LISA: Astrophysics out to z~10 with low-frequency gravitational waves

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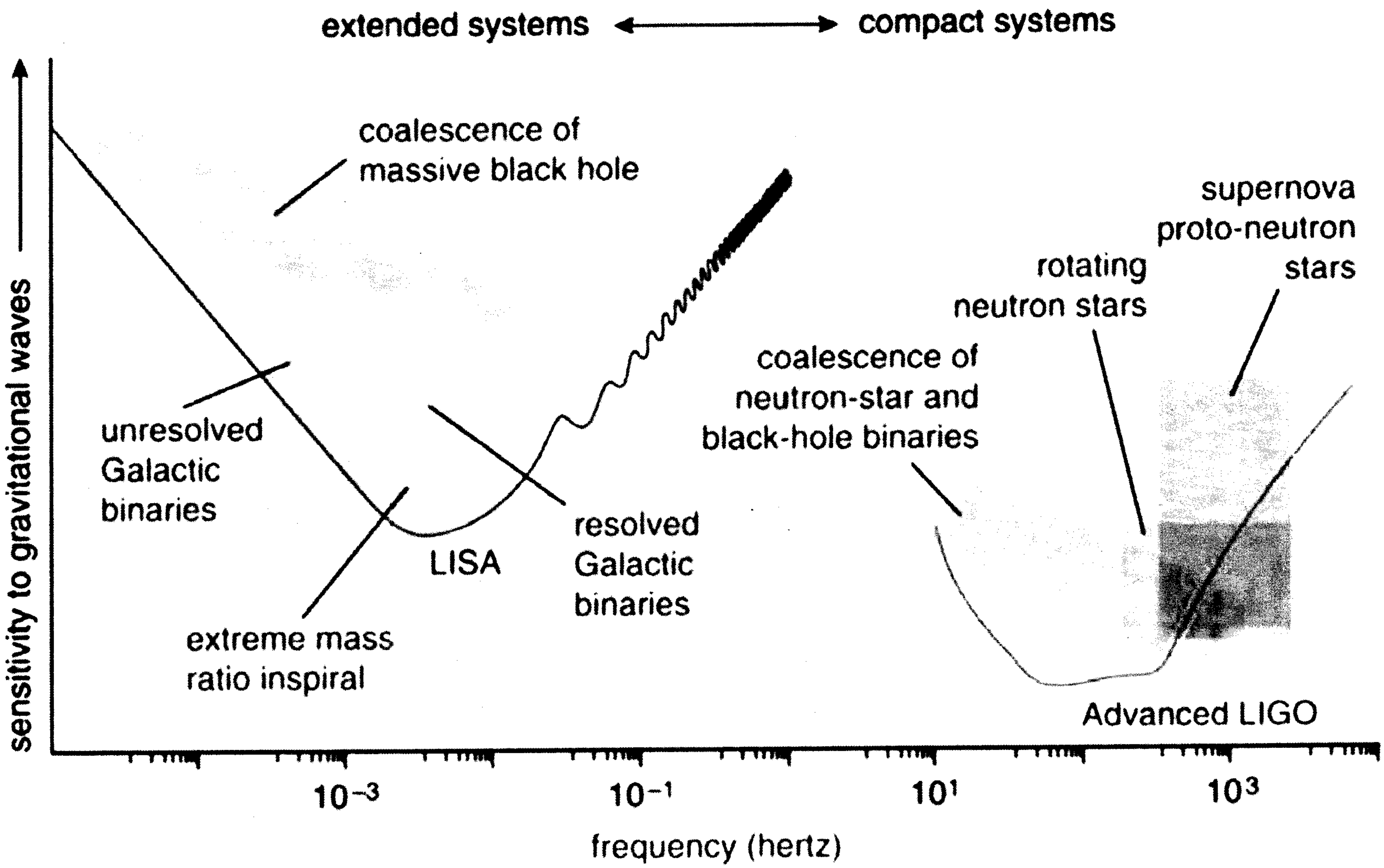
LISA Overview

- ***The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational wave detector.***
- ***The 5 million kilometer long detector will consist of three spacecraft orbiting the Sun in a triangular formation.***
- ***Space-time strains induced by gravitational waves are detected by measuring changes in the separation of fiducial masses with laser interferometry.***

- LISA is expected to detect signals from merging massive black holes, compact stellar objects spiraling into supermassive black holes in galactic nuclei, thousands of close binaries of compact objects in the Milky Way and possibly backgrounds of cosmological origin.

LIGO and LISA



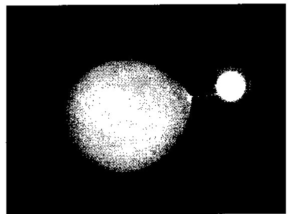
Gravitational Waves: A new way to study the Universe

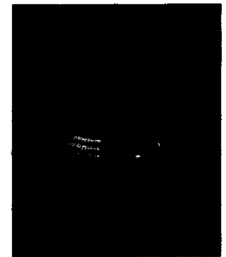
- ***Signals direct from the most extreme conditions throughout the Universe***
  - *Radiation from the primary objects, not secondary processes*
  - *Source dynamics are directly encoded in the waveforms.*
- ***High precision measurements with simple interpretations***
  - *High signal-to-noise enables precision measurements of mass, spin, and distance*
  - *Systems are simple, have few parameters, and are well described by General Relativity*
- ***Most powerful events in the Universe***
  - *Any pair of merging black holes - of any size - produce more energy than all the stars in the Universe.*
- ***Many phenomena not observable in any other way***
  - *Phenomena are too obscured or too far away or simply electromagnetically dark*
  - *Gravity shapes the Universe. What better to map the Universe with!*

The LISA Sky

Ultra-compact binaries

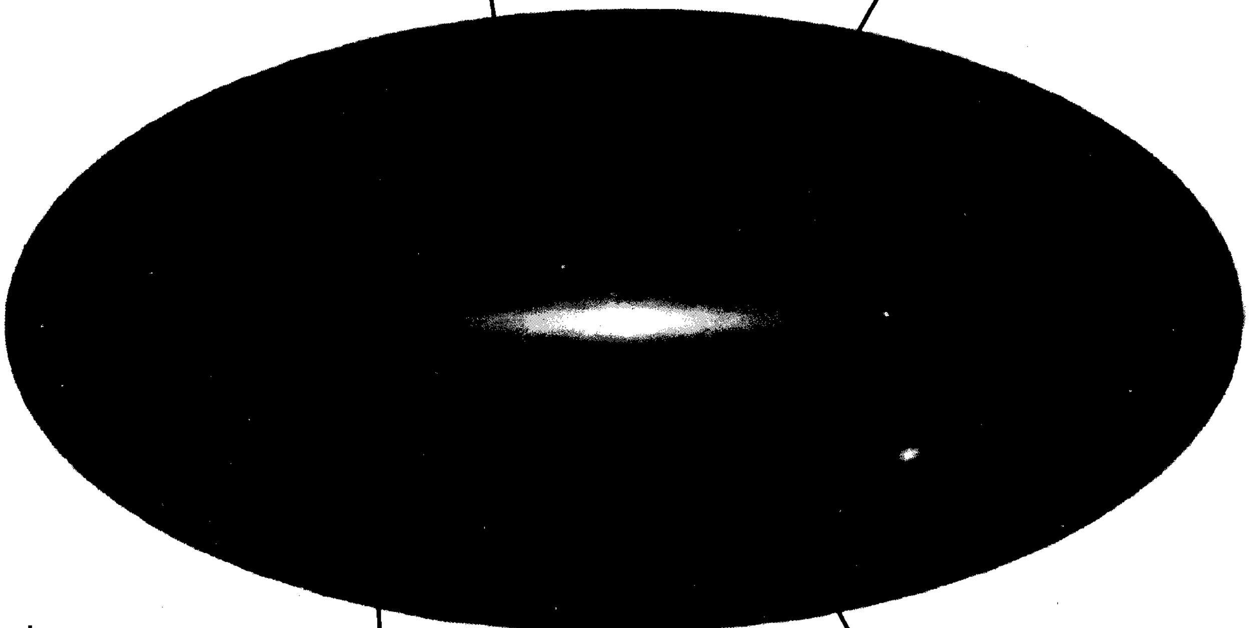
- *~1 $M_\odot$*
- Galactic and extragalactic
- 1000's - 10,000
- Confusion foreground





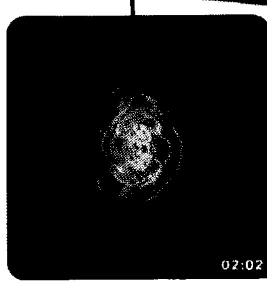
Extreme mass-ratio inspirals

- *~10/ 10^6 $M_\odot$*
- *$z < 1$*
- 10's - 100 per year



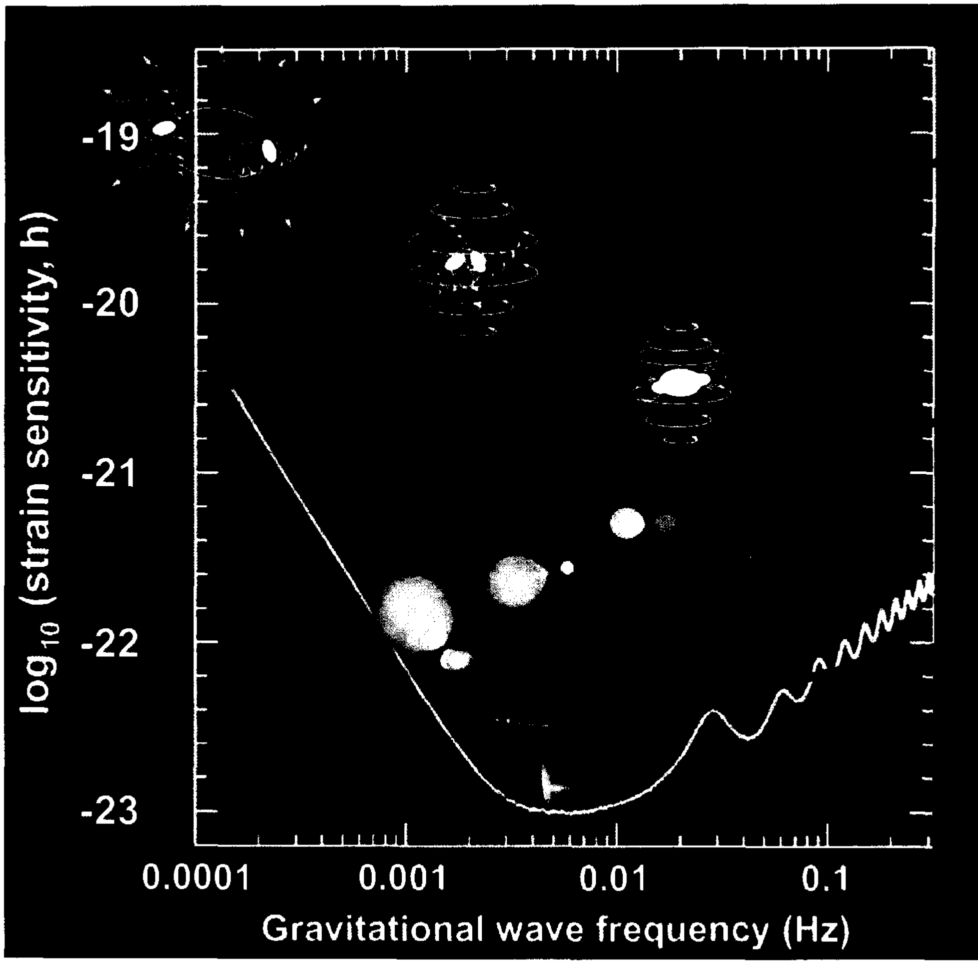
Massive and intermediate-mass black hole binaries

- *10^2 - 10^7 $M_\odot$*
- *$z < 20$*
- 10's to 100 per year



Cosmological back-grounds, bursts and unforeseen sources

Sources and Science Objectives



Formation and growth of massive black holes

Dynamical strong-field gravity

Evolution of ultra-compact binaries in the Galaxy

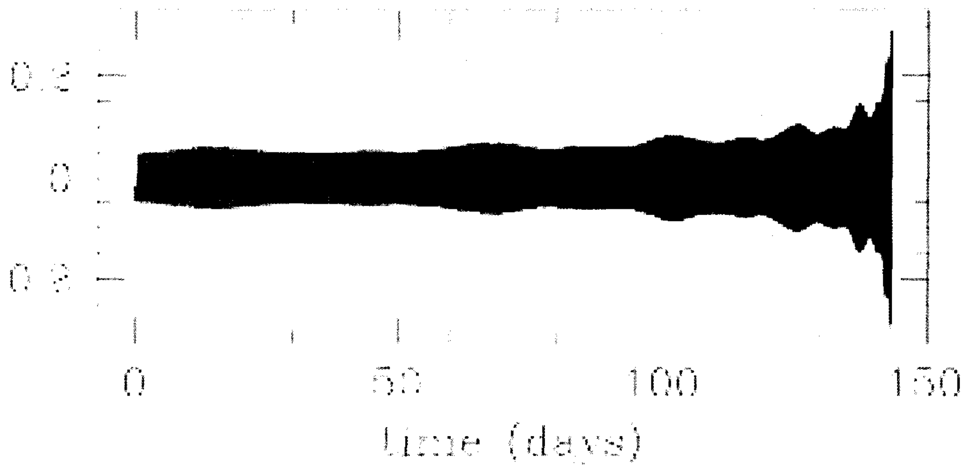
Precision tests of General Relativity

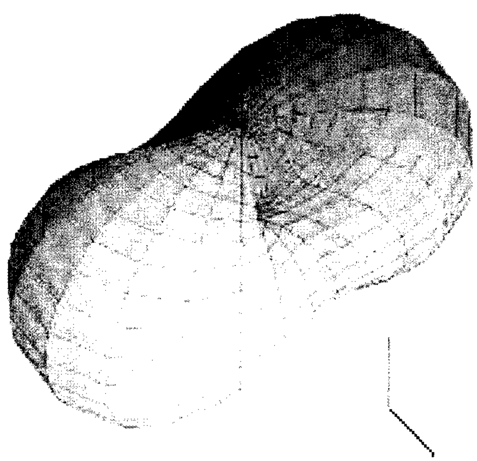
Dynamics of stars in galactic nuclei

New physics: cosmic backgrounds and superstring bursts

What do we measure?

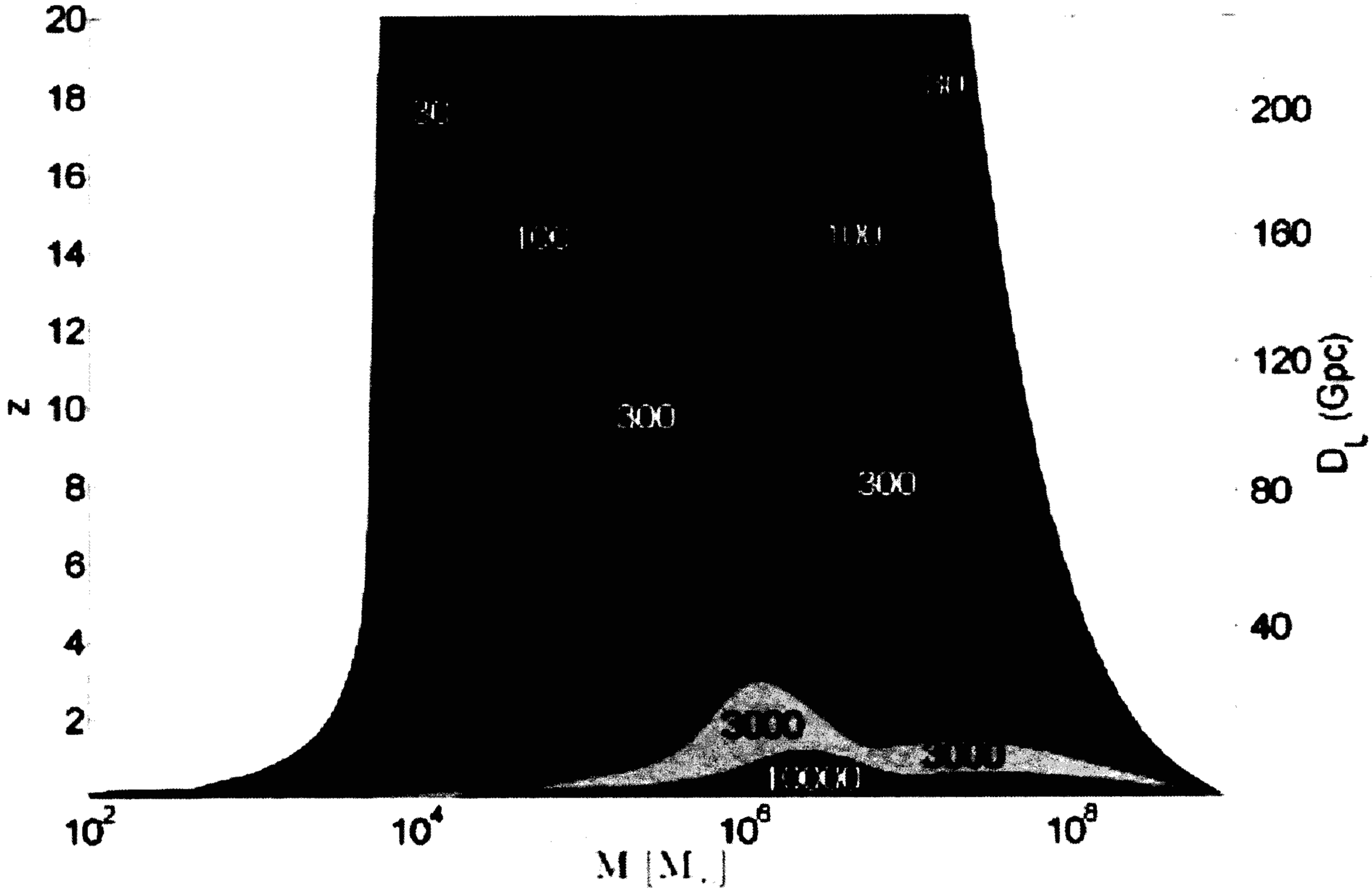
$$h \quad \frac{[G(1+z)\mathcal{M}/c^2]^{5/3}\,[\pi f(t)/c]^{2/3}}{D_L}\mathcal{F}(\text{“angles”})\cos[\Phi(t)]$$





- ***Observe waveforms from months to years***
  - *–10's to 100's of thousands of cycles*
  - *–SNRs from 10 to more than 1,000s*
- ***Waveform depends on 17 parameters***
  - *–Intrinsic parameters of the source*
  - *–Extrinsic parameters of the observer*
- ***Detection vs parameter estimation … an important distinction***

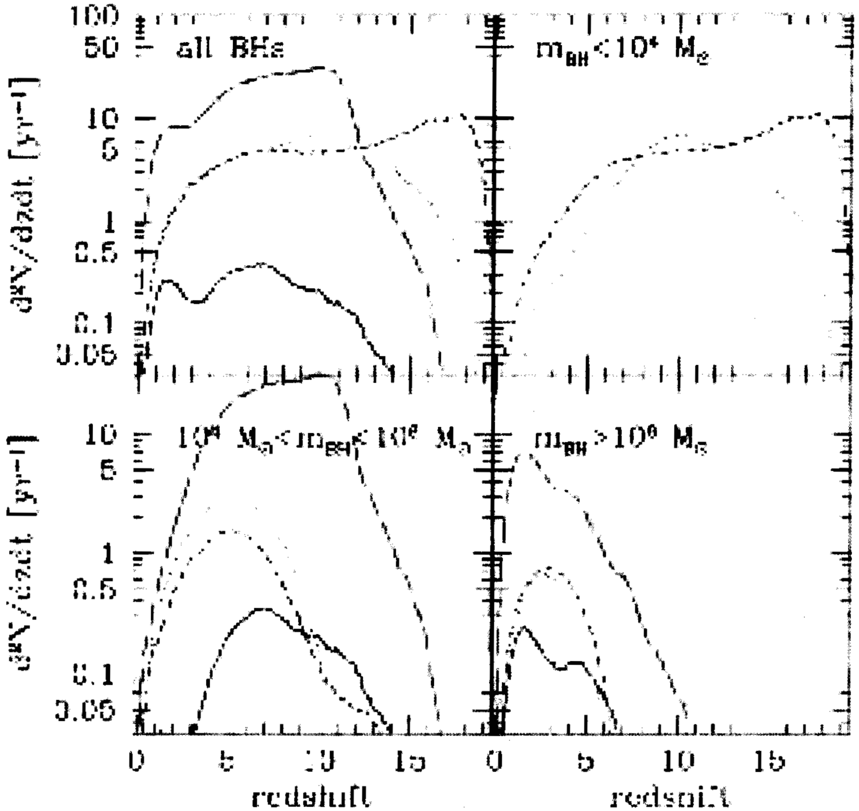
Detection with LISA



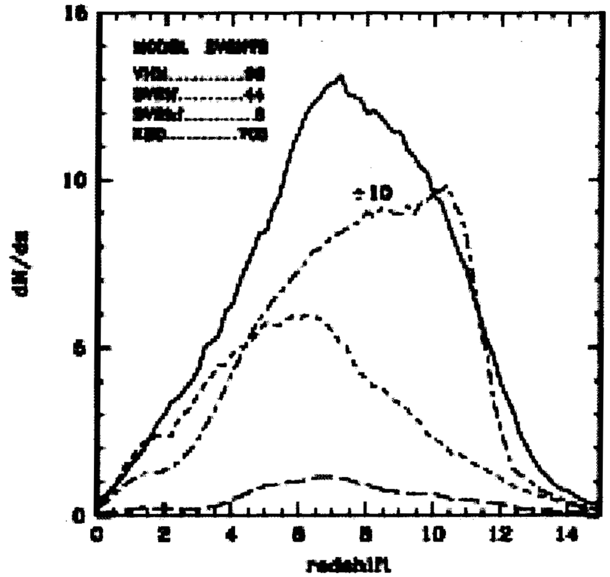
Understanding the Formation and Growth of MBHs

