Sixth International LISA Symposium

June 19-23, 2006

Goddard Space Flight Center
Greenbelt, Maryland

Program and Abstracts

PROGRAM

Monday, June 19, 2006 — **Tutorial and Overview**

Pre-Program

8:30	Tuck Stebbins	LISA Mission Tutorial
9:15	Scott Hughes	Astrophysics Tutorial
10:00	Alberto Vecchio	Data Analysis Tutorial
10:45	Break	

Opening Session

11:00	Colleen Hartman	Symposium Opening Speaker
11:20	Roger Blandford	Astronomy/observations in the LISA Timeframe
12:10	Clifford Will	Fundamental Gravitational Physics in the LISA Timeframe
13:00	Lunch	
14:30	Sterl Phinney	LISA science
15:20	Karsten Danzmann	Status/overview of LISA
16:10	Break	
16:25	Peter Saulson	Status/overview of ground based GW detectors
17:15	Paul McNamara	Status/overview of LPF
18:05	Adjourn	

Tuesday, June 20, 2006 — **Central Massive Black Holes, Cosmological Implications, and the Very Low End of the LISA Sensitivity Band**

9:00	Marta Volonteri	Supermassive black hole mergers and cosmological structure formation
9:40	Steinn Sigurdsson	Dynamics of supermassive black holes
10:20	Break	
10:50	Stephen Merkowitz	Achieving the very low end of the LISA sensitivity band
11:30	Joan Centrella	Numerical relativity, waveforms of comparable-mass BH mergers
12:10	Lunch	
13:40	Alessandra Buonanno	Data analysis and source modeling of central massive black holes

Astrophysics and Analysis Talks

14:20	Emanuele Berti	Black hole spectroscopy with LISA
14:40	Manuela Campaneli	Gravitational radiation from spinning-black-hole binaries
15:00	Frank Herrmann	Binary Black Hole Simulations
15:20	Break	

Low-Frequency DRS and LPF Talks

15:50	William Joseph Weber	Free-fall and LISA sensitivity below 0.1 mHz
16:10	Peter Bender	Proof Mass Accelerations And Optical Path Length Changes Due To Temperature Fluctuations
16:30	Mauro Hueller	Torsion pendulum investigation of thermal gradient-induced forces on LISA test masses
16:50	Stephan Schlamminger	A sensitive torsion balance for LISA proof mass modeling
17:10	Scott Pollack	Outgassing, Temperature Gradients & the Radiometer Effect in LISA: A Torsion Pendulum Investigation
17:30	Markus Schulte	Charge Management for Lisa Pathfinder and development for LISA
17:50	Diana Shaul	Solar, cosmic ray and environmental physics for, and with, LISA
18:10	Adjourn	
19:00	Banquette	

Wednesday, June 21, 2006 — **Dynamics Around a Central Black Hole and the Mid-High End of the LISA Sensitivity Band**

9:00	Scott Hughes	Testing general relativity with extreme-mass ratio inspirals
9:40	Clovis Hopman	Astrophysics of extreme-mass ratio inspirals
10:20	Break	
10:50	Gerhard Heinzel	Achieving the mid-high end of the LISA sensitivity band with the LISA short arm
11:30	Daniel Shaddock	Achieving the mid-high end of the LISA sensitivity band with the LISA long arm
12:10	Lunch	
13:40	Curt Cutler	Data analysis and source modeling of EMRIs

<u>Astrophysics and Analysis Talks</u>

14:20	Pau Amaro-Seoane	GWs from MBHs in colliding clusters: Implications for LISA (and the BBO)
14:40	Tamara Bogdanovic	Electromagnetic Signatures of Massive Black Hole Binaries
15:00	Gareth Jones	Testing models of black hole merger
15:20	Break	

<u>IMS and LPF Talks</u>

15:50	Christian Killow	Construction of the LISA Technology Package Optical Bench Interferometer
16:10	Ulrich Johann	Novel Payload Architectures for LISA
16:30	Bill Klipstein	Clock noise removal in LISA
16:50	Rachel J. Cruz	Time Delay Interferometry using the UF LISA Benchtop Simulator
17:10	Anthony Martino	LISA telescope and aft optics design
17:30	Clive Speake	An interferometric based optical read-out scheme for the LISA proof-mass
17:50	Poster Session	
18:50	Adjourn	

Thursday June 22, 2006 — **Stellar-Mass Binaries, Stochastic Sources, and the Mid-Low End of the LISA Sensitivity Band**

9:00	Gijs Nelemans	Astrophysics of white dwarf binaries
9:40	Chris Belczynski	Astrophysics of neutron star binaries
10:20	Break	
10:50	Stefano Vitale	Achieving the mid-low end of the LISA sensitivity band
11:30	Neil Cornish	Data analysis and source modeling of binaries and stochastic backgrounds
12:10	Lunch	

<u>Astrophysics and Analysis Talks</u>

13:40	Shane Larson	The Resolving Power of LISA: Comparing Techniques for Binary Analysis
14:00	Patrick Motl	Angular Momentum Transport in Double White Dwarf Binaries
14:20	Rajesh Nayak	Tomographic method for resolving the Galatic binaries: including multiple
14:40	Jeremy Schnittman	Gravitational Waves from Compact Objects Accreting onto Active Galactic Nuclei
15:00	Alexander S. Stroeer	An automatic RJMCMC analysis approach to study white dwarf binary systems
15:20	Odylio Aguiar	If PBHs exist, what would be the gw background noise they would produce for LISA, DECIGO, and BBO?
15:40	Break	

<u>DRS and LPF Talks</u>

16:10	Aaron J. Swank	Determining Gravitational Attraction by Mass Property Measurements
16:30	Alberto Lobo	In-flight diagnostics in LISA PathFinder
16:50	Peiman Maghami	Control of Space Technology 7 Disturbance Reduction System Experiment
17:10	Fabio Nappo	Experiences and design drivers for the Inertial Sensor on the LISA Pathfinder Mission

17:30	Davide Nicolini	LISA Pathfinder FEEP Subsystem
17:50	John Ziemer	Colloid Micro-Newton Thruster Development for the ST7-DRS and LISA Missions
18:10	Adjourn	

Friday June 23, 2006 **Exotic Science, Data Analysis, and LISA System Technology**

9:00	Craig Hogan	New Physics with LISA
10:00	Break	

Parallel Sessions: Data analysis Talks

10:30	Linquing Wen	Detecting Extreme-Mass-Ratio-Inspirals With LISA Using Time-Frequency Methods
10:50	Jeff Crowder	Gazing at the Haystack: An Approach for Parameter Extraction for Multiple, Overlapping Signals from
11:10	Edward Porter	Searching for Supermassive black hole binaries in LISA using an MCMC search algorithm
11:30	Louis Rubbo	When is Enough Good Enough in Source Modeling?
11:50	Sukanta Bose	Parameter estimation of stellar-mass binaries with eccentric orbits in LISA
12:10	Alberto Vecchio	Overview of the Mock LISA Data Challenges
12:30	Michele Vallisneri	A Mock LISA Data Challenge How-To
12:50	Eric Plagnol	The Lisa-Code Software simulator

Parallel Sessions: LISA System and Technology Talks

10:30	Peter Gath	LISA System Design Overview
10:50	Daniel Shaddock	Overview of the LISA Phasemeter
11:10	James Ira Thorpe	Arm-locking in a LISA-like hardware model
11:30	Axel E. Hammesfahr	The LISA Technology Package - System Design and Operations
11:50	Cesar Garcia-Marirrodriga	Lessons learnt on LTP development – From basic technology to detailed design
12:10	Walter Fichter	Calibration Methods for the LISA Pathfinder Drag-Free System and Expected Performance
12:30	Dave Wealthy	Managing Disturbance Sources on LISA Pathfinder
12:50	Vinzenz Wand	LISA Phasemeter prototyping
13:10	Lunch	
14:00	Tours	

MONDAY

Tutorials

8:30 LISA Mission Tutorial
Tuck Stebbins/NASA Goddard Space Flight Center

9:15 Astrophysics Tutorial
Scott Hughes/Massachusetts Institute of Technology
LISA will provide a unique window into dynamical processes in astrophysics, opening a gravitational window that will complement the view that has developed (primarily) using the electromagnetic interaction. This talk will survey the astrophysical sources that we expect will be prime targets of this new technology. Our focus will be on what we expect LISA can tell us about these various sources, and the unique complementary information channel that gravitational waves provide for astrophysics.

10:00 Data Analysis Tutorial
Alberto Vecchio/University of Birmingham

Opening Session

11:00 Opening Speaker
Colleen Hartman/NASA Deputy Assistant Administrator

11:20 Astronomy/observations in the LISA Timeframe
Roger Blandford/California Institute of Technology

12:10 Fundamental Gravitational Physics in the LISA Timeframe
Clifford Will/Washington University, St. Louis
We review the current status of experimental tests of gravitational physics, and discuss the progress that might be anticipated during the next 10 years. We will describe tests of the Einstein Equivalence Principle, which underlies the concept of curved spacetime, tests of weak-field, or post-Newtonian gravity, tests of gravity in the strong-field regime, and tests using future direct detection of gravitational waves.

14:30 LISA science
Sterl Phinney/California Institute of Technology

15:20 Status/overview of LISA
Karsten Danzmann/Albert Einstein Institute

16:25 Status/overview of ground based GW detectors
Peter Saulson/Syracuse University
Ground-based gravitational wave detector technology has taken a major step forward in the past few years. Resonant mass detectors, long the mainstay of the field, continue to improve their sensitivity. Interferometers have improved even more, and are now making observations at unprecedented sensitivity levels. The talk will survey the detectors now in operation, giving an account of their present status and future plans. Some emphasis will be given to the most sensitive gravitational wave detection system, the Laser Interferometer Gravitational Wave Observatory (LIGO). LIGO has three interferometers (with arm lengths of 4 km, 4 km and 2 km) at two sites in the United States. In 2005, the LIGO interferometers reached their design goal, sensitivity to millisecond bursts with strain amplitudes of 10^-21. Since November 2005, LIGO has been collecting data, hoping to make the first confirmed detection of gravitational waves and to open the field of gravitational wave astronomy.

17:15 Status/overview of LPF
Paul McNamara/European Space Agency
LISA Pathfinder (formerly known as SMART-2) is an ESA mission designed to pave the way for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission by testing in flight the critical technologies required for space-borne gravitational wave detection: it will put two test masses in a near-perfect gravitational free-fall and control and measure their motion with unprecedented accuracy. This is achieved

through technology comprising inertial sensors, high precision laser metrology, drag-free control and an ultra-precise micro-Newton propulsion system. LISA Pathfinder is due to be launched in late 2009, with first results on the performance of the system being available 6 months later.
Here I will give an introduction to, and status of, the mission, followed by a more detailed discussion on the technologies to be tested. Finally I will discuss the ways in which the LISA Pathfinder mission will be used for preparation of LISA (e.g. ground segment development as well as technology development) and for other future missions (formation flying, Fundamental Physics Explorer, etc.).

TUESDAY

9:00 Supermassive black hole mergers and cosmological structure formation
Marta Volonteri/University of Cambridge

9:40 Dynamics of supermassive black holes
Steinn Sigurdsson/Penn State University

10:50 Achieving the very low end of the LISA sensitivity band
Stephen Merkowitz/NASA Goddard Space Flight Center
The Laser Interferometer Space Antenna (LISA) mission, a space based gravitational wave detector, uses laser metrology to measure distance fluctuations between proof masses aboard three sciencecraft. The total acceleration disturbance to each proof mass is required to be below $3x10^{-15}$ $m/s^2/\sqrt{Hz}$ at 0.1 mHz. Extending this performance to lower frequencies will enable better distance and angular resolution of several sources including massive black hole mergers. This talk presents the design and technology aspects that contribute to achieving good performance to frequencies down to 0.03 mHz.

11:30 Numerical relativity, waveforms of comparable-mass BH mergers
Joan Centrella/NASA Goddard Space Flight Center

13:40 Data analysis and source modeling of central massive black holes
Alessandra Buonanno/University of Maryland

Astrophysics and Analysis Talks

14:20 Black hole spectroscopy with LISA
Emanuele Berti/Washington University, St. Louis
Newly formed black holes are expected to emit characteristic radiation in the form of quasi-normal modes, called ringdown waves, with discrete frequencies. LISA should be able to detect the ringdown waves emitted by oscillating supermassive black holes throughout the observable Universe. We developed a multi-mode formalism, applicable to any interferometric detectors, for detecting ringdown signals, for estimating black hole parameters from those signals, and for testing the no-hair theorem of general relativity. We use current LISA sensitivity models to compute the expected signal-to-noise ratio for ringdown events, the relative parameter estimation accuracy, and the resolvability of different modes. We also discuss the extent to which uncertainties on physical parameters, such as the black hole spin and the energy emitted in each mode, will affect our ability to do black hole spectroscopy.

14:40 Gravitational radiation from spinning-black-hole binaries
Manuela Campaneli/University of Texas at Brownsville
We study the dynamics of spinning-black-hole binaries by numerically solving the full nonlinear field equations of General Relativity. We compute trajectories, merger times, and radiation waveforms. We find that the last stages of the orbital motion of black-hole binaries are profoundly affected by the individual spins. In order to cleanly display its effects, we consider two equal mass holes with individual spin parameters $S/m^2=0.75$, both aligned and anti-aligned with the orbital angular momentum. We choose initial data corresponding to quasicircular orbits with a period of 125M for both cases. The computed merger time for the aligned spin case is ~225M, performing nearly three orbits before merger, while for the anti-aligned case the merger time is ~105M, performing just less than one orbit before merger. The total energy radiated for the former case is ~6\% while for the latter it is only ~2\%. The final Kerr hole remnants have rotation parameters a/M=0.9 and a/M=0.44 respectively, showing the difficulty of creating a maximally rotating black hole out of the merger of two spinning holes.

15:00 Binary Black Hole Simulations
Frank Herrmann/Center for Gravitational Wave Physics
We present results from fully nonlinear simulations of inspiralling, unequal mass binary black holes. We show waveforms of dominant l=2,3 modes. The power spectrum of these modes yields insight on how the mass ratio in a binary impacts the degree of complexity of the emitted waveforms. In addition, we provide

approximate estimates of energy and angular momentum radiated as well as kick velocities from gravitational radiation recoil.

Low-Frequency DRS and LPF Talks

15:50 Free-fall and LISA sensitivity below 0.1 mHz
William Joseph Weber/University of Trento
The LISA sensitivity curve below 0.1 mHz will have an impact on the possible observation of the largest massive black hole mergers. This sensitivity will be limited by noisy stray forces acting on the free-falling LISA test masses. This talk will focus what we have learned experimentally, and what we can still learn, both on ground and with the LTP flight test, about very low frequency force noise and its impact on the LISA sensitivity.

16:10 Proof Mass Accelerations And Optical Path Length Changes Due To Temperature Fluctuations
Peter Bender/JILA, University of Colorado
Five different sources of proof mass accelerations due to temperature fluctuations will be discussed. Thermally driven fluctuations in optical path lengths also have to be considered. These effects involve temperature variations in different parts of the spacecraft bus and the payload, and at different frequencies. Information that is currently available on such effects will be described. It now appears, for present spacecraft bus and payload designs, that the safety margins on the temperature fluctuations are much higher than are needed at frequencies of 0.1 mHz and higher. Thus substantial simplifications of the designs probably are possible. At considerably lower frequencies, the cost/benefit tradeoffs for a modest level of active temperature control of the main spacecraft structure should be investigated.

16:30 Torsion pendulum investigation of thermal gradient-induced forces on LISA test masses
Mauro Hueller/University of Trento
The LISA low frequency gravitational wave sensitivity will be limited by the quality of free-fall of its test masses. One source of acceleration noise arises in the fluctuations of thermal gradients across the Gravitational Reference Sensor, through the radiometric effect, radiation pressure fluctuations, and thermally activated differential outgassing. We have performed an extensive measurement campaign to study thermal gradient-related forces, by heating opposing surfaces of a GRS prototype and detecting the coherent force on the test mass, which is suspended as the inertial member of a torsion pendulum. We present here experimental results which test the model for the different thermal gradient effects in two representative prototype sensors having different geometry, materials, and construction techniques.

16:50 A sensitive torsion balance for LISA proof mass modeling
Stephan Schlamminger/University of Washington
Modeling the LISA GRS performance requires experimental verification near the LISA operating conditions. Torsion balances are ideal an testbed to investigate forces which act on the LISA proof masses. A vertical, gold coated silicon plate is suspended by a thin tungsten wire parallel to a split copper plate, which is also gold coated. The surfaces emulate the proof mass and the housing of the GRS. The separation of the two surfaces can be varied.
We measure the angular excursion of the torsion balance with an autocollimator. The restoring torque is either provided by the torsion fiber or, for larger torques, by an electrostatic feedback system located far behind the pendulum.
With this apparatus we are able to address some of the leading uncertainties in the modeling of the LISA GRS. This talk will focus on the detailed description of the apparatus and its capabilities as well as some of our measurements.

