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Mike Cruise (University of Birmingham)
Jim Hough (University of Glasgow)
Oliver Jennrich (ESTEC)
Philippe Jetzer (University Zurich)
Alberto Lobo (ICE-CSIC and IEEC, chair)
Yannick Mellier (IAP, Paris)
Bernard Schutz (AEI Potsdam)
Tim Sumner (Imperial College, London)
Jean-Yves Vinet (OCA Nice)
Stefano Vitale (University of Trento)
Peter Bender (University of Colorado)
Sasha Buchman (Stanford University)
Joan Centrella (NASA/Goddard)
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Curt Cutler (NASA/JPL)
Sam Finn (Penn State University)
Jens Gundlach (NPL)
Craig Hogan (University of Washington)
Scott Hughes (MIT)
Piero Madau (Lick Observatory)
Tom Prince (NASA/JPL)
Sterl Phinney (Caltech)
Doug Richstone (University of Michigan)
Robin Stebbins (NASA/Goddard)
Kip Thorne (Caltech)
Roger Blandford (Stanford University)
Eugenio Coccia (University of Roma-2)
Carlos F. Sopuerta (ICE-CSIC and IEEC)
Enrique Garcia-Berro (Universitat Politècnica de Catalunya)
Seiji Kawamura (National Observatory, Japan)
Jay Marx (LIGO Laboratory)
Stephen Merkowitz (NASA/Goddard)
Benoit Mours (Laboratoire d'Annec)
Gijs Nelemans (IMAPP, Nijmegen)
Enric Verdaguer (University of Barcelona)
Clifford M. Will (Washington University, St Louis)

Local Organising Committee

Anna Bertolín (IEEC)
Priscilla Cañizares (ICE-CSIC and IEEC)
Carlos F. Sopuerta (ICE-CSIC and IEEC)
Ivan Lloro (IEEC, chair)
Alberto Lobo (ICE-CSIC and IEEC)
Nacho Mateos (ICE-CSIC and IEEC)
Pilar Montes (IEEC)
Miquel Nofrarias (IEEC)
Juan Ramos (Universitat Politècnica de Catalunya)
Josep Sanjuán (IEEC)
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3. Abstracts for Plenary Talks 17

4. Abstracts for Contributed Talks 23

5. Abstracts for Posters 42

6. List of Participants 56
## 1. Programme Summary

### Monday 16th

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<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Location</th>
<th>Chair</th>
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<tbody>
<tr>
<td>08:00 - 09:00</td>
<td>Registration</td>
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<tr>
<td>09:00 - 09:30</td>
<td><strong>Local Authorities</strong> Welcome</td>
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**Session Chair:** J.A. Lobo

| Time         | Event                                      | Location | Speaker       | Title                                                |
|--------------|--------------------------------------------|----------|---------------|
| 09:30 - 10:00| K. Danzmann                                 | Auditori | LISA: The Science and the Mission                     |
| 10:05 - 10:35| S. Vitale                                  | Auditori | LISA PathFinder: The experiment and the road to LISA  |
| 10:40 - 11:10|                                            |          | Break         |
| 11:10 - 11:50| P. Madau                                   | Auditori | Impact on Astrophysics and Cosmology                  |
| 12:00 - 12:20| J. Marx                                    | Auditori | GWIC’s Gravitational Wave Global Roadmap              |
| 12:30 - 12:50| R. Stebbins                                | Auditori | LISA and NASA’s Physics of the Cosmos Theme           |
| 13:00 - 13:20| J. Clavel                                  | Auditori | LISA and ESA’s Cosmic Vision 2015-2025                |
| 13:30 - 15:00|                                            | Auditori | Lunch         |

### Parallel Sessions

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Convenor</th>
<th>Room</th>
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<tbody>
<tr>
<td>15:00 - 16:30</td>
<td>LISA Technology I</td>
<td>S. Merkowitz</td>
<td>Auditori</td>
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<tr>
<td></td>
<td>Gravitational-Wave Sources for LISA</td>
<td>J. Baker</td>
<td>Agora</td>
</tr>
<tr>
<td>16:30 - 17:00</td>
<td></td>
<td></td>
<td>Break</td>
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<tr>
<td>17:00 - 18:30</td>
<td>LISA Technology I</td>
<td>S. Merkowitz</td>
<td>Auditori</td>
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<td></td>
<td>Gravitational-Wave Sources for LISA</td>
<td>J. Baker</td>
<td>Agora</td>
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Tuesday 17th

