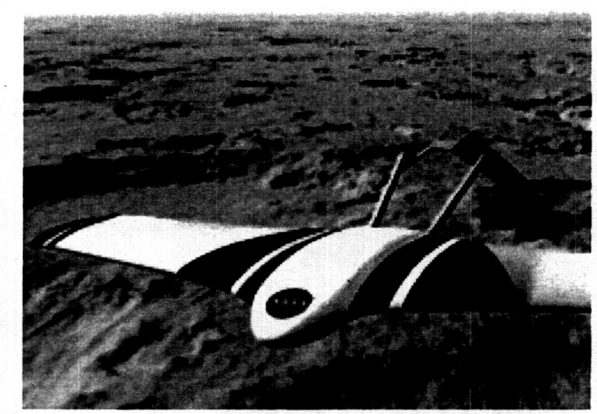
- Robotic Exploration…
  - Mars Recon Orbiter (MRO '05)
  - Lunar Recon Orbiter (LRO '08)
  - Mars Landers (Phoenix '07, Mars Science Lab '09-11, Sample return)
  - Lunar Landers (Sample return)
  - Europa, Titan, Venus, Comet Nucleus

The Orbit of Comet Tempel 1







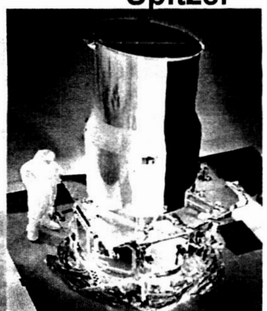


Science: The Universe

Current

HST

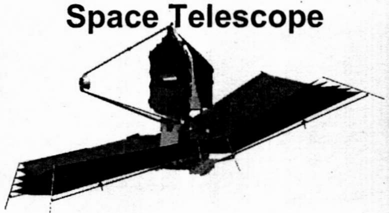
Spitzer



Chandra X-ray Telescope:

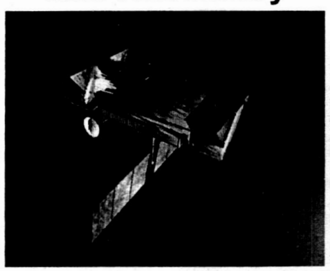
In Development

James Webb Space Telescope



6.5m Segmented Telescope
Wavefront Sensing/Control
Sunshade Pass. Cooling to 35K
Large Deployables

SIM: Astrometry



- Precision Metrology Interferometry

2005-2015

TPF-C

4x8 meter primary
Prec. Optics/occulters
Deformable mirrors/
Advanced Algorithms
Stable strucutres/
Active Control

LISA

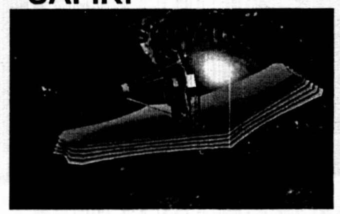
Gravity Wave Detection:
3 space craft constellation.
Sub nm displacements measured by laser/interferometery
Mircro-thrusters

2015-2025

TPF-I

Nulling Interferometry
Formation Flying

SAFIR:



10-meter FIR Telescope
5-Kelvin Mirrors
Active/Passive Cooling

Constellation X:

4 Co-pointed 1 meter
X-ray <15" Telescopes

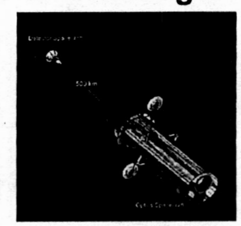
20+ Years

Sample Long Term Missions That Drive Technology

Life Finder And Planet Imager:

FIR Interferometer

Black Hole Imager



Large UV-Optical

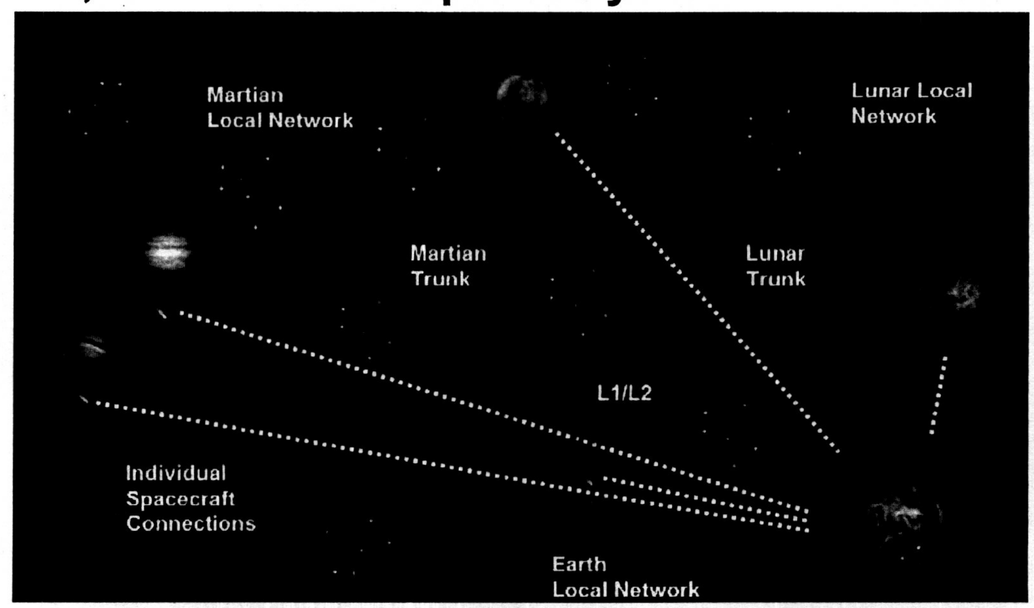
Science: The Earth-Sun System

- Living with a Star
  - Solar Dynamic Observatory
  - Geospace Missions
- Solar Terrestrial Probes
  - Solar-B (with Japan)
  - STEREO
  - Magnetic Multiscale Mission
  - Radiation Belt Mapper

MMS photo

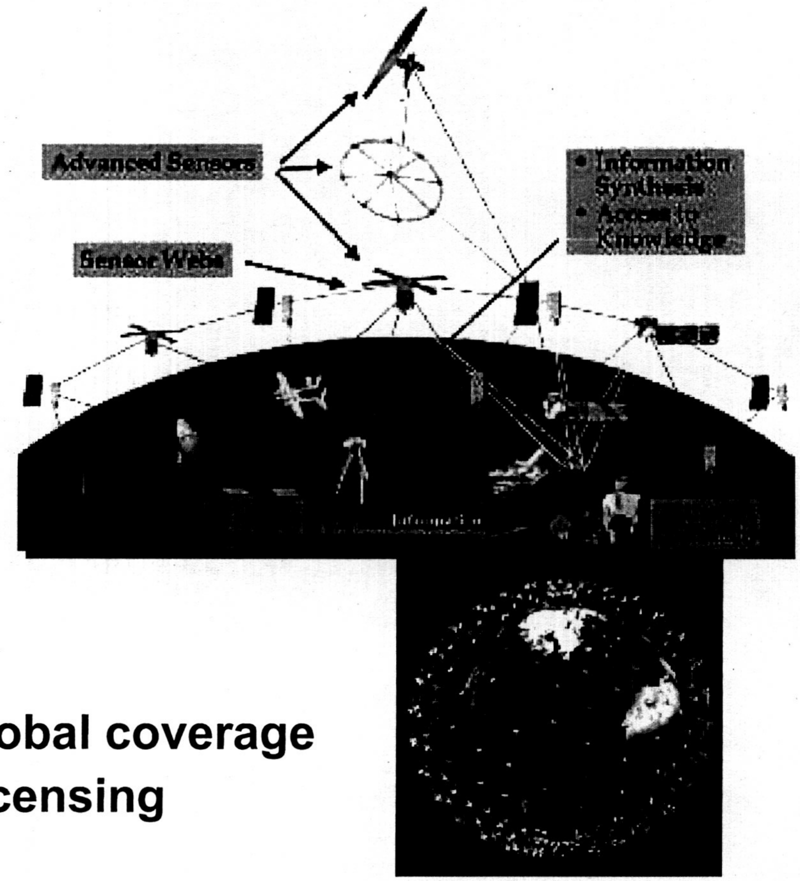
Communications

- "Transformational Comm"
  - IP based… networks make and break as needed
  - Mixed nodes: Space, Air, Ground, Personal
  - Mixed modes: RF (moving to higher bands) and Laser
- Bandwidth growth
  - Commercial: HDTV, satellite radio, mobile internet
  - Military: imagery to the soldier, information superiority
  - Supporting Exploration
    - Deep Space Network to Ka band
    - Mars Lasercom Demo (> 1 Mbps from Mars)