17:10 Outgassing, Temperature Gradients & the Radiometer Effect in LISA: A Torsion Pendulum Investigation
Scott Pollack/University of Washington
Thermal modeling of the LISA GRS includes such effects as outgassing from the housing and proof mass in addition to the radiometer effect due to differential heating of the involved surfaces. Experimental data relating to these effects on the proof mass in close to LISA relevant conditions are required to confidently

predict the GRS performance. The small forces due to outgassing and the radiometer effect are similar in characteristics and are difficult to decouple experimentally.
The design of the torsion balance constructed at the University of Washington has allowed us to investigate both the radiometer effect and outgassing on closely separated conducting surfaces with high sensitivity. In addition, we have been able to determine limits on each effect individually. Using the thermal control of the split copper plate in the torsion balance apparatus we have investigated the effects on our pendulum by heating each half of the copper plate to different temperatures while at different pendulum-plate separations. Measurements of forces relating to outgassing, temperature gradients, and the radiometer effect will be presented.

17:30 Charge Management for Lisa Pathfinder and development for LISA
Markus Schulte/Imperial College, London
Test mass charging is one of the main noise sources for LISA. The test masses are electrically isolated, and hence, to avoid excessive charge build up, it is necessary to discharge them using the photoelectric effect. LISA will use a UV light system to deliver UV photons to the inertial sensor surfaces. One of the primary goals of LISA PF is to test this system. Here we describe the charge management device that is being built for LISA PF, and its basic operational modes that will be tested during the mission. We also present the results of a test mass discharge simulation, illustrating the different factors that can influence the discharging rate and associated noise. Finally, we discuss our ongoing development programme, testing potential improvements to this system, for LISA.

17:50 Solar, cosmic ray and environmental physics for, and with, LISA
Diana Shaul/Imperial College London
With data analysis preparations for LISA underway, there has been a renewed interest in studying solar, cosmic ray and environmental physics in preparation for, and using, LISA. The motivation for these studies is two fold. The primary incentive is to predict and consequently minimise the impact of disturbances associated with these factors, to maximise LISA's gravitational wave scientific yield. For example, implementing models which use realistic simulation codes will give us more accurate SEP predictions and will potentially allow us to reduce the length of science data interruptions, beyond current estimates. The second stimulus is the unique opportunity that is afforded by LISA's long-baseline 3 spacecraft configuration for studies of solar, cosmic ray and environmental physics. Here we present an overview of the current status of these studies.

WEDNESDAY

9:00 Testing general relativity with extreme-mass ratio inspirals
Scott Hughes/Massachusetts Institute of Technology

9:40 Astrophysics of extreme-mass ratio inspirals
Clovis Hopman/Weizman Institute of Science

10:50 Achieving the mid-high end of the LISA sensitivity band with the LISA short arm
Gerhard Heinzel/Albert Einstein Institute

11:30 Achieving the mid-high end of the LISA sensitivity band with the LISA long arm
Daniel Shaddock/Jet Propulsion Laboratory

13:40 Data analysis and source modeling of EMRIs
Curt Cutler/Jet Propulsion Laboratory
I will discuss the current state of the art in constructing accurate EMRI waveforms by solving for the inspiral of a point mass in Kerr, as well as approximate versions of those waveforms that have been developed for testing or exploratory purposes. I will also discuss various strategies for digging EMRI signals out of the noisy LISA data, and mention some related work on the problem of confusion due to many overlapping EMRI sources (embedded in confusion noise from an even larger number of Galactic binaries). I will conclude by reviewing the EMRI searches that form part of the upcoming Mock LISA Data Challenges.

Astrophysics and Analysis Talks

14:20 GWs from MBHs in colliding clusters: Implications for LISA (and the BBO)
Pau Amaro-Seoane/Albert Einstein Institute
HST observations reveal that young massive star clusters form in gas-rich enviroments like the Antennae galaxy which will merge in collisional processes to form larger structures. If these clusters harbour a massive black hole in their centres, they can become a strong source of gravitational waves when the massive objects merge.
In order to understand the dynamical processes that are into play in such a scenario and the implications for the future space-born mission LISA, one has to carefully study the evolution of the merger of two of such young massive star clusters and more specifically their respectives massive black holes.
I will present high-resolution direct summation N-body simulations with relativistic corrections for the merging massive black holes to study the orbital evolution of two colliding globular clusters with different initial conditions. This allows us to make analytical estimates for the rates of such events.

14:40 Electromagnetic Signatures of Massive Black Hole Binaries
Tamara Bogdanovic/Penn State University
We model the electromagnetic signatures of massive black hole binaries (MBHBs) with associated gas disks. The focus of our investigation is on the intermediate phase binaries which have just completed the dynamical friction phase but did not yet enter the gravitationalradiation phase. We carried out numerical simulations of relativistic binaries and gas, assessed the physical properties of the emitting gas, and calculated the UV/X-ray and optical light signatures (i.e., the light curves and emission line profiles). The binary simulations have been carried out with the parallel code Gadget. The heating, cooling, and radiative processes in the gas have been evaluated with help from the photo-ionization code Cloudy. The modeled observational signatures can be used to identify MBHB systems in the intermediate phase of evolution from observations and to determine their kinematic properties and orbital parameters.

15:00 Testing models of black hole merger
Gareth Jones/Cardiff University
Gravitational-wave observations of inspiralling and merging supermassive black hole binaries in LISA will provide a unique opportunity to test the strong-field, regime of General Relativity where the dimensionless gravitational potential can reach values of order unity. In this presentation we propose how one might test General Relativity, and in particular models of binary black hole merger, with LISA.

IMS and LPF Talks

15:50 Construction of the LISA Technology Package Optical Bench Interferometer
Christian Killow/Glasgow University
The Optical Bench Interferometer for LISA technology Package is required to monitor the distance between the test masses at the level of 10pm/sqrt(Hz) in the measurement band. The alignment tolerances for the flight model optical bench require advanced metrology and alignment techniques in combination with flight worthy bonding processes. The design, construction and current status of the flight model LISA Technology Package Optical Bench Interferometer will be presented.

16:10 Novel Payload Architectures for LISA
Ulrich Johann/EADS Astrium Germany
Within the context of the LISA Mission Formulation Study, we have developed a detailed concept for the optical layout of the LISA payload, which consists of two movable assemblies per spacecraft, each pointing to its respective remote spacecraft to form a constellation triangle of 5 million kilometer arm length. The movable assemblies comprise a Cassegrain telescope, an optical bench, and a gravity reference sensor with a free floating proof mass, which delimits the respective arm.
Differential changes in the distances between the two proof masses of each arm, caused by the passage of a gravitational wave, are detected by a combination of heterodyne interferometry and differential wavefront sensing. The optical metrology is characterized by a "strap-down" approach, in which an optical readout provides position as well as attitude information of each test mass with respect to its local optical bench. This information is combined with a second interferometric measurement of the distance between the local and the remote optical bench to yield the science signal for one interferometer arm. A "frequency swap" between transmitted and local reference beam is introduced to minimize the impact of straylight from each high power transmit beam on the local heterodyne detection.
The above measurement principles are reflected in the current optical bench design, which includes ultra high precision opto-mechanics, all optical detectors, as well as appropriate imaging optics for transmit and receive beam mode matching. It is currently being analyzed with a specialized optics code to verify the nominal performance and give a preliminary assessment of alignment tolerances and critical elements. Preliminary results both for the local imaging and the far field will be presented.

16:30 Clock noise removal in LISA
Bill Klipstein/Jet Propulsion Laboratory
The relative motion of the LISA spacecraft will Doppler shift the laser frequencies by approximately 10 MHz. These Doppler shifts introduce undesired sensitivity to the phase noise of the master clock. Using the most stable clocks available, this effect would degrade the LISA sensitivity by more than a factor of 100. This clock noise can be removed in post-processing if the clock phase can be transferred between the spacecraft with a fidelity of a few microcycles/rt(Hz). In the LISA baseline design, the clock phase is imposed as sidebands on the science laser beams exchanged between spacecraft. Interference between the outgoing and the incoming sidebands contains the information necessary to remove the clock noise in post-processing. The details of the LISA clock noise removal scheme are described and results of a recent successful demonstration of the clock noise transfer are presented.

16:50 Time Delay Interferometry using the UF LISA Benchtop Simulator
Rachel J. Cruz/University of Florida
At UF, we are developing an experimental LISA simulator to test implementation of various aspects of LISA interferometery including arm-locking and TDI. Realistic light travel times are created in the lab using an electronic phase delay technique and signals are read with a LISA-like phasemeter. Implementation of the TDI algorithms relies on a strong correlation between the LISA signals at different times. We will present results from the first-generation of the simulator showing that we are able to create LISA-like optical signals in the lab and measure and recombine them to cancel several orders of magnitude laser phase noise.

17:10 LISA telescope and aft optics design
Anthony Martino/NASA Goddard Space Flight Center

The LISA telescope design is constrained by requirements on physical size, wavefront error, aperture size, field of view, and magnification. Field of view may be required to allow for in-field pointing by steering a flat mirror at a pupil plane behind the telescope, rather than steering the telescope itself.
Telescope designs that meet different variations of the requirements are presented. The designs are compared according to nominal performance, and according to the sensitivity of performance to various off-nominal conditions, such as manufacturing errors and misalignments. It is shown that telescope and aft optics designs exist that nominally meet the requirements, including in-field pointing. The sensitivity studies indicate that a very high level of precision will be required in manufacture and alignment of the optical elements, particularly the telescope primary and secondary mirrors.

17:30 An interferometric based optical read-out scheme for the LISA proof-mass
Clive Speake/University of Birmingham
We discuss a polarisation based homodyne interferometer under development at the University of Birmingham that has shown promising sensitivities down to 10-4 Hz. A compact interferometer, measuring 85 x 45 x 25 mm, has been fabricated that employs a VCSEL laser diode source operating at 850 nm. The VCSEL has been fully characterised and has demonstrated mono-mode behaviour over a wavelength tuning range of 1.5 nm. This provides the option of adopting a wavelength modulation technique, which will enable the absolute difference in interferometric armlengths to be determined.

THURSDAY

9:00 Astrophysics of white dwarf binaries
Gijs Nelemans/ Radboud University Nijmegen

9:40 Astrophysics of neutron star binaries
Chris Belczynski/New Mexico State University

10:50 Achieving the mid-low end of the LISA sensitivity band
Stefano Vitale/University of Trento
In the 0.1-3 mHz band LISA sensitivity will be limited by spurious acceleration of the proof-masses deviating their trajectories out of the geodesic motion required to define the Transverse-Traceless reference frame.
The talk will illustrate how the combination of the LTP experiment on LISA Pathfinder and of ground testing with torsion pendulums will give us an acceleration noise model for LISA proof-masses experimentally tested with accuracy close to LISA requirements.

11:30 Data analysis and source modeling of binaries and stochastic backgrounds
Neil Cornish/Montana State University

Astrophysics and Analysis Talks

13:40 The Resolving Power of LISA: Comparing Techniques for Binary Analysis
Shane Larson/Penn State University
Millions of short period binaries in the Milky Way will radiate gravitational waves in the low-frequency band with enough power to be detectable by LISA, making the foreground of galactic binaries the most prolific source in the band.
Characterizing the resolving power of LISA is important for understanding what science will be possible with LISA observations of these binaries (e.g., mass transfer rates in accreting binaries, the structure of the galaxy, etc.) and understanding how well other sources can be resolved amidst the myriad of resolvable LISA sources.
This talk will report the initial results of an ongoing study comparing and contrasting the performance of two science analysis techniques, gCLEAN and MaxEnt, in binary identification. The study is built around common data sets, and a fixed comparison criterion used to contrast the two techniques. Particular questions of interest include how well can LISA resolve two sources with identical frequencies on the sky (the gravitational wave analog of the Rayleigh criterion), and for a single fixed location on the sky how well can LISA resolve sources of different frequencies.

14:00 Angular Momentum Transport in Double White Dwarf Binaries
Patrick Motl/Louisiana State University
We present simulations of dynamical mass transfer in a double white dwarf binary with an initial mass ratio of 0.4. The binary components are approximated as polytropes of index $n = 3/2$ and the synchronously rotating, semi-detached equilibrium binary is evolved hydrodynamically with the gravitational potential being computed through the solution of Poisson's equation. Upon initiating deep contact, the mass transfer rate grows by more than an order of magnitude over approximately ten orbits, as would be expected for dynamically unstable mass transfer. However, the mass transfer rate then reaches a peak value, the binary expands and the mass transfer event subsides over approximately 30 orbits. Despite the loss of orbital angular momentum into the spin of the accreting star, we find that the accretor's spin saturates and the binary responds as one would expect for a system with an accretion disk filling a substantial fraction of the accretor's Roche lobe. It appears that double white dwarf binaries may be more resilient against merger than previously anticipated though our simulations do not include radiation forces which may ultimately fill a common envelope which dooms the binary. This work has been supported in part by NSF grants AST 04-07070 and PHY 03-26311 and in part through NASA's ATP program grant NAG5-13430. The computations were performed primarily at NCSA through grant MCA98N043 and at LSU's Center for Computation & Technology.

14:20 Tomographic method for resolving the Galatic binaries: including multiple
Rajesh Nayak/University of Texas at Brownsville
A Tomographic approach was recently proposed by Mohanty and Nayak[1] for resolving Galactic binaries, both spatially and in source frequency, in the LISA data stream. Using Doppler modulation alone, the method can unambiguously resolve binaries with a matched filtering signal to noise ratio higher than about 7 and spaced apart by 5 or more 1 year frequency bins. In the present work we extend the method to include the multiple Michelson interferometers in LISA and their rotating antenna patterns. We find a substantial improvement in the resolving power of the tomographic method across all frequencies. (The resolution may be increased further when combined with a deconvolution method that has been developed separately[2].) Since the tomographic method is linear, One can combine the TDI data combinations before or after the reconstruction. We show that the GW signal completely cancels out for the Symmetric Sagnac data combination.
This is useful in estimating the instrumental noise contaminating tomographically reconstructed sky maps.
References:
[1] S.D. Mohanty and K.R. Nayak "Tomographic approach to resolving the distribution of LISA Galactic binaries" in press (2006), gr-cc/0512014.
[2] K. Hayama, "A modified CLEAN method and its application to tomographic reconstruction of LISA Galactic binaries", abstract submitted to this conference.

14:40 Gravitational Waves from Compact Objects Accreting onto Active Galactic Nuclei
Jeremy Schnittman/University of Maryland
We consider a model in which massive stars form in a self-gravitating accretion disk around an active galactic nucleus (AGN). These stars will evolve and collapse to form compact objects on a time scale shorter than the accretion time, thus producing an important family of sources for LISA. Assuming the compact object inspiral rate is proportional to the steady-state gas accretion rate, we use the observed extra-galactic X-ray luminosity function to estimate expected event rates and signal strengths. We find that these sources will produce a stochastic background detectable by LISA if more than ~1% of the accretion is in the form of compact objects with mass <~ 10^3 Msun. However, if less than ~1% of the accretion is in compact objects and/or the typical mass is larger than ~10^3 Msun, LISA could detect individual inspiral events above 1 mHz.

15:00 An automatic RJMCMC analysis approach to study white dwarf binary systems
Alexander Stephan Stroeer/University of Birmingham
We have developed a general automatic Reversible Jump Markov Chain Monte Carlo sampler applicable to the analysis of LISA data within the framework of Bayesian inference. We demonstrate the implementation of this sampler in the context of the study of the LISA verification binaries and other (previously unknown) white dwarf binary systems.

15:20 If PBHs exist, what would be the gw background noise they would produce for LISA, DECIGO, and BBO?
Odylio Aguiar/ Instituto Nacional de Pesquisas Espaciais-INPE
According to the standard model primordial black holes (PBHs) could have been generated during the first few moments after the big bang as consequence of density fluctuations of matter. Although most regions of high density would be quickly dispersed by the expansion of the universe, primordial black holes would be stable, persisting to the present. If this really happened the Laser Interferometer Space Antenna (LISA), the DECihertz Interferometer Gravitational wave Observatory (DECIGO), and the Big Bang Observer (BBO) will probably detect the gravitational wave background produced by those PBHs. Here we calculated this background as a function of the PBH population in the neighborhood of Earth. Depending of what population is assumed the gravitational wave background produced may give trouble for these space interferometers in their task to detect other signals. Very large ground base interferometers such as LIGO and VIRGO can soon give information that would put stringent !
constraints on this population.

DRS and LPF Talks

16:10 Determining Gravitational Attraction by Mass Property Measurements
Aaron J. Swank/Stanford University

One parameter critical to drag-free performance is the acceleration generated by the gradient of the mass attraction field between the spacecraft and proof mass. Historically for drag-free satellite design, stringent requirements are placed on the density distribution within satellite components to ensure that the mass attraction noise budget allocation will not be exceeded due to the associated uncertainty in mass properties. Yet, due to the precision required by LISA, this requirement can easily impose the use of special materials or manufacturing processes impractical with today's technology. It is therefore desirable to develop a method to physically measure the gravitational attraction forces and force gradients which would include the mass property uncertainties. Although the gravitational mass attraction force cannot be easily measured directly, the mass attraction formula through a second order expansion consists of the measurable quantities of mass, mass center, and moment of inertia. Thus, the gravitational attraction force can be indirectly measured and only the third order terms and higher need to be calculated using estimates for the geometry and density. The method for determining the gravitational self-attraction properties by utilizing mass property measurements is described in this work. Additionally, this work introduces a new method for measuring the moment of inertia using a novel five-wire torsion pendulum which reduces errors due to translational degrees of freedom. The five-wire pendulum is integrated with optical angular sensing using diffraction grating angular magnification to provide a sensor with both a large dynamic range and high resolution.