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Chair/Presenter</th>
<th>Title/Description</th>
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<tbody>
<tr>
<td>Rightsizing LISA</td>
<td>Stellar dynamics around Galactic Centers</td>
<td>Break</td>
<td>The LISA PathFinder Mission</td>
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Parallel Sessions

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<th>Time</th>
<th>Session</th>
<th>Convenor</th>
<th>Room</th>
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<tr>
<td>15:00 - 16:30</td>
<td>LISA PathFinder I</td>
<td>G. Heinzel</td>
<td>Auditori</td>
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<tr>
<td></td>
<td>LISA Astrophysics</td>
<td>A. Vecchio</td>
<td>Agora</td>
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<td>16:30 - 17:00</td>
<td>Break</td>
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<tr>
<td>17:00 - 18:30</td>
<td>LISA PathFinder Data Analysis</td>
<td>P. McNamara</td>
<td>Gamma</td>
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<tr>
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<td>Other Gravitational-Wave Detectors</td>
<td>S. Kawamura</td>
<td>Agora</td>
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<td>18:30</td>
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Wednesday 18th

**Session Chair:** P. Jetzer

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
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<tbody>
<tr>
<td>09:00 - 09:40</td>
<td>M. Sallusti</td>
<td>LISA Mission Design Review highlights</td>
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<tr>
<td>09:50 - 10:30</td>
<td>M. Colpi</td>
<td>Evolution of Massive Black Hole Binaries</td>
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<tr>
<td>10:40 - 11:10</td>
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<td>Break</td>
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<tr>
<td>11:10 - 11:35</td>
<td>A. King</td>
<td>On the Spin of Massive Black Holes</td>
</tr>
<tr>
<td>11:45 - 12:10</td>
<td>N. Cornish</td>
<td>Advances in LISA data analysis techniques</td>
</tr>
<tr>
<td>12:20 - 12:45</td>
<td>M. Hewitson</td>
<td>Data Analysis for LTP</td>
</tr>
<tr>
<td>12:55 - 13:20</td>
<td></td>
<td><strong>Poster Session</strong></td>
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<tr>
<td>13:30 - 15:00</td>
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<td>Lunch</td>
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**Parallel Sessions**

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<thead>
<tr>
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<th>Title</th>
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<tbody>
<tr>
<td>15:00 - 16:30</td>
<td>Auditori</td>
<td>LISA Technology II Cosmology and Fundamental Physics with LISA</td>
</tr>
<tr>
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<td>Convenor: S. Merkowitz</td>
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<tr>
<td>16:30 - 17:00</td>
<td>Agora</td>
<td>Break</td>
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<tr>
<td>17:00 - 18:30</td>
<td>Gamma</td>
<td>LISA Technology II Cosmology and Fundamental Physics with LISA</td>
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<td>Convenor: S. Merkowitz</td>
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<td>Room: Gamma</td>
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**Public Lecture**

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<th>Time</th>
<th>Speaker</th>
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<tbody>
<tr>
<td>19:00 - 20:30</td>
<td>C.M. Will</td>
<td>Black Holes, Waves of Gravity, and other Warped Ideas of Dr. Einstein</td>
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</table>
**Thursday 19th**