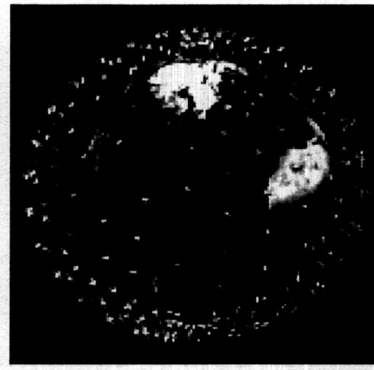
Earth Observing / Intelligence

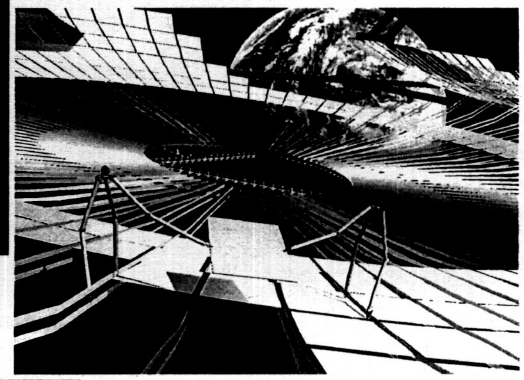
- Weather: NPOESS (LEO), GOES (GEO)
  - Lots of instruments on one bus
- Co-orbiting LEO observers
  - The A-train (Aura, CALIPSO, Cloudsat)
- Imagery:
  - Landsat (data continuity)
  - SPOT (Europe)
  - Commercial: 0.6 m resolution
- Future
  - LEO orbit:
    - Military RadarSat constellation for global coverage
    - Commercial / government imagery licensing
  - High and GEO orbit:
    - Large and/or sparse aperture optical telescopes for persistent surveillance (military, intelligence, weather) and LIDAR (science)
    - Large (500+ m) radio apertures for climate science

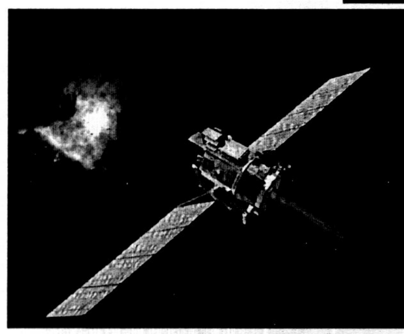


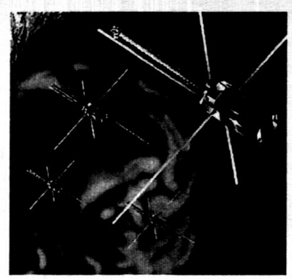
Trends

- Increasing scope
  - "Complex" systems
  - "Evolvable" systems
  - "Large" systems
  - "Distributed" systems
- Increasing autonomy
  - Dominating role of software
  - Vehicle health management
  - Robotics
- Increasing multi-partner missions
- Increasing reliance on models and analysis for verification



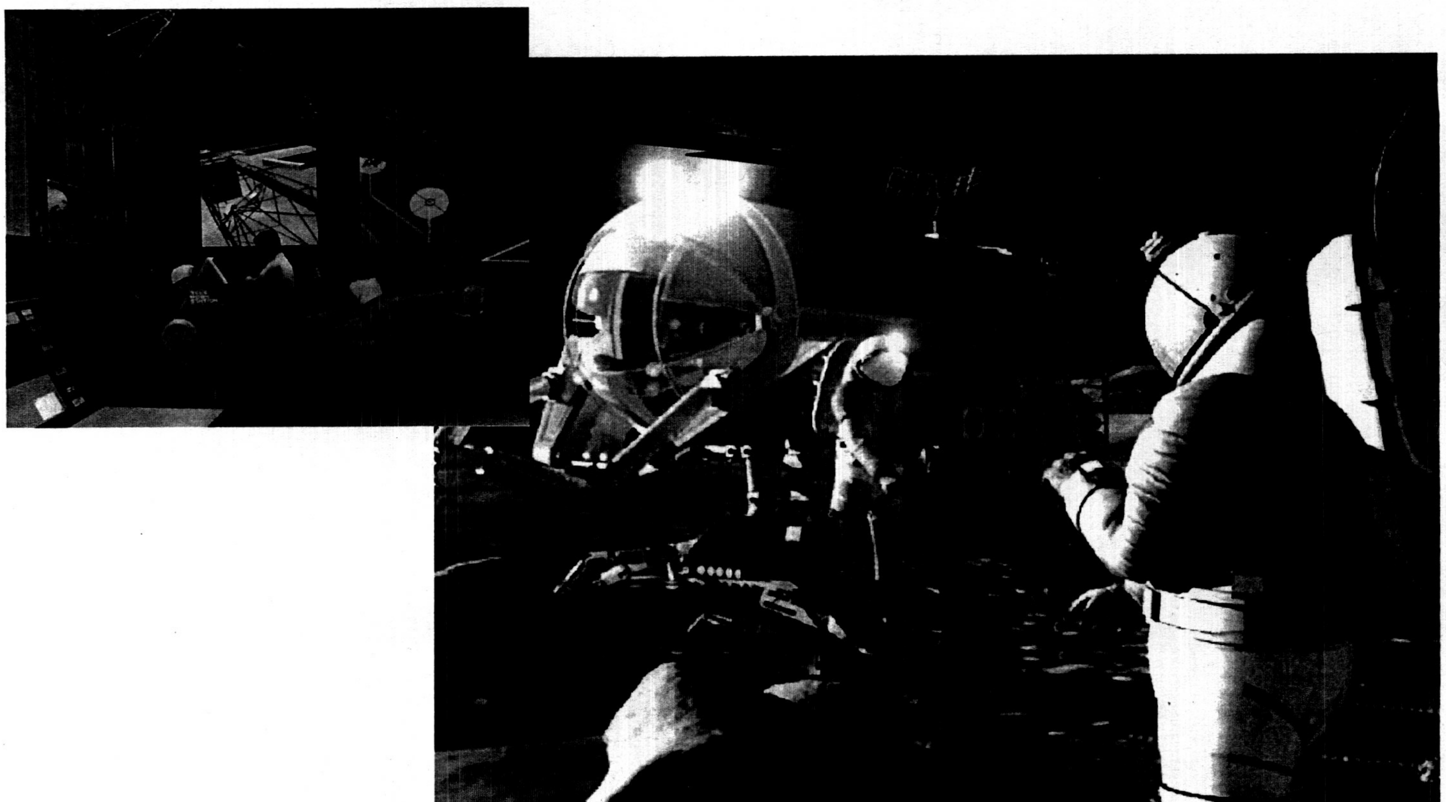






“Complex” Systems

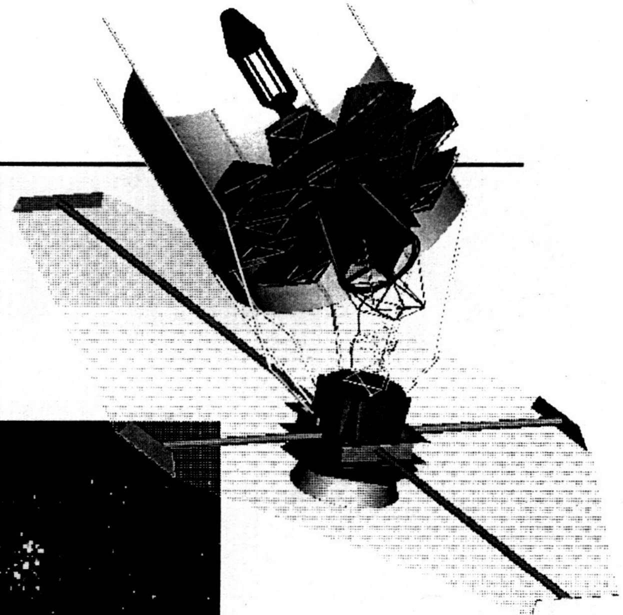
- Systems of systems
  - Some elements stand alone, yet are also part of bigger thing
- Nested, Multi-level Systems Architectures
  - Bigger than one person/team/group can understand at once