- ***Massive black holes grew from one of two kinds of seeds***
  - *Large stellar mass black holes (~100 $M_\odot$) left over from the first stars (Pop III) at z>20*
  - *~$10^{4\text{-}5}$ $M_\odot$ black holes formed directly by the collapse of supermassive star clusters or gas clouds z~15*
- ***Massive black holes must grow at least fast enough to form ~10^9 $M_\odot$ quasars at z~6.4 (~1 Gyr after the Big Bang).***
  - *Accretion*
  - *Mergers*
  - *The gravitational rocket*
- ***LISA will detect ~10^4 $M_\odot$ black holes merging at z=30 with SNR=10.***
- ***LISA will observe 300 $M_\odot$ black holes merging with ~10^4 $M_\odot$ black holes at z=10 with a luminosity distance uncertainty of >35%, redshifted masses <1%, spins <0.2.***

Merger Rates



Sesana et al 2004 ApJ, 611, 623

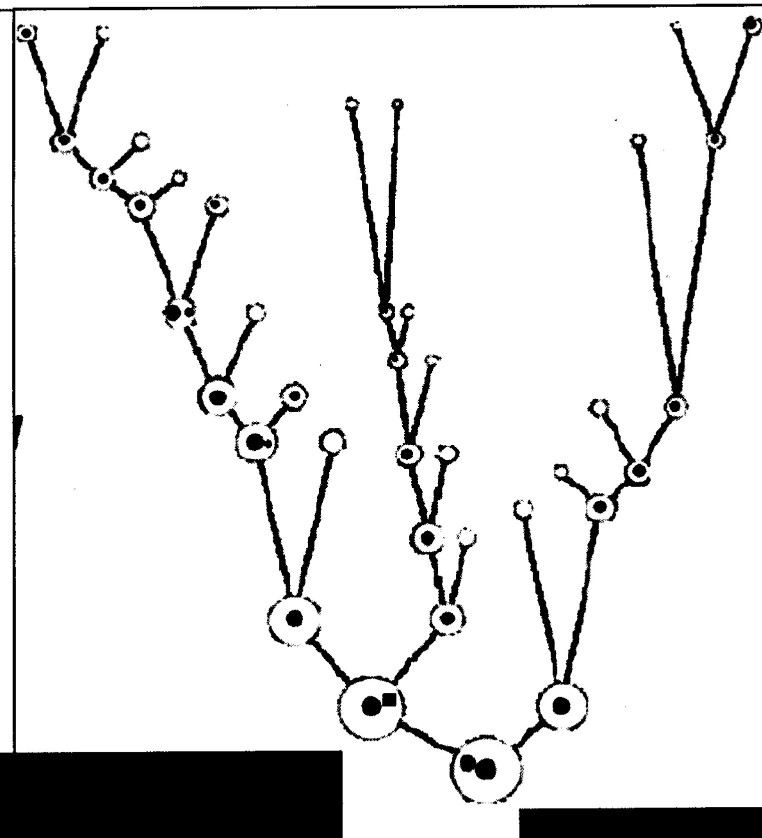


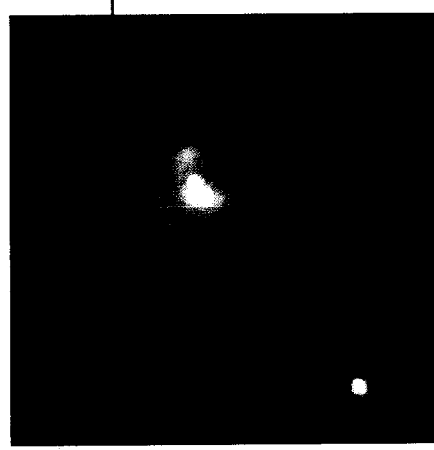
Trace the merger history of MBHs and their host galaxies

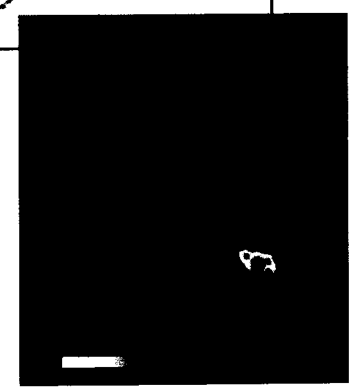
- ***The standard model of hierarchical structure growth calls for***
  - *Formation of small dark matter haloes*
  - *Formation of proto-galaxies within those haloes*
  - *Progressive mergers to form modern galaxies*
- ***Coevolution of galaxies and massive black holes***
  - *Scaling relations between MBH masses and galaxy properties (e.g. bulge mass/luminosity, velocity dispersion) over >3 decades suggest that MBHs grow in conjunction with their host galaxies.*
- ***LISA will observe a wide range of merger events between z=10 and the present:***
  - *At z=10, events with total masses ranging from ~10^4 to 10^6 $M_\odot$, with luminosity distance uncertainties <35%, mass uncertainties <1%, spin uncertainties <0.2*
  - *At z=1, events with total masses ranging from ~10^5 to 10^7 $M_\odot$, with luminosity distance uncertainties <0.4%, mass uncertainties <1%, spin uncertainties <0.01*
  - *Mass ratios can range from 1000 to 1.*

Merger Trees

- *LISA will produce a source catalog with the 17 parameters, and their uncertainties.*
- *Accretion will spin up MBHs to near maximal values*
- *Mergers will randomize spins and leave relatively low average spins.*
- *The gravitational rocket should preferentially affect lower mass haloes and near equal mass mergers.*
- *MBHs (~10^4 $M_\odot$) formed in globular clusters may also merge with central MBHs, revealing other galactic dynamics*





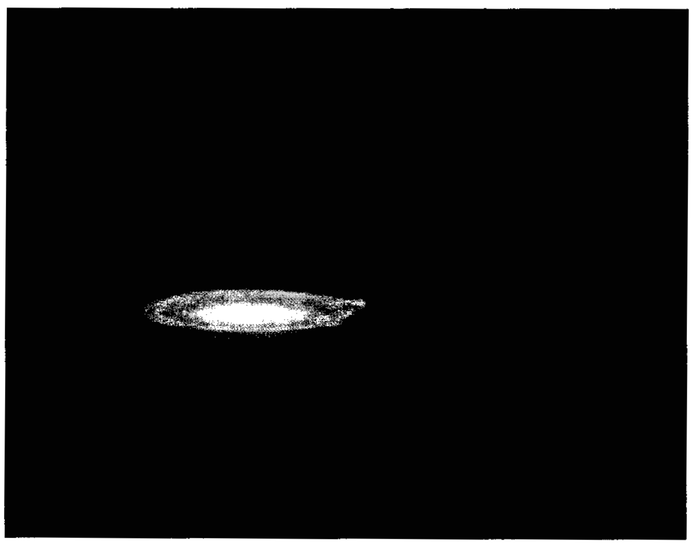


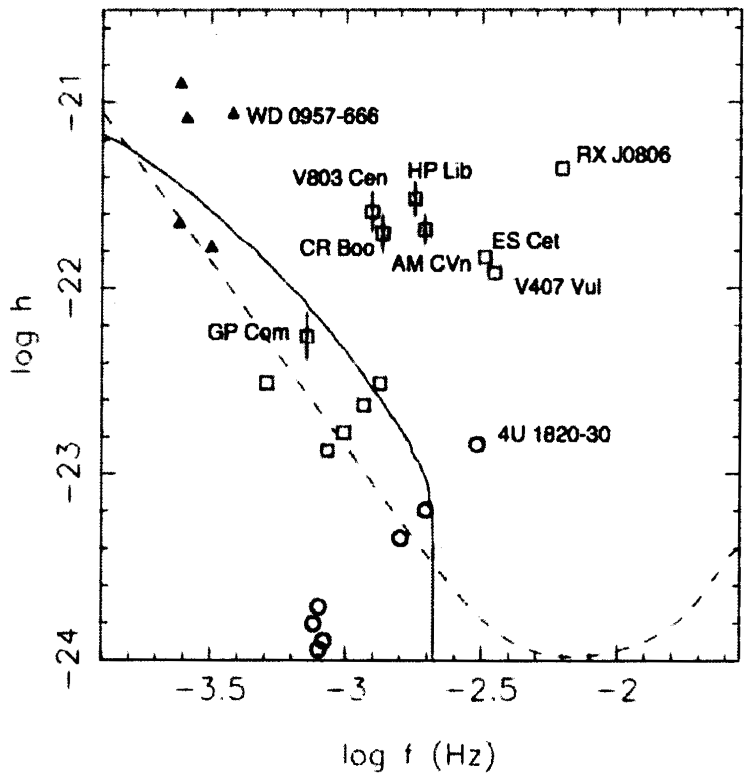
Survey binaries of stellar mass objects

- ***There are an estimated 26 million compact-star binaries in the Milky Way that will radiate appreciable gravitational radiation in the LISA band.***
  - *Mostly WD-WD binaries*
  - *Some NS-NS binaries*
  - *Possibly a few BH-BH binaries*
- ***LISA should separate about 10,000 of them.***
- ***There are currently about 10 known sources that LISA can detect, making them guaranteed gravitational wave sources with optical counterpart. Many more will be known by the time that LISA flies.***
- ***The known sources can be used to verify the***

Science with stellar-mass binaries

- *Study demographics of these endpoints of stellar evolution*
- *Study exotic binary systems, e.g., common envelope, contact binaries*
- *Map the distribution of these stars in the Milky Way*



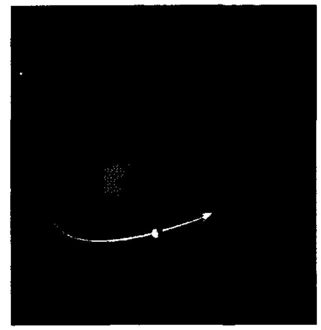


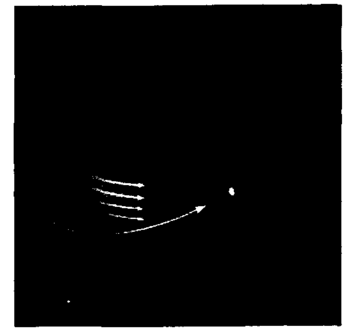
Testing theories of relativity

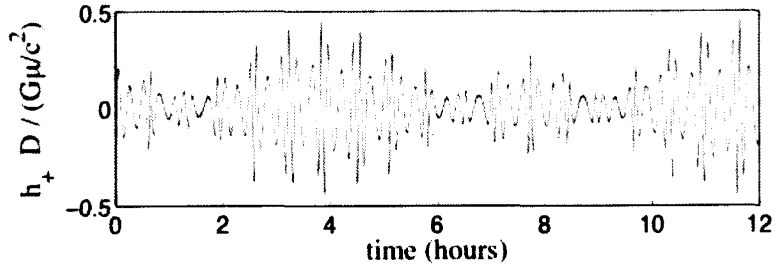
- ***Stellar mass black holes (~10 $M_\odot$) will be gravitationally scattered into highly eccentric orbits about central MBHs (~10^6 $M_\odot$). These "Extreme Mass Ratio Inspirals" (EMRIs) are estimated to occur at the rate of 20-40 per year out to z~1.***
- ***SMBH mergers (~10^6 $M_\odot$) result from the mergers of their host galaxies, and are estimated to occur at the rate of a few per year.***
- ***Observations of compact-star binaries will directly verify the propoeries of gravitational waves four decades of frequency below the LIGO band. The "verification binaries" alone will directly confirm***

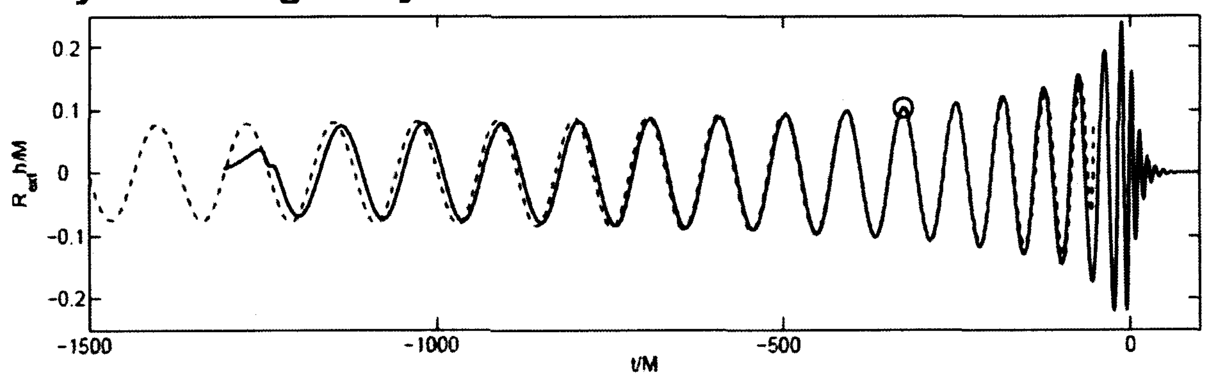
Waveforms

- ***"Verification binaries" will directly confirm the properties of gravitational waves four decades below the LIGO band with known sources.***
- ***EMRIs have rich waveforms which enable :***
  - *Mapping the spacetime around*
  - *Testing the "No-hair Theorem" of General Relativity to ~1% accuracy*
  - *Measuring the dynamical tide on horizon to ~10%*
- ***Testing extreme dynamical gravity with MBH binaries.***







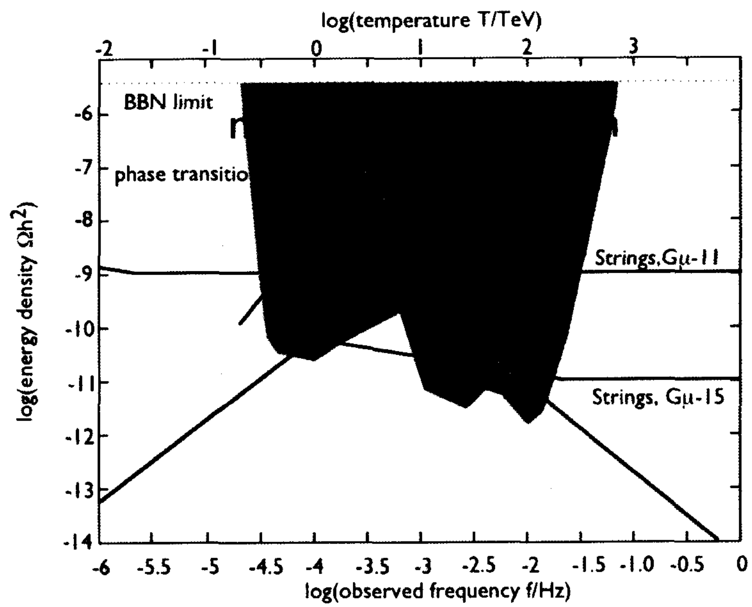


Probing New Physics and Cosmology

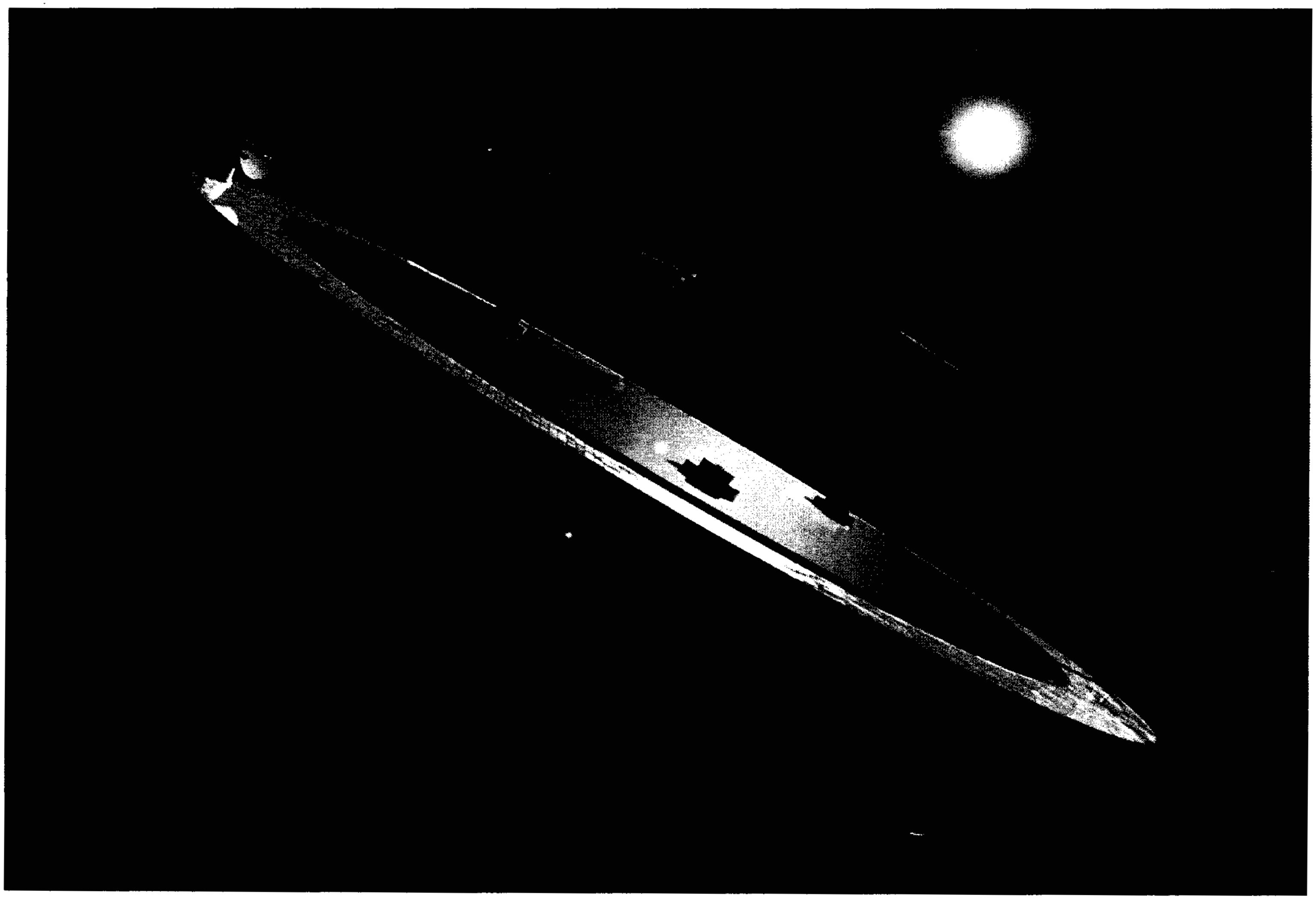
- ***MBH mergers with electromagnetic counterparts***
  - *LISA can predict merger time well in advance*
  - *For the strongest sources, LISA can locate the sources within 10's of arc minutes on the sky and within a few percent in redshift from the inspiral phase*
- ***Possible electromagnetic counterparts***
  - *Pre-merger variability*
  - *Post merger from disturbance of the accretion ring by the lost of mass (Phinney 2007)*
  - *Post merger signal from re-establishing accretion (Phinney and Milosavlejvic 2007)*
- ***Search for cosmological gravitational wave background.***
- ***Search for unexpected sources***

New Physics and Cosmology

- ***MBH mergers with electromagnetic counterparts***
  - *Measure the Hubble constant*
  - *Map cosmic acceleration to ~1% with absolute distance measurement from GWs and redshift from EM spectroscopy*
- ***Search for cosmological gravitational wave background***
  - *Not likely*
  - *Probe Terascale, electro-weak phase transitions*
- ***Search for a background from decaying cosmic string loops***
- ***Search for burst events from cosmic string cusps***
- ***Search for unexpected sources***