**Session Chair:** O. Jennrich

<table>
<thead>
<tr>
<th>Time</th>
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<th>Title</th>
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<tbody>
<tr>
<td>09:00 - 09:40</td>
<td>B. Schutz</td>
<td>Fundamental Physics and LISA</td>
</tr>
<tr>
<td>09:50 - 10:30</td>
<td>D. Reitze</td>
<td>The Status of the Terrestrial Gravitational Wave Detector Network</td>
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<tr>
<td>10:40 - 11:10</td>
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<td><strong>Break</strong></td>
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<tr>
<td>11:10 - 11:35</td>
<td>H. Ward</td>
<td>High precision interferometry in space</td>
</tr>
<tr>
<td>11:45 - 12:10</td>
<td>G. Heinzel</td>
<td>LISA Breadboarding</td>
</tr>
<tr>
<td>12:20 - 12:45</td>
<td>L. Barack</td>
<td>Modeling of EMRI orbits and waveforms</td>
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<tr>
<td>13:30 - 15:00</td>
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<td><strong>Lunch</strong></td>
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**Parallel Sessions**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tbody>
<tr>
<td>15:00 - 16:30</td>
<td>LISA PathFinder II Data Analysis for LISA</td>
</tr>
<tr>
<td></td>
<td><strong>Convenor:</strong> W. Weber <strong>Room:</strong> Auditori</td>
</tr>
<tr>
<td></td>
<td><strong>Convenor:</strong> N. Cornish <strong>Room:</strong> Agora</td>
</tr>
<tr>
<td>16:30 - 17:00</td>
<td><strong>Break</strong></td>
</tr>
<tr>
<td>17:00 - 18:30</td>
<td>LISA PathFinder II Data Analysis for LISA</td>
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<tr>
<td></td>
<td><strong>Convenor:</strong> W. Weber <strong>Room:</strong> Auditori</td>
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<td></td>
<td><strong>Convenor:</strong> N. Cornish <strong>Room:</strong> Agora</td>
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<td>18:30</td>
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### Friday 20th

**Room:** Auditori  

**Session Chair:** S. Finn

<table>
<thead>
<tr>
<th>Time</th>
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<th>Title</th>
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</thead>
<tbody>
<tr>
<td>09:00 - 09:40</td>
<td>C. Cutler</td>
<td>Parameter estimation and implications for LISA science</td>
</tr>
<tr>
<td>09:50 - 10:15</td>
<td>J.A. Lobo</td>
<td>LTP Diagnostics</td>
</tr>
<tr>
<td>10:20 - 10:45</td>
<td>T. Sumner</td>
<td>LISA and LPF charging</td>
</tr>
<tr>
<td>10:50 - 11:20</td>
<td></td>
<td><strong>Break</strong></td>
</tr>
<tr>
<td>11:55 - 12:20</td>
<td>J. Garriga</td>
<td>Cosmology in the LISA era</td>
</tr>
<tr>
<td>12:30 - 12:55</td>
<td>C. Miller</td>
<td>Intermediate-Mass Black Holes</td>
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<tr>
<td>13:05 - 13:30</td>
<td>S. Dhurandhar</td>
<td>General Relativistic treatment of LISA optical links and TDI</td>
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13:30  

**Symposium closes**

15:00  

**LIST Meeting**
### 2. Parallel Sessions Programme

**Monday 16th**  
**Room:** Auditori

#### Session 1: LISA Technology I  
**Convenor:** Stephen Merkowitz

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
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<tbody>
<tr>
<td>15:00-15:18</td>
<td>W. Weber</td>
<td>Experimental tests of low frequency acceleration noise for free-falling LISA test masses</td>
</tr>
<tr>
<td>15:18-15:36</td>
<td>L. di Fiore</td>
<td>Ground testing, with a Four-mass Torsion Pendulum Facility, of an Optical Read-Out for the LISA Gravitational Reference Sensor</td>
</tr>
<tr>
<td>15:36-15:54</td>
<td>K.-X. Sun</td>
<td>The First Year of Stanford Modular Gravitational Reference Sensor (MGRS) Program</td>
</tr>
<tr>
<td>15:54-16:12</td>
<td>Z.-B. Zhou</td>
<td>Progress of performance measurements of the inertial sensor with an electrostatic-controlled torsion pendulum</td>
</tr>
<tr>
<td>16:12-16:30</td>
<td>F. Guzmán</td>
<td>Test facility for prototypes of the LISA point-ahead angle mechanism</td>
</tr>
<tr>
<td>16:30-17:00</td>
<td>Break</td>
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<tr>
<td>17:00-17:18</td>
<td>P. Bender</td>
<td>Other Possible Missions using LISA-Type Technology</td>
</tr>
<tr>
<td>17:18-17:36</td>
<td>D. Weise</td>
<td>Alternative Opto-Mechanical Architectures for the LISA Instrument</td>
</tr>
<tr>
<td>17:36-17:54</td>
<td>F. Cirillo</td>
<td>Control System Design for the Constellation Acquisition Phase of the LISA Mission</td>
</tr>
<tr>
<td>17:54-18:12</td>
<td>J. Conklin</td>
<td>Mass Center Measurement for Drag-free Test Masses</td>
</tr>
<tr>
<td>18:12-18:30</td>
<td>C. Trenkel</td>
<td>Ground-based self-gravity tests for LISA PathFinder and LISA</td>
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Monday 16th  Room: Agora