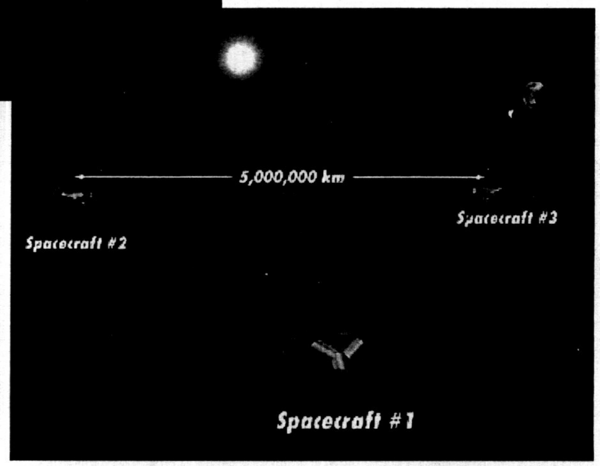
“Evolvable” Systems

- Evolvable vehicle and mission architectures
  - Perform in one role, yet adapt to new roles in future
- Sustainability / Logistics
  - Design for affordability over life…Infrastructure for later missions, In-situ resource utilization.
- “Responsive”
  - Improving need to orbit timeline (NASA’s Rapid Spacecraft Development Office, AF’s RASCAL program)
- Modular / Reconfigurable Systems
  - Historically poor track record…Needs economy of scale and standard interfaces
  - Adaptive wireless, cooperative networks, sensor-web
- Model Based Acquisition
  - Plug-n-fly models before you buy

“Large” Systems

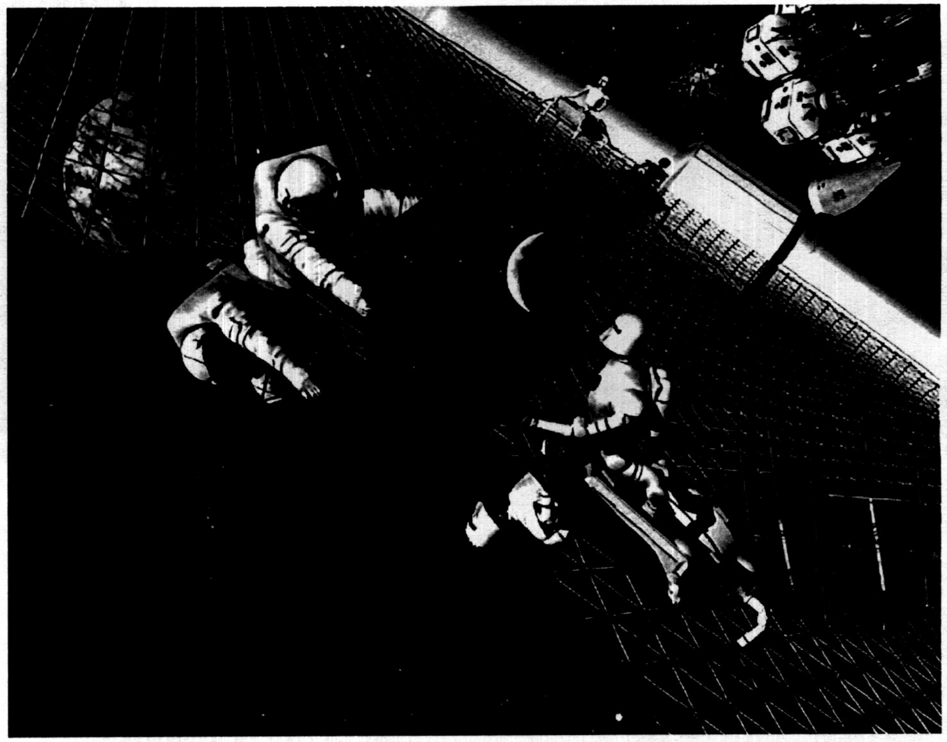


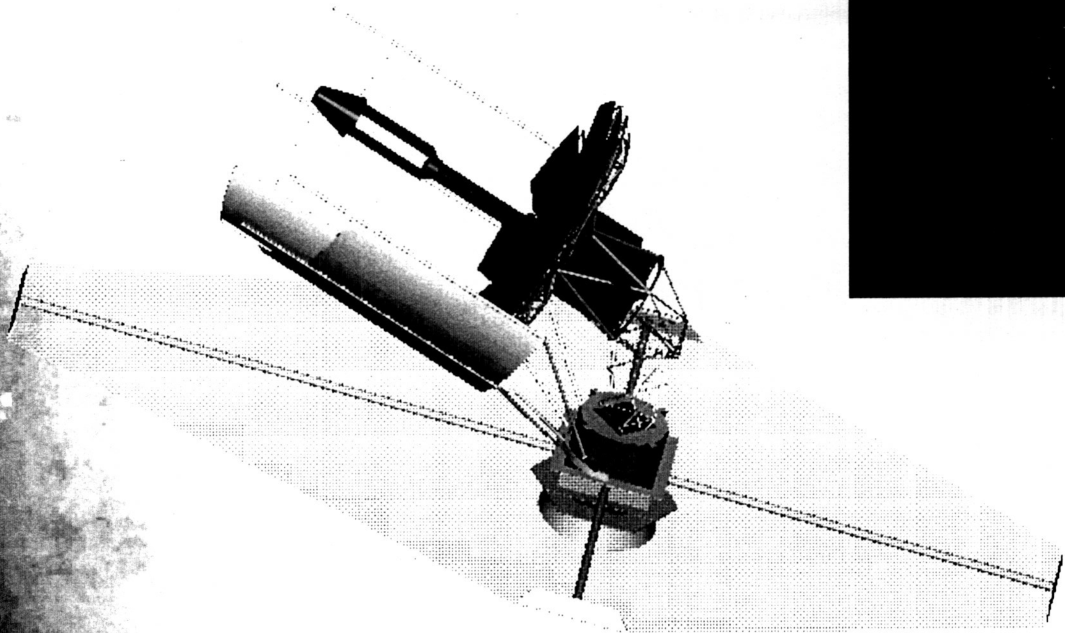
- Big Aperture
- Sparse Aperture / Interferometer
- Nuclear Fission
- Surface Bases



Large Monolithic Telescopes

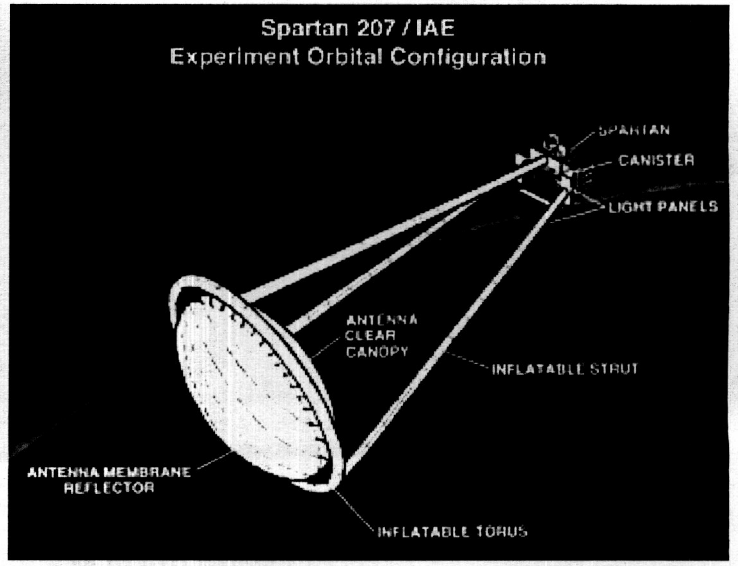
10 m is about the biggest deployed telescope one can get in a Delta4 H 5x19.8m fairing (Single Aperture Far Infrared, SAFIR)