16:30 In-flight diagnostics in LISA PathFinder
Alberto Lobo/IEEC, Barcelona
LISA PathFinder (LPF) will be flown with the objective to test in space key technologies for LISA. However its sensitivity goals are, for good reason, one order of magnitude less than those which LISA will have to meet, both in drag-free and optical metrology requirements, and in observation frequency band. While the expected success of LPF will of course be of itself a major step forward to LISA, one might not forget that a further improvement by an order of magnitude in performance is still needed for LISA. Clues for the latest jump are to be derived from proper disentanglement of the various sources of noise which contribute to the total noise, as measured in flight during the PathFinder mission. This presentation describes the principles, workings and requirements of one of the key tools to serve the above objective: the diagnostics subsystem. This consists in sets of temperature, magnetic field, and particle counter sensors, together with generators of thermal and magne!
tic controlled perturbations. At least during the commissioning phase, the latter will be used to identify feed-through coefficients between diagnostics sensor readings and associated actual noise contributions. A brief progress report summary of the current state of development of the diagnostics subsystem will be presented as well.

16:50 Control of Space Technology 7 Disturbance Reduction System Experiment
Peiman Maghami/NASA Goddard Space Flight Center
The Space Technology 7 (ST7) experiment will perform an on-orbit system-level validation of micronewton colloidal thruster technology. DRS will fly as a part of the European Space Agency (ESA) LISA Pathfinder (LPF) spacecraft along with a similar ESA experiment, the LISA Technology Package (LTP). The ST7 Disturbance Reduction System (DRS) is designed to maintain the spacecraft_fs position with respect to a free-floating test mass to less than 10 nm/_ãHz over the frequency range of 1 to 30 mHz, using the colloidal thrusters. It also has a goal of maintaining the residual acceleration of the test masses of the two LTP gravitational sensors to below 30(1+(f/3mHz)^2) fm/s^2/_ãHz, in the science band. This paper presents the overall design and analysis of the spacecraft DRS controllers. These controllers close the loop between a pair of gravitational sensors and the micronewton colloidal thrusters. There are several control modes in the operation of the ST7 DRS, with the 18-DOF mode as the primary mission mode. In this mode, darg-free motion of six degrees of freedom of the test masses is established. The design and analysis of this mode, as well as its performance are presented.

17:10 Experiences and design drivers for the Inertial Sensor on the LISA Pathfinder Mission
Fabio Nappo/Carlo Gavazzi Space SpA
LISA scientific requirements are defined to have a freely floating Test Mass (TM) falling under the effect of the large scale gravitational field only within the minimum achievable acceleration noise, relative to a free falling frame in the frequency range of 0.1mHz-0.1Hz. The TMs serving as the interferometry end mirrors must be in a perfect free fall. To maintain a higher level of isolation from stray forces, the TMs are shielded

by a spacecraft that employs precision thrusters to follow the "drag-free" TM orbits, based on a relative position sensor, called inertial or gravitational sensor (IS).
This paper deals with the development of IS that will fly on board of the Laser Interferometer Space Antenna (LISA) Pathfinder mission.
We summarise the engineering model development of the IS, in terms of technological solutions needed to map the scientific requirements into engineering specifications. And we present the main results of the Assembly, Integration and Test campaign. All these activities constitute a huge set of learnt lessons that drive the development of the subsequent flight model.
We report on the progresses of the design of the current IS, providing spotlights on the main updates with respect to the first development and on the key achievements of the bread-boarding campaign. We then show the verification approach that combines characterizations on model replicas in collaboration with University of Trento, such as sensitivity and force noise measurements to within an order of magnitude of the LISA Pathfinder mission goals, with calibrations carried out on the real hardware at CGS.
The IS is designed to the LISA scientific specifications and, tested aboard LISA Pathfinder mission, will establish a bridge between ground testing and the final LISA mission.

17:30 LISA Pathfinder FEEP Subsystem
Davide Nicolini/European Space Agency
The industrial development of the FEEP technology required for LISA Pathfinder began with ESA funded technology development activities, which then evolved to subsystem industrial development work in the frame of initially precursor programs as the CNES mission Microscope. For the slit Cs FEEP most of the system and thruster development of the past 5 years was carried out in the in the frame of the Microscope Electric Propulsion System (EPS) activities at ESA, in close coordination with the LISA Pathfinder project. For the needle In FEEP most of the system and thruster development was carried out in the frame of a technology activity, follow up of the initial GOCE activities, led by the LISA Pathfinder project at ESA. The paper will discuss the evolution of requirements, design and test results achieved relevant to LISA Pathfinder in the frame of the Microscope EPS activities and Technology Activities on both slit and needle FEEP. Furthermore, the paper will describe the subsystem layout and the verification approach as currently envisioned and the planned activities in the frame of the LISA Pathfinder project.

17:50 Colloid Micro-Newton Thruster Development for the ST7-DRS and LISA Missions
John Ziemer/Jet Propulsion Laboratory
We present recent progress and development of the colloid microthruster technology for the Space Technology 7 Disturbance Reduction System (ST7-DRS) and the Laser Interferometer Space Antenna (LISA) missions. ST7-DRS is a NASA New Millennium Program technology demonstration mission on board the ESA LISA Pathfinder Mission. The LISA Mission is a joint NASA/ESA mission scheduled to launch in the next decade. These drag-free missions require precision microthrusters to provide low-noise spacecraft position control within approximately 10 nm of free-floating proof masses, used to detect gravitational waves. Both missions have similar microthruster performance requirements: a thrust range of 5-30 μN, a thrust resolution <0.1 μN, and thrust noise <0.1 μN Hz-1/2 over the ST7-DRS and LISA measurement bandwidths. Although other microthrust propulsion systems are currently under development for this purpose at ESA, this paper focuses on the NASA microthruster technology development of the Busek Colloid Micro-Newton Thruster (CMNT) including recent developments to provide flight hardware for ST7-DRS.

FRIDAY

9:00 New Physics with LISA
Craig Hogan

Parallel Sessions: Data analysis Talks

10:30 Detecting Extreme-Mass-Ratio-Inspirals With LISA Using Time-Frequency Methods
Linquing Wen/Albert Einstein Institute
The inspiral of a stellar-mass object into a supermassive BH constitutes one of the most important sources for LISA. Fully coherent matched filtering has been shown to be computationally intractable. We discuss an efficient and robust detection method that utilizes the time-frequency evolution of such systems. The feasibility of this method as a first step of a hierarchical search will be discussed.

10:50 Gazing at the Haystack: An Approach for Parameter Extraction for Multiple, Overlapping Signals from
Jeff Crowder/Montanna State University - Bozeman
Tens of millions of galacitc binary systems are expected to be emitting on the low end of the LISA band. Many thousands of these low frequency gravitational wave sources will be detectable by LISA. A data analysis method has to be found to handle the large number of sources, many of which will have overlapping signals. Simultaneous, multi-source searches using a template grid may become computationally prohibitive due to the large number of low frequency sources, while iterative techniques can suffer from the inability to properly address the overlapping signals. This talk will introduce Markov Chain Monte Carlo (MCMC) methods of data analysis. MCMC algorithms have shown great promise in dealing with large parameter spaces. Results, extracted from a simulated LISA data stream containing a modeled (Nelemens/Yungelson/Portegies-Zwart)
galactic background, will be presented showing how the MCMC method will be able to address the problem of large numbers of overlapping signals.

11:10 Searching for Supermassive black hole binaries in LISA using an MCMC search algorithm
Edward Porter/Montana State University – Bozeman
We demonstrate, using a Markov Chain Monte Carlo algorithm, that we can detect the inspiral of two Schwarzschild Supermassive black holes. The MCMC method also allows us to extract the parameters of the binary and map the posterior distributions in the errors of the parameters.

11:30 When is Enough Good Enough in Source Modeling?
Louis Rubbo/Penn State University
How complex must a source model be in order to accurately analyze LISA data? For example, a number of the galactic binary systems that LISA will observe will have a significant, measurable frequency evolution. Still, for other systems, the frequency evolution will be so small as to be undetectable. Using a signal model that includes an $\dot{f}$ parameter to characterize such binaries would be inappropriate, while using a monochromatic signal model would be inappropriate for binaries with ``significant'' frequency evolution. Therefore, when should the model used for the analysis of data from an evolving binary include an $\dot{f}$ term, and when is it more appropriate to regard the binary as monochromatic?
Similar problems in the choice of model complexity arise in many places in LISA data analysis. For example, when are the post-Newtonian effects of a given order important parts of the template model and when is a simpler model, or lower post-Newtonian order, a better choice of template. The answer to questions like these have important repercussions for the complexity of the analysis involved in the identification and characterization of LISA sources. Here we describe a Bayesian approach to the problem of determining when a simple model (e.g., a monochromatic binary) more than suffices for the analysis of data from a more complex systems (e.g., a chirping binary). This is part of a work in progress addressing the question of appropriate model complexity for a wide range of LISA sources.

11:50 Parameter estimation of stellar-mass binaries with eccentric orbits in LISA
Sukanta Bose/Washington State University

The ability to resolve or mitigate the confusion noise in LISA is tightly coupled to the problem of how well one can estimate the parameters of the contributing sources. One of these source species is the galactic stellar-mass binary. Here we examine the effects of time-delay interferometry on the estimation of the parameters of such binaries, including those that have eccentric orbits and chirp. The waveform used are 2.5PN accurate and include periastron precession and radiation reaction.

12:10 Overview of the Mock LISA Data Challenges
Alberto Vecchio/University of Birmingham
The LISA International Science Team Working Group on Data Analysis (LIST-WG1B) is sponsoring several rounds of mock data challenges, with the purpose of fostering development of LISA data-analysis capabilities, and of demonstrating technical readiness in exploiting LISA data. I present an overview of the challenges and the programme aimed at tackling open data analysis issues.

12:30 A Mock LISA Data Challenge How-To
Michele Vallisneri/Jet Propulsion Laboratory
The LISA International Science Team Working Group on Data Analysis (LIST-WG1B) is sponsoring several rounds of mock data challenges, with the purpose of fostering development of LISA data-analysis capabilities, and of demonstrating technical readiness in distilling a rich science payoff from the LISA data. The first round of challenge datasets are being released at this Symposium. I discuss the mechanics of participating in the challenges, and I present the theory, computation, and collaboration tools and resources made available by the LIST-WG1B Mock LISA Data Challenges Taskforce to support participants.

12:50 The Lisa-Code Software simulator
Eric Plagnol/APC Paris, France
A Lisa data simulator "Lisa-Code" has been written by a collaboration between APC(Paris) and Artemis(Nice). The aim of this software is to simulate the response of the Lisa detector and test its sensitivity to key instrumental parameters. It will also be used to generate realistic data streams that would take part in the Mock Data Challenge.
Using inputs from gravitational wave stress time sequences, the simulator takes into account realistic orbits and a variety of noise sources: inertial mass noise, "shot+optical" noise, laser noise and, soon, galactic confusion noise.
The raw output (Lisa detector response) can either be stored as such or inputted to a variety of TDI (Time delay Interferometry) configurations to suppress the laser noise.
The code is operational and can be distributed to the Lisa community.
Apart from an explanation of the structure of the code and of its main features, the talk will present :

i) a calculation of the Lisa sensitivity curve obtained with different TDI combinations,
ii) the effect of the uncertainty of the Time Delay on the sensitivity curve,
iii) The effect of a variation of the arm length on the sensitivity curve,
iv) the response of Lisa+TDI on a variety of gravitational waves.

Parallel Sessions: LISA System and Technology Talks

10:30 LISA System Design Overview
Peter Gath/EADS Astrium Germany
An overview of the LISA measurement chain is given and the design of the spacecraft with the main focus on the LISA payload is described.
The main highlights of the current payload design baseline are the introduction of the strap-down system in connection with a dedicated actuator for the point-ahead angle compensation, and the laser frequency swap. The strap-down system separates the problems of the 5 mio km interferometry from the proof-mass metrology. This gives more design freedom in the mechanical configuration, a clear separation of the different subsystems, and it also improves the testability on ground. The laser frequency swap significantly reduces the problems of straylight and also yields a clear separation between the incoming and outgoing laser beam which introduces the possibility of an optimal adjustment of the local oscillator independently from the outgoing beam. Both design changes are presented and their impacts on the overall system design and the measurement performance is discussed.

Compared to the last study in 2000, the mechanical design has changed in an effort of reducing the overall system mass while keeping a reliable and technologically feasible design. The design baseline is supported by the corresponding structural, thermal, drag-free and attitude control, vacuum, and optical analyses such that the revised error budgets are now supported by results from more detailed models instead of rough estimates. Finally, an overview of the latest performance estimates is given and the derived requirements on the main subsystems are discussed.
The paper presents the current status of the LISA system design as it is established in the framework of the European Space Agency's Mission Formulation Study at EADS Astrium.

10:50 Overview of the LISA Phasemeter
Daniel Shaddock/Jet Propulsion Laboratory
We describe a design for the LISA phasemeter that meets the demanding requirements on sensitivity, dynamic range, and frequency response. Key features of the FPGA implementation include automatic acquisition, frequency tracking, rejection of aliasing products, and digital dithering. Test results from a prototype phasemeter, meeting the 1 ucycle/rt(Hz) sensitivity requirement are presented.

11:10 Arm-locking in a LISA-like hardware model
James Ira Thorpe/University of Florida
Arm locking is a potentially attractive solution for addressing laser phase noise in LISA. If implemented, it will reduce the requirements on Time Delay Interferometry (TDI) and the laser pre-stabilization system. This in turn may affect ranging requirements, data rates, and the complexity/cost of the prestabilization system. The disadvantage of arm-locking is increased complexity, particularly when more sophisticated versions such as direct arm locking [LIMAS 2006-001] are considered. Examples of open questions are how to interface arm-locking with existing prestabilization, and what requirements arm-locking will place on other components such as the phasemeters.
We present a method whereby arm-locking can be implemented in an electro-optic model of the LISA IMS. This model includes both realistic laser phase noise and realistic light travel times. The former is achieved using cavity-stabilized lasers while the latter is achieved using the Electronic Phase Delay (EPD) technique [Class. Quantum Grav. 22 (2005) S227-S234]. Current progress and results will be presented. This work is supported by NASA grant BEFS04-0019-0019.

11:30 The LISA Technology Package - System Design and Operations
Axel E. Hammesfahr/EADS Astrium Germany
The LISA Technology Package (LTP) will be one of the core experiments on-board the LISA Pathfinder mission going to be launched in 2009 as the precursor mission to LISA. The development of this instrument has been started by a multinational team in 2004 under contracts with seven national space agencies and the European Space Agency.
This paper will present the key issues of the system engineering and instrument operations aspects as performed by the EADS Astrium GmbH on behalf of the German Space Agency DLR and the ESA. We will briefly show the basic features of the instrument and discuss the most critical instrument design and operations issues and its sensitivity to the achievement of the mission goals. Special emphasis will be given to recent design solutions as generated to meet specific aspects of the mission operations concept, to optimize for dedicated performance and operational needs of the LPF drag-free attitude control subsystem (DFACS). The LTP as the instrument hardware and the DFACS are two elements that are extremely closely related in its performance and operation. This is reflected by performance requirements and most important by the operational procedures that are defined in the LTP operations master plan. In this paper some of the major operational issues will be addressed in more detail. This concerns specifically critical operational phases as the initial test mass release and the acquisition sequence of the Optical Measurement Subsystem, which requires a search procedure to be carried out through DFACS controlled test mass motions. Another very important operational interface aspect is the test mass charge measurement and control, especially when it is to be performed continuously during the science operation.

11:50 Lessons learnt on LTP development – From basic technology to detailed design
Cesar Garcia-Marirrodriga/European Space a Agency
The industrial development of the LISA Technology Package (LTP) started off from earlier development activities at technology level. In some cases the industrial development is quite similar to earlier

developments. In some other cases, the current design significantly deviates from earlier work. In all cases, though, design adaptations have been necessary for the purpose of performance, system compatibility and flight worthiness.
At the time of writing, the LTP and all its sub-systems and units have undergone their Preliminary Design Reviews, and the detailed design phase is proceeding.
The paper will discuss the evolution of requirements and design features from earlier phases to the present time in order to show the roadmap from basic technology to flight hardware. Furthermore, the paper will describe the verification approach of the instrument as currently envisioned. Finally, the related learnt lessons will be discussed.