**Session 2: Gravitational-Wave Sources for LISA**

<table>
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<tbody>
<tr>
<td>15:00-15:18</td>
<td>M. Hannam</td>
<td>Production of full black-hole binary waveforms for LISA using numerical relativity</td>
</tr>
<tr>
<td>15:36-15:54</td>
<td>S. McWilliams</td>
<td>Observing mergers of nonspinning black hole binaries with LISA</td>
</tr>
<tr>
<td>15:54-16:12</td>
<td>I. Hinder</td>
<td>Eccentric binary black holes in numerical relativity and post-Newtonian theory</td>
</tr>
<tr>
<td>16:12-16:30</td>
<td>I. Mandel</td>
<td>Can we detect intermediate-mass-ratio inspirals?</td>
</tr>
<tr>
<td>16:30-17:00</td>
<td></td>
<td><strong>Break</strong></td>
</tr>
<tr>
<td>17:00-17:15</td>
<td>C. Sopuerta</td>
<td>On the construction of 'kludge' gravitational waveform templates for Extreme-Mass-Ratio Inspirals</td>
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<tr>
<td>17:15-17:30</td>
<td>S. Drasco</td>
<td>Verifying black hole orbits with EMRIs</td>
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<tr>
<td>17:30-17:45</td>
<td>B. Whiting</td>
<td>Post-Newtonian and self force calculations for EMRI sources</td>
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<tr>
<td>17:45-18:00</td>
<td>N. Sago</td>
<td>Gravitational self-force effects on a point mass around a Schwarzschild black hole</td>
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<tr>
<td>18:00-18:15</td>
<td>R. Fujita</td>
<td>An efficient numerical calculation of gravitational waves from extreme mass ratio inspirals</td>
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<tr>
<td>18:15-18:30</td>
<td>S. Detweiler</td>
<td>Gravitational self-force for an extreme mass ratio binary</td>
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### Tuesday 17th

**Room:** Auditori

#### Session 1a: LISA PathFinder I  
**Convenor:** Gerhard Heinzel

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<th>Duration</th>
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<tr>
<td>15:00-15:22:30</td>
<td>[20+2.30]</td>
<td>F. Steier</td>
<td>The LISA PathFinder interferometry: experience for the LISA local readout</td>
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<tr>
<td>15:22-15:45:00</td>
<td>[20+2.30]</td>
<td>P. Wass</td>
<td>Direct-force measurements for testing the LISA PathFinder gravitational reference sensor</td>
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<td>16:07-16:30:00</td>
<td>[20+2.30]</td>
<td>J. Bogenstahl</td>
<td>Prototype LTP optical bench</td>
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<td>16:30-17:00</td>
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### Tuesday 17th

**Room:** Agora

#### Session 2a: LISA Astrophysics  
**Convenor:** Alberto Vecchio

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<tr>
<td>15:00-15:15</td>
<td>[12+3]</td>
<td>M. Benacquista</td>
<td>Contribution of disk, bulge, and halo white dwarf binaries to the LISA data stream</td>
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<tr>
<td>15:15-15:30</td>
<td>[12+3]</td>
<td>J. Gair</td>
<td>Probing black holes at low redshift through LISA EMRI observations</td>
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<tr>
<td>15:30-15:45</td>
<td>[12+3]</td>
<td>A. Sesana</td>
<td>The impact of seed black hole formation scenarios and of extreme GW recoil on LISA detections</td>
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<tr>
<td>16:29-16:30</td>
<td>[1]</td>
<td>A. Sesana</td>
<td>Observing white dwarfs orbiting massive black holes in the gravitational wave and electro-magnetic window [Poster Presentation]</td>
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<td>16:30-17:00</td>
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<tr>
<td>17:00:00-17:22:30</td>
<td>20+2:30</td>
<td>A. García Marín</td>
<td>LTP Experiment Master Plan</td>
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<tr>
<td>17:22:30-17:45:00</td>
<td>20+2:30</td>
<td>L. Ferraioli</td>
<td>LTP Data Analysis Algorithm Development</td>
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<tr>
<td>17:45:00-17:07:30</td>
<td>20+2:30</td>
<td>A. Grynagier</td>
<td>Drift Mode for the LISA Technology Experiment</td>
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<tr>
<td>17:07:30-18:30:00</td>
<td>20+2:30</td>
<td>A. Monsky</td>
<td>The First LTP Mock Data Challenge</td>
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**Session 2b: Other Gravitational Wave Detectors**