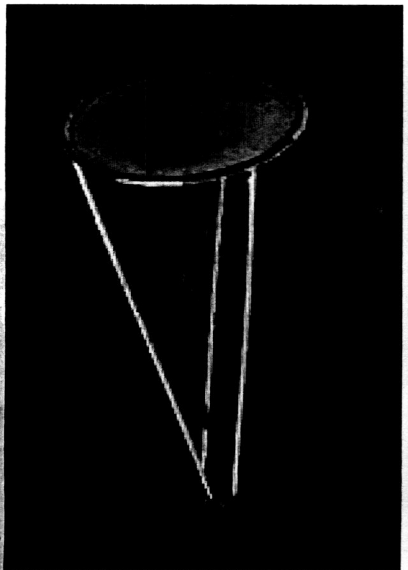


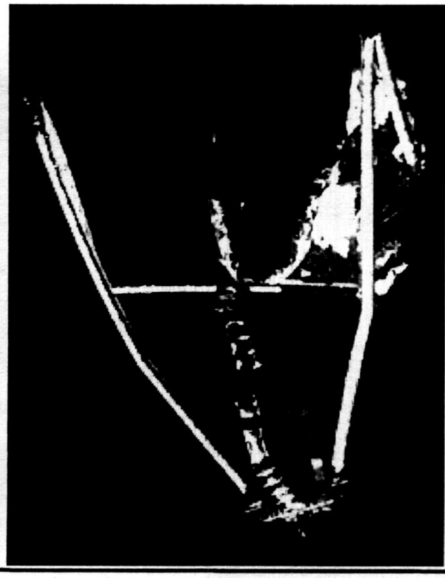


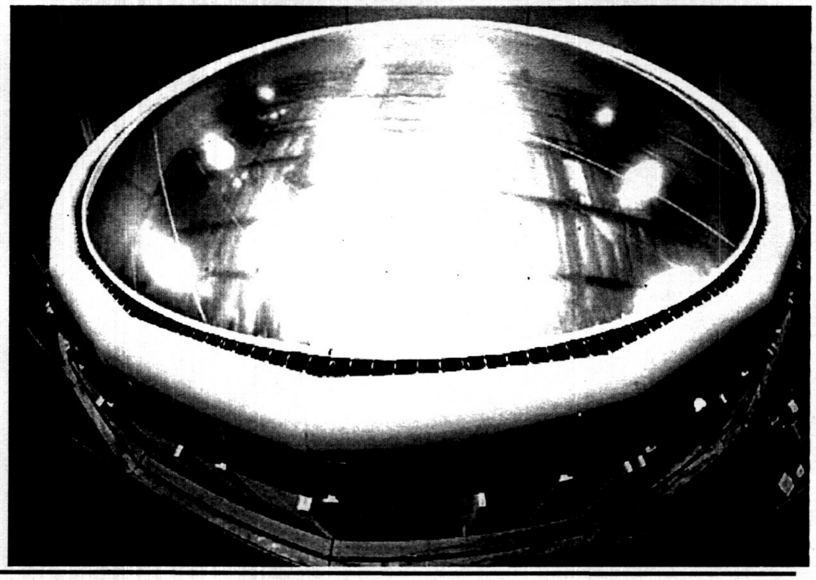
Inflatables

- Breaks the rigid deploy paradigm
- Can't be fully tested on ground
- Inflatable Antenna Experiment, 1996
  - 14 meters in diameter mounted on three 28 meter struts



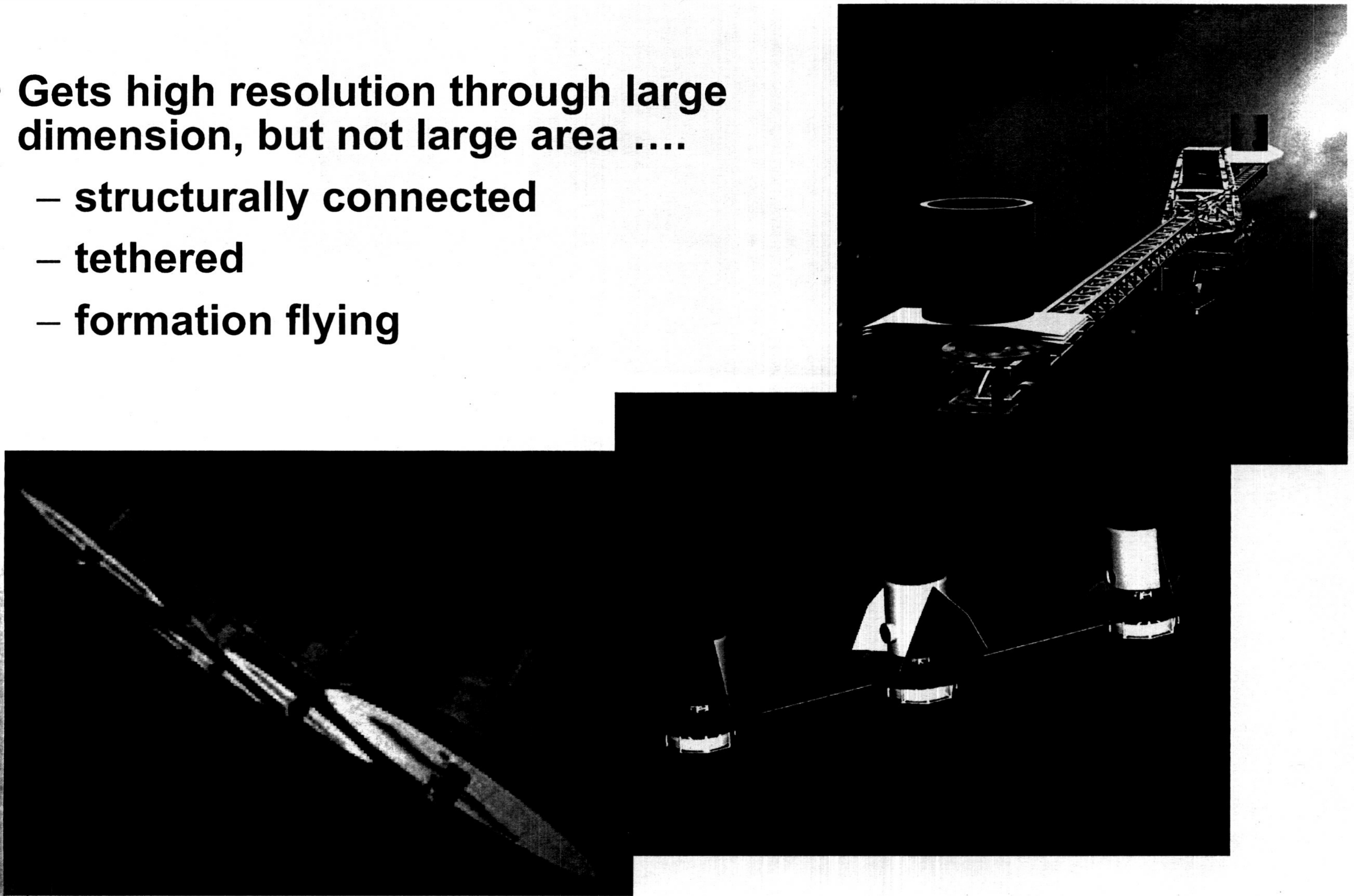




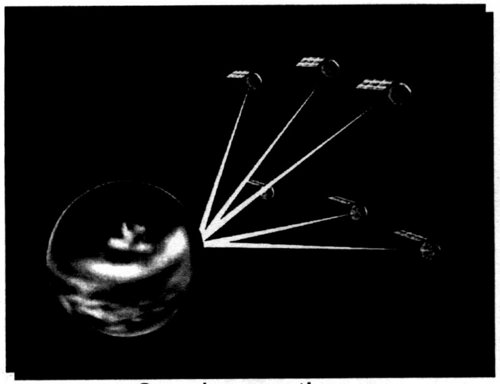


Sparse Apertures

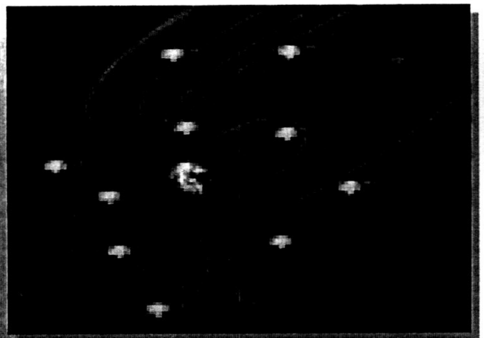
- Gets high resolution through large dimension, but not large area ….
  - structurally connected
  - tethered
  - formation flying