12:10 Calibration Methods for the LISA Pathfinder Drag-Free System and Expected Performance
Walter Fichter/EADS Astrium Germany
The drag-free, attitude, and suspension control system (DFACS) is one of the key elements for the test runs to be performed with the LISA Technology Package (LTP). Before science measurements are taken, it must be ensured that the DFACS is properly working and/or the DFACS must be optimized. To this end, a number of calibration procedures must be performed. These are (but are not limited to)

- alignment calibration of sensor systems
- stiffness estimation, including cross-axes
- electrostatic actuation calibration
- controller transfer function identification
- preliminary charge measurement
- thruster calibration

This paper consists of three parts. First, the calibration problems are stated together with two fundamental calibration approaches: Optimal filtering, which allows for quick assessment of the achievable performance without explicit numerical simulations, and parameter identification, which is appropriate for actual implementation. Pros and Cons are summarized.
Next, the DFACS design is outlined and the user interface for calibration tasks is described (which is the same for science measurement). Emphasis is put on the test signal description to the DFACS control loops, i.e. the number, level (set point vs. acceleration, voltage vs. axes-related, etc), and parameterization.
Finally, the design of the calibration experiments (test signal specifications, integration times, etc.) are presented. These were tested with a full 15 DoF nonlinear simulator and LTP model down to voltage level. The simulated telemetry data was fed into the calibration routines. It is shown that most parameters can be calibrated with a typical accuracy of 1-2 percent. Performance limitations will be addressed, together with practical constraints such as downlink rate, etc

12:30 Managing Disturbance Sources on LISA Pathfinder
Dave Wealthy/EADS Astrium Germany
LISA Pathfinder is a technology demonstration pre-cursor mission to verify the technologies required for the LISA mission. The mission will be launched into a Lissajous orbit about the Earth-Sun L1 Lagrange point. This orbit provides a benign operational environment, minimising the effect of external forces, torques and gradients acting upon the spacecraft.
The ultimate performance of the mission in achieving disturbance-free flight of the test masses is influenced by force fields and gradients originating from the spacecraft elements. Chief among these internal forces, torques and gradients are self-gravity effects, magnetic field effects and thermoelastic effects. Since each of these effects can directly influence the mission performance, it is necessary to ensure that they can be controlled and, where feasible, eliminated by design.
This paper will describe the activities carried out by the LISA Pathfinder team to understand and model each of these effects, the design decisions made to minimise or eliminate certain aspects of each effect and, finally, the processes employed to control the effects that cannot be eliminated through design.

12:50 LISA Phasemeter prototyping
Vinzenz Wand/Albert Einstein Institute
The primary measurement of the LISA interferometers will be the phases of a set of sinusoidal beat notes coming from photodetectors on the optical bench. These beat notes are in the range 1...20 MHz, and their frequency varies by up to 4 Hz/s due to the varying Doppler shift. The beatnotes in those phasemeter channels used for the long arm measurement originate from the interference of a local oscillator with the incoming

very weak light (100 pW), and hence have a small amplitude, The required sensitivity of the phase measurement is 6.3 urad/sqrt(Hz)@1mHz, corresponding to a pathlength noise of 1 pm/sqrt(Hz). Besides the beatnotes, the incoming signal also contains a spread-spectrum encoded datastream that is used for inter-spacecraft communication and ranging, which also needs to be detected and decoded. We present our approach of an all digital implementation of such a phase measurement system.

POSTER TITLE LISTING

Posters are listed here alphabetically by last name of the first author. Abstracts are in the next section.

Allen, Graham	A Grating Cavity as a Displacement Sensor in Drag-Free Satellites
Barausse, Enrico	Extreme mass ratio inspirals in black hole plus torus spacetimes
Bentivegna, Eloisa	The effect of gauge conditions on waveform templates from binary black hole coalescence
Biserni, Mario	Caging Mechanism for LISA Pathfinder
Bode, Tanja	Black Hole Spectroscopystudying nonlinear mode mixing in the end phases of binary black hole mergers
Bortoluzzi, Daniele	Test-mass release phase ground testing for the LISA Pathfinder mission
Bose, Sukanta	Parameter estimation of stellar-mass binaries with eccentric orbits in LISA
Branduardi-Raymont, Graziella	Multi-band astronomy with LISA
Burko, Lior	Orbital evolution for extreme mass-ratio binaries: conservative self forces and spin-orbit coupling
Camp, Jordan	Iodine laser frequency stabilization for LISA
Carbone, Ludovico	Development of a facility for direct force measurements of LISA G.R.S. related disturbances
Choi, Dale	Gravitational Radiation Recoil from Merging Massive Black Hole Binaries
Conklin, John	Center of Mass Determination by Optical Sensing of Velocity Modulation
Cruise, A.M.	The Phasemeter for Lisa Pathfinder
Cutler, Curt	BBO/Decigo and the NS-binary Subtraction Problem
Delgadillo, Rodrigo	Laser communication and ranging for interferometric space missions.
Demorest, Paul	Pulsar Timing Limits on the nHz Gravitational Wave Background
Di Fiore, Luciano	Some progress in the development of an optical readout system for the LISA reference sensor
Dolesi, Rita	The LTP Gravitational Reference Sensor for LISA: experimental verification of the noise model
Fernandez Sopuerta, Carlos	Time Domain Simulations of EMRIs using Finite Element Methods
Finn, Lee	Testbed For LISA Science Analysis
Frolov, Valery	The LIGO searches for compact binary inspiral events and stochastic background radiation
Garcia Marin, Antonio	Interferometric characterization of an optical window for LISA and LISA Pathfinder
Garcia-Cuadrado, Gloria	Graviton Production in Scalar-Tensor Gravitational Theories
Gerardi, Domenico	A Nonlinear Optical Metrology Model and Its Use For Drag-Free System Verification
Goh, Allex	Analytical Solutions for Electrostatic Forces due to Stray Charges and Patch Effects in GRS
Gopstein, Avi	Self-gravity analysis and visualization tool for LISA
Graber, James	Comparing Template-Count-Limited Search Strategies for High Mass-ratio LISA inspirals
Grimani, Catia	Cosmic-ray observations on board the LISA missions
Guntaka, Tulasi Sridhar Reddy	Dimensional Stability of Hexoloy SA® Silicon Carbide and Zerodur™ Materials for the LISA Mission
Hagedorn, Charles	Improved torsion fibers for small force tests
Hayama, Kazuhior	A modified CLEAN method and its application to tomographic reconstruction of LISA Galactic binaries
Higuchi, Sei	Active Thermal Control Experiments for LISA Ground Verification Testing
Himemoto, Yoshiaki	Detecting a stochastic background of gravitational waves in the presence of non-Gaussian noise
Holley-Bockelmann, Kelly	LISA Observations of Galaxy Structure
Holley-Bockelmann, Kelly	A Full Loss Cone in Triaxial Galaxies
Johann, Ulrich	Novel Payload Architectures for LISA
Killow, Christian	Construction of the LISA Technology Package Optical Bench Interferometer
Kopparapu, Ravi Kumar	Population Boundaries for Galactic White Dwarf Binaries in LISA's
Koppitz, Michael	Gravitational Waves from Binary Black Hole Mergers

Lauben, David	Performance Limits for Electrostatic Sensing and Forcing
Livas, Jeffrey	System Validation and Verification Testing for LISA
Lu, Patrick	Methods of Fabricating Grating Patterns on Dielectric and Metal Surfaces
McWilliams, Sean	The Application of Numerical Relativity to LIGO and LISA Data Analysis
Micic, Miroslav	Gravitational Waves From The Hierarchical Buildup Of Intermediate And Supermassive Black Holes
Montemurro, Fabio	Control Design of the Test Mass Release Mode for LISA Pathfinder Mission
Nofrarias, Miquel	Thermal diagnostics tests in the LISA Pathfinder mission
Numata, Kenji	Interferometry testbed platform for LISA ground testing and other telescope missions
Ortega-Ruiz, Jose Antonio	Mission-critical Software Development in LISA Pathfinder
Pai, Archana	Source tracking by LISA with optimal TDI data streams
Peabody, Hume	Low-frequency Thermal Performance of the LISA Sciencecraft
Porter, Edward	A new method for modelling the gravitational wave phase of an insprialling binary system.
Povoleri, Angelo	LISA orbit stability and mission analysis
Regimbau, Tania	Relativistic analysis of the LISA long range optical links
Regimbau, Tania	Stochastic Background from NS-NS binaries
Robertson, David	LTP Interferometry, quadrant photodidodes and dust
Rubbo, Louis	Identification and Removal of Bright Galactic Binaries from LISA's Data
Rubbo, Louis	Event Rate for Extreme Mass Ratio Burst Signals in the LISA Band
Ruiter, Ashley	The Influence of Galactic Mass-Transferring Binaries on the Gravitational Wave Background
Schuldt, Thilo	A High Sensitivity Heterodyne Interferometer as Optical Readout for the LISA Inertial Sensor
Schulte, Hans Reiner	Laser Frequency Stabilization by Using Arm-Locking
Stanga, Ruggero	Ground based 2 DoF test for LISA: a status report and first results
Sum, Ke-Xun	A Robust, Symmetric Grating Angular Sensor for Space Flights
Sun, Ke-Xun	Spectral and power stability tests of deep UV LEDs for AC charge management
Takahashi, Ryuichi	Amplitude and Phase Fluctuations for GWs Propagating through Inhomogeneous Mass Distribution
Taruya , Atsushi	Probing anisotropies of gravitational-wave backgrounds with a space-based interferometer
Thompson, David E.	Framework for Benchmarking Signal-Extraction and Noise-Removal Techniques Supporting GW Detection
Tinto, Massimo	The zero-signal solution as a veto for detecting gravitational wave bursts
Tinto, Massimo	Simulating the White Dward- White Dwarf Galactic background in the LISA data
Vaishnav, Birjoo	Impact of finite differencing accuracy on templates from Numerical relativity
Wand, Vinzenz	LISA Phasemeter prototyping
Ward, Harry	A monolithic fibre collimator for space applications
Wass, Peter	Ground testing of the UV discharge system for LISA and LISA Pathfinder
Wass, Peter	The LISA Pathfinder Radiation Monitor
Weise, Dennis	Optical Design of the LISA Interferometric Metrology System
Wen, Linquing	Studies of the LISA source 4U 1820-30

POSTER ABSTRACTS

Posters are listed alphabetically by last name of the first author..

A Grating Cavity as a Displacement Sensor in Drag-Free Satellites

Graham Allen
Stanford University

We have demonstrated a novel, compact optical sensor suitable for use as a position sensor in a drag-free satellite. The sensing element is a low-finesse Fabry-Perot cavity formed by a Littrow-mounted diffraction grating and the surface of the proof-mass. A fiber delivery system isolates the sensor electronics from the GRS, allowing for better shielding. Using sub-microwatt optical power, the sensor has near zero force noise and stiffness, independent of the gap size. Compared to our prior work, the detection efficiency was improved by adding RF modulation to enable Pound-Drever-Hall locking. A 1.55 um single-frequency fiber laser serves as source and a fiber optic phase modulator is used to apply 800 MHz sidebands. The high modulation frequency maintains a large phase difference between the carrier and side bands in the reflected signal.
The sensor performance was limited to 30 pm/sqrt(Hz) at 10 kHz with 300 uW of optical power and is currently limited by noise in the photo-detector electronics. An improved detector would drop the required optical power to less than 10 uW, while maintaining a sensor resolution of 1 pm/sqrt(Hz). The low frequency performance was limited by the mechanical stability of the cavity itself and does not represent a realistic noise floor. We have estimated the low frequency noise sources and show that they do not represent a significant limitation to the sensor performance.

Extreme mass ratio inspirals in black hole plus torus spacetimes

Enrico Barausse, L. Rezzolla, D. Petroff, M. ansorg
SISSA/ISAS

We compute the waveforms produced by a solar-mass black hole moving along equatorial geodesics in a spacetime containing a massive Kerr black hole and a self-gravitating torus with comparable mass and spin. While the waveforms are calculated using a flat-spacetime approximation (i.e. "kludge" waveforms), the spacetime is the result of accurate and self-consistent solutions of the full Einstein equations. Considering the same orbital parameters or initial velocities, we compare the waveforms obtained over the radiation-reaction timescale with those obtained in a pure Kerr spacetime having comparable mass and spin. Overall, we find that a detector with LISA's sensitivies will be able to determine the differences between the two spacetimes and infer the physical properties of the black hole-torus system. We also investigate in what regions of the space of parameters a "confusion problem" between the two spacetimes may rise and show that a systematic analysis of this type can be crucial for an accurate determination of the properties of the system.

The effect of gauge conditions on waveform templates from binary black hole coalescence

Eloisa Bentivegna, Deirdre Shoemaker, Birjoo Vaishnav
Penn State University

The coalescence of two, supermassive black holes are one of the primary sources of gravitational waves for LISA. The recent success in numerical relativity community to simulate the coalescence of black holes and produce waveforms will give us new insight into the detecion of the binaries. It is well known that numerical simulations of Einstein Equations are greatly affected by the gauge conditions imposed introducing issues such as co-ordinate pathologies and the well-posedness of the equations in the given gauge. A consistency check is therefore needed in order to verify that the various gauge conditions that lead to stable evolutions indeed give rise to the same physical observation. We investigate the impact that the gauge choice can have on detection and parameter estimation if matched filtering was to be used for data analysis of the templates constructed from the full 3D code output.

Caging Mechanism for LISA Pathfinder

Mario Biserni, P. Radaelli, D. Teti, G. Lesci, Alcatel Alenia Space Italia
Alcatel Alenia Space Italia

LISA Pathfinder is a technological precursor of the LISA mission.

To achieve the “free fall” condition of the 2 kg test mass is a major issue of this precursor. A Caging Mechanism Assembly (CMA) is being developing by Alcatel Alenia Space Italia (AASI) devoted to keep the test mass caged, during the launch and the in-orbit commissioning phase, releasing it with a residual translational velocity lower than few micro-meters/sec and an angular velocity lower than about 100 micro-radians/sec.
The Caging Mechanism has to provide two main functions: on one side it should guarantee the grabbing, the positioning and the releasing of the test mass for which an applied very low load is needed, on the other hand the mechanism has to be able to cage the test mass with high loads during the launch (3000 N) without any degradation of the test mass coating and avoiding any surface deformations.
These two such different functions will be provided by two subsystems inside the CMA:
• The Caging Mechanism S/S (CMSS)
• The Grabbing, Positioning and Release Mechanism S/S (GPRM)
In the related Poster the architecture of the Caging Mechanism Assembly and the characteristics, in terms of expected performances, of the two Subsystems (CMSS & GPRM) are given.

Black Hole Spectroscopystudying nonlinear mode mixing in the end phases of binary black hole mergers

Tanja Bode
Penn State

Black Hole Spectroscopy: studying nonlinear mode mixing in the end phases of binary black hole mergers. The coalescence of supermassive black holes is one of the primary sources for LISA. We investigate the effects and relative importance of mode mixing on the complexity of gravitational waveforms emitted during the ringdown phase. In these initial studies we use single black holes created by non-linear waves to control the type and strength of distortion. The simulations use three-dimensional, fully nonlinear code to solve the Einstein equations in full generality.

Test-mass release phase ground testing for the LISA Pathfinder mission

Daniele Bortoluzzi, L. Baglivo, M. Benedetti, F. Biral, P. Bosetti, A. Alcatel
University of Trento

Aim of the LISA Test-flight Package on board the LISA Pathfinder mission is to provide in-flight demonstration of some of the LISA critical technologies in achieving the free-fall condition of a LISA-like test-mass in the bandwidth from 1 to 30mHz. The 2kg test-mass is hosted in the electrode housing inside the Gravitational Reference Sensor with millimetre-scale gaps along all axes. Accordingly, owing to high inertial loads arising during the launch phase the test-mass needs to be firmly secured to the GRS, in order to avoid collision with the surrounding electrodes and housing parts. After the launch and orbit commissioning, the test-mass must be released to floating conditions, in compliance with strict requirements of initial position and velocity, due to the low force and torque authority made available by the capacitive actuation system. The Caging Mechanism Assembly is being designed by Alcatel Alenia Space Italia and it constitutes the GRS subsystem dedicated to cage and release the test-mass.
The release phase to floating conditions has been identified as critical for the entire mission, therefore a ground-based verification of such a function has been deemed necessary. The verification approach adopted is to set both test-mass and release-dedicated plunger mock-ups in representative tribological conditions of the in-flight situation, which influence the imparted velocity to the test-mass. An effort is being made to build a facility that enables to characterize the momentum transfer between the two suspended bodies and verify the compliance of the design of the release-dedicated mechanism subsystem of the Grabbing Positioning and Release Mechanism of the CMA. The proposed experiment and the facility status are here presented and discussed.

Parameter estimation of stellar-mass binaries with eccentric orbits in LISA

Sukanta Bose
Washington State University

The ability to resolve or mitigate the confusion noise in LISA is tightly coupled to the problem of how well one can estimate the parameters of the contributing sources. One of these source species is the galactic stellar-mass binary. Here we examine the effects of time-delay interferometry on the estimation of the parameters of such binaries, including those that have eccentric orbits and chirp. The waveform used are 2.5PN accurate and include periastron precession and radiation reaction.