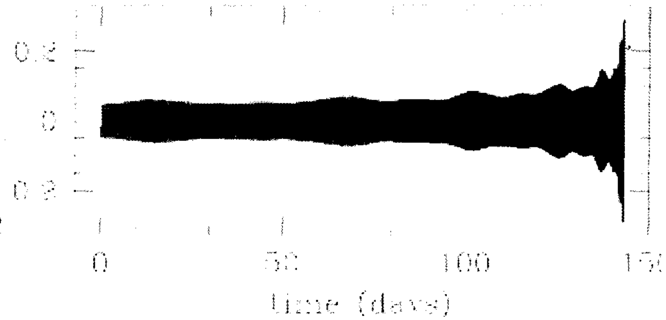


Mission Concept

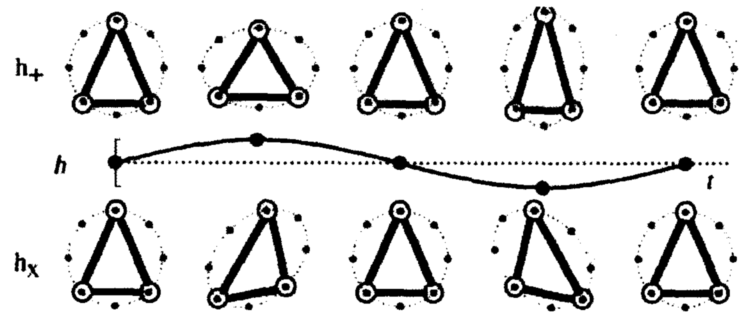


Measurement Concept

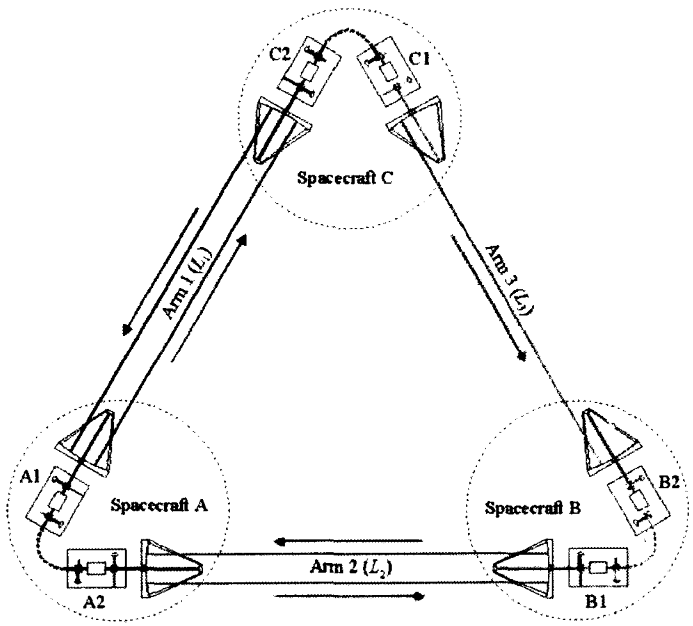
- ***What's to be measured***
  - *Time-varying strain ($\Delta L/L$) in spacetime as small as $10^{-22}/\sqrt{Hz}$*
  - *Variations are periodic or quasi-periodic between $3x10^{-5}$ and 0.1 Hz, observable for months to years*

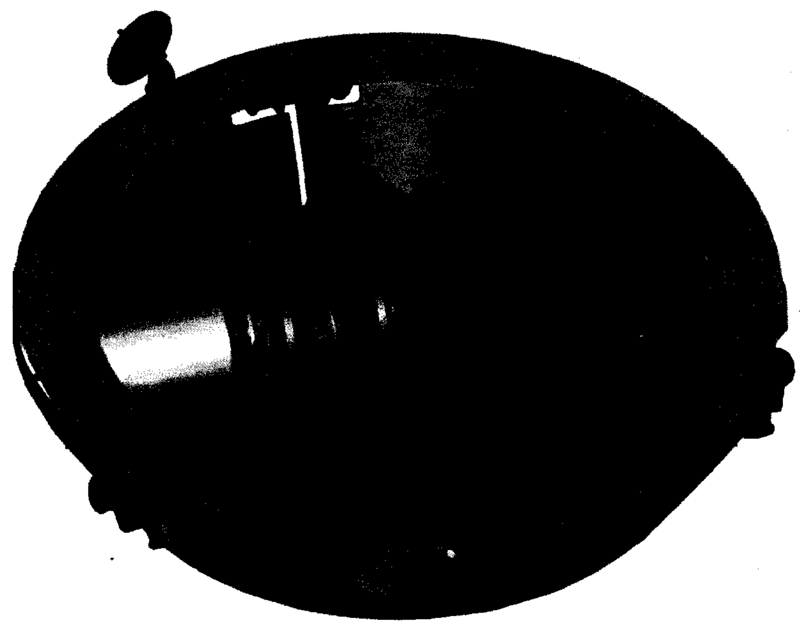


- ***Measurement concept***
  - *Measure distance changes between free-falling mirrors (Bondi)*
    - *Proof masses are the mirrors*
    - *Interferometric measurement of distance changes*
  - *Desired*
    - *A long measurement path to make ΔL large*
    - *A very quiet place to avoid disturbances to the proof masses*



Sciencecraft



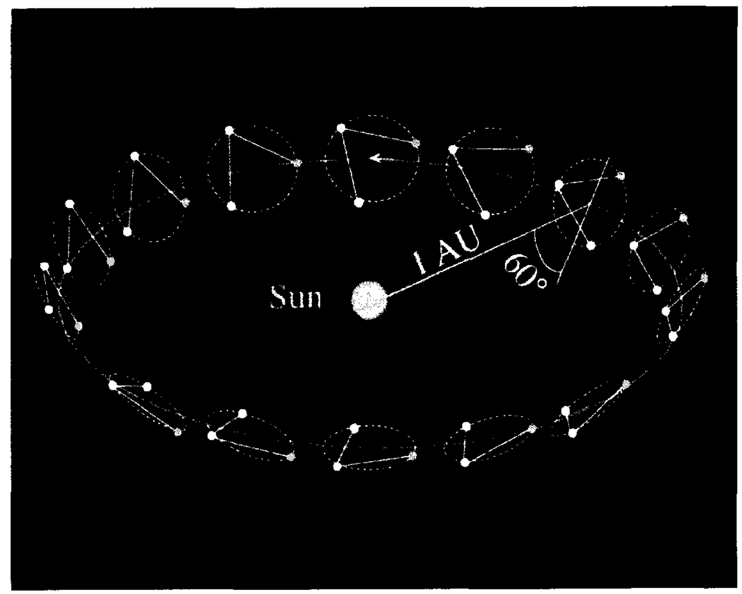


- *Three interacting spacecraft make up the "science instrument"*
- *Multiple combinations of one-way measurements.*

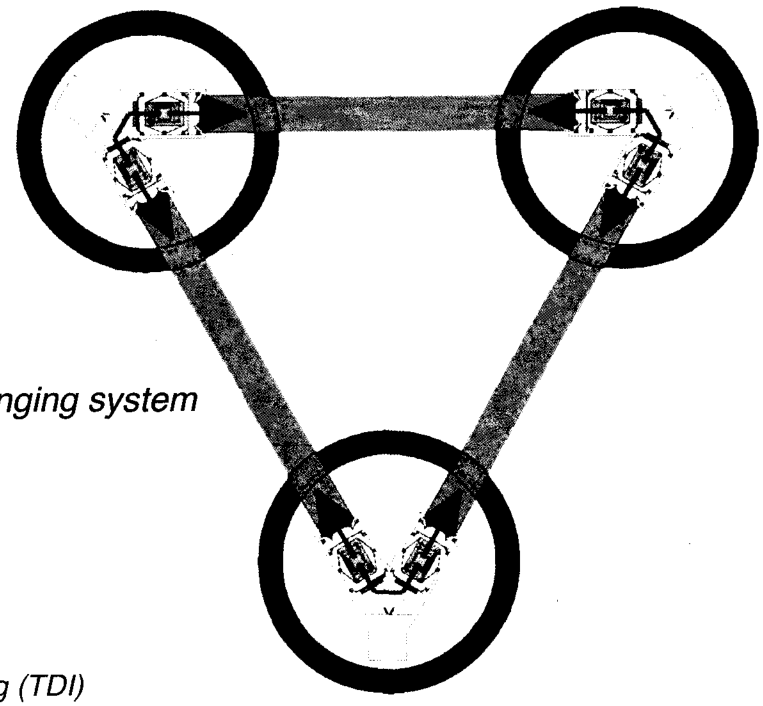
- *Drag-free control protects the proof masses from the ambient environment and reduces the disturbances on the proof masses from the spacecraft.*

What the science instrumentation does

- ***Measure changes in relative separation between proof masses***
  - *Continuous laser ranging between free-falling proof masses*
  - *Interferometric readout (μcycles/√ Hz over gigameters with 1μ light)*
  - *Performance characterized by displacement noise*
- ***Reduce disturbances***
  - *Benign environment*
  - *Enclosed proof masses*
  - *Control disturbances from spacecraft*
  - *Limit relative motion of spacecraft with "drag-free" control*
  - *Performance characterized by residual acceleration noise*



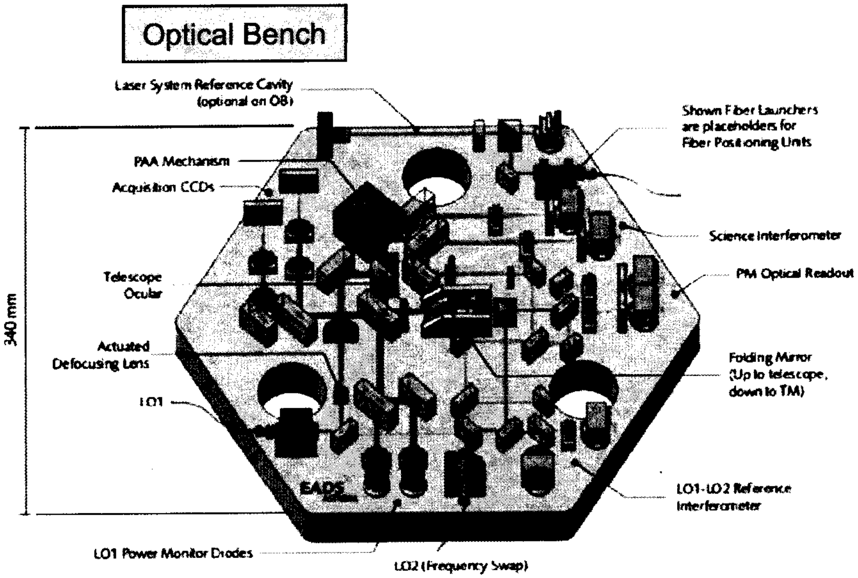
How the science instrumentation works

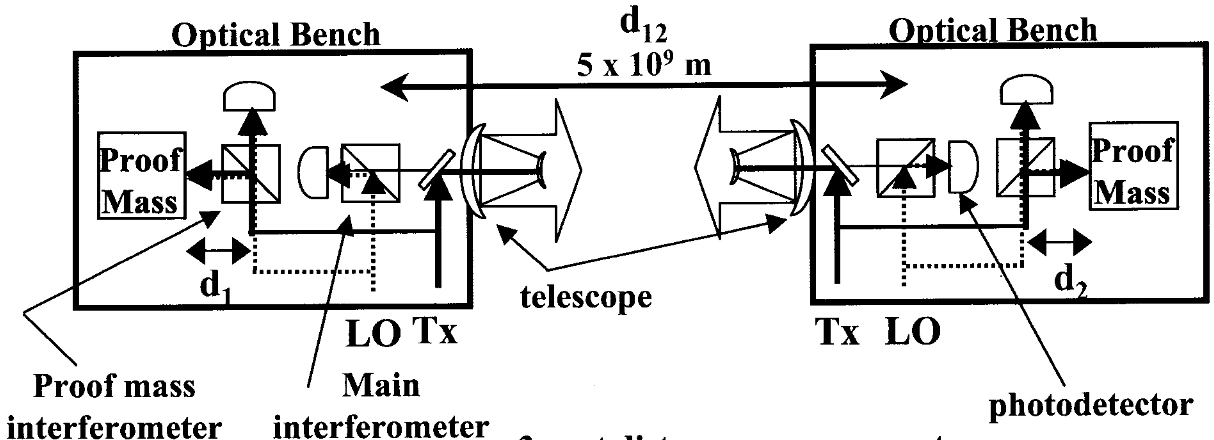


- ***The Constellation is the Instrument***
  - *Orbits passively maintain formation*
  - *"Sciencecraft" houses*
    - *Proof masses*
    - *Interferometry equipment*
- ***Interferometer Measurement System (IMS)***
  - *Active transponder offset phase-locked laser ranging system*
  - *3-part distance measurement*
    - *(2) "short-arms" from proof mass to sciencecraft*
    - *"Long-arms" measure between sciencecraft*
  - *Laser frequency noise correction*
    - *Pre-stabilization, arm-locking, and post-processing (TDI)*
  - *Phasemeter records fringe signal*
- ***Disturbance Reduction System (DRS)***
  - *Free-falling proof masses don't contact the sciencecraft*
  - *Drag-free stationkeeping reduces sciencecraft proof mass relative motion and force gradients*
  - *Design to limit thermal, magnetic, electrostatic, mechanical, self-gravity disturbances*

Interferometry - what it does

- ***Laser system***
  - *Transmitter and local oscillator*
  - *Modulation sidebands*
- ***Frequency control***
  - *Pre-stabilize*
  - *Doppler shift compensation*
- ***Clock noise transfer***
  - *Record and remove in post-processing*
- ***Pointing***
- ***Optical bench***
  - *Acquisition CCD*
  - *Beam combining/mode matching*
- ***Telescope for transmit/receive over long arm***



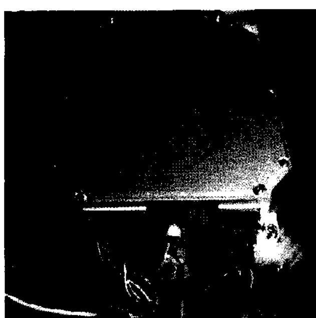


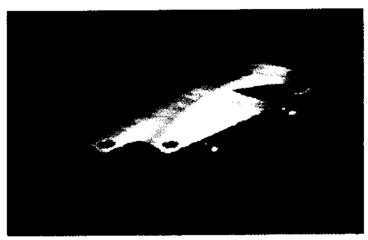
3 part distance measurement:

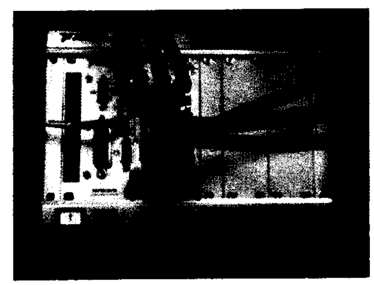
Short arm (d_1+d_2) + long arm (d_{12}) = d_total

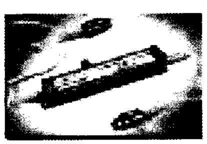
Interferometry - what it takes

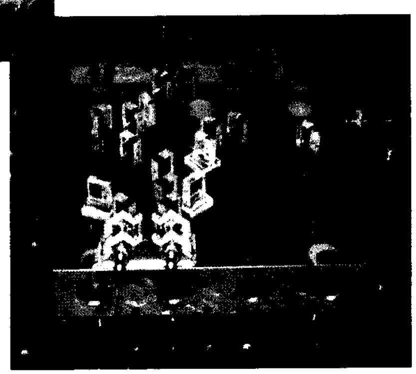
- ***Laser:***
  - *Diode-pumped solid state (Nd:YAG)*
  - *Fiber coupled master-oscillator (25 mW), power-amplifier (1 W) architecture*
  - *Electro-optic phase modulator*
  - *Fully redundant*
- ***Laser frequency control: 3-stage***
  - *Reference cavity*
  - *Arm-locking control loop and actuator*
  - *Post-processing (TDI)*
- ***Optical Bench***
  - *ULE or Zerodur for stability*
  - *Hydroxy-catalysis bonding*
- ***Phasemeter***
  - *Photoreceiver*
  - *1 μcycle/√ hz demonstrated*
- ***LTP Short arm***
  - *Performance exceeds requirements*
- ***Telescope***
  - *40 cm, f/1.5 Cassegrain*
  - *λ/30 wavefront error*

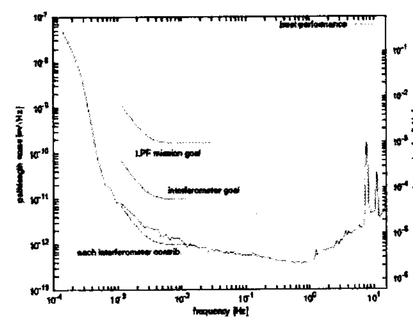


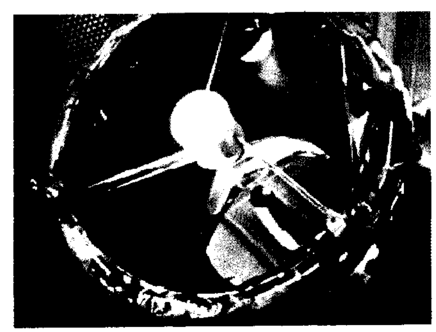






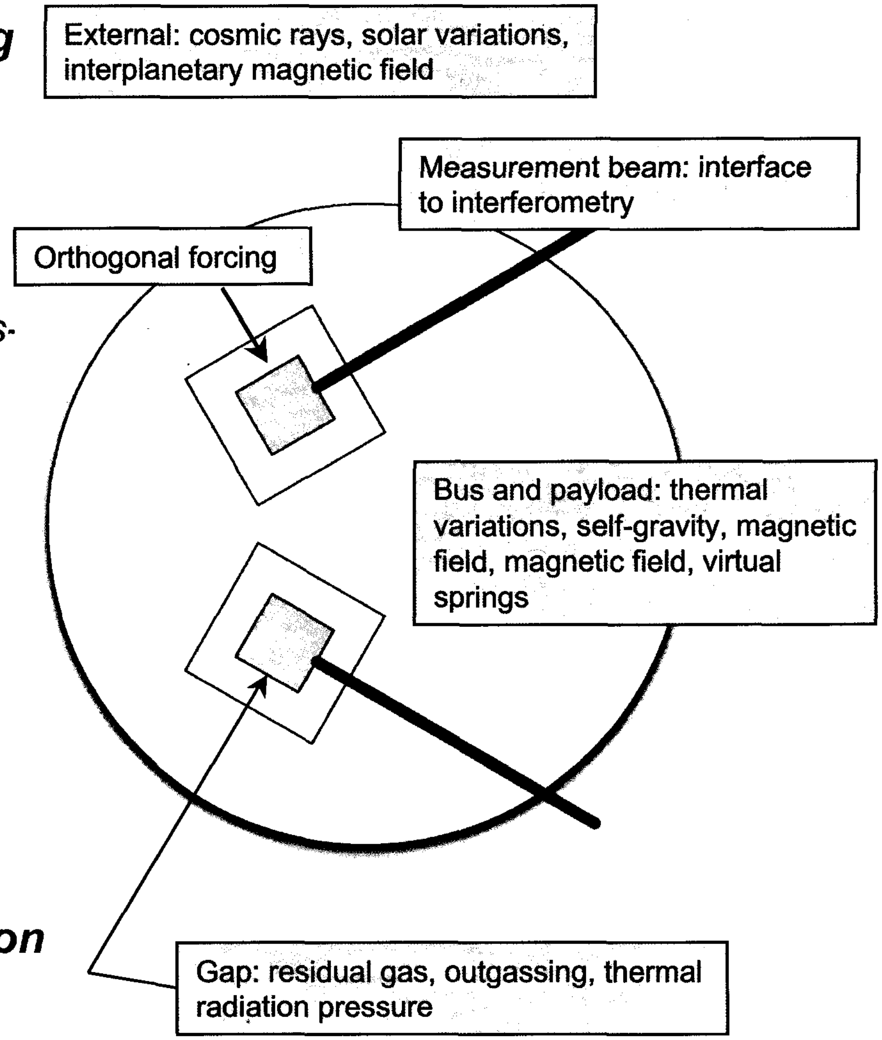






Disturbance Reduction - what it does

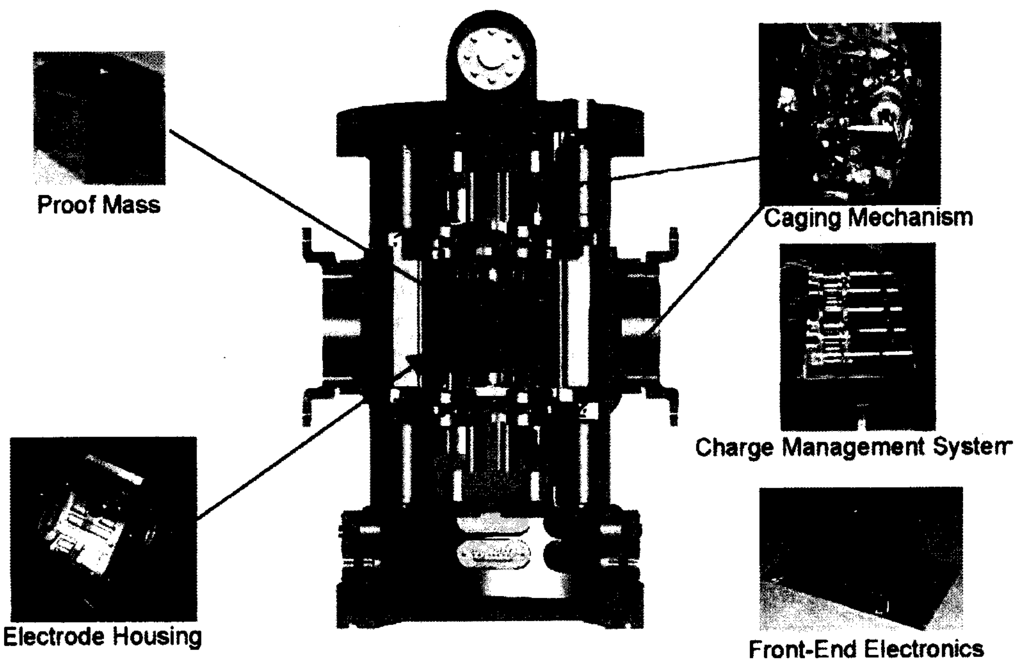
- ***Proof mass is the free-falling mirror***
- ***Housing***
  - *Sensing for drag-free and charge control*
  - *Forcing in orthogonal degrees-of-freedom*
- ***Active discharging***
- ***Quiet environment***
  - *Vacuum enclosure*
  - *Thermal isolation*
  - *Low magnetic field from payload and bus*
  - *Low self-gravity*
- ***Caging***
- ***Sensor for spacecraft position and attitude control***