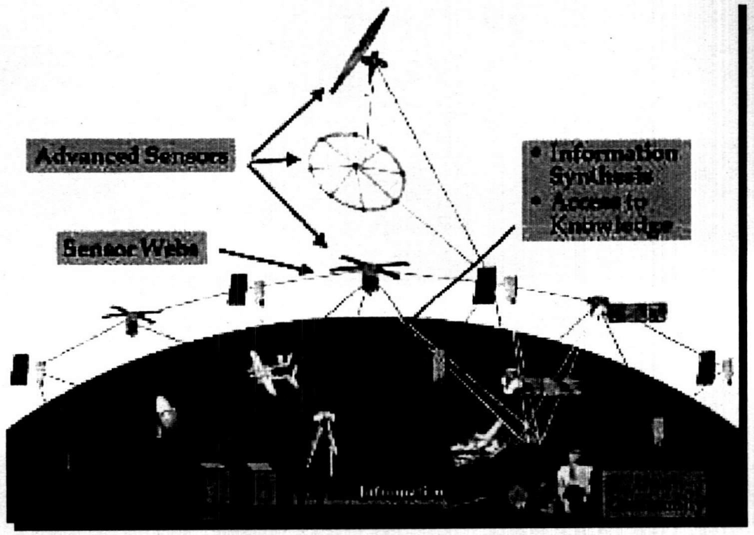
“Distributed” Systems



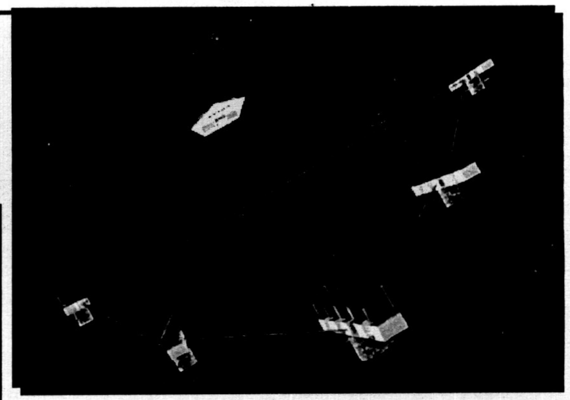
Co-observation



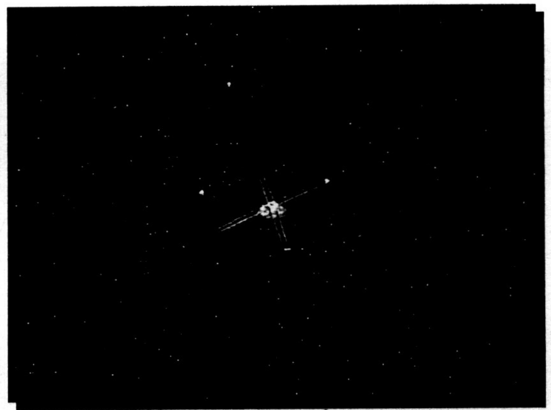
Multi-point observation



Coincidental Observations



Interferometry



Tethered Interferometry

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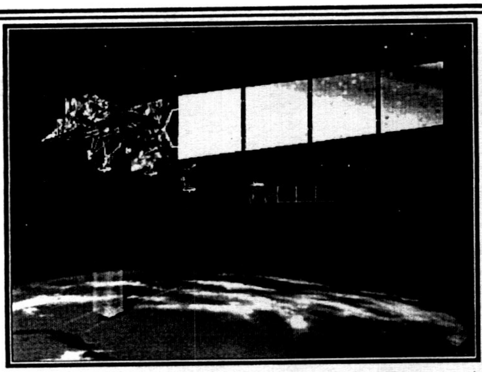
Distributed Space Systems (DSS)

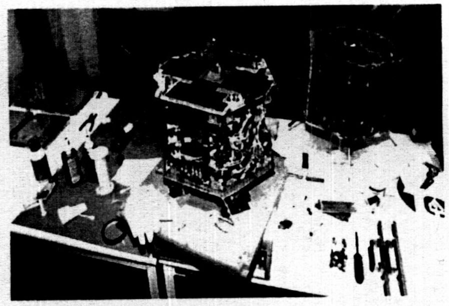


Formation Sensing and Control

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

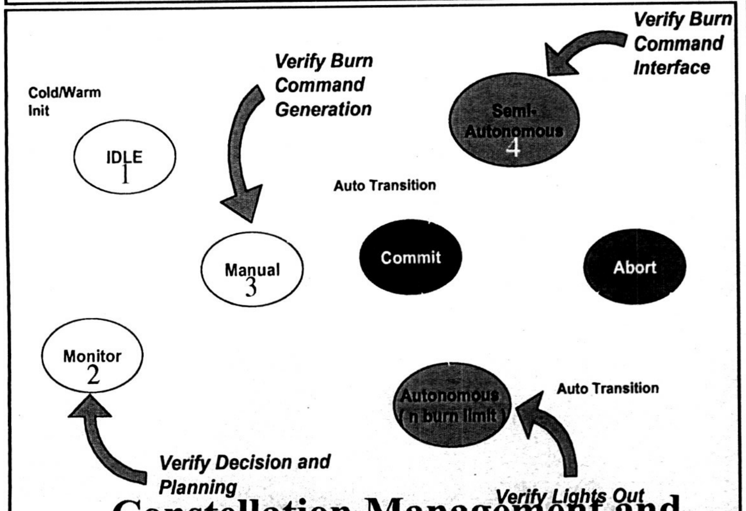
Intersatellite Communications

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



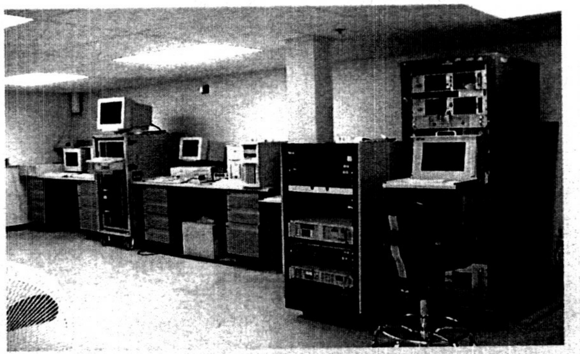
Miniaturized Spacecraft Technology

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



Constellation Management and Mission Operations

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



Mission Synthesis, Design, and Validation

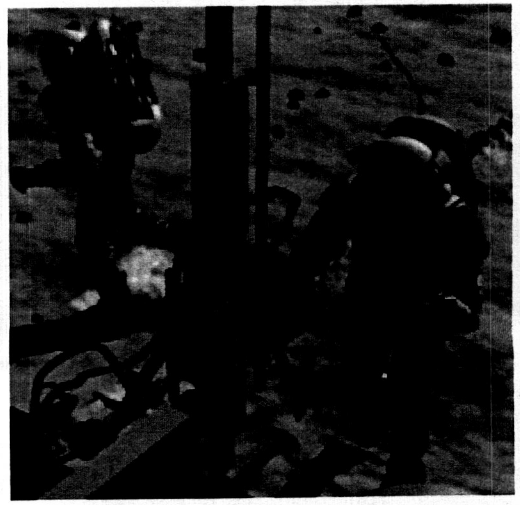
The end-to-end DSS systems analysis

Data Acquisition, Processing, Fusion, and Analysis

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

Autonomy

- Robotic surface operations
- Auto ship and habitat operations
- Auto diagnostics & prognostics
- Robotic inspection / maintenance
- Auto entry, descent, land
  - Today is sequencers
  - Future is precision land
- Auto construction (surface, orbit)