Multi-band astronomy with LISA

Graziella Branduardi-Raymont
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LISA will return un-precedented data on GW sources; however, its full science potential will be realised only by matching the sources with astrophysical counterparts and correlating their properties over the EM spectrum. Different types of sources require different approaches: direct identification with known EM sources in some cases (like for ultra-compact binaries), and statistical estimation from the systems EM characteristics in others (such as for MBH merger and EMRI rates). In turn, knowledge of the EM properties (e.g. for the ultra-compact binaries) will be crucial in constructing accurate waveforms to aid LISA's signal processing. The consequences of the interaction between GW and EM radiation may also have important implications, for instance on events such as gamma-ray bursts. It is clear that a large degree of synergy is needed between the GW and EM astrophysical communities, in order to build a strong programme of coordinated studies targeted to the needs of LISA. We will describe on-going astrophysical work relevant to these considerations.

Orbital evolution for extreme mass-ratio binaries: conservative self forces and spin-orbit coupling

Lior Burko
University of Alabama in Huntsville

We compare the corrections to Kepler's law with orbital evolution under a self force, and find the finite, already regularized part of the latter in a specific gauge. We apply this method to a quasi-circular orbit around a Schwarzchild black hole for an extreme mass ratio binary, and determine the first- and second-order gravitational self force in a post Newtonian expansion.

Specifically, we find the part of the self-force that is quadratic in the mass ratio to 2PN order, and the part that is cubic in the mass ratio to 1PN (including the Newtonian self force for either order of the self force). Next, we use these results to compute the orbital evolution including both dissipation and the PN conservative self force, and find the gravitational wave forms. Finally, we include spin-orbit coupling, and find that the orbit-integrated conservative spin effects are comparable in magnitude to the conservative self force effects on the waveforms, even though the leading post Newtonian order of the former (1.5PN) is higher than that of the latter.

Iodine laser frequency stabilization for LISA

Jordan Camp, Volder Leonhardt
NASA/GSFC

The use of molecular iodine as a frequency reference for the LISA laser offers a number of advantages, including an absolute reference frequency that lowers the risk of lock acquistion of the constellation; insensitivity to temperature and alignment variations; and frequency tunability. We have built and tested an iodine stabilized laser system that demonstrates these advantages, and that shows a measured frequency stability of ~30Hz/sqrt(Hz) at 10 mHz. These measurements will be described, along with some issues related to space qualification of the system.

Development of a facility for direct force measurements of LISA G.R.S. related disturbances

Ludovico Carbone, Ludovico Carbone, Antonella Cavalleri, Giacomo Ciani, Rita Dolesi, Mauro Hueller, David Tombolato, Stefano Vitale, William Joseph Weber
University of Trento

A four mass torsion pendulum facility for testing of the LISA GRS is currently under development in Trento. With a LISA-like test mass suspended off-axis with respect to the pendulum torsion fiber, the facility allows for a direct measurement of surface force disturbances arising in the GRS. We present here results with a prototype pendulum integrated with a very large-gap sensor that allows an estimate of the intrinsic pendulum noise floor in the absence of sensor related force noise.

The apparatus is currently less than a factor 2 from its mechanical thermal noise limit in the low frequency sensitive bandwidth between 0.1mHz and few mHz. This performance would allow to place upper limit on force noise at the level of 800 fN/sqrt(Hz) between 0.2mHz and few mHz on the overall force noise associated with different GRS prototypes, and with a maximum sensitivity of 300 fN/sqrt(Hz) at 1mHz, within a factor 50 of the LISA goal.

In addition to the characterization of the environmental noise sources that set the ultimate performance of this apparatus, we report on the status of development of testing facilities we are developing for LTP and LISA.

Gravitational Radiation Recoil from Merging Massive Black Hole Binaries

Dale Choi
NASA GSFC

One key area of interest for numerical relativity is calculation of kicks in merging massive black hole binaries where linear momentum, as well as energy and angular momentum, is lost due to asymmetric radiation of gravitational waves. As a result, the merger remnant receives a kick also known as gravitational rocket effect.

High kick velocities, comparable or higher than escape velocites of the host structures, will provide a critical input to our understanding of various aspects of massive black hole evolutions in the universe.

I describe a recent calculation of the kick velocities from simulations of the merging massive black hole binaries. Starting from reasonable initial data for quasi-circular configurations of non-equal mass and non-spinning black hole binary, simulations are carried out through merger and ringdown. From mergers with different mass ratio and different initial separations, kick velocities are estimated based on gravitational waveforms extracted in the wave-zone. I discuss astrophysical implications of the magnitude of the kicks.

Center of Mass Determination by Optical Sensing of Velocity Modulation

John Conklin, Ke-Xun Sun, Dan B. DeBra
Stanford University

Future space-born gravitational wave observatories will measure distance variations between test masses housed inside free flying spacecraft to an accuracy of 20 pm or better. In a dynamic spacecraft environment, such precision requires a large dynamic range measurement, which in turn requires knowledge of the test mass center of mass (CM) location to 0.1 µm or better.

A new technique for determining the center of mass relative to the center of geometry (CG) of a spherical test mass to 0.1 µm or better is being developed. Previous methods involve the pendulous technique, which is typically limited to CM offsets greater than 1 µm due to the increase in 1/f noise as the CM and CG come closer together. The new technique avoids the 1/f noise boundary by rolling the sphere down a set of parallel rails so that the CM offset modulates the sphere’s velocity at the rolling rate frequency. This technique uses a novel optical detection sensor to measure the sphere's trajectory and a Monte Carlo parameter search to recover the phase and magnitude of the CM offset. Initial validation of the technique will occur using spherical proof masses. Later, the apparatus may be modified to accommodate faceted test masses for LISA as well as cylindrical test masses for the STEP mission. The measurement apparatus and optical detection system are discussed, and pre!
liminary results are presented.

The Phasemeter for Lisa Pathfinder

A.M. Cruise
University of Birmingham

The Phasemeter for LISA Pathfinder provides the basic phase data for the mission which relates the laser interferometry to the required acceleration performance. The system has to meet demanding mass, power, performance and environmental specifications. The design chosen has met the performance requirements in laboratory testing and is now close to an operational state. This paper reviews the design, fundamental limitations on phase accuracy and main constraints on the future developments of the system for LISA and beyond.

BBO/Decigo and the NS-binary Subtraction Problem

Curt Cutler
Jet Propulsion Laboratory

The Big Bang Observer (BBO) is a proposed space-based gravitational-wave (GW) mission designed primarily to search for an inflation-generated GW background in the frequency range 0.1-1 Hz. The major astrophysical foreground in this range is gravitational radiation from inspiraling compact binaries. This foreground is expected to be much larger than the inflation-generated background, so to accomplish its main goal, BBO must be sensitive enough to identify and subtract out practically all such binaries in the observable universe.

It is somewhat subtle to decide whether BBO's current baseline design is sufficiently sensitive for this task, since, at least initially, the dominant noise source impeding identification of any one binary is confusion noise from all the others. Here we present a self-consistent scheme for deciding whether BBO's baseline design is indeed adequate for subtracting out the binary foreground.

We conclude that the current baseline should be sufficient. However if BBO's instrumental sensitivity were degraded by a factor 2-4, it could no longer perform its main mission.

Laser communication and ranging for interferometric space missions.

Rodrigo Delgadillo
University of Florida LISA Lab

Gravitational wave detector missions like LISA (Laser Interferometer Space Antenna) require interferometric resolutions on the order of 10 picometers. LISA consists of three spacecraft flying in formation and separated by up to 5Gm. For the laser interferometry used, the spacecraft need to be able to exchange information about the absolute distance between its neighbors, also known as ranging. In addition, the spacecraft need to communicate clock signals for synchronization and other status information about the spacecraft. The challenge is to communicate between the spacecraft without losing the interferometric signal. That is, the mission must have the capacity to leave the interferometric signal pristine while still being able to communicate between the different spacecraft. We hope to achieve this by adding one pair of sidebands, on the laser carrier, for each communication channel that is desired. By modulating the amplitude of the sidebands, we will encode the sid!

ebands with the necessary data signals and leave the carrier signal alone. This project will study the laser communication and ranging systems for interferometer space missions. The laser communication and ranging system will be able to measure both microscopic and macroscopic distances, transfer and synchronize clocks, and transfer data between spacecraft. The goal is to reduce cross coupling between the different communication channels and minimize the number of hardware components.

Pulsar Timing Limits on the nHz Gravitational Wave Background

Paul Demorest, Don Backer
UC Berkeley

High-precision pulsar timing experiments are sensitive to gravitational waves with periods comparable to the experiment duration (~10^-9 Hz). The dominant sources in this frequency range are the stochastic background emitted by unresolved binary massive black holes and/or the decay of cosmic strings associated with early universe phase transitions. We present up to date experimental limits on this emission, which are less than an order of magnitude above the theoretically predicted level of the MBH spectrum, and comparable to cosmic string predictions. We also describe recent instrumentation advances and present preliminary results from an expanded observing program. These new developments will provide improved constraints within the next 5 years. Implications of these results for the LISA MBH merger event rate will also be discussed.

Some progress in the development of an optical readout system for the LISA reference sensor

Luciano Di Fiore, F. Acernese, R. De Rosa, F. Garufi, A. La Rana, L. Milano
INFN - Napoli

The possibility of using an optical readout system, in addition to the capacitive one, for measuring the position of the LISA test masses with respect to the spacecrafts, has been considered since a long time and is encountering increasing interest. This would add some redundancy on the test mass readout, with consequent risk reduction and it could possibly increase the performances of the system because the optical sensor is potentially more sensitive. In this paper, we report on some progress in the development of an optical sensor based on optical levers and position sensitive detectors. In particular, we report the achieved sensitivity and discuss the possible improvements. We also present preliminary results on a real scale, bench top prototype of the optical sensor. The layout is compatible with the present design of the LTP capacitive sensors, and is designed for the measurement of all the six degrees of freedom of the test mass. Finally, we discuss the influence of sensor noise and geometry in the reconstruction of test mass displacements in view of its implementation in LISA.

The LTP Gravitational Reference Sensor for LISA: experimental verification of the noise model

Rita Dolesi, M. Armano, P. Bosetti, L. Carbone, A. Cavalleri, G. Ciani, I. Cristofolini, M. Hueller, D. Tombolato, S. Vitale, W.J. Weber
University of Trento

The LISA low frequency gravitational wave sensitivity will be limited by the quality of free fall of its test masses. Surface effects, such as electrostatics and thermal gradients, play a paramount role within the test masses acceleration noise budget. An experimental campaign to characterize the disturbances generated by the Gravitational Reference Sensor (GRS) employed for drag-free control is crucial to validate the noise modelling associated with a sensor design.

We present here measurements performed with a prototype of the GRS for LISA, with the same large gap capacitance geometry and gold-coated dielectric electrodes of the GRS that will be tested with LTP. These measurements add to the results already obtained with a similar GRS prototype with smaller sensing gaps, different materials and construction technique.

Measured torque noise acting onto a LISA-like test mass, suspended as inertial member of the torsion pendulum, can be converted into significant upper limits to the acceleration noise induced by surface disturbance effects. Single noise source were also characterized at a level significant for LISA: residual dc voltages on the GRS surfaces and their fluctuations, the test mass electrostatic charge, thermal noise associated to electrostatic dissipations, residual spring-like coupling with the spacecraft, and disturbances arising from thermal gradients. The implications of these measurements on the validation of the GRS design and noise model will be discussed.

Time Domain Simulations of EMRIs using Finite Element Methods

Carlos Fernandez Sopuerta
The Pennsylvania State University

I will report on the results of time domain numerical simulations of Extreme-Mass-Ratio Inspirals based on Finite Element Methods. A new technique for solving the perturbative equations corresponding to a point-like object orbiting a non-rotating massive black hole will be described and results corresponding to arbitrarily eccentric orbits will be discussed. Computations performed in the Lorentz gauge

will be also shown and I will discuss the prospect of using these calculations for the evaluation of the gravitational self-force responsible of the inspiral of these binary systems. Finally, I will discuss how to transfer this "technology" to the case in which the central massive black hole is rotating, which is the astrophysically relevant case.

Testbed For LISA Science Analysis

Lee Finn, M Benacquista(1), S Koch(2), S Larson(2), J Romano(3), P Roming(2), L Rubbo(2), H Williams(2)
Penn State

LISA will be sensitive to the grav. wave signature of coalescing supermassive black hole (SMBH) binaries in the centers of distant galaxies, the capture of stellar mass compact objects (SMCOs) about intermediate mass black holes (IMBH), and SMCOs and IMBHs about SMBHs, and the millions of galactic binaries with periods ranging from hours to tens of seconds. The analysis of LISA data to detect and learn from these signals poses unique and exciting statistical, computational, and algorithmic challenges. The Testbed for LISA Analysis (TLA) Project provides collaborative infrastructure to enable and facilitate burgeoning LISA science community's development, validation and comparison of different methods for LISA science analysis to meet these challenges. It includes a well-defined Simulated LISA Data Product (SLDP), whose clean interface allows for the easy exchange information between who model the LISA constellation and its response, the sources LISA will observe, and the analysis methods that can be used to analyze LISA observations; a web-based clearinghouse (at <http://tla.gravity.psu.edu>) providing SLDP libraries and other relevant software and documentation, and links to summaries of proof-of-principle analysis demonstrations and studies; a repository for the SLDP data sets that have been used in these different studies to enable others to extend them; mailing lists for communication among LISA modelers, source modelers, and data analysts; and a program of workshops to allow the burgeoning LISA science community to define and report the results of LISA analysis challenges.

The LIGO searches for compact binary inspiral events and stochastic background radiation

Valery Frolov
LIGO Livingston/Caltech

The LIGO interferometers have reached design sensitivity over a broad frequency range in the last year. The fifth LIGO science run is underway and expected to produce one year of triple coincidence data. The combined LIGO and LISA frequency range of several decades will enable a complementary approach to study astrophysical and cosmological sources such as the stochastic gravitational wave background as well as testing gravitational theory in the regime of strong coupling. In this talk I will present the status of LIGO searches for compact binary inspiral events and stochastic background radiation and discuss the prospect of detecting signals from such sources in the future.

Interferometric characterization of an optical window for LISA and LISA Pathfinder

Antonio Francisco Garcia Marin, Frank Steier, Felipe Guzman, Jens Reiche, Vinzenz Wand Gerhard Heinzel, Karsten Danzmann, Miguel Nofrarias, Josep Sanjuan
Albert-Einstein-Institut Hannover

In LISA and LISA Pathfinder the position fluctuations of drag free test masses will be determined interferometrically to picometer precision. To this end, laser light is brought to interference on an ultra stable optical bench after being reflected on the test mass, which needs to be in an ultra-high vacuum. The present baseline for both missions includes a separate vacuum enclosure for each test mass, so that the sensing laser beam has to pass through an optical window. This window is therefore a transmissive element in the interferometer and its associated pathlength fluctuations are potentially significant.

We have selected an athermal glass that should minimize the thermally induced pathlength changes. Several prototype windows, both mounted and unmounted, have been produced and characterized. The pathlength sensitivity to both temperature fluctuations and temperature gradients has been measured with a dedicated interferometer prototype. We have also compared the long-term stability of the LISA Technology Package interferometer when an optical window is present in the optical path to the situation without window. Finally, glass samples have been radiated and the absorption in the glass after the radiation tests has been measured to be negligible. We present here the results of our measurements, which indicate that using a window does not spoil the interferometer performance.

Graviton Production in Scalar-Tensor Gravitational Theories

Gloria Garcia-Cuadrado
Institute of Space Studies of Catalonia (IEEC)

The emission of gravitational waves by multiple phenomena of astrophysical, cosmological and fundamental physics origin, is predicted not only in Einstein's General Relativity Theory, but also in other theories of gravity. The Universe must be filled with this type of radiation, from the emission due to binary systems, black holes, and supernova explosions… to the Big Bang itself.

Our group works in the arena of scalar-tensor gravitational theories and in that context we study the generation of primordial gravitational waves.

In this contribution we will sketch the main ideas and steps underlying the computation of primordial gravitational wave spectrums arising from these type of theories. We will present a general scheme for this computation and comment on the power that these kind of relic spectrums open to us for testing effective theories of a more fundamental theory of gravitation.

We will focus our attention on the graviton production in different transition epochs of interest during the universe evolution, with gravity described by a general Lagrangian density, and the metric of spacetime described by the usual Friedman–Lemaître–Robertson–Walker (FLRW) line element. In this context, the generation of gravitons arises from the amplification of vacuum fluctuations during the transition epochs. This mechanism was first discussed by Grishchuk in the middle 1970s using a formalism earlier established by Bogoliubov in the completely different arena of Solid State Physics.

Discussion on the possibility of their detection by means of upcoming and upgrades of gravitational wave detectors will also be presented.