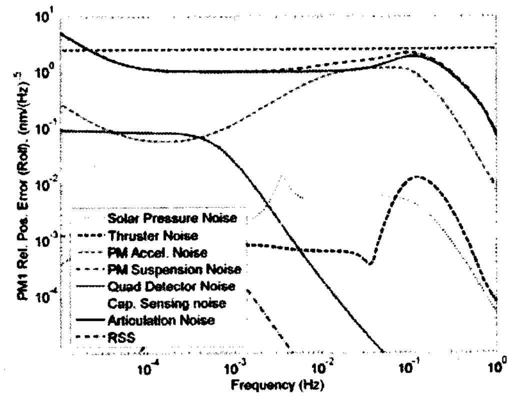


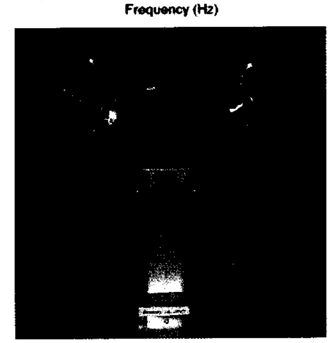
Disturbance Reduction - what it takes

- ***Gravitational Reference Sensor***
  - *Proof mass - 44 mm cube, Au:Pt*
  - *Reference housing with capacitive sensing and electrostatic forcing*
  - *Charge control with UV light*
  - *Caging, vacuum system*
- ***"Drag-free" control laws***
  - *3 x 19 Degrees of freedom*
  - *Acquisition*

- ***Micronewton thrusters***
  - *Electro-spray of nano-droplets or metal ions, neutralizer*
  - *30 μN authority, 0.1μN/√ Hz noise*
- ***General design features***
  - *Low self-gravity*
  - *Low magnetism spacecraft*
  - *Passive thermal shielding*







Requirements Flowdown

- ***The Instrument Sensitivity Model is a combination of***
  - *Displacement noise from the IMS*
  - *Acceleration noise from the DRS*
  - *Arm Length (5x10⁶ km)*
- ***The arm length also determines the instrument transfer function***
- ***The requirements for the DRS and IMS are then suballocated.***

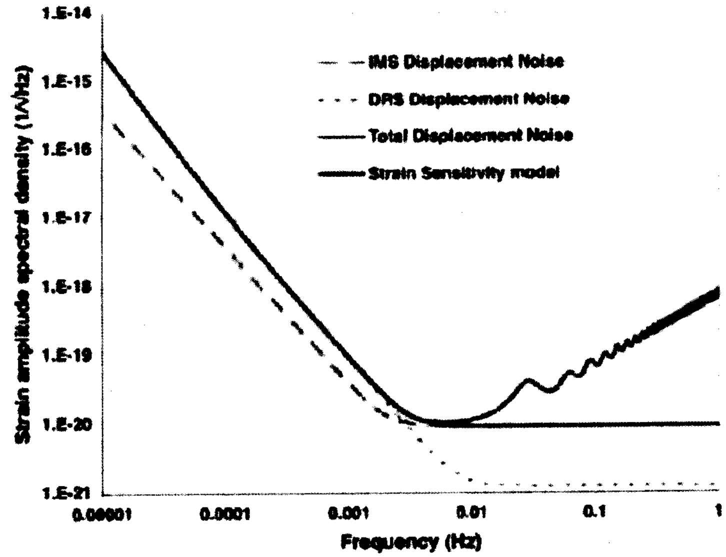


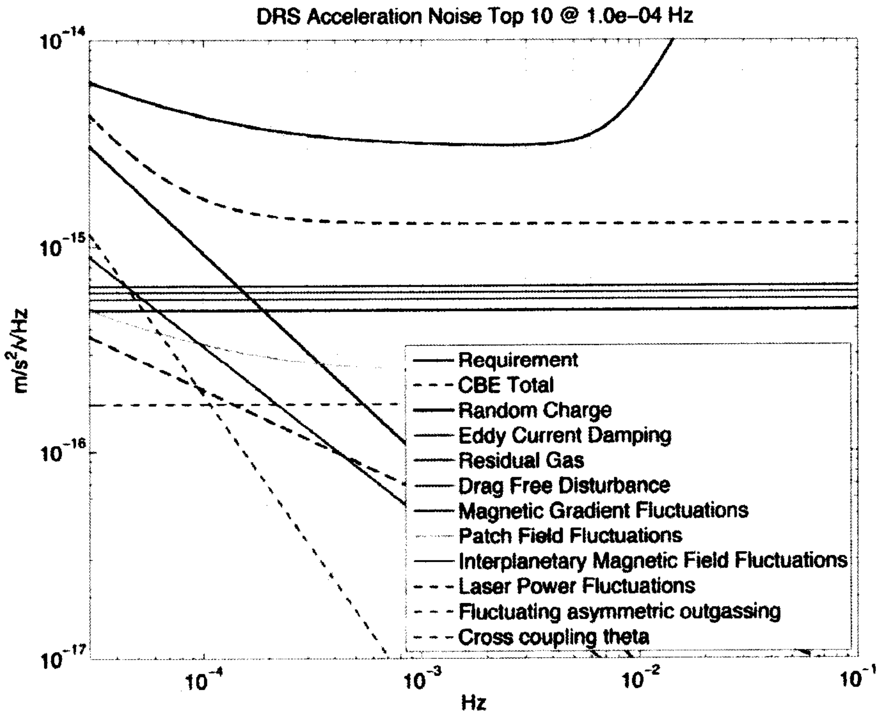
Table 1: Summary of IMS subsystem noise allocations.

	$\times 10^{-12}\frac{m}{\sqrt{Hz}}\sqrt{1+\left(\frac{2\,mHz}{f}\right)^4}$		
Effect	**Total per group**	**Sub -Allocation**	**Comments**
Total Error Budget	**18.0**		
Contingency (35%)	**6.3**		Held by System Engineering
Total available for allocation	**11.7**		RSS of subsystems
Subsystem Allocations			
Shot noise	**7.7**		100 pW received power
Pathlength noise	**7.0**		RSS of sub-allocations
Pointing Errors		5.3	
Telescope pathlength stability		1	
Optical bench pathlength stability		4.5	
Measurement noise	**5.4**		RSS of sub-allocations
Photoreceiver errors		3	
Residual laser frequency noise		2	
Residual clock frequency noise		3	
Phasemeter noise		1	
ADC jitter		1	
Phase reconstruction		1	
straylight		2	

Table 1: Summary of DRS Subsystem allocations

	$\times 10^{-16}\frac{m}{s^2\sqrt{Hz}}\sqrt{1+\left(\frac{f}{8\,mHz}\right)^4}\sqrt{1+\left(\frac{0.1mHz}{f}\right)}$		
Effect	**Total per group**	**Per group**	**Comments**
Total Acceleration noise	**30.0**		
Contingency (35%)	**10.5**		Held by System Engineering
To be allocated (linear subtract)	**19.5**		RSS of sub-allocations
Disturbance Groups			
Electrostatics		12.0	
Brownian		9.1	
Spacecraft magnetic		7.0	
Spacecraft coupling		6.0	
Spacecraft cross coupling		4.5	
Thermal		4.0	
Interplanetary Magnetic		4.0	
Misc small effects		4.0	

DRS Requirements

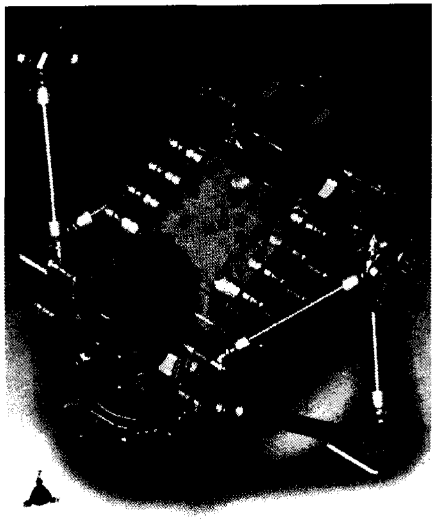


- ***Flow-down***
  - *35% contingency*
  - *Allocation*
  - *Sub-allocation*
  - *Roll-up arithmetic (RSS or linear)*
- ***Current best estimate***
  - *Models*
  - *Laboratory anchor points*
  - *LPF testing (presently ground, eventually flight)*

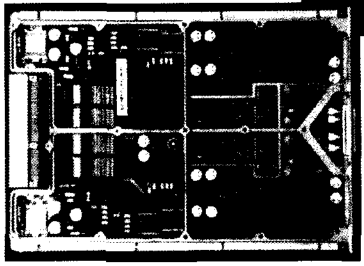
Table 1: Summary of DRS Subsystem allocations

	$\times 10^{-16} \frac{m}{s^2\sqrt{Hz}} \sqrt{1+\left(\frac{f}{8\,mHz}\right)^4} \sqrt{1+\left(\frac{0.1\,mHz}{f}\right)}$		
Effect	**Total per group**	**Per group**	**Comments**
Total Acceleration noise	**30.0**		
Contingency (35%)	**10.5**		Held by System Engineering
To be allocated (linear subtract)	**19.5**		RSS of sub-allocations
Disturbance Groups			
Electrostatics		12.0	
Brownian		9.1	
Spacecraft magnetic		7.0	
Spacecraft coupling		6.0	
Spacecraft cross coupling		4.5	
Thermal		4.0	
Interplanetary Magnetic		4.0	
Misc small effects		4.0	

Technology - LISA Pathfinder

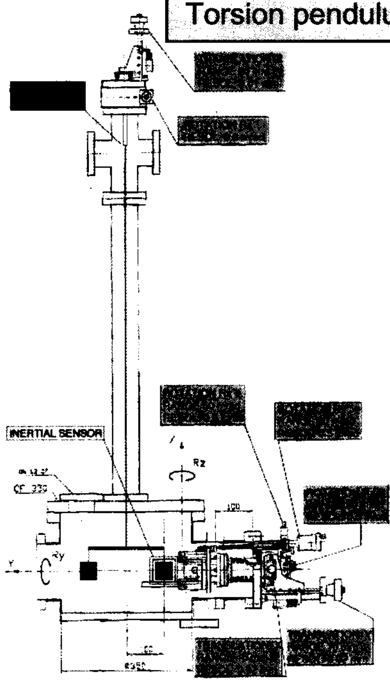


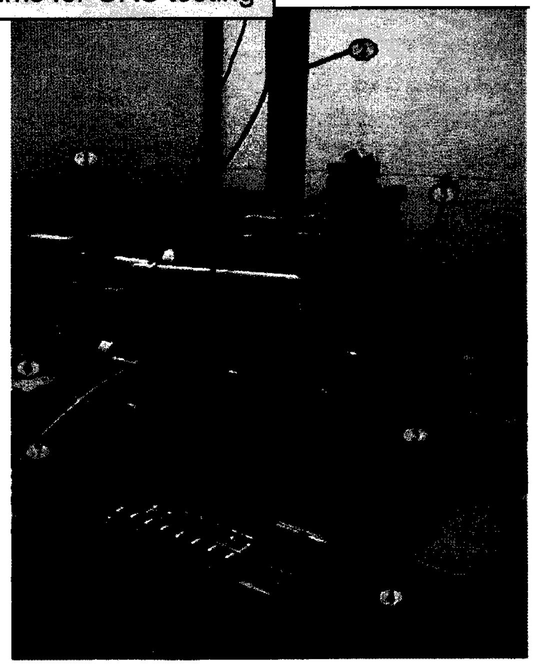
- ***Pathfinder status***
  - *Pathfinder now in implementation phase.*
  - *Ground development is complete.*
- ***GRS***
  - *The Pathfinder GRS is the LISA GRS.*
  - *Demonstrated engineering model performance on torsion pendulum.*
  - *EM successfully passed thermal-vac and vibration testing.*
- ***Drag-free control laws***
  - *Drag-free control similar to LISA configuration will be demonstrated on LPF.*
  - *Better than required performance predicted from full non-linear simulations.*
- ***Laser master oscillator***
  - *Pathfinder flight-qualified laser is LISA Master Oscillator.*
- ***Optical block and opto-mechanical construction***
  - *LTP Bench demonstrates construction materials and techniques.*
  - *Measured performance exceeds requirements.*
- ***[For Thrusters, see Architecture section]***



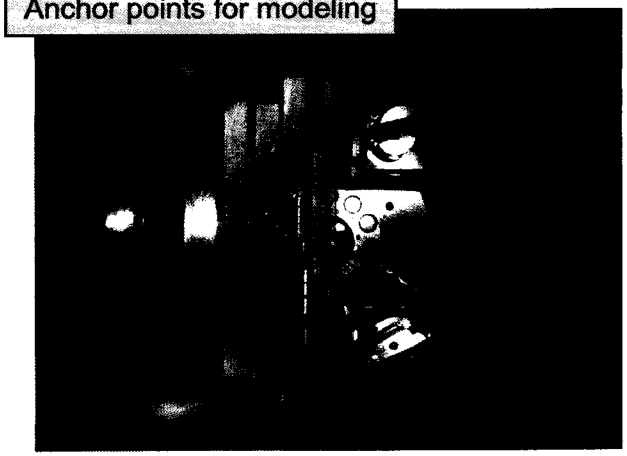
Technology - Ground Development

Torsion pendulums for GRS testing

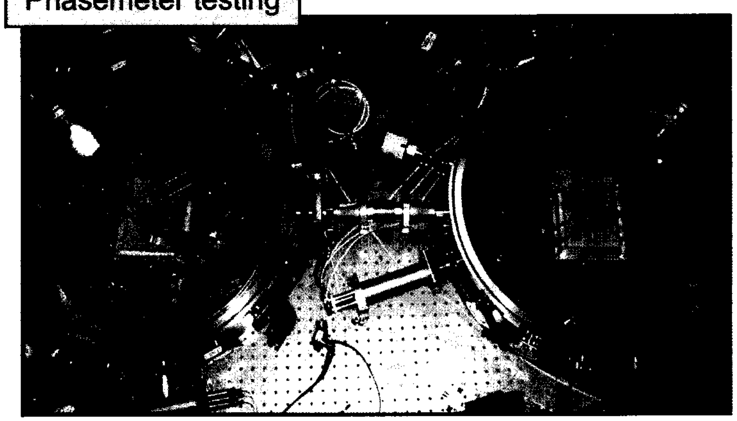




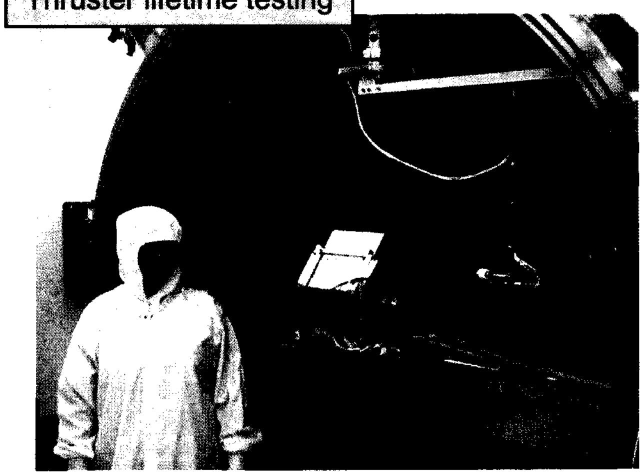
Anchor points for modeling



Phasemeter testing

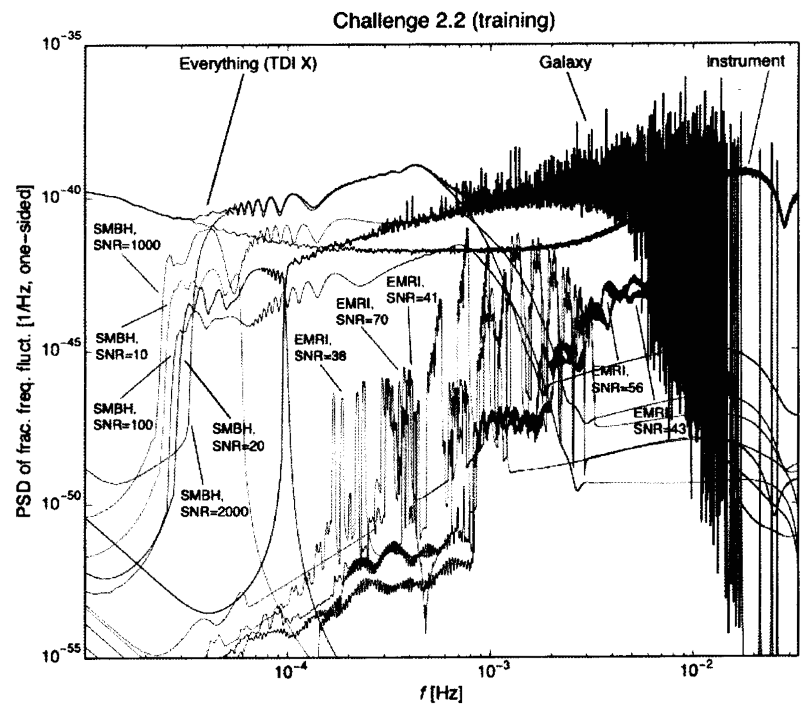


Thruster lifetime testing



Science Operations and Data Analysis

- ***Science operations are straightforward***
  - *Single science mode: observes all the sky, all the sources, all the time*
  - *No pointing of the constellation, no scheduling of detectors or observing slots necessary (or possible)*
  - *Science data volume is small (< 30 Gbyte for 5 year mission)*
- ***Analysis methodology is well-developed***
  - *Time-Delay Interferometry*
    - *High-fidelity simulations*
    - *Laboratory hardware validation*
  - *Algorithms for source detection and parameter estimation*
- ***Data analysis algorithms are being validated with sophisticated high-fidelity simulations***
  - *Planning and implementation underway since 2005*
  - *"Mock LISA Data Challenges provide validation testbed*
  - *Results of round 2 challenge due in June 2007*
    - *All classes of LISA sources + instrumental background (see figure)*



Training data for the ongoing round of data challenges (to be completed in June 2007). The simulated data stream is a high-fidelity representation of the full LISA data set containing instrumental noise plus 4 massive black hole events, 5 EMRI events, and 26.1 million Galactic binaries.