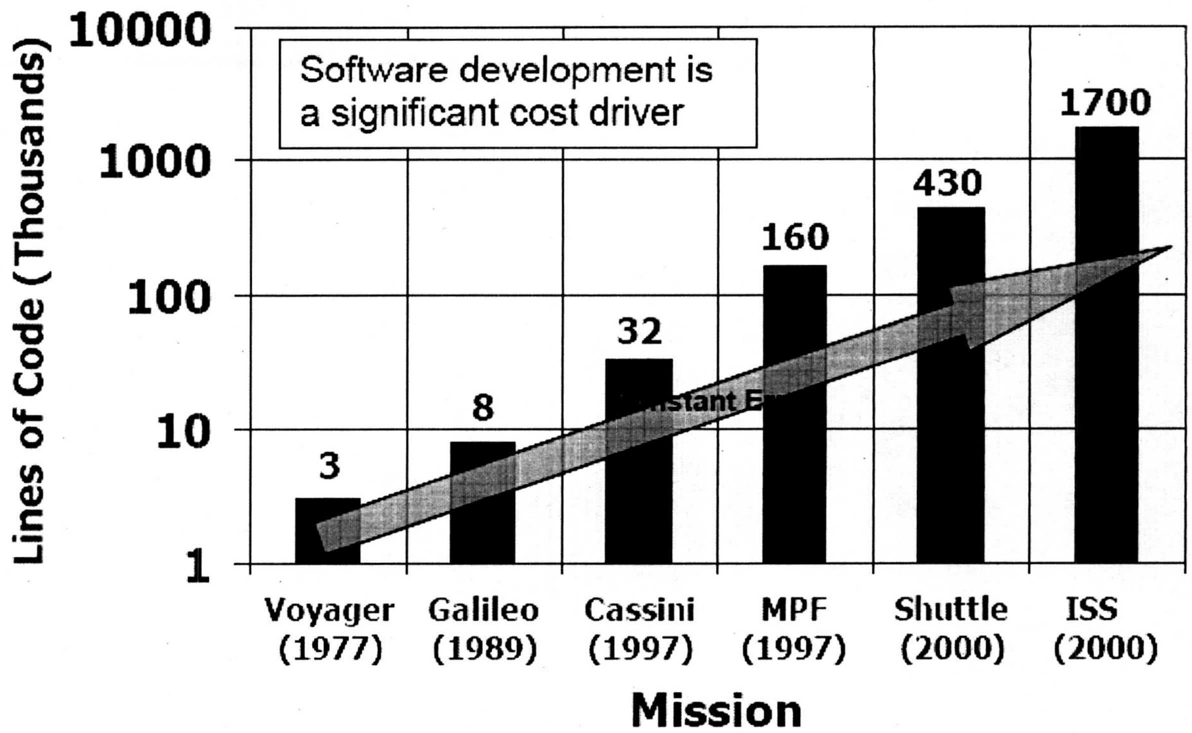


Construction photo

ISS ground controllers send up 500,000 commands/year

Dominating Role of Software

- Of all the disciplines, software feels the most direct influence of SE.
- Software provides autonomy and flexibility
  - Fault detection and correction (hardware -> software)
- But is expensive and requires maintenance
- SEs need to manage software development



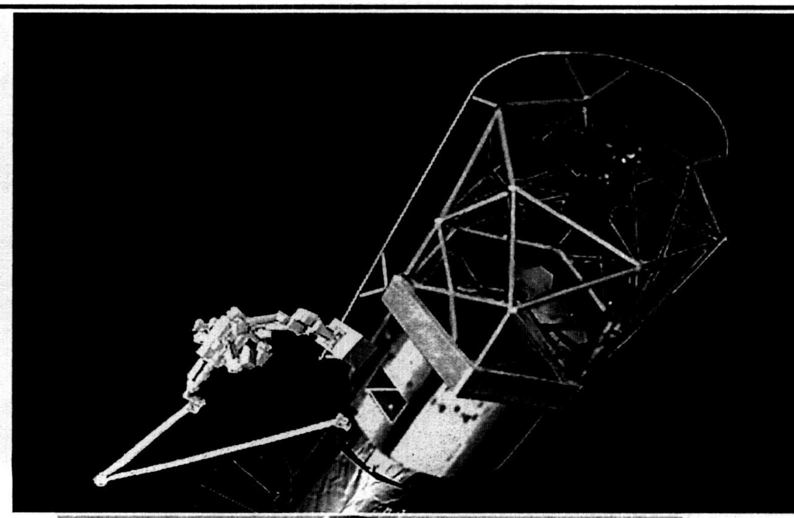
Vehicle Health Management

- Large, complex systems with significant autonomy
  - Will require less human intervention
    - Some decisions must be made faster than a human can
    - No set of people can know everything relevant
    - Too much data to fit down deep-space pipe
    - Autonomous diagnostics and self-healing
  - AND will require more human intervention
    - Info to support crew decisions to save life or mission
    - Info to direct crew or ground operator investigation/maintenance

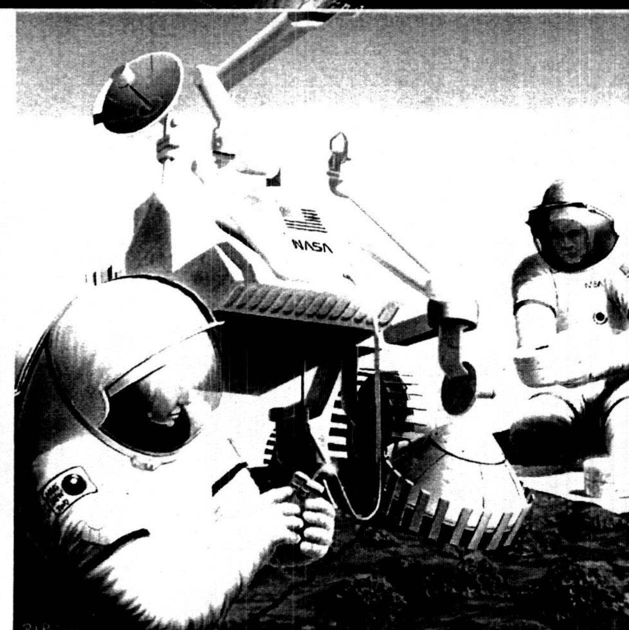
photo

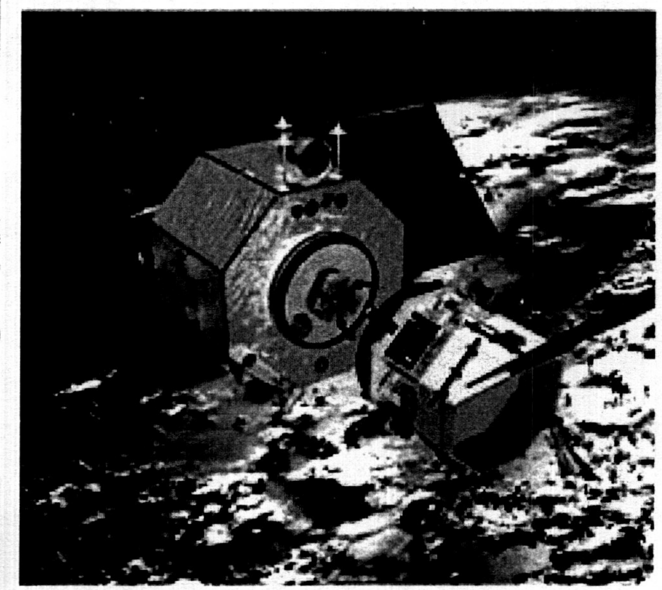
Robotics

- Duties:
  - Inspection
  - Maintenance
  - Servicing
  - Assembly



- Modes:
  - Free-flying
  - Arm
  - Crawling
  - Wheeled
  - Tele-op / auto
  - Human-robot coordination