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<tbody>
<tr>
<td>17:00-17:20</td>
<td>15+5</td>
<td>D. Gerardi</td>
<td>Advanced concepts for future space-based interferometers: design and performance considerations</td>
</tr>
<tr>
<td>17:20-17:35</td>
<td>12+3</td>
<td>S. Sato</td>
<td>The Japanese Space Gravitational Wave Antenna - DECIGO</td>
</tr>
<tr>
<td>17:35-17:50</td>
<td>12+3</td>
<td>M. Ando</td>
<td>DECIGO Pathfinder</td>
</tr>
<tr>
<td>17:50-18:10</td>
<td>15+5</td>
<td>W.-T. Ni</td>
<td>SUPER-ASTROD: Probing Primordial Gravitational Waves and Mapping the Outer Solar System</td>
</tr>
<tr>
<td>18:10-18:30</td>
<td>15+5</td>
<td>S. Rajendran</td>
<td>Gravitational Wave Detection with Atom Interferometry</td>
</tr>
<tr>
<td>18:30</td>
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**Wednesday 18th**

**Session 1: LISA Technology II**

<table>
<thead>
<tr>
<th>Time</th>
<th>Speakers</th>
<th>Title</th>
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<tbody>
<tr>
<td>15:00-15:15</td>
<td>G. de Vine</td>
<td>First experimental demonstration of clock-noise cancellation for LISA</td>
</tr>
<tr>
<td>15:15-15:30</td>
<td>J. Livas</td>
<td>Frequency-Tuneable pre-stabilized lasers for LISA via sideband locking</td>
</tr>
<tr>
<td>15:30-15:45</td>
<td>S. Barke</td>
<td>Phase Characterization of EOM Sidebands well within the Mission Requirements of the Laser Interferometer Space Antenna</td>
</tr>
<tr>
<td>15:45-16:00</td>
<td>V. Wand</td>
<td>The UF LISA Interferometry Simulator (UFLIS)</td>
</tr>
<tr>
<td>16:00-16:15</td>
<td>D. Robertson</td>
<td>Fibre Injectors for LISA</td>
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<td>16:15-16:30</td>
<td>M. Troebs</td>
<td>Laser systems for LISA: overview and phase characteristics</td>
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<td>16:30-17:00</td>
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<tr>
<td>17:00-17:15</td>
<td>A. Preston</td>
<td>Back Link Fiber Stability Measurements</td>
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<td>17:15-17:30</td>
<td>R. Fleddermann</td>
<td>Measurement of the nonreciprocal phase noise of a single mode polarization maintaining optical fiber</td>
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<td>17:30-17:45</td>
<td>K. McKenzie</td>
<td>Fiber noise measurements and photoreceiver development</td>
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<td>17:45-18:00</td>
<td>E. Fitzsimons</td>
<td>Ultra-stable Interferometry Investigations for LISA</td>
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<td>18:00-18:15</td>
<td>J.J. Esteban Delgado</td>
<td>LISA Phasemeter Development: Advanced Prototyping</td>
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<td>18:15-18:30</td>
<td>C. Diekmann</td>
<td>Analog phase lock between two lasers at LISA power levels</td>
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## Session 2: Cosmology and Fundamental Physics with LISA