* http://www.tapir.caltech.edu/dowiki/listwg1b:home & http://astrogravs.nasa.gov/docs/mldc

Summary

- ***LISA will perform a wide range of science***
  - *Formation and growth of massive black holes*
  - *Assembly of galaxies*
  - *Compact-star binaries*
  - *High precision tests of relativity in extreme field limit*
  - *Exploration of cosmology and new physics*
- ***The current mission concept is mature and well-understood***
  - *The science requirements and the associated performance requirements are well understood.*
  - *Architecture is well defined, and extensively analyzed.*
- ***The technology is well advanced.***
  - *LISA Pathfinder has completed ground development and is now in implementation*
  - *Substantial progress has been made on ground-based technology demonstrations*

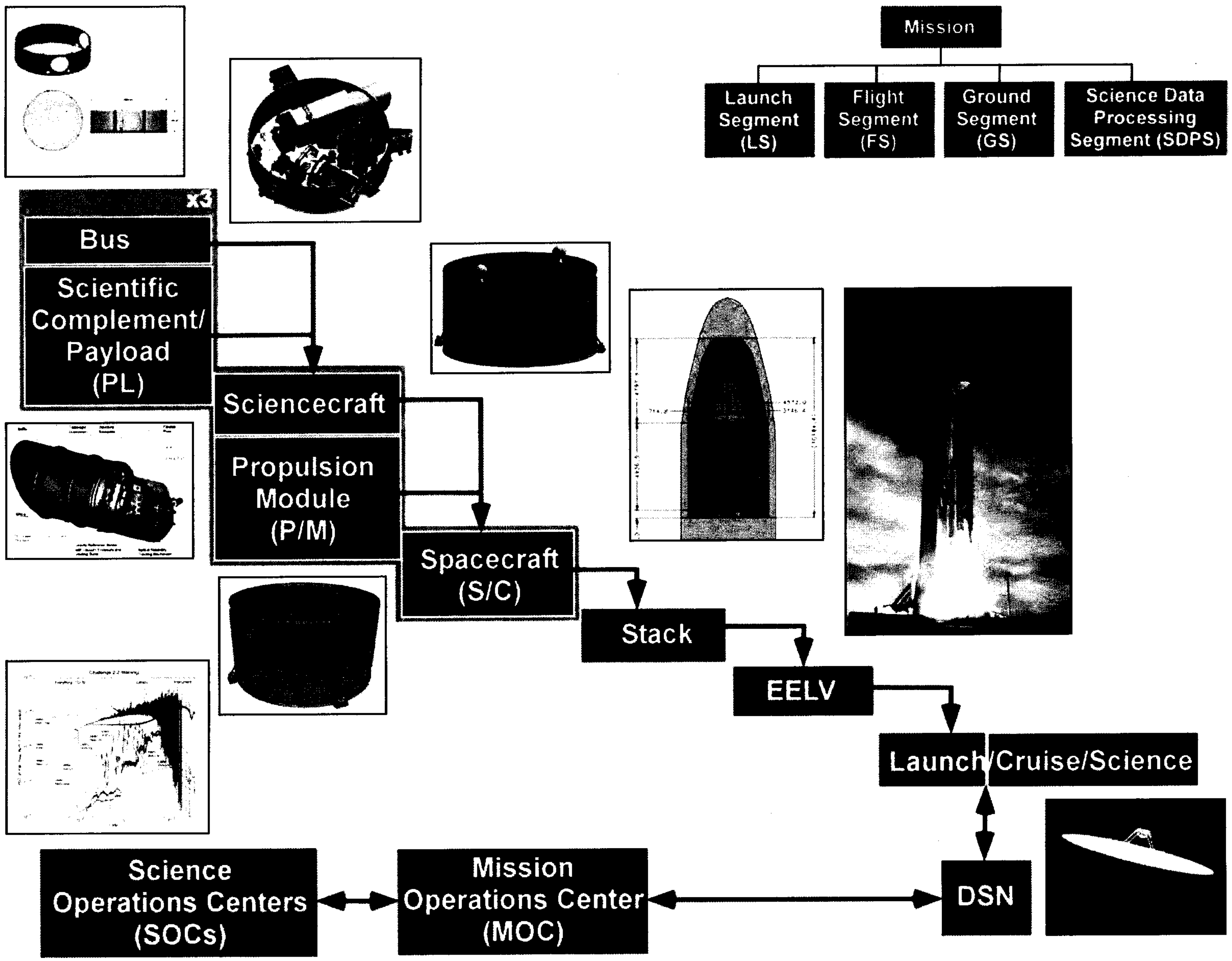
LISA

Backup Slides

NASA

esa

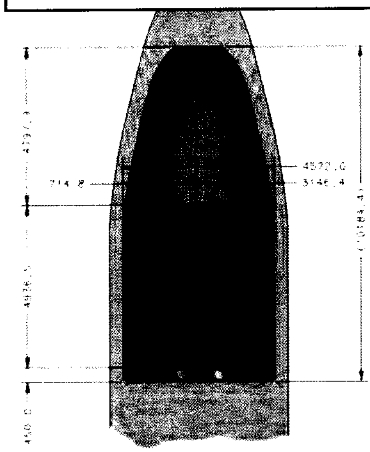
Mission Elements and Integration



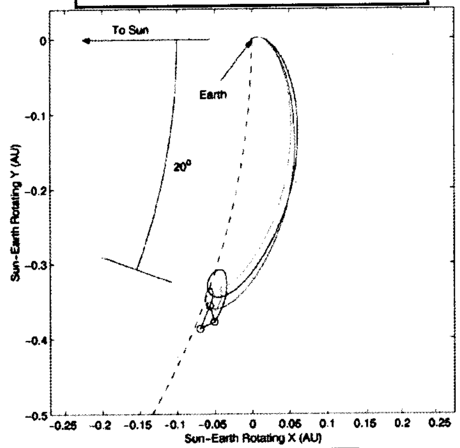
Mission Design

Atlas 531 EELV

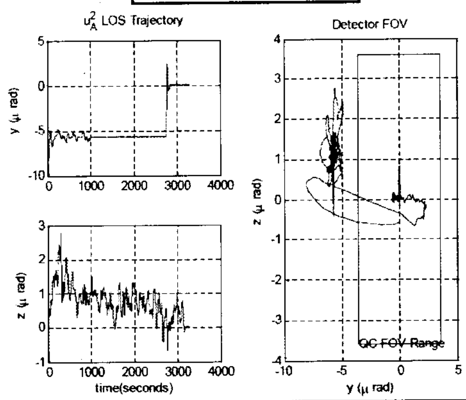
Stack in Atlas 5 m PLF



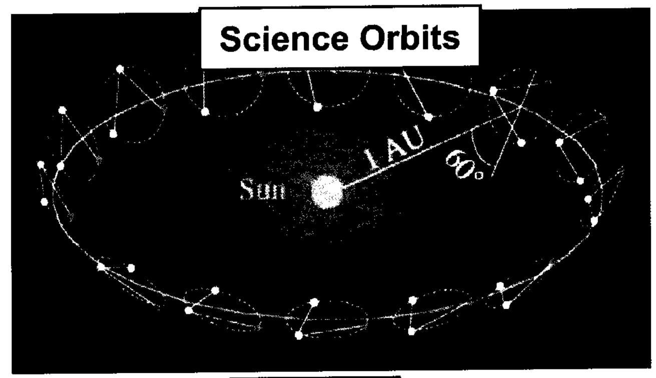
Cruise Trajectories



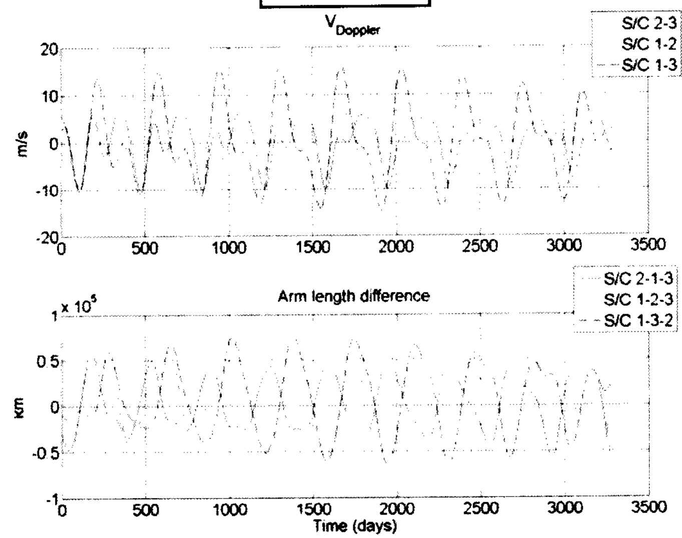
Acquisition



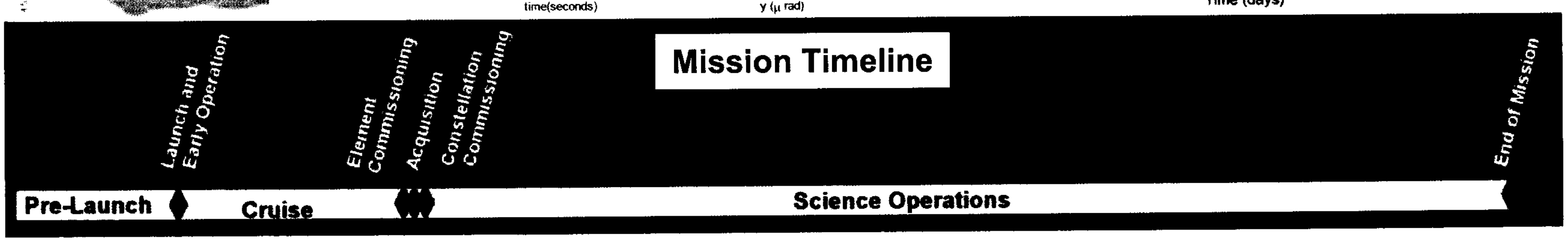
Science Orbits



Doppler

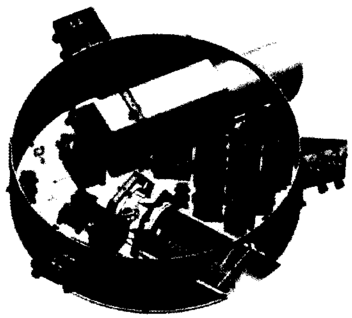


Mission Timeline

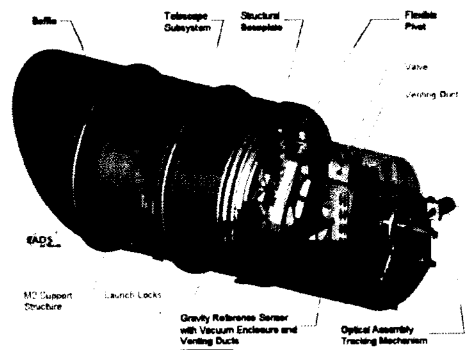


Science Complement (i.e. Payload)

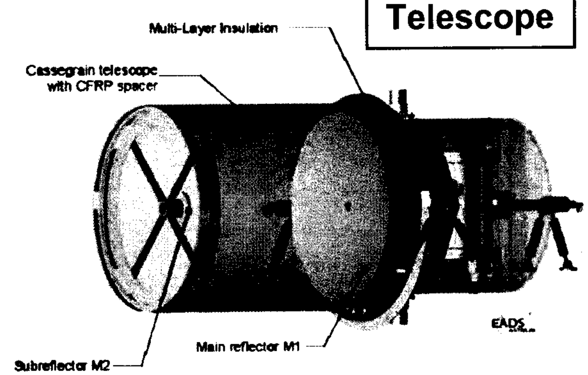
Layout in Bus

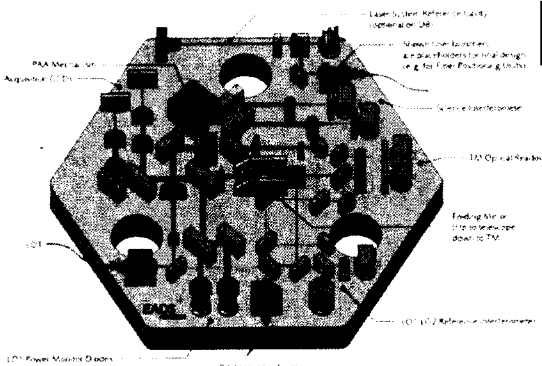


Optical Assembly

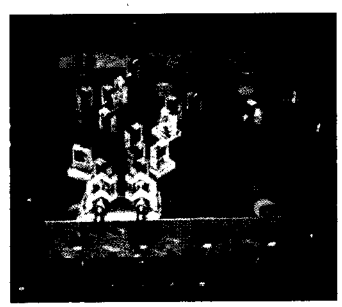


Telescope

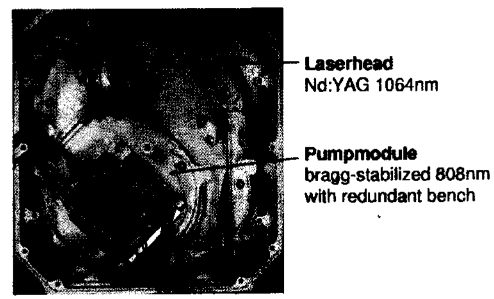




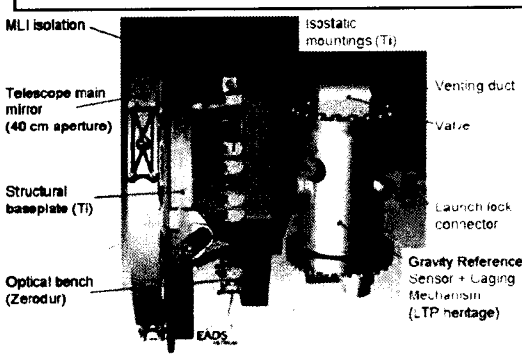
Optical Bench



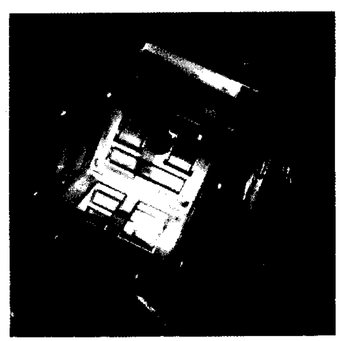
Laser



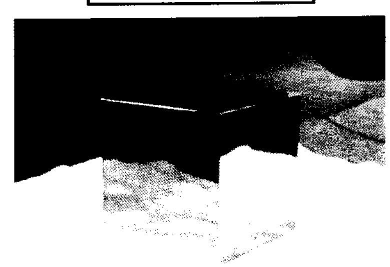
GRS-Optical Bench Assembly



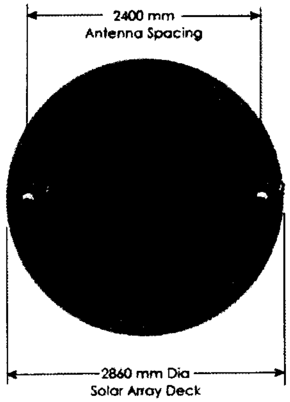
Proof Mass Housing

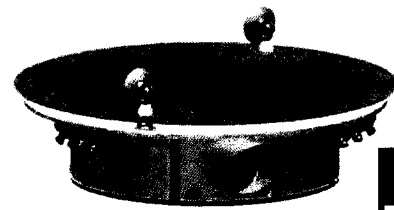


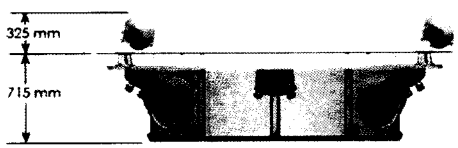
Proof Mass

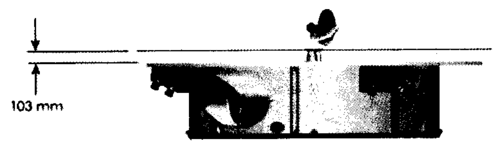


Bus – "Designed around the Science Complement"

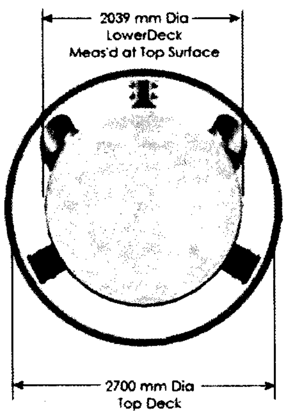


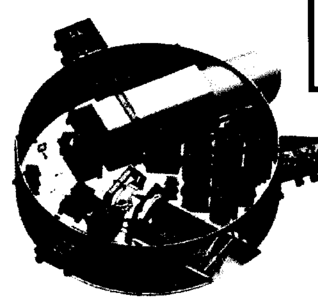






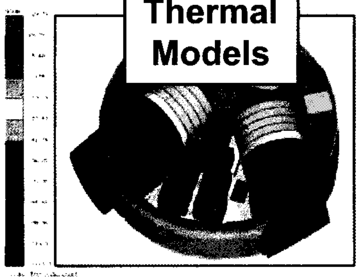
Propulsion	▪µN thrusters
ACS	▪Star Trackers ▪Sun Sensors ▪Gyros
Comm.	▪2 Ka-Band HGAs ▪4 X-Band Omni LGAs
C&DH	▪Flight Proven CPU ▪Standard Serial Bus
Thermal	▪Passive Design
Power	▪Triple junction GaAs fixed SA ▪Li-Ion Battery
Structures and Mechanisms	▪Aluminum Honeycomb Composite ▪2 mechanisms