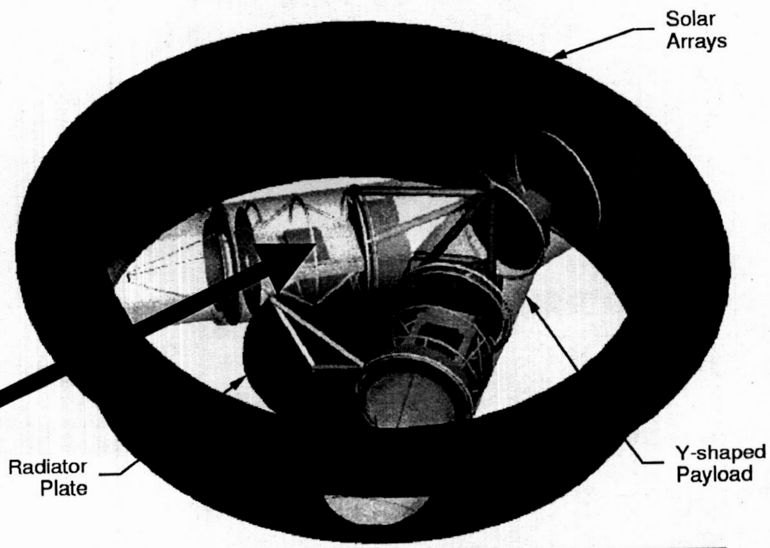


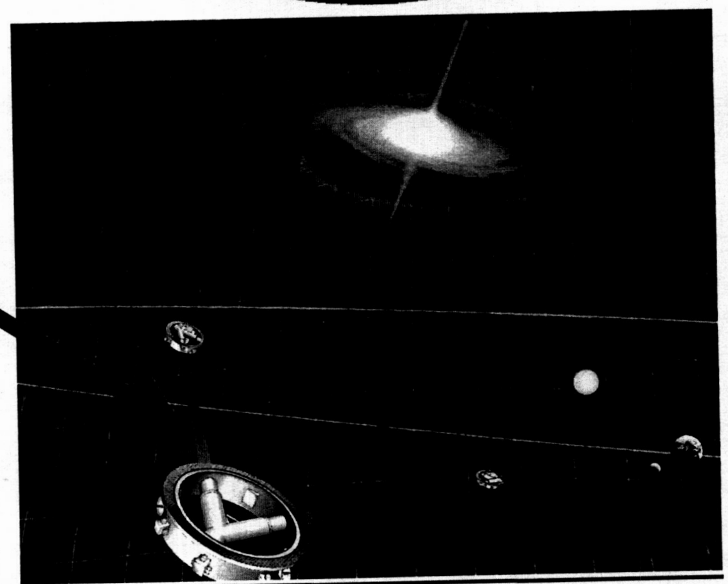
Increasing Multi-Partner Missions

- Large, complex missions increasingly...
  - Require substantial investment
    - Multi $B costs are shared with other nations and agencies
  - Have multiple customers
    - Earth resources data has scientific, civil, and military applications.
- Challenges of project management are shared with SE...
  - Differing processes among partners
    - Engineering process
    - Funding cycle
    - Review requirements
  - Technical exchange among partners
    - Working technically challenging projects with foreign partners under current ITAR rules is difficult

"Cannot be Verified Fully Before Launch"

- Untestabilities on the ground
  - 0-g (or reduced-g on Moon,Mars)
    - Sag in optics
    - Fluid flows
    - Mounts for free-floating items
      - LISA: Free fall proof masses
    - Off-load for deployed elements
  - Vacuum and thermal environment
    - Large deployed/constructed size
    - Interspacecraft distances
      - LISA: 5 mil. km laser gauges

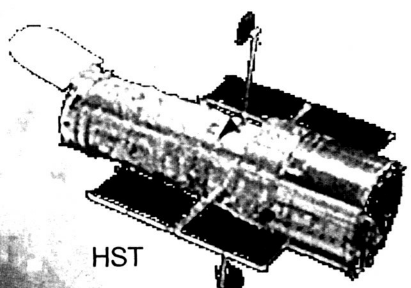




Evolution of I&T for space telescopes

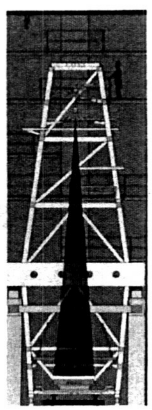
1960's – 2005
Large systems to 2.5m

Full Aperture Verification Using Standard Vacuum Chambers



HST

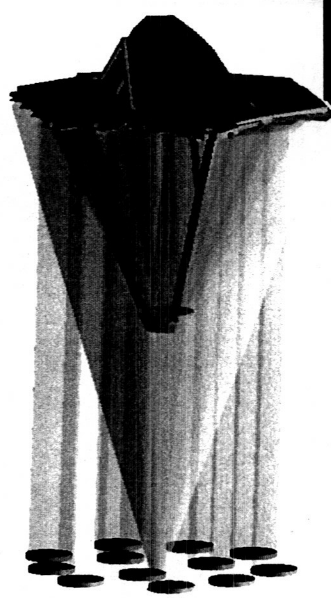
IKONOS



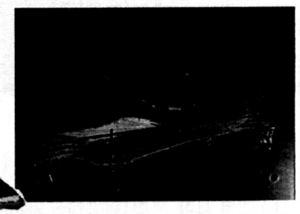
Verification Test Tower

2005 – 2025
Large systems to 8-10m

Sampled Full Aperture Verification of Observatory



JWST Verification



JWST

2025 – 2035
Large systems > 15m

Verify Subassemblies on Ground, Certify Performance After Launch(s) and Potentially On-orbit Assembly

Robust Analytical Tool Set Insures On-orbit Performance

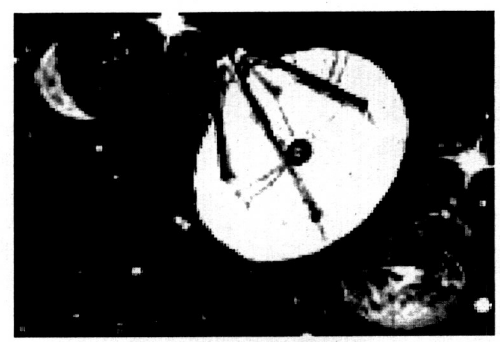
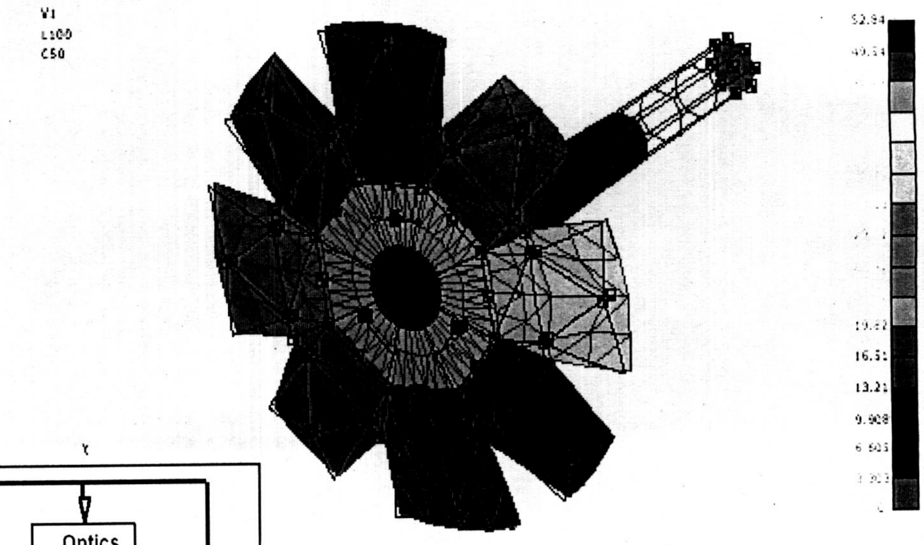
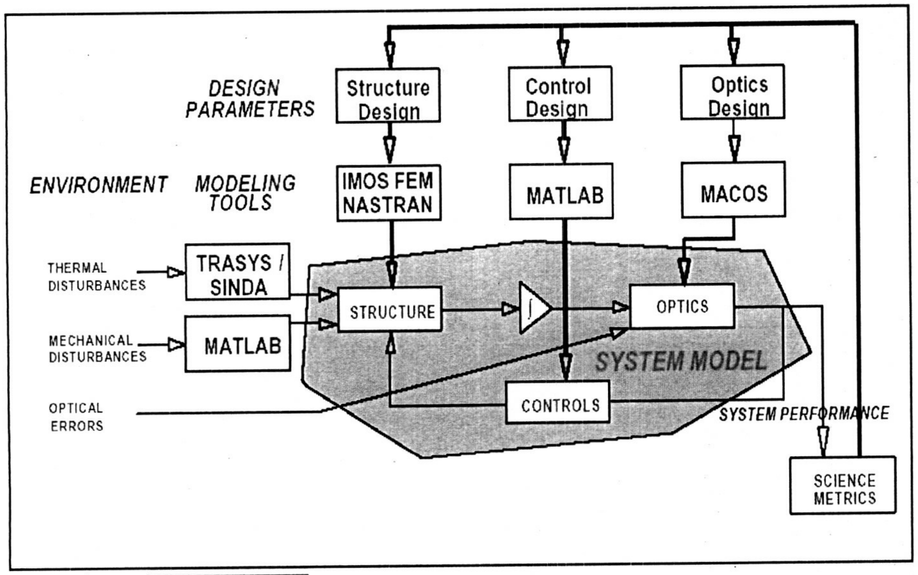