A Nonlinear Optical Metrology Model and Its Use For Drag-Free System Verification

Domenico Gerardi
EADs Astrium GmbH

For the Lisa Technology Package, heterodyne laser interferometry is used to measure the distance between two free-falling proof masses. In order to achieve the mission requirements, an Optical Metrology System (OMS) is designed that must be able to monitor the position of the masses along a certain axis (sensitive axis) with a displacement noise level of 10pm/sqrt(Hz)between 3mHz and 30mHz, relaxing as 1/f^2 towards 1mHz. Furthermore, it must provide tilt measurements with an expected noise level of 10nrad/sqrt(Hz) in the same frequency range. Once switched to operation, the OMS serves as both: a science measurement device and a sensor for the Drag-Free control system.

This paper describes a nonlinear OMS model that is used for verification purposes; its key properties are:

- main noise sources and nonlinearities of the LTP optical metrology are reproduced
- high frequency effects in the data processing electronics are mapped to low frequency (10Hz) simulations.

Independent Montecarlo simulations have been carried out to set main model parameters and reproduce the effects of several imperfections of the optical layout on the readout performance.

The model can be used for a variety of analyses such as: demonstration of the OMS initial acquisition (with large test masses angular deviations), verification of Drag-Free System calibration strategies, Drag-Free System real time testing, investigation of the impact of several interferometer readout cross-coupling effects on the overall system performance, assessment of some additional in-flight measurements (currently included in the Operational Master Plan) for characterisation and optimisation of the on-orbit performance of the interferometer. Selected results from the above applications are presented in this paper.

Analytical Solutions for Electrostatic Forces due to Stray Charges and Patch Effects in GRS

Allex Goh
Stanford University

Forces due to stray charges or patch effects are a disturbance source to gravitational reference sensors, including the LISA proof mass. Stray charges accumulate on the non-conductive surfaces of the housing walls of the gravitational reference sensor. Solving the charge-induced potential is a necessary step for calculating the forces.

Numerical methods of calculating the potential may become inaccurate for extreme aspect-ratio cases, corresponding to large depth of the coating gap. In formulating the problems more directly by specifying the governing differential equations and boundary conditions, we obtain analytic solutions for the charge-induced potential using separation of variables, domain decomposition, and enforcing compatibility conditions across the common boundaries.

We also investigate the field around an edge of a cubical GRS proof mass, and compare these results to a spherical GRS model.

Self-gravity analysis and visualization tool for LISA

Avi Gopstein, William Haile, Stephen Merkowitz
Swales Aerospace

Self-gravity noise due to sciencecraft distortion and motion is expected to be a significant contributor to the LISA acceleration noise budget. To minimize these effects, the gravitational field at each proof mass must be kept as small, flat, and constant as possible. Most likely it will not be possible to directly verify that the LISA sciencecraft meets these requirements by measurements; they must be verified by models. The LISA Integrated Modeling team developed a new self-gravity tool that calculates the gravitational forces, moments, and gradients on the proof masses and creates a color coded map of the component contributions to the self-gravitational field. The color mapping provides an easily recognized and intuitive interface for determining the self-gravitational hot-spots of a spacecraft design. Self-gravitational color maps can be generated as true representations of the steady-state, or as an approximation of the variability through computation of the difference values across multiple physical states. We present here an overview of the tool and the latest self-gravity results calculated using a recent design of LISA.

Comparing Template-Count-Limited Search Strategies for High Mass-ratio LISA inspirals

James Graber
Library of Congress

We consider how to search for complex inspiral chirps when constrained by realistic computing resource limits. We compare three alternate strategies for template allocation:

- Allocating templates uniformly throughout the LISA high sensitivity band from .003 Hz to .01 Hz
- Concentrating most templates on a single frequency at the entrance to this band (.003 Hz.)
- Concentrating most templates on a single frequency at the exit from this band (.01 Hz.)

We argue that a search strategy focusing most resources on a single frequency is favored by:

- The ease of "following" a signal once it has been found versus the difficulty of finding it initially,
- The shape of the LISA sensitivity curve
- Computational resource and template count limits.

We devise a combined strategy that uses all three of the above strategies, but primarily the last two. This combined strategy is quite powerful and able to detect inspirals that would be missed by using only the uniform search strategy with the same total template count. Its results are roughly equivalent to a loss in distance of about a factor of three or a loss in event rate of about a factor of 27 compared to estimates based on the computationally unfeasible strategy of coherent integration for a full year.

Cosmic-ray observations on board the LISA missions

Catia Grimani, Michele Fabi
University of Urbino

Galactic and solar cosmic rays with energies larger than 100 MeV/n penetrate and charge the test masses of the LISA missions.
It has been shown that solar gradual
events and galactic cosmic-ray short time fluctuations due to interplanetary processes generate signals that exceed the LISA noise budget.
Silicon detectors will be placed on board the LISA spacecraft to monitor the overall particle flux incident on the test masses. These instruments will allow us to study spatial and temporal characteristics of solar energetic particle (SEP) fluxes associated to evolving coronal mass ejections (CME) and the role of the global solar magnetic field in modulating galactic cosmic-ray fluxes.

Dimensional Stability of Hexoloy SA® Silicon Carbide and Zerodur™ Materials for the LISA Mission

Tulasi Sridhar Reddy Guntaka, A. Preston, G. Mueller, R. Cruz, G. Boothe
University of Florida

In the LISA mission, incoming gravitational waves will modulate the distance between proof masses while laser beams monitor the optical path length changes with 20pm/rtHz accuracy. Optical path length changes between bench components or the relative motion between the primary and secondary mirrors of the telescope need to be well below this level to result in a successful operation of LISA. The reference cavity for frequency stabilization has to have a dimensional stability of a few fm/rtHz. While the dominant effect of temperature fluctuations are well understood in most materials, material internal processes and long term processes in the bonds between different components can dominate the dimensional stability at the pm or fm levels. Zerodur and ULE have been well studied, but the ultimate stabilities of other materials like Silicon Carbide or CFRP are virtually unknown. Chemical bonding techniques, like hydroxide bonding, provide significantly stronger bonds than the standard optical contacts. However, the noise levels are also unknown. In this poster we present our latest results on the stability of Silicon Carbide and hydroxide bonds on Zerodur.

Improved torsion fibers for small force tests

Charles Hagedorn, J.H. Gundlach, S. Schlamminger, S. Pollack
University of Washington/CENPA

Torsion balance-based simulations of the LISA GRS are fundamentally limited by the intrinsic thermal torque noise of the torsion fiber. The torque noise of a torsion fiber is inversely proportional to the square root of the fiber's quality factor Q. While the mechanical Qs of many materials are known from moderate to high frequencies, the Qs of high Q materials at very low frequencies (mHz) is a topic of current research. The traditional torsion fiber choice in modern balances, tungsten, has a Q of approximately 10,000. The Qs accessible with uncoated quartz glass fibers are certainly larger than 100,000 and may be higher than 1,000,000. This poster will describe our efforts, successes, lessons learned, and difficulties encountered when making high-Q fibers from quartz glass.

A modified CLEAN method and its application to tomographic reconstruction of LISA Galactic binaries

Kazuhior Hayama, S. Mohanty, R. Nayak
Center for Gravitational Wave Astronomy, UTB

The tomographic approach [1][2][3] to resolving Galactic binaries is a promising method for characterizing one of the most important class of sources for LISA. As with any other reconstruction method, when binaries are spaced closely in the sky or in frequency, spurious sources appear in the sky maps due to the superposition of the sidelobes of the point spread function (psf) of the tomographic method. We are investigating the usefulness of deconvolution methods in removing these spurious sources, thus increasing the density of sources that can be well resolved. Specifically, we will describe an algorithm based on CLEAN, which we call Penalized CLEAN, that has been implemented on tomographic sky maps of a realistic Galactic binary distribution. Penalized CLEAN differs from the standard CLEAN algorithm in that it uses a criterion for peak selection based on our prior knowledge of the tomographic psf: unlike CLEAN, the peak selected at any given level of iteration need not be the most prominent one in the image. This idea may be useful for other applications of CLEAN in the context of LISA. The performance of penalized CLEAN is demonstrated to be significantly better than standard CLEAN.

[1] S. Mohanty, R. Nayak, gr-qc/0512014
[2] S. Mohanty, R. Nayak, talk in GWDAW10 [3] R. Nayak's talk in this symposium, "Tomographic method for resolving the Galatic binaries: including multiple interferometers and antenna patterns"

Active Thermal Control Experiments for LISA Ground Verification Testing

Sei Higuchi
Stanford University

The Laser Interferometer Space Antenna (LISA) mission uses laser metrology to measure the distance between proof masses in three identical spacecrafts. The total acceleration disturbances to each proof mass are required to be below 3x10^-15 m/s^2 sqrt(Hz) over 0.1 mHz to 1 Hz. Optical path length variations on each optical bench must be kept below 40 pm/sqrt(Hz) over the same frequency range. Thermal noise due to, for example, solar radiation or temperature gradients across the proof mass housing are expected to be significant disturbance sources.

This work focuses on a thermal control system developed for LISA gravitational reference sensor (GRS) ground testing which provides thermal stability better than 1 mK/sqrt(Hz) for f > 0.1 mHz. Such a system could also be used, by further development, as in-flight thermal control of the LISA spacecraft to compensate solar radiation 1/f fluctuations. In a lab environment these specifications can be met fairly readily with sufficient insulation and thermal mass. For spacecraft, the very limited thermal mass requires the use of an active control system that can simultaneously meet disturbance rejection and stability requirements in the presence of a long time delay.

A simple proportional plus integral control law presently provides approximately 1 mK/sqrt(Hz) for over 80 hours. Continuing development of a model predictive feedforward control algorithm will extend performance to below 1 uK/sqrt(Hz) for f > 0.01 mHz and possibly lower.

Detecting a stochastic background of gravitational waves in the presence of non-Gaussian noise

Yoshiaki Himemoto
The University of Tokyo

We discuss the signal processing for detecting a stochastic background of gravitational waves in the presence of non-Gaussian noise. Fundamental methodology to detect weak stochastic signals is to use the cross-correlation statistic which combines the outputs of two gravitational detectors. However, the standard cross-correlation is optimal only if the detector noise obeys a stationary Gaussian process. In reality, deviation from Gaussian process becomes significant and it is important to explore robust statistic for the data analysis in the presence of non-Gaussian noise. In this paper we analyze a generalized cross-correlation statistic which is nearly optimal even in the presence of non-Gaussian noise.

To demonstrate the detection efficiency of generalized cross-correlation statistic, we speciffically consider the two-component Gaussian noise model, where one component forms the main Gaussian and another component forms the non-Gaussian tail. We analytically investigate the performance of this statistic by computing the probability of false alarm versus that of false dismissal and the minimum detectable amplitude.

The resultant detection efficiency of the generalized cross-correlation statistic improves compared to the standard cross-correlation statistic, as the contribution of non-Gaussian tail increases. In particular, as the broadness of non-Gaussian tail increases, the performance of the standard cross correlation get worse, while that of the generalized cross correlation is insensitive.

Validity of our analytical results are also confirmed by performing Monte Carlo simulations.

LISA Observations of Galaxy Structure

Kelly Holley-Bockelmann, Louis Rubbo, Sam Finn
Penn State University

Millions of close white dwarf binaries (CWDBs) throughout the galaxy are expected to generate an unresolved gravitational wave foreground for the proposed Laser Interferometer Space Antenna (LISA). Although LISA is an all-sky, large bandwidth gravitational wave detector, the constellation's motion around the sun will locate a source on the celestial sphere with an accuracy of about 1 square degree. The resolution depends on the source frequency, the angular height of the source from the ecliptic plane, and its signal-to-noise ratio. By convolving LISA's detector response with the distribution of CWDBs, we construct detailed gravitational wave maps of the CWDB sky as seen by LISA. Our CWDB distribution is based on a model of the Milky Way thin disk, thick disk, halo, and bar, as well as a model for the Large and Small Magellenic clouds and globular clusters. We include the positions of the verification binaries, seen as bright resolved objects above the foreground. This map will be useful both as a visualization tool and as a template to discriminate between different models of the CWDB spatial and frequency distribution. We demonstrate how LISA can be used as a tool to measure those structural parameters of our galaxy that are difficult to obtain electromagnetically and how multi-band LISA observations can constrain theories of late-stage binary evolution.

A Full Loss Cone in Triaxial Galaxies

Kelly Holley-Bockelmann, Steinn Sigurdsson
Penn State University

Stars and compact objects that plunge toward a black hole are either 1) captured, emitting gravitational waves as the orbit decays, 2) tidally disrupted, leaving a disc of baryonic material, 3) scattered to a large radius, where they may thereafter avoid encounters with the black hole or 4) swallowed whole, contributing to black hole growth. These processes occur on a dynamical time, which implies that for a static spherically symmetric stellar system, the loss cone is quickly emptied. However, most elliptical galaxies and spiral bulges are thought to be triaxial in shape. The centrophilic orbits comprising the backbone of a triaxial galaxy have been suggested as one way to keep the loss cone around a supermassive black hole filled with stars, stellar remnants, and intermediate mass black holes. We investigate the evolution of the loss cone population in a triaxial galaxy model with high resolution N-body simulations. We find that enough regular orbits flow through angular momentum space to maintain a full loss cone for a Hubble time. This increases the astrophysical capture rate by several orders of magnitude. In the Milky Way, for example, we find that the white dwarf capture rate can be as high as 10^{-5} per year, 100 times larger than previous estimates based on spherical models for the bulge.

Novel Payload Architectures for LISA

Ulrich Johann, Astrium LISA Team
EADS Astrium Germany

As part of the current LISA Mission Formulation Study, Astrium Germany has defined and preliminary assessed novel payload architectures, potentially reducing overall complexity and improving budgets and costs. A promising concept is characterized by a single optical bench and a single active inertial sensor, serving both adjacent interferometer arms via two rigidly connected off-axis telescopes. In-plane triangular constellation "breathing angle" compensation is accomplished in the fixed telescope configuration by common in-field of view pointing actuation of the transmit/received beams line of sight. Therefore a dedicated actuation mechanism located on the optical bench is employed in addition to the mandatory on bench actuators for differential pointing of the transmit and received direction perpendicular to the constellation plane. Both actuators operate in a sinusoidal yearly period. A technical challenge is the actuation mechanism pointing jitter and the monitoring and calibration of the laser phase walk which occurs while changing the optical path inside the optical assembly during re-pointing. Presumably, an internal laser metrology truss derived from the existing interferometry is required. Two-step interferometry (strap down) and a dedicated full laser interferometer (ORO) read out of critical degrees of freedom of the test mass are employed. The single test mass is maintained as cubic, but in free-fall in the lateral degrees of freedom within the constellation plane. Also the option of a completely free spherical test mass with full laser interferometer readout has been conceptually investigated. The spherical test mass would rotate slowly, and would be allowed to tumble. Imperfections in roundness and density would be calibrated by providing attitude information via a grid of tick marks etched onto the surface and monitored by the laser readout.

Construction of the LISA Technology Package Optical Bench Interferometer

Christian Killow, J. Bogenstahl, F. Guzman Cervantes, M. Perreur-Lloyd, D. Robertson, F. Steier, H. Ward
Glasgow University

The Optical Bench Interferometer for LISA technology Package is required to monitor the distance between the test masses at the level of 10pm/sqrt(Hz) in the measurement band. The alignment tolerances for the flight model optical bench require advanced metrology and alignment techniques in combination with flight worthy bonding processes. The design, construction and current status of the flight model LISA Technology Package Optical Bench Interferometer will be presented.

Population Boundaries for Galactic White Dwarf Binaries in LISA's

Ravi Kumar Kopparapu, Prof. Joel E. Tohline
Louisiana State University

Double white dwarf (DWD) binary systems are considered to be among the most promising sources of gravitational waves for LISA. The path that DWD binaries traverse across LISA's "absolute" strain-frequency domain during the detached, inspiral phase of their evolution is well-understood.

Theoretical constraints on the properties of the white dwarf stars allow us also to map out the evolutionary trajectories of DWD binaries during a phase when they are semi-detached and undergoing stable mass transfer. We have identified population boundaries that define distinct sub-domains in LISA's strain-frequency diagram where inspiraling and/or mass-transferring systems will and will not be found; sub-domains where progenitors of Type Ia supernovae reside also are identified. We identify for what subset of these populations it should be possible to measure frequency shifts and, hence, directly follow orbit evolutions, given LISA's anticipated operational time. We show how such measurements should permit the determination of binary system parameters, such as luminosity distances and chirp masses, for mass-transferring as well as inspiraling systems.

This work has been supported in part by NSF grants AST 04-07070 and PHY 03-26311 and in part through NASA's ATP program grant NAG5-13430.

Gravitational Waves from Binary Black Hole Mergers

Michael Koppitz, J. Baker, J. Centrella, D. Choi, J. va Meter
NASA/GSFC

The last several cycles of binary black hole merger represent a large contribution to the expected signal-to-noise ratio. In order to make predictions for this period numerical calcuations of Einsteins equations are necessary. Recent advances in numerical relativity techniques have dramatically improved our ability to make predictions from Einsteins equations for the final stages of the coalsecence of supermassive black hole binaries.

I will report on the latest numerical simulations of binary black holes mergers, their dynamics, and wavesforms. The implications for astrophysics and especially LISA will be dicussed.