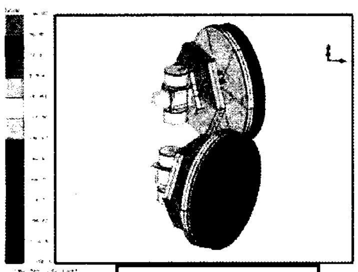




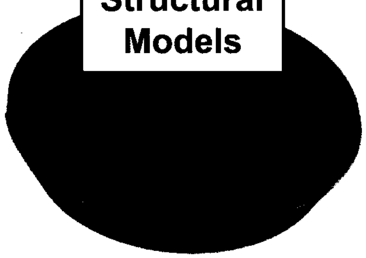
Sciencecraft

Thermal Models

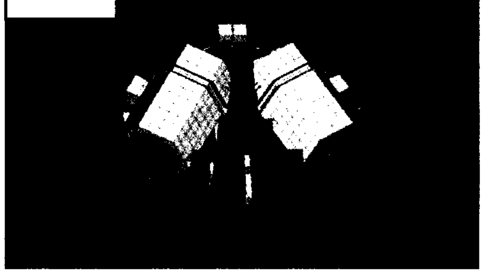




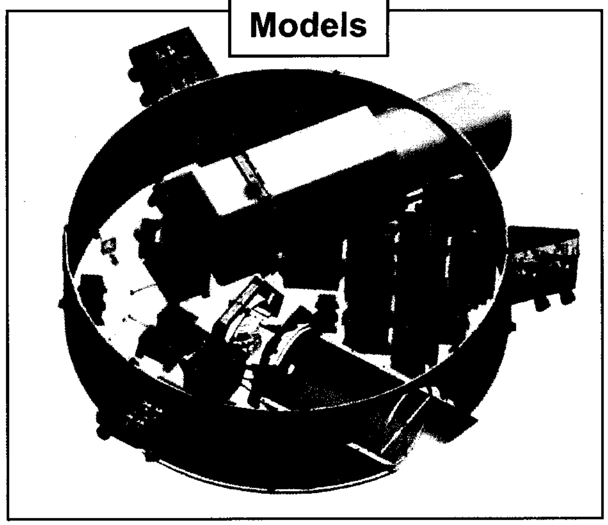
Structural Models



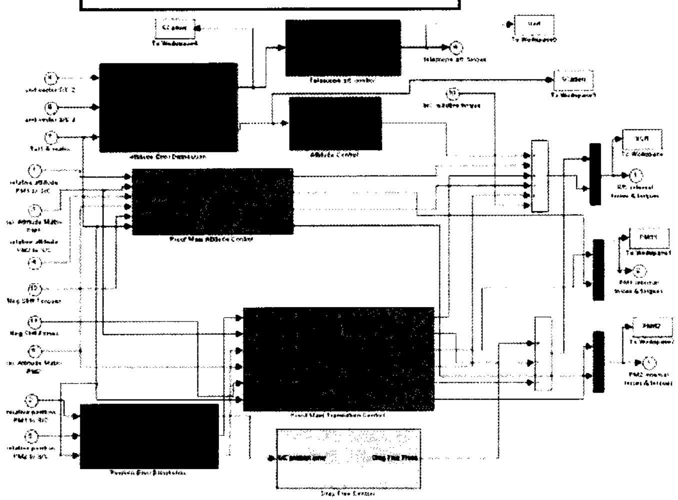
FEM



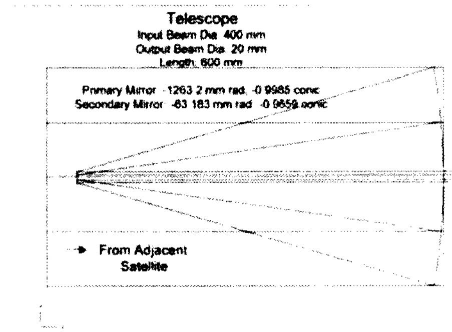
CAD Models



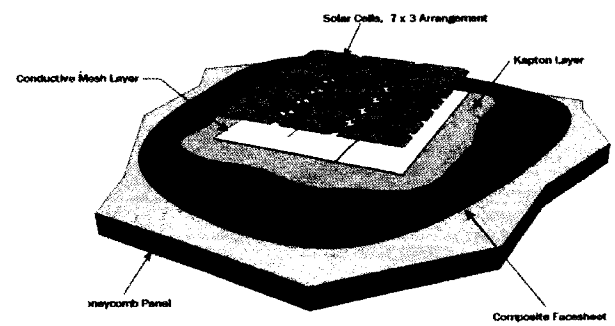
Simulink®/Stateflow® DRS Controls Model



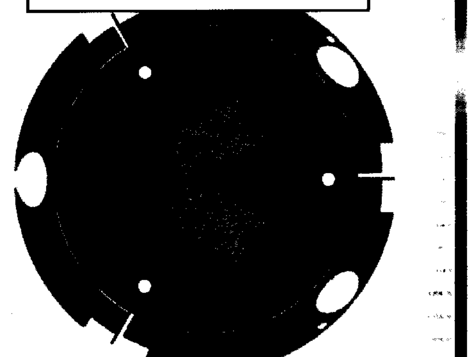
Optics Models



SA Assembly Magnetics

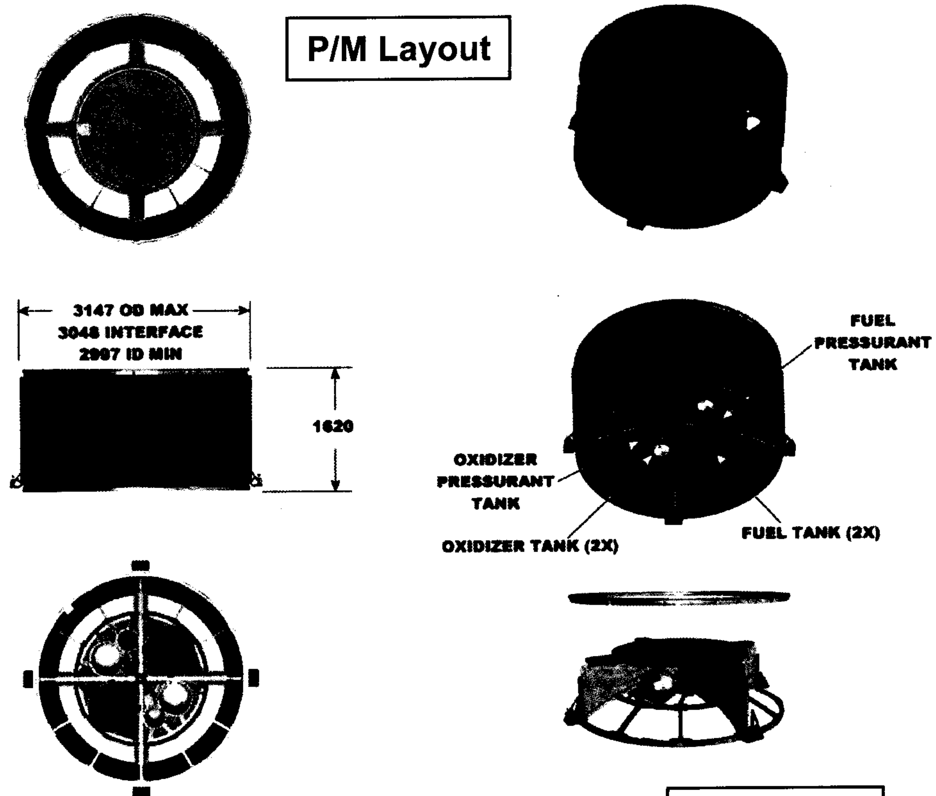


Self Gravity Model

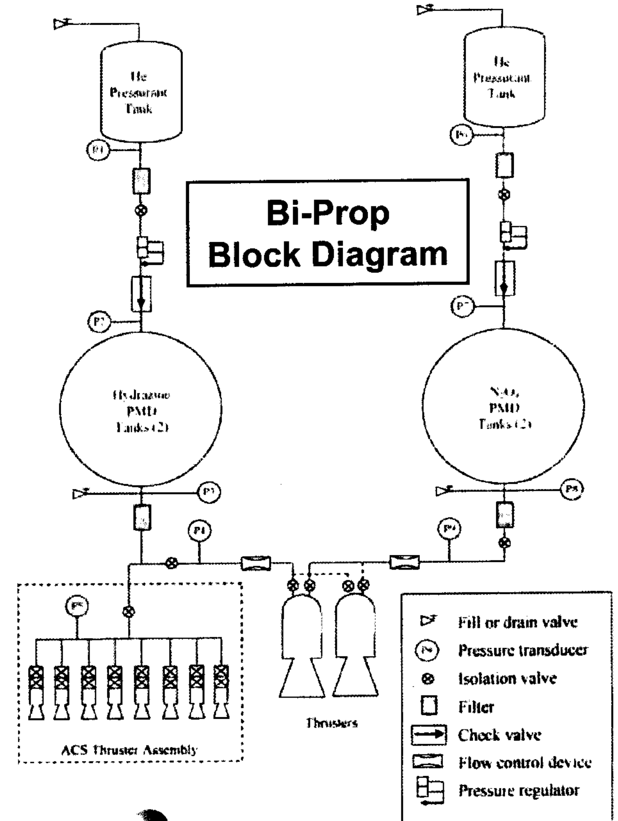


Propulsion Module (P/M) / Spacecraft (S/C)

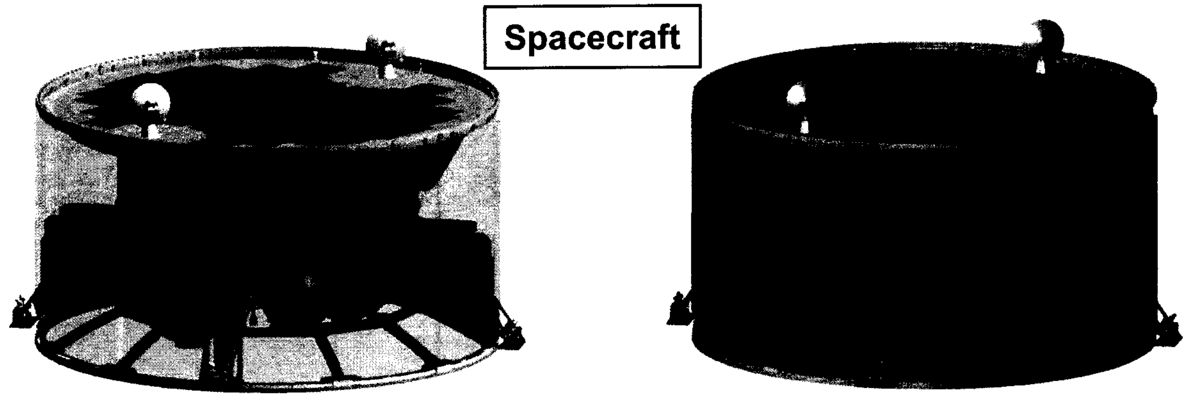
P/M Layout



Bi-Prop Block Diagram



Spacecraft



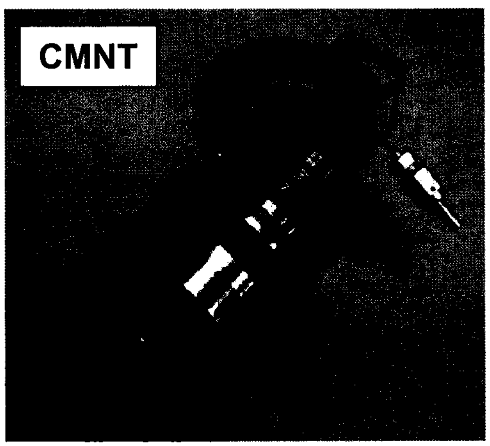
Operations / Science Data

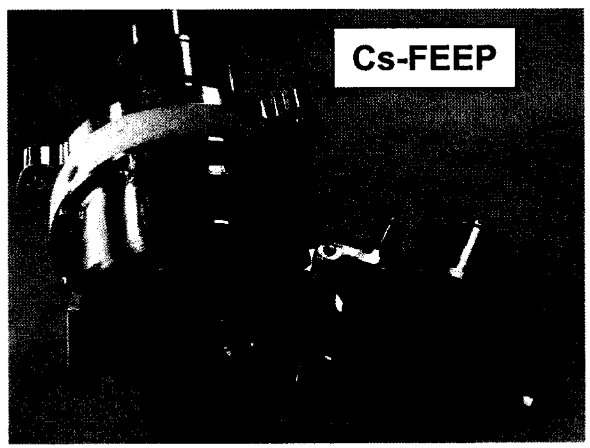
- ***Simple Operations***
  - No instrument pointing or scheduling of observation time
  - LISA observes "all the sky, all the time"
    - Scheduled interruptions approximately every 2 weeks for HGA re-pointing and to switch laser offset frequencies
- ***Routine Communications Strategy***
  - Ka-Band downlink every 2 days with one spacecraft (6 days for the constellation)
  - Up to 8-hr contacts with DSN 34m at 90 kbps (allows downlink of 6 days telemetry generated at 5 kbps)
- ***Science Data***
  - **No on-board science processing**
  - Mission Ops Team (at JPL) will send science data, science housekeeping, and engineering data to Science Data Centers in U.S. and Europe (where performance and data quality is assessed)

Note: Observation of special merger events may require more frequent contact (2 weeks advance notice)

Technologies – μN Thrusters

- ***Three different thrusters under development -***
  - Busek Co. Colloid Micro-Newton Thruster (CMNT), ARC Seibersdorf indium needle Field Emission Electric Propulsion (FEEP) and ALTA S.p.A cesium slit FEEP
- ***Engineering models for all three types have met performance requirements***
- ***Lifetime demonstration is the major remaining task***
  - > 50,000 hours of operation with multiple thruster units and 3000-hour class long-duration tests over the past 3 years
  - Full EM-level life tests completed for all 3 Pathfinder candidates up to 3400 hours

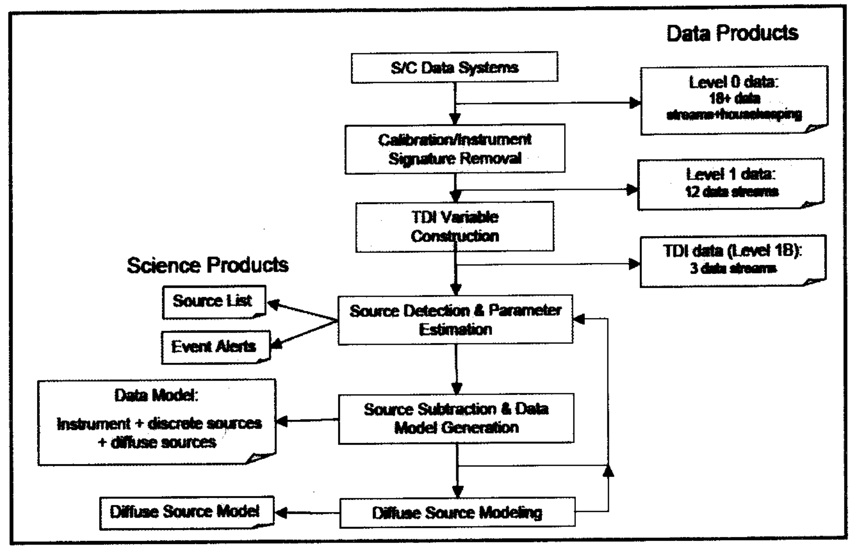


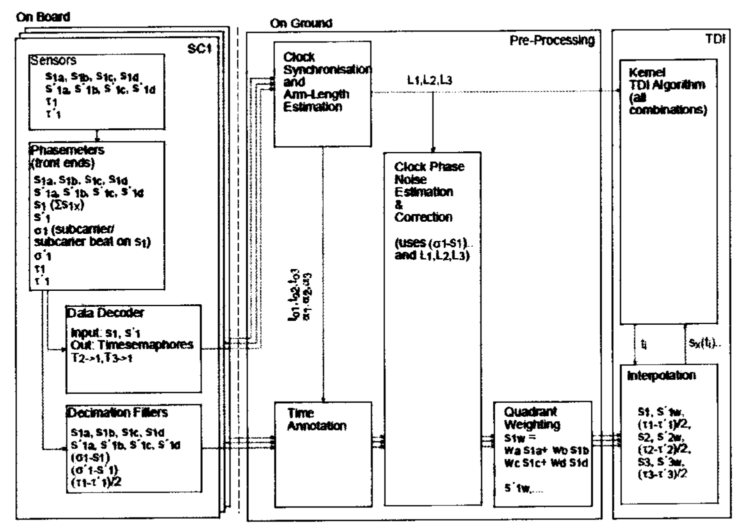


Data Analysis

- ***On-board***
  - *Sensor and clock information processed by phase meter*
- ***Telemetry***
  - *Decimated phase meter and timing data sent to ground*
- ***On-ground***
  - *Calibration of data via clock synchronization, arm-length estimation, and clock phase noise correction*
  - *Formation of interferometric combinations (TDI variables)*
  - *Detection of sources, parameter determination and source subtraction/regression*
  - *Construction of data model: instrument + sources*
- ***Science Products***
  - *Source catalog*
  - *Event alerts*
  - *Data model*
  - *Diffuse source model*

LISA Data Flow





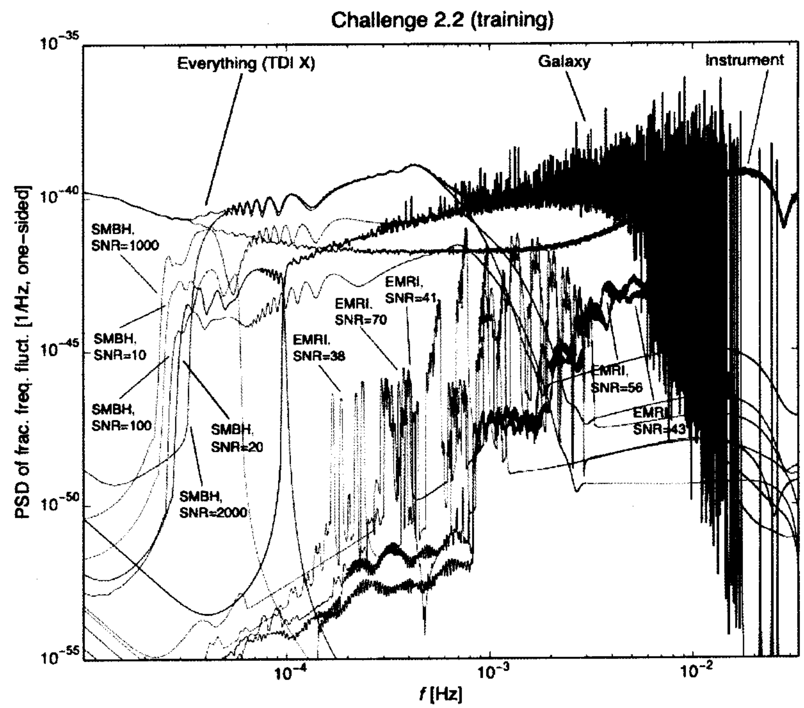
Data Analysis Methods

- ***Time-Delay Interferometry (TDI)***
  - *Basic technique for forming Level 1B science data*
    - *3 interferometric data streams (X,Y,Z interferometers created from 3 pairs of LISA arms)*
  - *TDI is well-understood, well-documented, and accurately simulated*
    - *Extensive published literature*
    - *High-fidelity "Synthetic LISA" simulator*
    - *Validated with ground hardware tests*
- ***Source detection and parameter estimation***
  - *Significant heritage from operating ground-based gravitational wave detectors, particularly for massive black hole inspiral events*
  - *Relies on implementation of well-known techniques*
    - *Template matching, optimal filtering, Markov Chain Monte Carlo (MCMC) methods*
  - *Validated via "Mock LISA Data Challenges"*
    - *Synthesized data streams with increasing level of complexity and realism*
    - *Participating groups test algorithms and software*
    - *Round 1 completed*
    - *Round 2 will validate algorithms on a high-fidelity LISA data stream (see accompanying slide)*
  - *Diffuse source characterization requires further development*

LISA Data Analysis

LISA Data Analysis is being validated with sophisticated high fidelity simulations

- ***Planning and implementation have been underway since 2005***
- ***"Mock LISA Data Challenges" provide testbed***
- ***Round 1 completed***
  - *Report published* *
- ***Round 2 is in progress and will test the full LISA data stream***
  - *All classes of LISA sources + instrumental background (see figure)*
  - *Results of round 2 challenge due in June 2007*



Training data for the ongoing round of data challenges (to be completed in June 2007). The simulated data stream is a high-fidelity representation of the full LISA data set containing instrumental noise plus 4 massive black hole events, 5 EMRI events, and 26.1 million Galactic binaries.

* http://www.tapir.caltech.edu/dowiki/listwg1b:home & http://astrogravs.nasa.gov/docs/mldc

LISA International Science Team

- **European Members**

  Karsten Danzmann, MPI for Gravitationsphysik (Albert-Einstein-Institut) and U. Hannover, Co-Chair, ESA Mission Scientist

  Oliver Jennrich, ESTEC, ESA Project Scientist

  Pierre Binetruy, APC - College de France

  Massimo Cerdonio, U. of Padova

  Michael Cruise, U. of Birmingham

  Jim Hough, Glasgow University

  Philippe Jetzer, U. of Zurich

  Alberto Lobo, U. de Barcelona

  Yannick Mellier, Institut d'Astrophysique

  Bernard Schutz, MPI for Gravitationsphysik (Albert-Einstein-Institut)

  Tim Sumner, Imperial College

  Jean-Yves Vinet, Observatoire Cote d'Azur

  Stefano Vitale, U. Trento

- ***US Members***

  Tom Prince, Caltech/JPL, Co-Chair, NASA Mission Scientist

  Robin Stebbins, GSFC, NASA Project Scientist

  Peter Bender, U. of Colorado

  Sasha Buchman, Stanford U.

  Joan Centrella, GSFC

  Neil Cornish, Montana State U

  Lee Samuel Finn, Penn State U.