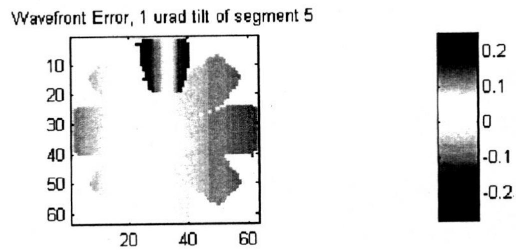
Photo: Space.com

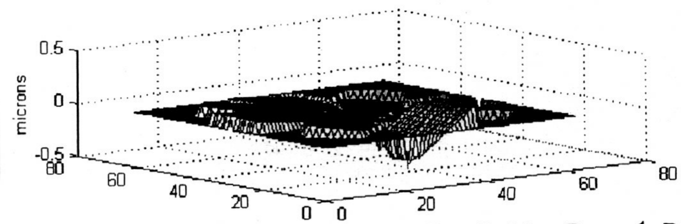
Integrated Modeling on JWST

- Multidisciplinary
- End-to-end performance modeling
- Nanometric precision
- Explore requirements
- Optimize design









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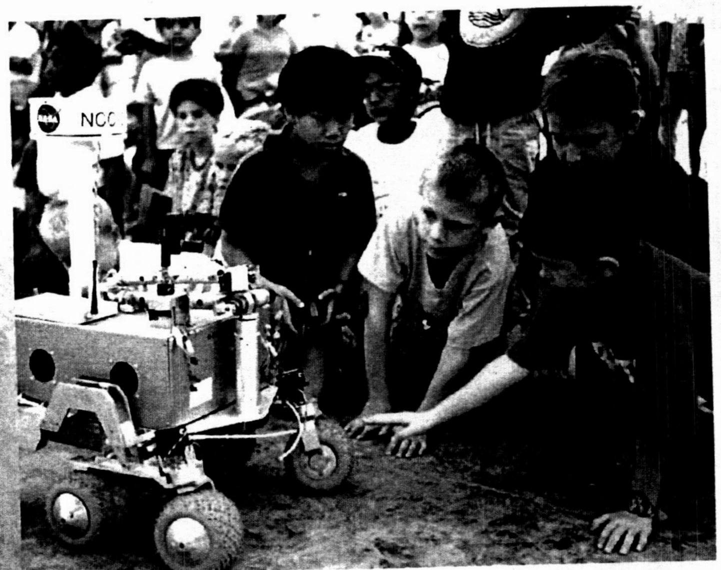
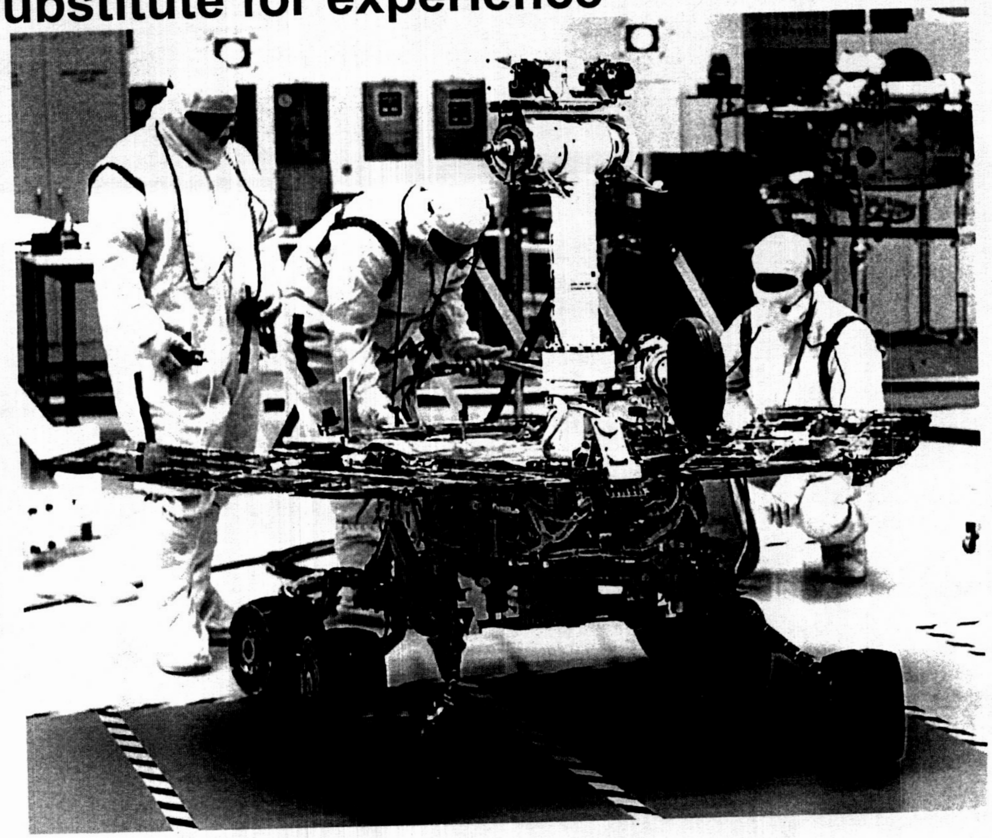
NGST integrated modeling environment

From Technology Development Strategyfor NGST Wavefront Sensing and Controlby D. Van Buren[1], D. Redding[1], T, Antczak[1], M. Levine[1] R. Burg[2],L. Feinberg[2], W. Hayden[2] (1 JPL. 2 GSFC)

Developing System Engineers

- NASA continuously needs experienced SEs
- How to grow good systems engineers?
  - Academia- start with rigorous thinking training
  - Career Path- there is no substitute for experience





Academic Development of SEs

- Train as discipline engineers as first priority
  - A strong technical depth in one area make a ‘wise’ SE
  - Every system is made of sub-systems
  - Exposure to parts, design, test at discipline level is key
- BUT… Do academic projects in a systems setting
  - Exposure to SE processes, tools valuable regardless of career
    - SE thinking promotes rigor and reduces mistakes
    - Any component or subsystem is part of a larger system
    - Working at several levels on several size projects is good
  - Provide end-to-end exposure on academic projects
    - Conceive, Design, Integrate, Operate
      - Real-world projects always have all four steps
      - Doing just one by itself has less educational value
      - Look at MIT’s CDIO three semester class as model

NASA GSFC Career Path Development of SEs

- A: Hire or train as discipline engineer through senior engineer
- B: Develop as systems engineer through three paths:
  - 1) SE experience through increased project responsibility
  - 2) Term assignment to project as SE with a mentor through Goddard Opportunity Bulletin Board System (GOBBS)
  - 3) Systems Engineering Education & Development (SEED) Program: an accelerated learning opportunity to take mid-level discipline engineers and train them as SEs through:
    - Rotational assignments
    - Individual mentoring and coaching
    - Technical training
    - Training in systems thinking/systems mindset
    - Applied human systems and leadership development.

Summary

- Future Space Missions
  - will push the envelope in exploration, science, communication, and earth observation / intelligence.
  - are increasing large, complex, distributed, autonomous, inter-related, manned & robotic, partnered, and un-testable on the ground.
  - will require improved system engineering people, processes, and tools.

Academia can step up to the challenge of educating future SEs as well as providing new training and tools.

We are looking for the best to tackle tomorrow's exploration challenges!

Are you up to it?