Performance Limits for Electrostatic Sensing and Forcing

David Lauben, Allen, Bencze, Byer, Dang, Dorlybonxou, Goh, et al
Stanford University

Engineering model electrostatic sensing and forcing electronics developed for LISA Pathfinder obtain measured displacement sensitivity ~1 nm/rtHz to f ~ 0.1 mHz with $<10^{-6}$ s-1 electrostatic stiffness, and precision forcing to

$a_{max} = 2x10^{-9}$ m/s2 with 20-bit resolution and acceleration noise a < 5x10-15 m/s2. DC bias control for electrode work function compensation achieves 8 uV/¡ÌHz stability for < 2 mV step resolution over +/-50 mV. High-authority forcing to amax = 2x10-7 m/s2 needed for proof-mass initialization and rapid charge measurement is provided by > 30 Vdc fields. Results allow to update noise terms for electrostatic sensing and forcing; a revised model is given.

System Validation and Verification Testing for LISA

Jeffrey Livas
NASA/GSFC

The ideal for system-level testing of instruments and spacecraft is to "test as you fly". Ground testing for the LISA instrument will not be able to meet this ideal in a number of areas, so a combination of testing, simulation, and analysis will be needed instead. This paper will outline some of the areas where direct testing on the ground will not be possible, and discuss some of ideas, concepts and methods to meet that challenge.

The focus of the discussion will be on the optical and system-level aspects of the testing, as many of the issues associated with the proof masses and drag-free spacecraft are covered by the LISA Pathfinder mission.

Methods of Fabricating Grating Patterns on Dielectric and Metal Surfaces

Patrick Lu
Stanford University

Grating angular sensors can accurately monitor angular orientation of LISA and LIGO test masses. We have demonstrated 5 nrad/Hz1/2 sensitivity with a grating. This paper presents the techniques used to create gratings on materials that will go into making the proof masses of future gravitational wave detectors. As grating tip/tilt sensing will require two-dimensional grating structures with duty cycles and unit cell shapes that are as of yet undetermined, we concentrate on approaches that allow us to readily generate complex patterns. This paper discusses e-beam lithography for dielectric surfaces, and mechanical trans-imprinting and focused ion-beam writing for gold. These methods are more flexible than more traditional techniques, such as the exposure of photoresist with crossed laser beams. Grating patterns suitable for optical sensing have been successfully demonstrated on dielectric and gold surfaces.

The Application of Numerical Relativity to LIGO and LISA Data Analysis

Sean McWilliams, John Baker, Evan Ochsner
University of MD, NASA/GSFC

Recent advancements in the field of numerical relativity now make it possible to utilize the previously-unmodeled merger segment of a binary black hole (BBH) inspiral, merger, and ringdown in the search for and characterization of gravitational wave signals. The implications for LIGO and LISA include an enhanced signal-to-noise ratio for all BBH events that merge in-band due to the increased contribution of the merger signal, which increases the event rate and improves parameter estimation, and a means to test different theories of gravity by comparing measured signals to simulations in the strong field regime of the merger. We present some preliminary expectations of the impact of these results on gravitational wave data analysis.

Gravitational Waves From The Hierarchical Buildup Of Intermediate And Supermassive Black Holes

Miroslav Micic, Kelly Holley-Bockelmann, Steinn Sigurdsson
Pennsylvania State University

We performed high-resolution cosmological N-body simulation using GADGET in LambdaCDM universe and created a merger tree for dark matter halos (DMH) , subhalos and massive black holes (MBH) in the redshift range $0<z<20$. MBHs are end product of Population III stars. We seed them by using Population III stars supernova rates at the centers of DMHs at redshifts $12<z<20$. DMHs merge and bring MBHs close enough to form binaries and coalesce. As black holes coalesce, they form more massive black holes which populate galaxies and cluster at galaxy centers through dynamical friction where they finally form supermassive black holes. Our merger tree tracks growth of MBHs through mergers and calculates MBHs merger rates for LISA. We also calculate the expected gravitational wave signal for massive black holes mergers as function of redshift independent of the mass ratio of merging black holes. This is the full treatment of the hierarchical buildup of intermediate mass and supermassive black holes where only the IMF and the mass growth scenario for MBHs is assumed. We study different MBHs growth scenarios, through black holes mergers only or mergers combined with gas accretion.

Control Design of the Test Mass Release Mode for LISA Pathfinder Mission

Fabio Montemurro
EADs Astrium GmbH

The LISA Technology Package (LTP) features two high precision gravitational reference sensors (GRSs). Each GRS encompasses a free floating cubic test mass (TM) surrounded by a capacitive housing. The electrodes, hosted by the housing, form a set of variable capacitors with the TM and are used both for TM sensing and suspension. Moreover, each GRS contains a Caging Mechanism (CM) which sustains the TM during launch. Before the science phase of the mission begins, each TM is set free and the control system performs the TM Release Mode. This mode shall: capture the TMs after release; guide and control them to their reference position; compensate disturbances; provide a three axis control attitude for the spacecraft; guarantee a safe backup mode for in-flight operations.

This paper presents the design of the TM Release Mode: it covers equipment modelling, actuation strategy selection, disturbances estimation, controller law definition, performance results, and stability and robustness analyses.

Thermal diagnostics tests in the LISA Pathfinder mission

Miquel Nofrarias, JA Lobo, J. Ramos-Castro, J. Sanuan
Institut d'Estudis Espacials de Catalunya

The LISA Technology Package (LTP) on board the LISA Pathfinder mission will provide a unique opportunity to characterize the disturbance forces affecting the geodetic motion of test masses in space gravitational wave detectors. Environmental conditions in the LTP are expected to contribute to the noise budget, limiting the mission performance at the lower end of the measurement bandwidth (MBW).

The LTP Diagnostic Subsystem has as main goal to monitorize and characterize disturbances arising from thermal, magnetics and particle charging effects. These tasks will be carried out by sets of sensors and active elements (in the thermal and magnetic case) which will induce controlled perturbations on selected sensitive positions. In this presentation, we will focus on the thermal diagnostic subsystem, composed by a set of 22 high stability sensors distributed within the LTP Core Assembly (LCA) and a set of 14 precision heaters located at some strategic points where thermal shocks are envisaged to produce an output signal, measurable by the metrology subsystem.

Both thermal simulations and experimental results are used to define a thermal test profile, to be performed in flight, in terms of power and signal characteristics which will allow for a detailed modeling of the thermal noise contribution in the measurement bandwidth. I will report on the results of this study.

Interferometry testbed platform for LISA ground testing and other telescope missions

Kenji Numata, Jordan Camp
NASA/GSFC

The LISA interferometer must be able to measure 10pm level of relative displacement between spacecrafts over 1000 seconds. Its ground verification is a very significant and critical task. However, the verification measurement is very difficult, because it must be done in the presence of huge environmental disturbances, such as seismic and thermal drifts. To overcome this problem, we built an interferometer testbed in which the environmental motions are measured and suppressed by an interferometric sensing and an active feedback control, resulting in an environment stable at the level of 30 pm over 1000 seconds (within a factor of 3 of the LISA requirements). The testbed has potential applications to other future NASA telescope missions which also demand precise long-term stability. In this talk, we will present the results obtained in our interferometry testbed.

Mission-critical Software Development in LISA Pathfinder

Jose Antonio Ortega-Ruiz
Institute for Space Studies of Catolonia (IEEC)

From a technological standpoint, LPF is a major engineering undertaking, which involves a variety of (sometimes brand new) hardware and software developments. One of the components of LPF is the Data

Management Unit (DMU), in charge of coordinating the acquisition of data from the laser interferometer as well as the different diagnostic subsystems that conform the mission. Thus, the DMU will play the part of a communications gateway between the central on-board computer in the spacecraft and several subsystems, with a considerable amount of autonomous operative and control responsibilities which grant a dedicated on-board computer and associated software. This presentation describes the architecture and main design traits of the software in charge of controlling the DMU. Functionally, it must meet a series of non-trivial requirements, including real-time performance and the adequate use of redundant communication channels. Moreover, the architecture must be flexible enough to accomodate in-flight modifications of the executable software (in the form of telemetry patches), while, at the same time, ensuring the robustness of this mission-critical application. In addition to describing how and why we combine off-the-self components (like real-time operating systems) with special purpose software in order to meet our ends, we intend to provide an overview of the engineering processes and development standards in place to ensure the accomplishment of the stringent requirements we face.

Source tracking by LISA with optimal TDI data streams

Archana Pai
Max Planch Institute fur Gravitationsphysik (AEI)

As LISA detector moves in its orbit around the sun, any stationary LISA source in the barycentric frame appears to follow a certain track in LISA frame. In our previous work -- PRD 68 (2003) 122001, we had shown how to optimally track a monochromatic LISA source by appropriately switching to the corresponding directional optimal TDI data combinations. We had obtained an improvement of 30% at low frequencies and as high as 90% at around 20mHz compared to Michelson combination while tracking these monochromatic sources if LISA is operated in a network mode. Here, we extend this approach to different LISA sources and show that our data combinations are general enough even to apply for evolving sources.

Low-frequency Thermal Performance of the LISA Sciencecraft

Hume Peabody, Stephen Merkowitz
Swales Aerospace

Thermal fluctuations are a major contributor to the low-frequency performance of LISA. The LISA orbits and sciencecraft are designed to provide as quiet a thermal environment as possible. Since producing such a quiet thermal environment on-ground is very challenging, detailed modeling is necessary to verify that the sciencecraft will meet its on-orbit performance requirements. We developed a thermal Finite Element Model (FEM) of the current LISA design based on the solid model. This thermal model is being used to understand the thermal behavior of the LISA sciencecraft design, in particular for the thermal isolation aspects. We present the latest LISA temperature fluctuation estimates and discuss some techniques developed to reduce the computation time. The FEM was imported into ThermalDesktop, which was used to generate radiation interchange factors and the corresponding FE thermal network. The complete model was then solved using the TMG solver, which is better optimized for this type of model. Various sinusoidal input heat loads were applied and a new curve fitting technique was used to extract the fluctuating component of the response signal before the solution had reached quasi-steady state, greatly reducing the necessary solution time. The transfer functions were then derived from the input signal and response fluctuations and are presented herein.

A new method for modelling the gravitational wave phase of an insprialling binary system.

Edward Porter
Montana State University - Bozeman

In order to improve convergence of the post-Newtonian approximation to the gravitational wave binding energy and flux functions appearing in the phase of the wave, many methods such as resummation have been proposed. The problem is that most of these methods, such as Pade approximation, suffer from the fact that their rate of convergence is intrinsicly linked to the convergence of the initial PN expansion. We propose a new approximation for the binding energy and flux functions based on Chebyshev polynomials. Not only does this method provide a better model for these functions, but the convergence of this method is independent of the convergence of the initial expression as it is closely linked to the minimax polynomial. Templates created with this method provide higher fitting factors and better parameter extraction, when compared to other methods currently in use by the ground-

based community. This work will also be extendable to the improved modelling of the inspiral of Supermassive black holes in LISA.

LISA orbit stability and mission analysis

Angelo Povoleri
EADS Astrium

LISA is composed of 3 spacecraft in an equilateral triangle formation. The baseline formation has a 5million km radius and lies in a heliocentric orbit 20deg away from the Earth.

Earth's gravity induces a perturbation on the nominal Keplerian motion of the formation, generating a change in the relative ranges and thus a Doppler that can be very harmful for the scientific goals of the mission. Zero station keeping options are preferred, so alternative passive solutions have to be found. This paper presents results obtained by optimising the formation design, particularly the orientation of the eccentricity vectors. Formation design optimisation proves to be an effective strategy, succeeding in keeping the relative range rate between any two spacecraft below 13m/s.

Another possible source of perturbation arises from the self-acceleration induced on the formation by the imperfect mass distribution on each spacecraft. The effect of this perturbing acceleration on the motion of the formation has been studied, and the formation design has been re-optimised assuming several levels of perturbation. This approach has shown the result that such effect can be even beneficial on the formation stability, provided that the acceleration doesn't exceed 1e-8m/s2.

The transfer to the optimal stability formation has then been optimised, assuming a launch window throughout the year. Mission Dv to a specific target is quite sensitive to the launch date: trailing formations are most effectively reached if the launch occurs at Earth's perihelion (summer), while the opposite applies to leading formations. A strategy where leading and trailing formations are alternatively targeted according to the launch date has proved to be the most effective in keeping the Dv as low as possible.

Relativistic analysis of the LISA long range optical links

Tania Regimbau, B. Chauvineau, S. Pireaux, J.Y. Viney
ARTEMIS/OCA

The joint ESA/NASA LISA mission consists in three spacecraft on heliocentric orbits, flying in a triangular formation of 5 Mkm each side, linked by infrared optical beams. The aim of the mission is to detect gravitational waves in a low frequency band. For properly processing the science data, the propagation delays between spacecraft must be accurately known. We thus analyse the propagation of light between spacecraft in order to systematically derive the relativistic effects due to the static curvature of the Schwarzschild spacetime in which the spacecraft are orbiting with time-varying light-distances. In particular, our analysis allows to evaluate rigorously the Sagnac effect, and the gravitational (Einstein) redshift.

Stochastic Background from NS-NS binaries

Tania Regimbau
Observatoire de la Cote d'Azur

I will present monte carlo simulations of the galactic and extra-galactic population of double neutron star binaries and will discuss their contribution to the gravitational stochastic background and to the LISA confusion noise.

LTP Interferometry, quadrant photodidodes and dust

David Robertson, H. Ward, J. Bogenstahl, F. Guzman Cervantes, C. Killow, M. Perreur-Lloyd
Glasgow University

The LTP interferometer uses heterodyne interferometry to measure the changes in separation between two freely floating test masses.

In the "measurement path" of the interferometer the optical beam is reflected from both test masses. Angular movements of the test masses will therefore lead to angular movements of the "measurement" beam. This angular movement, combined with imperfections in the interferometer, can lead to apparent longitudinal signals in the interferometer's output. We analyse the significance of this effect for the LTP interferometer for the cases of a quadrant photodiode, with a "dead space" between the quadrants, and for dust particle contamination of the interferometer. From the analysis we derive linked requirements on the allowable level of test mass angular noise, the precision of centering of the photodiodes, and the allowable level of dust contamination.

Identification and Removal of Bright Galactic Binaries from LISA's Data

Louis Rubbo, N. Cornish and R. Hellings
Penn State

Within the Laser Interferometer Space Antenna (LISA) band there will be thousands of quasi-monochromatic galactic binaries. The galactic binary population will form a confusion limited background below which individual systems cannot be distinguish from the collective population. Above the galactic background will be a few thousand relatively "bright" binaries, which due to their larger signal-to-noise ratios, can be individually resolved. However, significant correlations may still exist between the bright systems, which in turn will require unique analysis techniques capable of resolving the individual systems.

Here we describe a hierarchal and iterative data analysis algorithm used for searching and removing the bright monochromatic binaries from the LISA data streams. The algorithm uses an F-statistic as an initial solution finder followed by an iterative least squares fitting which refines the parameter estimates. Using the above algorithm, referred to as Slice & Dice, we demonstrate the removal of multiple correlated galactic binaries from simulated LISA data. Initial results indicate that Slice & Dice may be a useful tool for analyzing the forthcoming LISA data.

Event Rate for Extreme Mass Ratio Burst Signals in the LISA Band

Louis Rubbo, Kelly Holley-Bockelmann and Lee Samuel Finn
Pennsylvania State University

Stellar mass compact objects in short period ($P\lesssim10^3$~s) orbits about a $10^{4.5}$--$10^{7.5}\,\text{M}_{\odot}$ massive black hole (MBH) are thought to be a significant continuous-wave source of gravitational radiation for the ESA/NASA Laser Interferometer Space Antenna (LISA) gravitational wave detector. These extreme mass-ratio inspiral sources began in long-period, nearly parabolic orbits that have multiple close encounters with the MBH. The gravitational radiation emitted during the close encounters may be detectable by LISA as a gravitational wave burst if the characteristic timescale of a passage is less than 10^5~s. Scaling a static, spherical model to the size and mass of the Milky Way bulge we estimate an event rate of $\sim\!15~\textrm{yr}^{-1}$ for such burst signals, detectable by LISA with signal-to-noise greater than five, originating in our galaxy.

When extended to include Virgo cluster galaxies our estimate increases to a gravitational wave burst rate of $\sim\!18~\textrm{yr}^{-1}$. We conclude that these extreme mass-ratio burst sources may be a steady and significant source of gravitational radiation in the LISA data streams.