  Jens Gundlach, U. of Washington

  Craig Hogan, U. of Washington

  Scott Hughes, MIT

  Piero Madau, UC Lick Observatory

  Sterl Phinney, Caltech

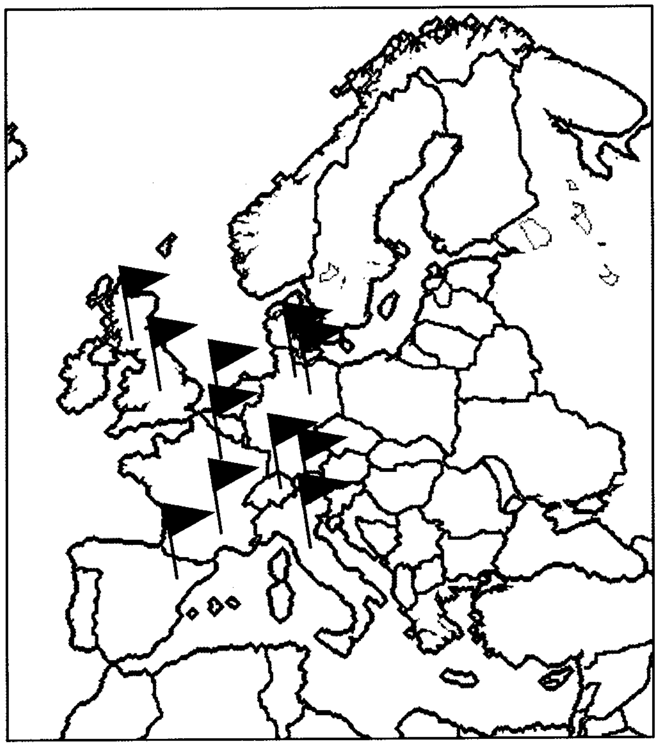
  Doug Richstone, U. Michigan

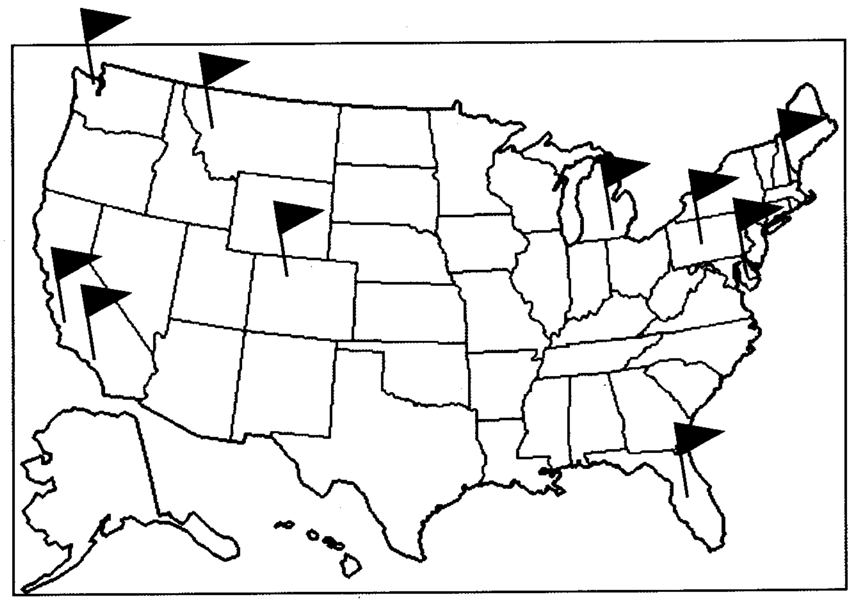
  Kip Thorne, Caltech

www.LISAscience.org
LISC
the LISA International Science Community

In addition, the *LISA International Science Community* has a membership of 240 scientists from 104 international institutions

LISA International Science Team





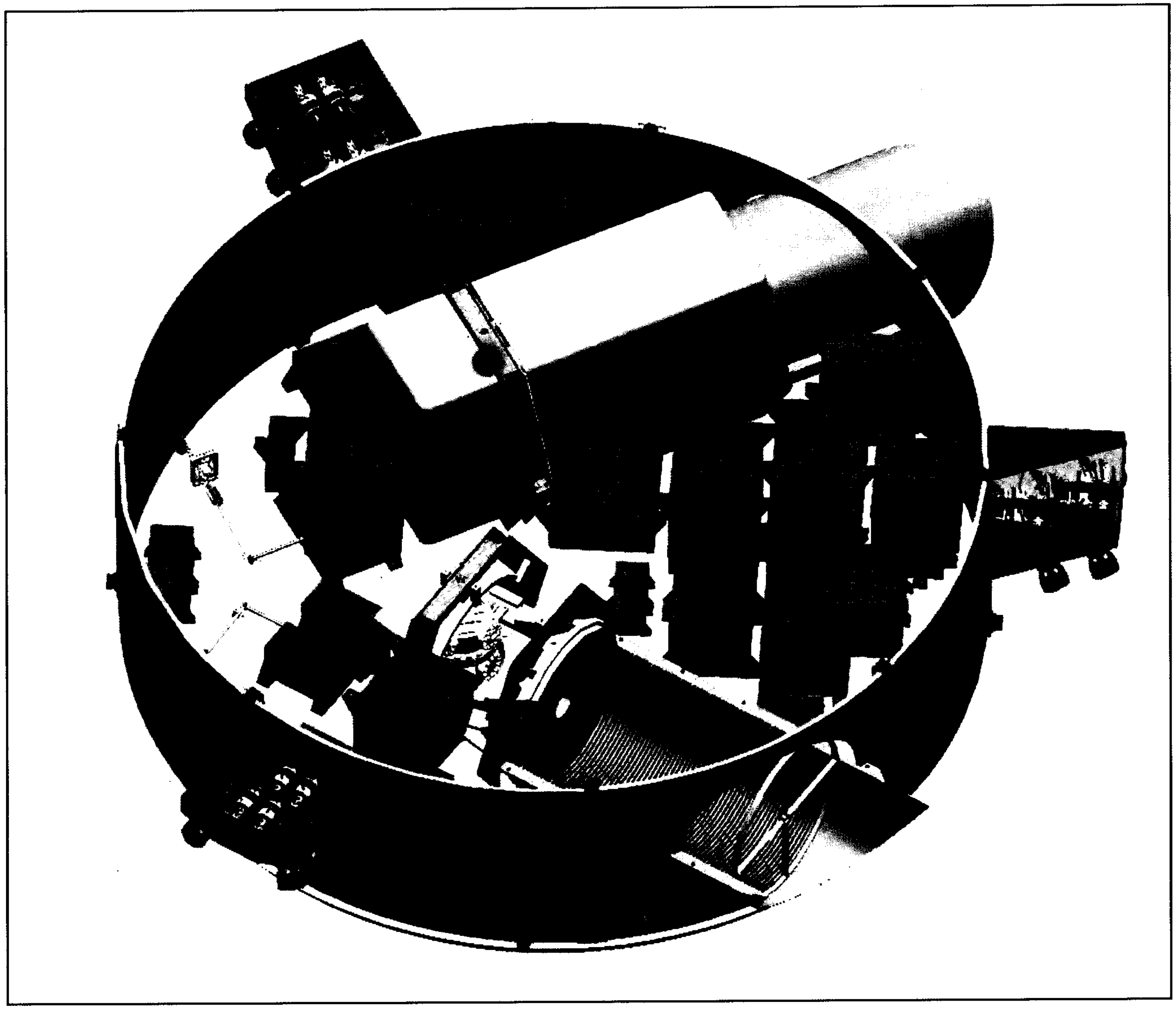
LISA Community Activity

- ***6th International LISA symposium in June 2006 show-cased many impressive and exciting developments***
- ***Significant efforts in data analysis community over last 1.5 years***
  - *Mock LISA Data Challenges*
  - *Results presented at 11th Gravitational Wave Data Analysis Worskhop (December 2006)*
- ***LISA International Science Community (LISC)***
  - *Over 250 members from more than 100 institutions*
  - *www.lisa-science.org*
- ***Large number of publications***

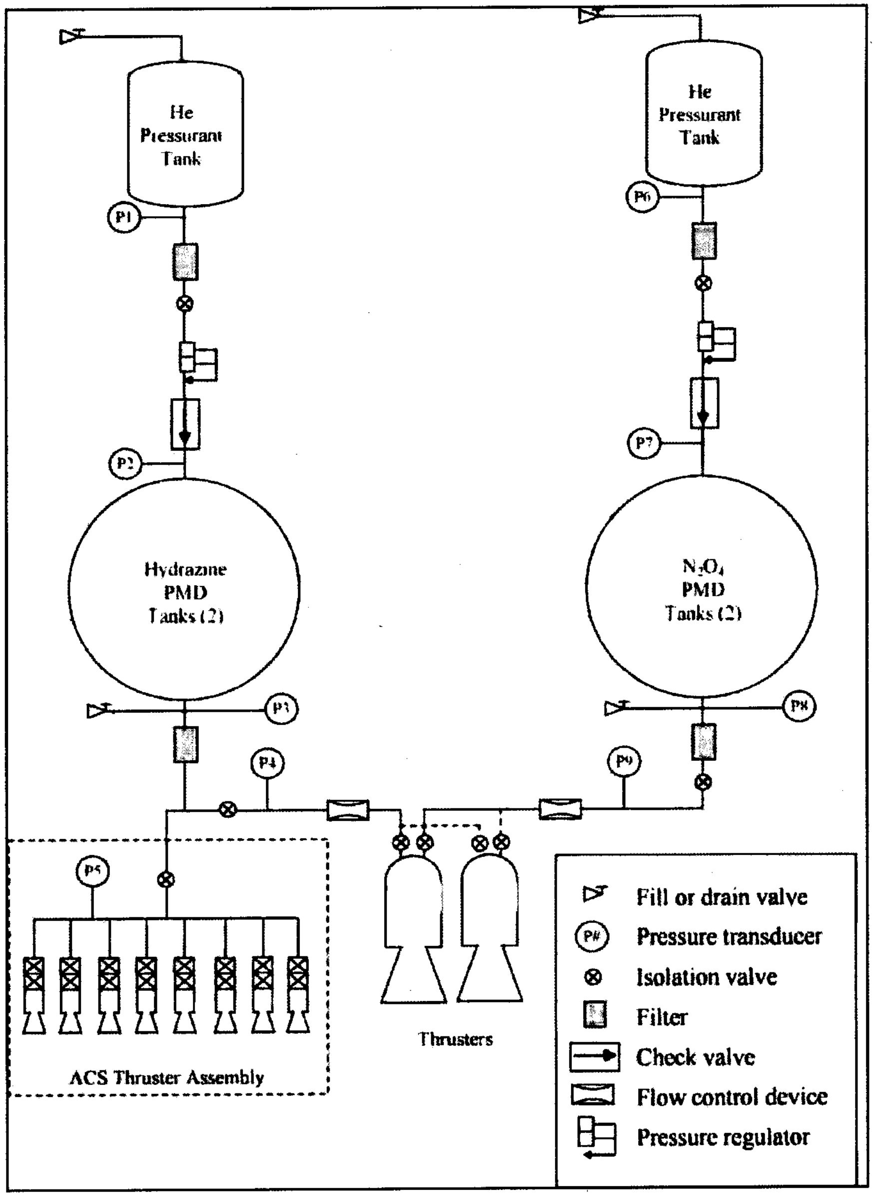
Subsystem Summary

Subsystem	*Attributes*	*Performance*	*Margin*
Propulsion	•Bi-Prop Propulsion Module (P/M) for Cruise Phase	•1169 ΔV (worst case launch date) •474 kg. propellant per P/M	•30% dry mass, with 3-sigma maneuver dispersions
	•μN Thrusters for Drag-Free Control during Science Phase	•Thrust Range 4-150 μN •Precision 0.05 μN	•Thrust Max 400% •Precision 50%
Attitude Control System	•2 Star Trackers •3 Sun Sensors •2 Sets of Gyros •DRS Control Laws	•1 arcsec RMS 3-sigma, only required during acquisition	**hardware from multiple vendors can provide performance in excess of required*
Communications	•2 Ka-Band HGAs •4 X-Band Omni LGAs •2 25W TWTAs	•90 kbps Downlink •2 kbps Uplink	•3 dB Ka-Band •14 dB X-Band
Command and Data Handling	•Flight Proven CPU •Standard Serial Bus	•Adequate processing power, memory, data storage, clock speed •Rad. tolerant, low power	**hardware from multiple vendors can provide performance in excess of required*
Thermal	•Passive Design	•Maintain temps. within acceptable limits	•Modeling effort to date shows temperatures maintained within limits
Power	•Fixed SA, triple junction GaAs •1.04 KWhr Li-Ion Battery	•957W (TBR) @EOL •589W required	•61% (TBR)
Structures and Mechanisms	•Aluminum Honeycomb Composite •2 mechanisms: Heritage Separation Sys, HGA drives	•Launch Loads thru Prop Module	•Minimum launch frequencies met

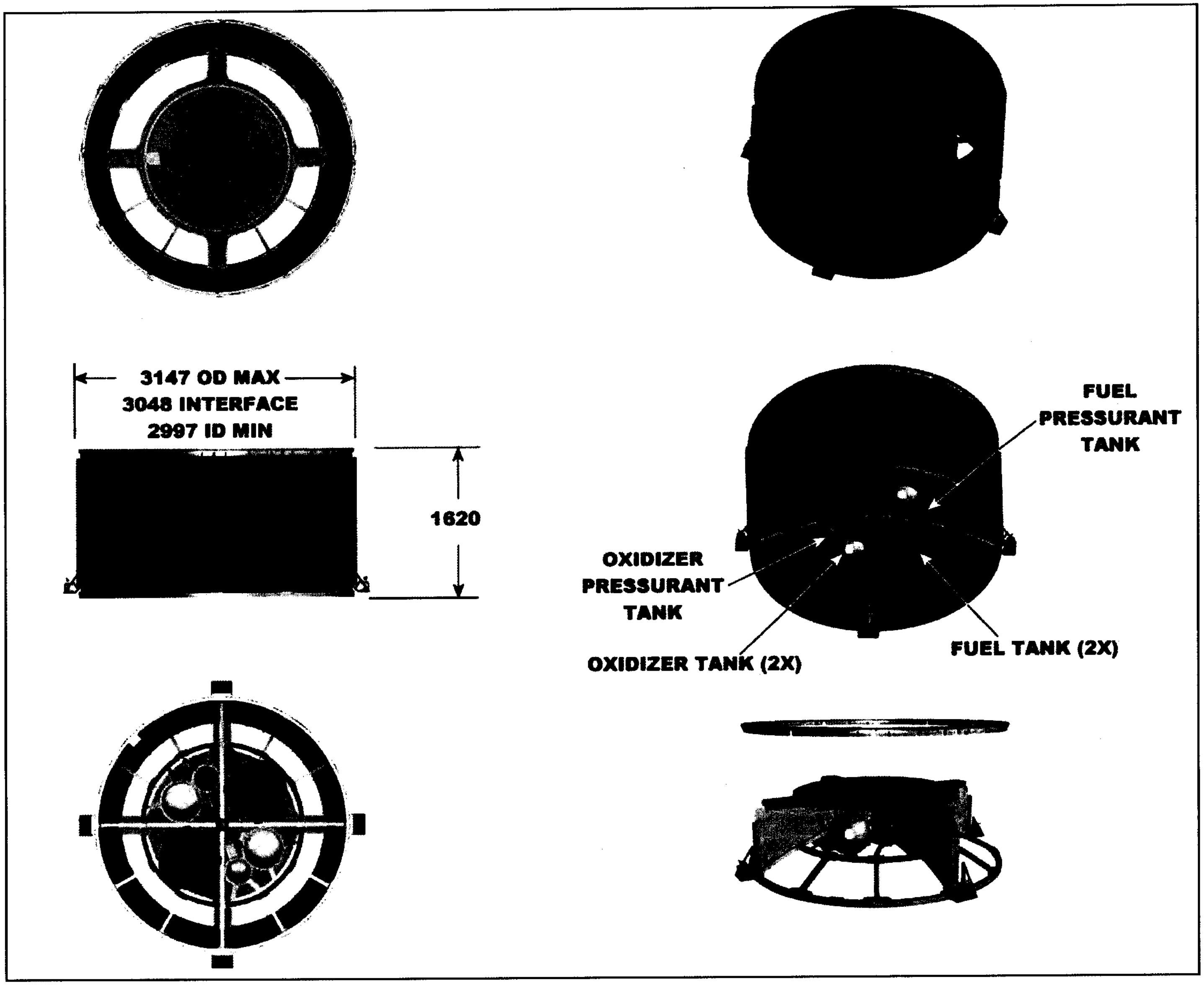
Sciencecraft Layout



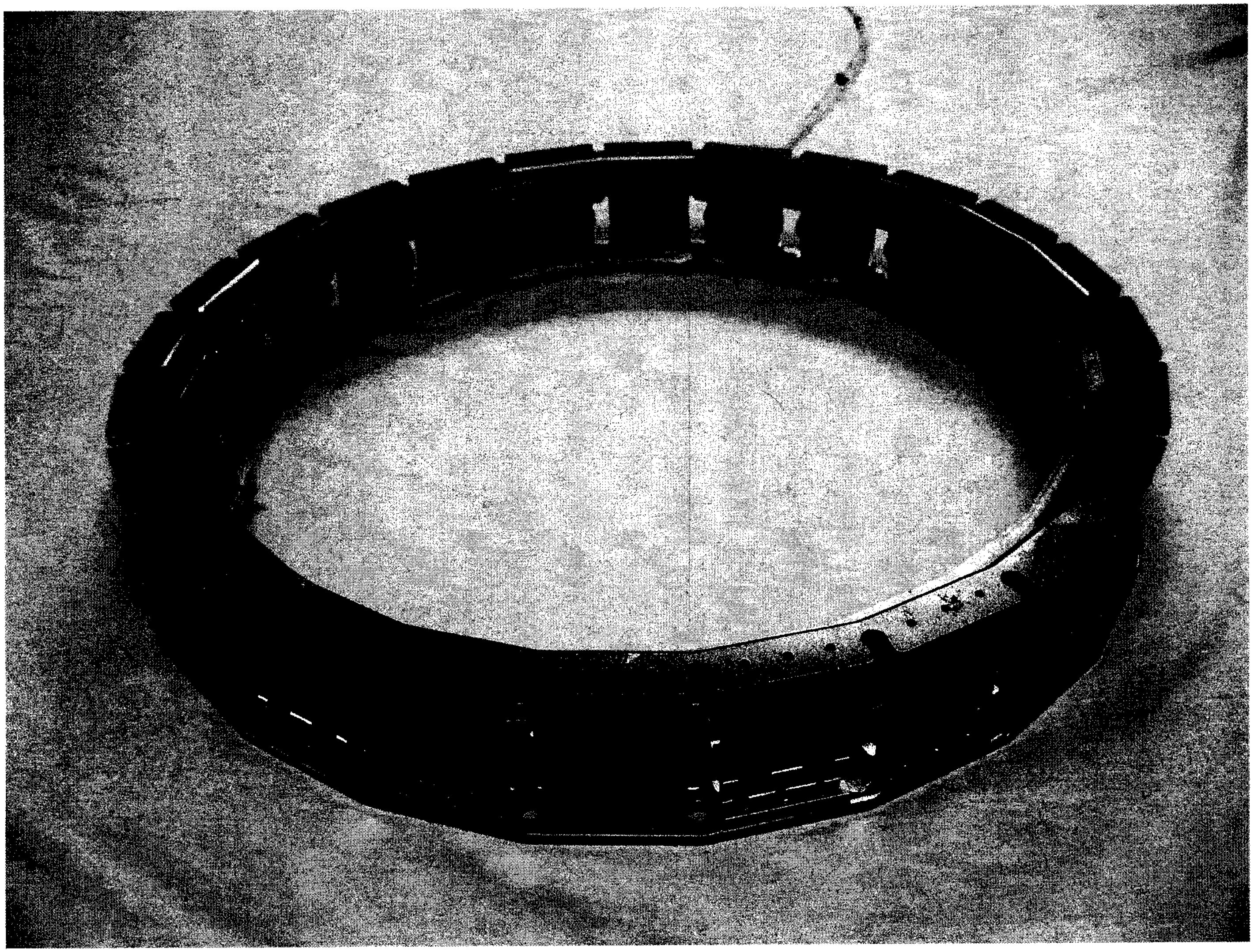
Propulsion Module Bi-Prop Block Diagram



Propulsion Module Layout



Lightband® Separation System



Trade Studies

COMPLETE

- PM-SM Separation
- Phased Array Antenna
- Point Ahead
- Stacking
- Solar Array Attach
- Colloid MicroThrusters
- Strap down
- Optical Readout
- Photodiode Bandwidth
- Science Data
- Telemetry
- E2E Comm
- Dynamics Parameters
- Orbits
- Acquisition
- Getting2Orbit
- [PAA Actuator]
- WFE Impact
- [No Vac]
- Telescope
- Redundancy Philosophy
- [OB layout], fiber positioner, freq swap
- Arm Locking Details

IN-PROCESS

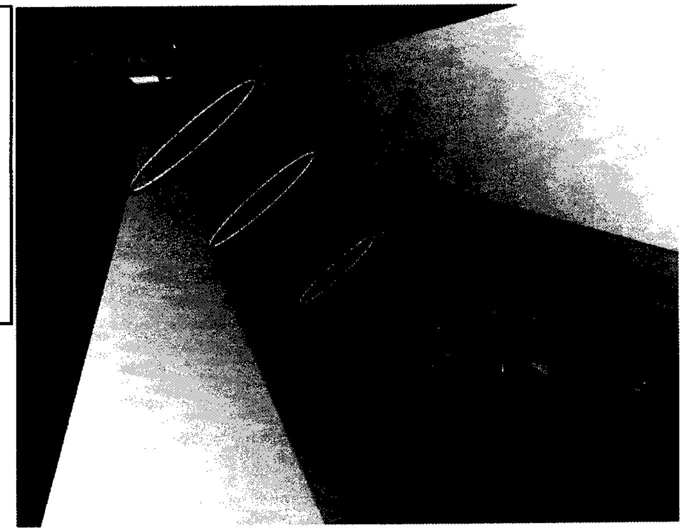
- Pointing (TA) Mechanism
- Thermal
- Frequency Plan
- Avionic Arch
- Magnetic Zones/PM mag reqs
- Ranging/Clock
- Microthruster orientations
- Critical Alignments
- Box layout
- In-field pointing feasibility
- "Simplification" Trades

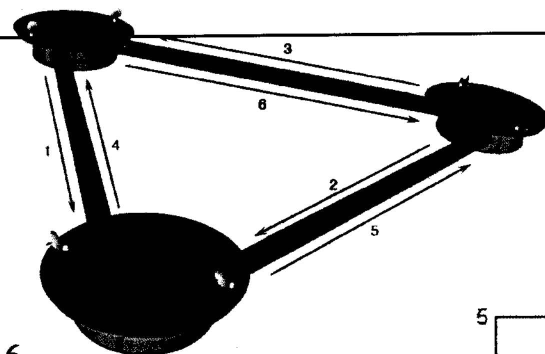
PLANNED

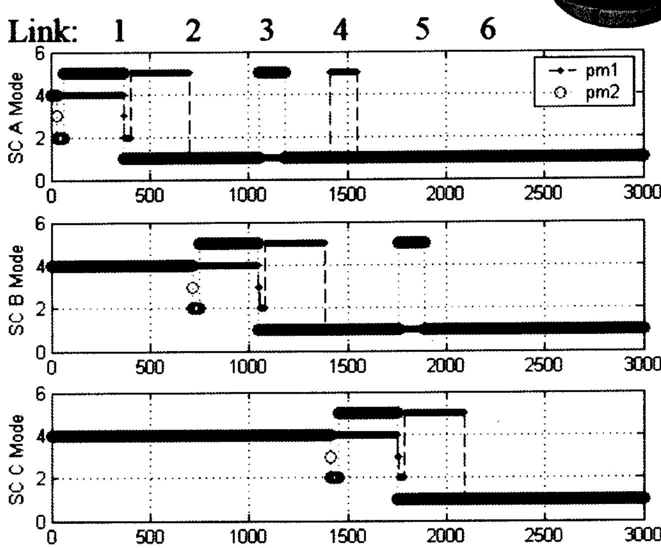
- DRS Cal
- FSW Arch
- Grounding / Power Distribution
- Science Cal
- SafeMode Comm
- Normal Ops Timeline (day, week in life)
- Commisioning Timeline