The Influence of Galactic Mass-Transferring Binaries on the Gravitational Wave Background

Ashley Ruiter, K. Belczynski, M. Benacquista, and S. Larson
New Mexico State University

Compact object binaries, mostly double white dwarfs, are believed to present a source of confusion-limited noise for LISA. In LISA's low-frequency regime, this noise may rise above that of the instrumental noise level and hence hinder the detection of other types of gravitational wave signals, e.g., from extreme mass ratio in-spirals. The level of noise will also be indicative of the number of double white dwarfs in the Galaxy, which will put constraints on the Galactic star formation history. At higher frequencies, many individual systems will be resolved with LISA, offering an opportunity to determine several physical quantities which will further extend our knowledge of binary evolution and progenitors of Type Ia supernovae. In most studies up-to-date, only detached populations of compact object binaries have been considered. Here, using population synthesis, we investigate the influence of the Galactic mass-transferring compact binaries on the shape and strength of the LISA signal, and compare our findings to the results corresponding to the signal arising exclusively from detached systems. We use the StarTrack population synthesis binary evolution code, which is significantly different from the codes used in earlier studies, to generate the population of Galactic binary systems. It is found that 99.5% of these systems are double white dwarfs. We present the resulting LISA gravitational wave signal and discuss the contribution to the noise arising from each population (Roche Lobe Overflow vs. detached systems), and comment on the importance of these populations concerning the confusion-limited regime. We also compare our results to those of the previous studies of Hils et al. and Nelemans et al.

A High Sensitivity Heterodyne Interferometer as Optical Readout for the LISA Inertial Sensor

Thilo Schuldt, D. Weisel, C. Braxmaier, A. Peters, U. Johann, FH Donstanz, Germany, HU Berlin, Germany
EADS-Astrium GmbH

LISA utilizes a high performance position sensor in order to measure the translation and tilt of the free flying test mass with respect to the optical bench. Depending on the LISA optical bench design, this position sensor must have up to pm/sqrt(Hz) sensitivity for the translation measurement and up to nrad/sqrt(Hz) sensitivity for the tilt measurement. For this purpose, EADS-Astrium GmbH – in collaboration with the Humboldt-University Berlin and the University of Applied Sciences Konstanz – develops a heterodyne interferometer combined with differential wavefront sensing for the tilt measurement where the kHz heterodyne frequency is generated by use of two acousto-optic modulators. The interferometer design exhibits maximum symmetry where measurement and reference arm have the same frequency and polarization. It is therefore, in principle, free of frequency and polarization mixing. The interferometer can be set up free of polarizing optical components preventing possible problems with thermal dependencies not suitable for space environment.

As a first demonstrator, we developed a mechanically highly stable and compact setup which is located in a temperature stabilized vacuum chamber. Preliminary results of the translation and tilt measurements of our interferometer will be presented and limitations will be discussed. A planned future setup will utilize hydroxide-catalysis bonding technology to realize a quasi-monolithic setup where both the optical components and the base plate are made out of glass materials (e.g. Zerodur). This bonding technology – already space qualified fulfilling the LISA Pathfinder requirements – will lead to a very compact, modular and high sensitivity interferometer suitable for LISA, but also with potential applications beyond.

Laser Frequency Stabilization by Using Arm-Locking

Hans Reiner Schulte, Peter Gath, Markus Herz
EADs Astrium GmbH

In order to achieve the required measurement performance on LISA, the laser frequency must be stabilized to approximately 30 Hz/sqrt(Hz)„e[1+(1mHz/f)^4]^(1/2) in the LISA measurement bandwidth from 0.03 mHz up to 1 Hz for the master laser in the constellation. All other lasers are offset locked to the master laser such that the Doppler shifts are taken into account and beat signals between 3 MHz and 18 MHz are produced on all detectors in the constellation.

Ensuring sufficient frequency stability can be established by different methods. A straight forward approach is to use an optical cavity. It turns out that a cavity alone significantly drives the thermal stability requirements at low frequencies. Therefore, different versions of arm-locking are considered in order to provide both, frequency stabilization at low frequencies as well as at high frequencies. While it is obvious how a stable feedback loop at low frequencies can be achieved, a stable control system with noise suppression also at high frequencies can only be achieved when at least two arms are combined in the overall control approach.

In the framework of this paper, the Sagniac and the Michelson locking scheme are described and it is shown that the resulting system is stable and achieves significant noise suppression at frequencies up to around 100 Hz. The theoretical results are supported by frequency and time-domain simulations. Results from the time-domain simulation are currently being used for an end-to-end simulation of the LISA measurement data chain that involves the Synthetic LISA simulator, the laser frequency noise generated from the arm-locking simulation, the digital part of the phasemeter, and the TDI data post-processing.

Ground based 2 DoF test for LISA: a status report and first results

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On-ground tests are required to study the couplings between LISA test masses and the spacecraft that host them. In order to study couplings that might act between two or more degrees of freedom in measuring the position and acting on the position of each test mass, a many degrees of freedom facility is needed. Here we present a status report and the first results of the 2 DoF double torsion pendulum that will be used to test LISA Gravitational Reference Sensor (GRS) on the ground. The facility will be located at INFN Laboratory at Gran Sasso (LNGS), in order to reduce the local ambient noise that limits the sensitivity of the system.

A Robust, Symmetric Grating Angular Sensor for Space Flights

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Angular sensing is needed in LISA and BBO for proof mass sensing and telescope steering. We have proposed using a grating as a high sensitivity angular sensor by measuring the movement of the diffracted beams. We have previously demonstrated a grating angular sensor with a quad detector, with an off-the-shelf grating and a 1064 nm laser. A grating with 935 lines/mm was custom designed and fabricated. This grating produces a symmetric first order diffraction angle of 84 degrees for normal incidence at a wavelength of 1064 nm. A symmetric grating sensor based on this grating has achieved a 5 nrad/Hz1/2 sensitivity with a 5 cm working distance. Compared with single-side grating sensors, symmetric grating sensors can give pure rotational information with appropriate signal processing. Using common mode rejection by subtracting the outputs from each detector, the two-detector symmetric grating sensor is also more robust against laser frequency and amplitude noise. We are making in-house efforts for fabricating grating patterns on dielectric and gold surfaces and are in the process of experimenting with these gratings as angular sensors.

Spectral and power stability tests of deep UV LEDs for AC charge management

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Deep UV LEDs have recently been used in AC charge management experiments for gravitational reference sensors. The UV LED based charge management system offers the advantages of small size, low weight, and low power consumption compared to plasma sources. The AC charge management technique, which is enabled by easy modulation of UV LED output, achieves higher dynamic range for charge control. Further, the high modulation frequency out of the gravitational wave detection band reduces disturbances to the proof mass. However, there is a need to test and possibly improve the lifetime of UV LEDs, which were developed only a year ago. We have initiated a series of spectral and power stability tests for UV LEDs and designed experiments according to the requirements of AC charge management. We operate UV LEDs with a modulated current drive, and maintain the operating temperature at 21 celsius, close to the LISA spacecraft working condition. The testing procedures involve measuring the baseline spectral shape and output power level prior to the beginning of the tests, and then re-measuring the same quantities periodically. These tests are in progress.

Amplitude and Phase Fluctuations for GWs Propagating through Inhomogeneous Mass Distribution

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When a gravitational wave (GW) from a distant source propagates through the universe, its amplitude and phase change due to gravitational lensing by the inhomogeneous mass distribution. We derive the amplitude and phase fluctuations, and calculate these variances in the limit of a weak gravitational field of density perturbation. If the scale of the perturbation is smaller than the Fresnel scale $\sim 100 {pc} (f/{mHz})^{-1/2}$ (f is the GW frequency), the GW is not magnified due to the diffraction effect. The rms amplitude fluctuation is $1-10 \%$ for $f > 10^{-10}$ Hz, but it is reduced less than 5% for a very low frequency of $f < 10^{-12}$ Hz. The rms phase fluctuation in the chirp signal is $\sim 10^{-3}$ radian at LISA frequency band ($10^{-5} - 10^{-1}$ Hz). Measurements of these fluctuations will provide information about the matter power spectrum on the Fresnel scale ~ 100 pc.

Probing anisotropies of gravitational-wave backgrounds with a space-based interferometer

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We discuss the reconstruction of a skymap of stochastic gravitational-wave backgrounds (GWBs) observed via space-based interferometer. In the presence of anisotropies in GWBs, the cross-correlation signals of observed GWBs are inherently time-dependent due to the non-stationarity of the gravitational-wave detector. Since the cross-correlation signal is obtained through an all-sky integral of primary signals convolving with detector's antenna pattern function, time-modulated cross-correlation signals can be used to reconstruct an intensity map of the GWB. We first investigate the angular sensitivity of the space interferometer LISA based on the spherical harmonic analysis. We found that the detectable multipole moments of LISA with high signal-to-noise ratio is restricted to the range, l<10. Based on this, we present a simple reconstruction method to make a skymap of GWB. The reconstruction technique is demonstrated for the specific model of GWB taking account of the intrumental noises.

Framework for Benchmarking Signal-Extraction and Noise-Removal Techniques Supporting GW Detection

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A team at NASA Ames is developing a Framework for benchmarking and comparing signal-extraction and noise-interference-removal methods that are applicable to interferometric Gravitational Wave (GW) detector systems. The primary use is towards comparing signal and noise extraction techniques at LISA frequencies from multiple (possibly confused) gravitational wave sources. The framework is built around readily available COTS products, but it includes substantial hybrid learning/classification algorithms. Published methods for signal extraction and interference removal at LISA frequencies are being encoded so that the "pathology" of GW Sensitivity Space can be explored under each method. These include coherent line removal through harmonics mappings; pattern tracking data transforms; isolation of specific Fourier Transform frequencies that minimize instrument response function; discovery of unexpected data patterns in LISA events; and specific GW filtering methods that could begin with PCA and incorporate a suite of statistical learning algorithms, parametric or non-parametric Bayesian estimation tools, physics-based regularization methods, and other Kernel and Support Vector Machine Methods for pattern recognition and classification. Where methods overlap, optimal, more flexible, and empirically justified choices can be made for both signal acquisition and noise removal development. Furthermore, synthetic datasets and source models can be created and imported into the Framework, and specific degraded numerical experiments can be run to test the flexibility of the analysis methods. The Framework should provide an extension beyond the On-line Sensitivity Curves Generator toolkit of the LISA Mission Science Office.

The zero-signal solution as a veto for detecting gravitational wave bursts

Massimo Tinto
Jet Propulsion Laboratory

Coherent analysis techniques for detecting gravitational-wave bursts simultaneously test multiple interferometric data for consistency with the expected properties of the signals. These techniques assume the output of the detectors to be the sum of a stationary Gaussian noise process and a gravitational-wave signal, and they may fail in the presence of transient non-stationarities affecting the LISA data. In order to address this problem we introduce an additional consistency test that is robust against noise non-stationarities and allows one to distinguish between gravitational-wave bursts and noise transients.

Simulating the White Dward- White Dwarf Galactic background in the LISA data

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In the low-part of its frequency band, the LISA data will contain a stochastic signal consisting of an incoherent superposition of hundreds of millions of gravitational wave signals radiated by inspiraling white-dwarf binaries present in our own galaxy. In order to estimate the LISA response to this background, we have simulated a population of white-dwarf binaries and used an analytic expression of the LISA Time-Delay Interferometric responses to the gravitational radiation emitted by such systems. This allowed us to implement a computationally e±cient and accurate simulation of the background in the LISA data. We find the amplitude of the galactic white-dwarf binary background in the LISA data to be modulated in time with a period of 1 year, reaching a minimum equal to about twice that of the LISA noise for a period of about two months around the time when the Sun-LISA direction is roughly oriented towards the Autumn equinox.

This modulation means that the galactic white-dwarfs background will be observable by LISA as a cyclostationary random process with a period of one year. We summarize the theory of cyclostationary random processes and present the corresponding generalized spectral method needed to characterize such a process in the LISA data. We find that, by measuring the generalized spectral components of the white-dwarf background, LISA will be able to infer properties of the distribution of the white-dwarfs binary systems present in our Galaxy [1].

[1] J. A. Edlund, M.Tinto, A. Krolak, and G. Nelemans, Phys. Rev. D, 71, 122003 (2005)

Impact of finite differencing accuracy on templates from Numerical relativity

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The promise of numerical relativity providing waveforms from the coalescence of supermassive black holes is within reach given the rapid progress in numerical relativity over the past year. Using these numerically generated waveforms to construct a template bank raises a crucial issue: How accurate these simulations have to be to enable the detection and parameter estimation of a binary black hole signal? We investigate the dependence of overlaps and parameter estimation on numerical resolution in the test case of numerically generated Zerilli ringdown waveforms. We use this simple case to propagate the numerical errors caused by truncation in the finite differencing for both second and fourth order schemes in terminology of the overlaps used in data analysis. The resolutions in our analysis are chosen to match those used in fully non-linear, three dimensional numerical relativity codes.

LISA Phasemeter prototyping

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The primary measurement of the LISA interferometers will be the phases of a set of sinusoidal beat notes coming from photodetectors on the optical bench. These beat notes are in the range 1...20 MHz, and their frequency varies by up to 4 Hz/s due to the varying Doppler shift. The beatnotes in those phasemeter channels used for the long arm measurement originate from the interference of a local oscillator with the incoming very weak light (100 pW), and hence have a small amplitude,

The required sensitivity of the phase measurement is 6.3 urad/sqrt(Hz)@1mHz, corresponding to a pathlength noise of 1 pm/sqrt(Hz).

Besides the beatnotes, the incoming signal also contains a spread-spectrum encoded datastream that is used for inter-spacecraft. We present our approach of an all digital implementation of such a phase measurement system.

A monolithic fibre collimator for space applications

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LISA Pathfinder – and LISA – present demanding performance requirements on the coupling of laser light from single mode fibre to free space. We present details of the design and construction of an all-fused-silica collimator, bonded together using the hydroxide-catalysis technique. During assembly the collimator can be adjusted for the desired output beam parameters, and, once bonded, the collimator provides excellent thermal stability of the output beam alignment. Further advantages are that the collimator is intrinsically magnetically clean and that it can be hydroxide-catalysis bonded to other parts of an associated interferometer.

Ground testing of the UV discharge system for LISA and LISA Pathfinder

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Imperial College London

We present the results of tests that demonstrate the functionality and performance of the test mass discharge system for LISA and LISA Pathfinder. Free floating in space, the LISA and LISA Pathfinder test masses will accumulate charge from cosmic rays and solar energetic particles. Using the photoelectric effect, a system of UV illumination will discharge the test masses. Testing of this UV discharge system, integrated with the LISA Pathfinder engineering model sensor in the torsion pendulum facility at the University of Trento has shown that: isolated test masses can be charged positively or negatively using UV light; the rate of charging can be measured; the test mass potential can be controlled by combining UV illumination and DC biases applied to the electrodes surrounding the test mass; the test mass charge can be continuously held near zero with a combination of light illuminating the test mass and the surrounding sensor housing, and a relevant upper limit placed on the acceleration noise caused by this continuous discharging.

The LISA Pathfinder Radiation Monitor

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We present the concept, design and testing of the radiation monitor for LISA Pathfinder. Cosmic rays and solar energetic particles will cause charging of the LISA Pathfinder test masses producing unwanted disturbances which could be significant during a large solar eruption. A radiation monitor on board LISA Pathfinder, using silicon PIN diodes as particle detectors, will measure the particle flux responsible for charging. It will also be able to record energy-spectral information to identify solar energetic particle events. The concept and design of the monitor were based on Monte Carlo simulations which allow detailed predictions of the radiation monitor performance. We present these predictions as well as the results of high energy proton tests carried out at the Paul Scherrer Institute, Switzerland. The tests show good agreement with our simulations and confirm the capability of the radiation monitor perform well in the space environment.

Optical Design of the LISA Interferometric Metrology System

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EADs Astrium GmbH

Within the context of the LISA Mission Formulation Study, we have developed a detailed concept for the optical layout of the LISA payload, which consists of two movable assemblies per spacecraft, each pointing to its respective remote spacecraft to form a constellation triangle of 5 million kilometer arm length. The movable assemblies comprise a Cassegrain telescope, an optical bench, and a gravity reference sensor with a free floating proof mass, which delimits the respective arm.

Differential changes in the distances between the two proof masses of each arm, caused by the passage of a gravitational wave, are detected by a combination of heterodyne interferometry and differential wavefront sensing. The optical metrology is characterized by a "strap-down" approach, in which an optical readout provides position as well as attitude information of each test mass with respect to its local optical bench. This information is combined with a second interferometric measurement of the distance between the local and the remote optical bench to yield the science signal for one interferometer arm. A "frequency swap" between transmitted and local reference beam is introduced to minimize the impact of straylight from each high power transmit beam on the local heterodyne detection.

The above measurement principles are reflected in the current optical bench design, which includes ultra high precision opto-mechanics, all optical detectors, as well as appropriate imaging optics for transmit and receive beam mode matching. It is currently being analyzed with a specialized optics code to verify the nominal performance and give a preliminary assessment of alignment tolerances and critical elements. Preliminary results both for the local imaging and the far field will be presented.

Studies of the LISA source 4U 1820-30

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4U 1820-30 is a Galactic X-ray binary with an 11-min orbital period and is one of the binaries detectable by LISA. The binary consists of a low-mass white dwarf and a neutron star, separated by only about 100 000 km. The system loses its energy and angular momentum by emission of gravitational waves, which leads to a high rate of mass transfer from the white dwarf onto the neutron star. There is also a very strong 170-d modulation, likely due to the presence of a 3rd, much more remote, star in the system.

I will present our study in the dynamical evolution of this system and our new discoveries in X-ray data. The implications in LISA detection will be discussed.