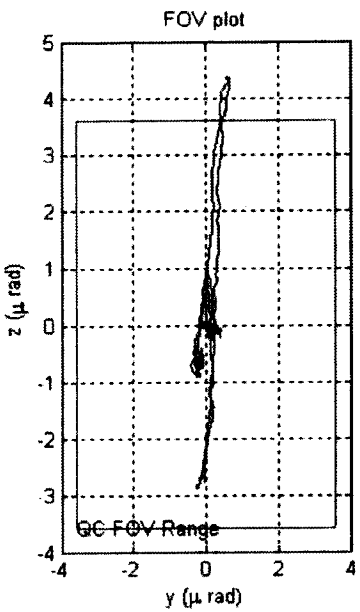
Acquisition

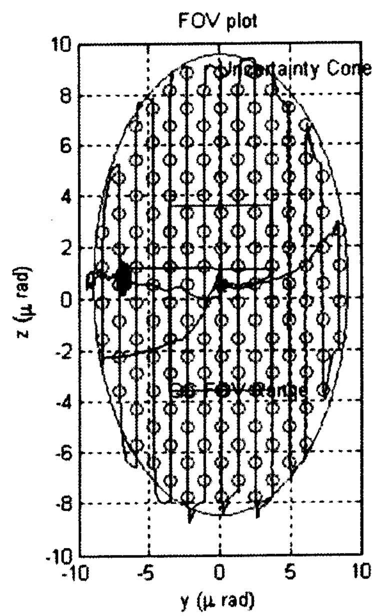
- *Two acquisition strategies are effective: scanning and defocus.*
- *A sequence of sensors with increasing resolution is used. Each sensor has the range to cover accuracy and bias of preceding sensor.*
- *High fidelity simulations show acquisition completes in only 50 minutes for defocus and 8 hours for scanning.*





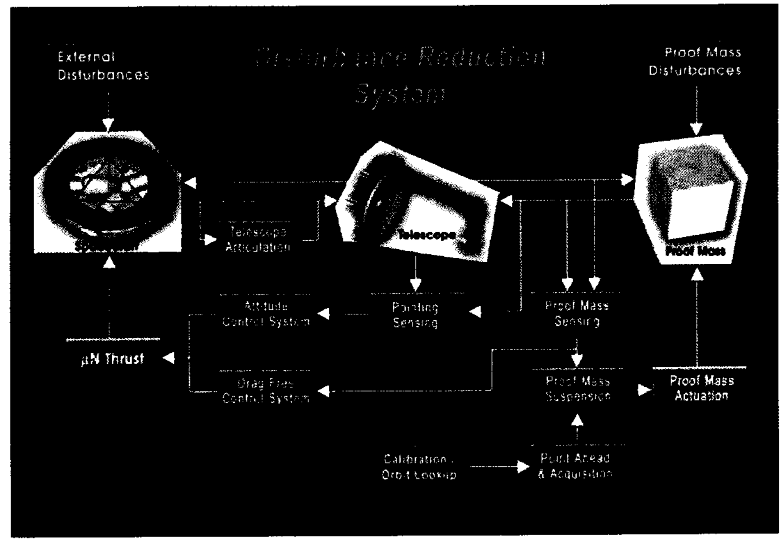


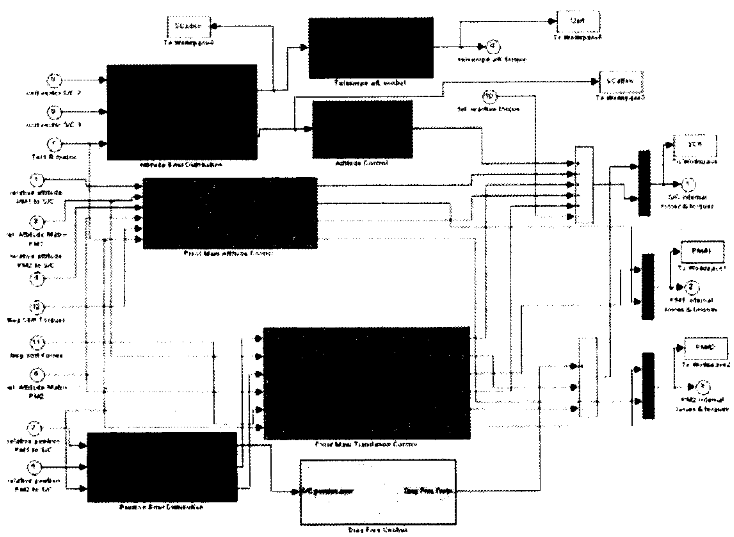


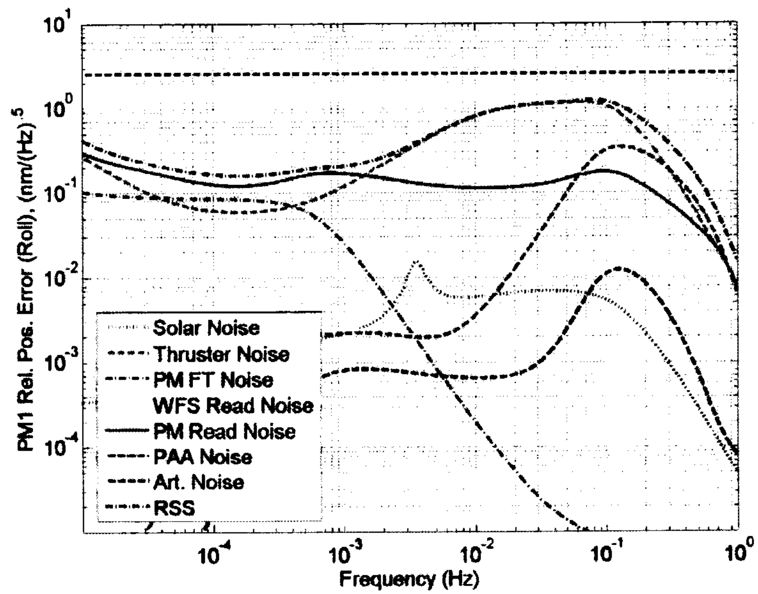


DRS Controls

- ***High fidelity LISA DRS dynamics model (SIMULINK and STATEFLOW):***
  - S/C (6-DOF), two Proof Masses (6-DOF each), and telescope articulation for total of 19-DOF
  - Nonlinear translational and rotational kinematics and dynamics included
  - Realistic sensor and actuator noise included
- ***Preliminary designs completed for all DRS control systems. Analysis shows adequate stability margins.***
- ***Control is straightforward and simulations predicts 0.18 nm/√ Hz @ 0.1 mHz (more than 10x better than requirement).***

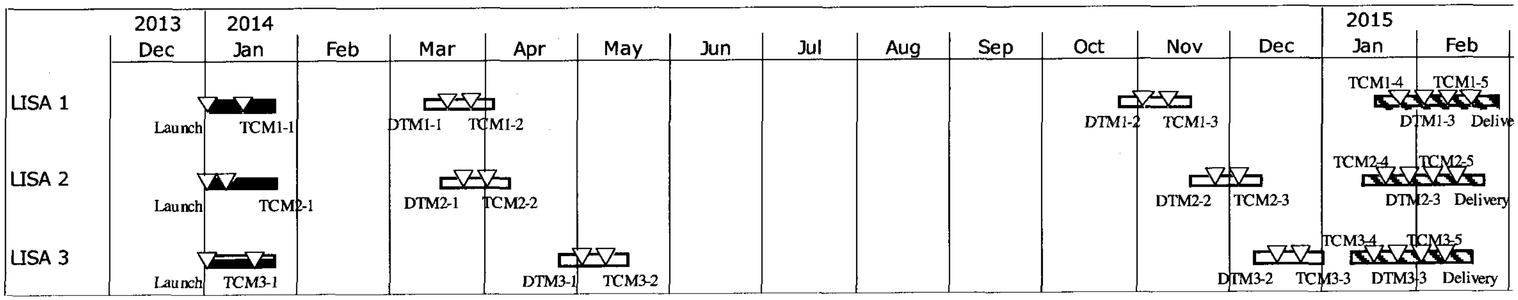






Cruise Phase

Representative Cruise Phase

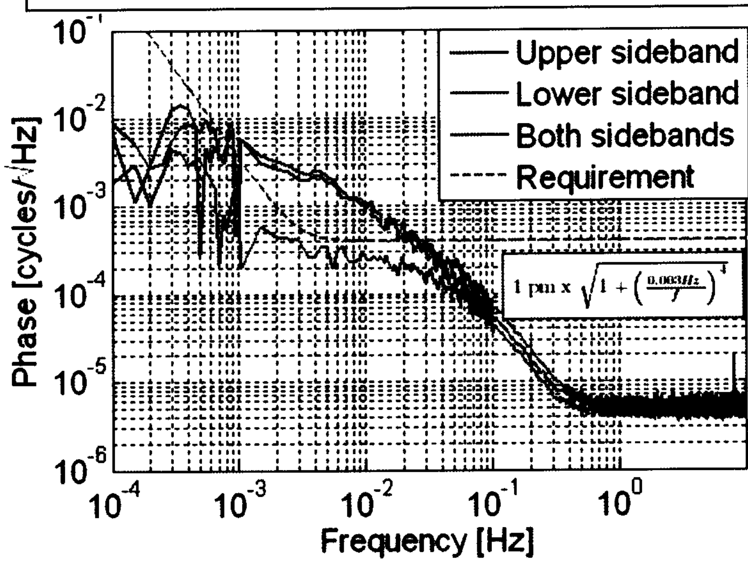


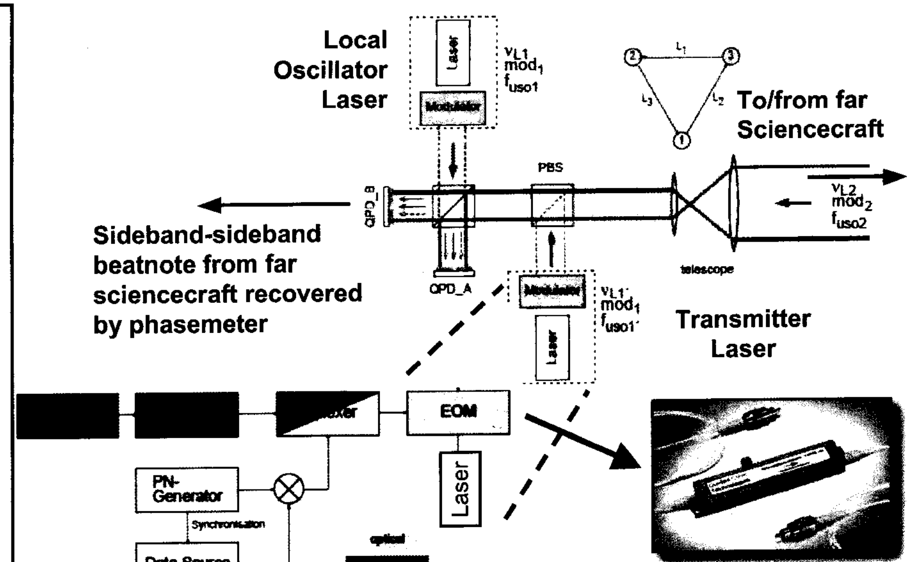
- **The timeline above showing maneuvers and communications modes for the three LISA S/C from launch through delivery to the science operations orbits**
  - Except as noted there would be one four-hour pass per week with each spacecraft
    - full comm. Coverage will be provided for all critical burns
  - Horizontal bars show the time periods when more frequent communications are taking place with a spacecraft
    - filled bar indicates continuous coverage
    - open bar indicates daily passes
    - striped bar indicates daily passes

Inter-Sciencecraft Signaling: Clock noise and ranging

- ***Requirement 1:*** **Clock Noise Transfer(< 50 fs/√ Hz)**
- ***Implementation: clock-coherent side tone***
  - **8 GHz nominal sidetones (~2 MHz offsets in send vs receive)**
  - **1% of power in sidebands**
  - **Sideband-sideband beat detection**
- ***Requirement 2:*** **inter-S/C ranging (25 m)**
- ***Implementation: interspacecraft comm***
  - **1% modulation on main science beam (carrier)**
  - **Manchester encoding (2 Mchips/s)**
  - **13-bit Gold code yields 2 m range accuracy**
  - **~100 bps required (400 kbps capable)**

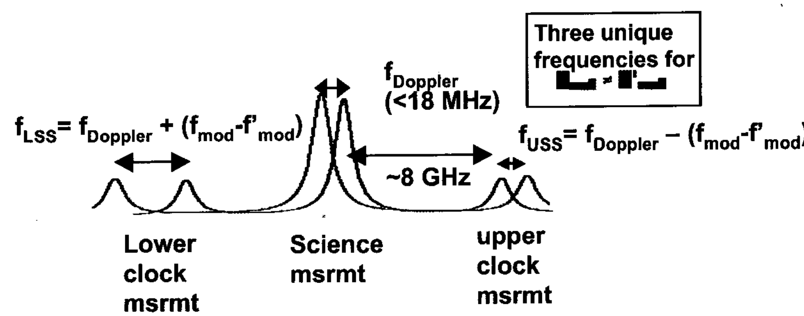
Phase modulator supports clock noise rqmts





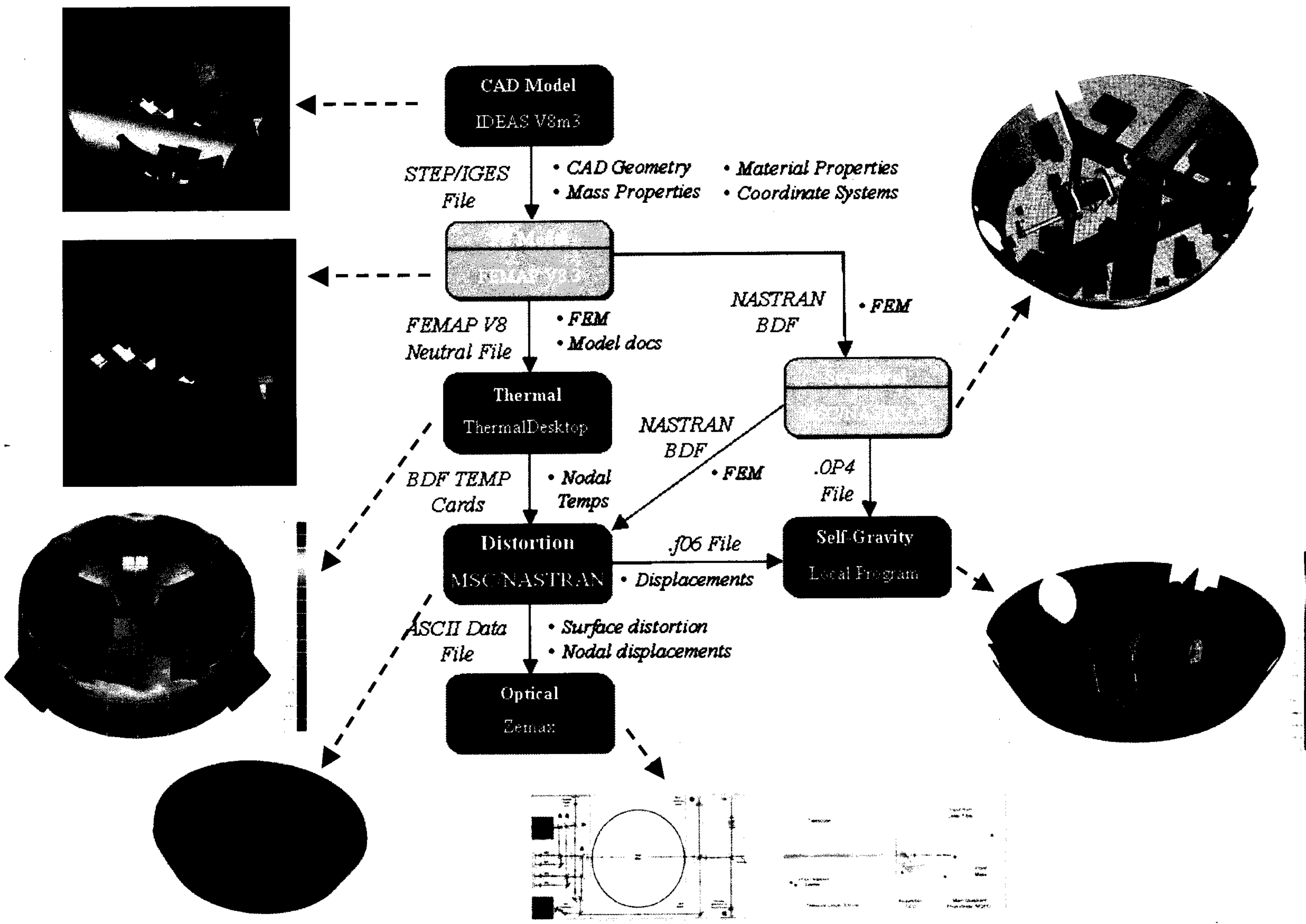
Ultra-stable oscillator (USO) modulated onto main science beam

Fiber-coupled electro-optic modulator (EOM)



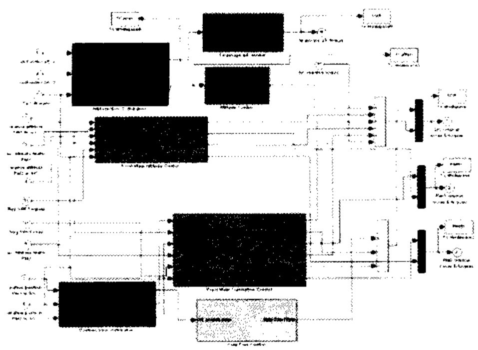
Using sideband-sideband beatnotes (instead of carrier-sideband) allows high modulation frequency and low photoreceiver BW

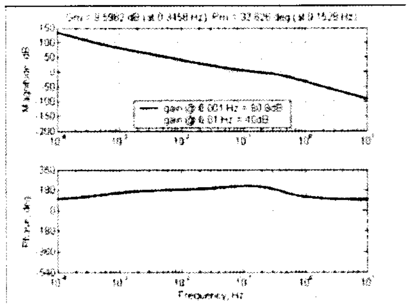
Integrated Modeling: Quasi-Static

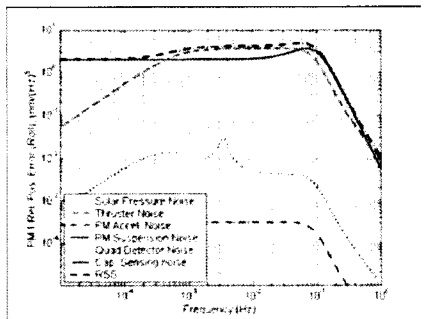


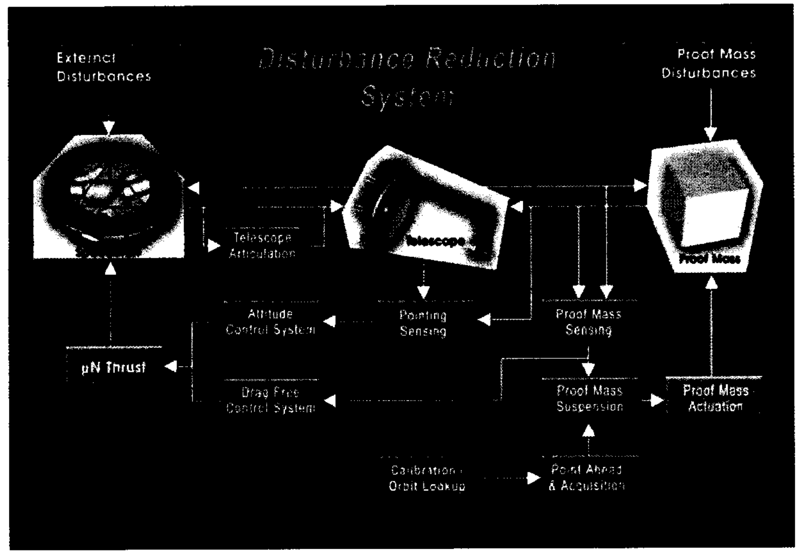
Integrated Modeling: Dynamic

Controls

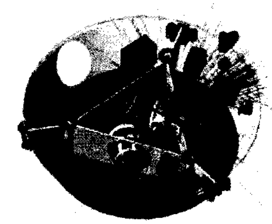








Proof Mass Charging



Acquisition Simulation