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<tr>
<th>Time</th>
<th>Speaker</th>
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<tr>
<td>15:00-15:30</td>
<td>M. Sereno</td>
<td>Local dark matter/dark energy searches with LISA</td>
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<td>15:30-16:00</td>
<td>C. Van Den Broeck</td>
<td>LISA as a dark energy probe</td>
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<td>16:00-16:30</td>
<td>N. Yunes</td>
<td>Constraining string theory with LISA</td>
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<td>17:00-17:30</td>
<td>M. Favata</td>
<td>Gravitational wave memory revisited</td>
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<td>17:30-18:00</td>
<td>P. Laguna</td>
<td>The issue of the final spin in hyperbolic black hole mergers</td>
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<td>18:00-18:30</td>
<td>X. Siemens</td>
<td>Cosmic (super)string detection with LISA</td>
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Thursday 19th

**Room:** Agora

### Session 2: Data Analysis for LISA

**Convenor:** Neil Cornish

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<tr>
<th>Time</th>
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<tr>
<td>15:00-15:15</td>
<td>J. Baker</td>
<td>The Mock LISA Data Challenge Round 3: New and Improved Sources</td>
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<td>15:15-15:30</td>
<td>J. Crowder</td>
<td>The BAM algorithm, now with a dash of f-dot: Extending a solution to</td>
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<td>the LISA Galactic Foreground Problem</td>
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<td>15:30-15:45</td>
<td>J. Whelan</td>
<td>F-Statistic Searches for White Dwarf Binaries in the Mock LISA Data</td>
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<td>Challenges</td>
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<td>15:45-16:00</td>
<td>J. Key</td>
<td>Characterizing the Gravitational Wave Signature from Cosmic String</td>
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<td>16:00-16:15</td>
<td>E. Robinson</td>
<td>Analysis approaches for detecting isotropic stochastic GW signals</td>
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<td>16:15-16:30</td>
<td>M. Tinto</td>
<td>Bayesian comparison of Post-Newtonian approximations of gravitational</td>
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<td>wave chirp signals</td>
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<td>16:30-17:00</td>
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<tr>
<td>17:00-17:15</td>
<td>M. Vallisneri</td>
<td>A toolkit for evaluating LISA’s performance in alternate configurations</td>
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<td>17:15-17:30</td>
<td>E. Porter</td>
<td>Improving Parameter Estimation For Supermassive Black Hole Binaries</td>
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<td>Using Higher Harmonic Corrections</td>
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<td>17:30-17:45</td>
<td>S. Babak</td>
<td>Resolving Supermassive Black Holes with LISA</td>
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<td>17:45-18:00</td>
<td>D. Shoemaker</td>
<td>Coupling Simulations with Data Analysis and Observations</td>
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<td>18:00-18:15</td>
<td>I. Thorpe</td>
<td>LISA Parameter Estimation using Numerical Merger Waveforms</td>
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<td>18:15-18:30</td>
<td>S. Husa</td>
<td>Toward LISA data analysis with full black-hole binary waveforms</td>
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3. Abstracts for Plenary Talks

TAL ALEXANDER  (Weizmann Institute of Science)

Stellar dynamics around Galactic Centers

A coincidence of LISA’s technical specification and the empirical M-sigma relation leads to the conclusion that LISA’s extragalactic sources will come from a special sub-class of galactic centers: those with a relaxed, high density stellar cusp. I will review several recent results on the dynamical relaxation processes of resonant relaxation, strong mass segregation and massive perturbers, which affect the rates and properties of EMRI and binary MBH coalescence events. I will describe evidence that these processes play a role in the Galactic Center, and can be studied there. I’ll conclude with some speculations on possible implications of strong mass segregation and resonant relaxation on the mass and spin evolution of MBHs.

CARL WARREN  (Astrium Ltd)

Engineering of the LISA PathFinder Mission - Making the experiment a practical reality

LISA PathFinder represents a unique challenge in the development of scientific spacecraft - not only is the LTP payload a complex integrated development placing stringent requirements on its developers and the spacecraft, but the payload also acts as the core sensor and actuator for the spacecraft, making the tasks of control design, software development and system verification unusually difficult. The micropropulsion system which provides the remaining actuation also presents substantial development and verification challenges.

As the mission approaches system CDR, flight hardware is completing verification, and the process of verification using software and hardware simulators and test benches is underway. Preparation for operations has started, but critical milestones for LTP and FEEP’s lie ahead. This paper summarises the status of the present development, and outlines the key challenges that must be overcome on the way to launch.

LEOR BARACK  (University of Southampton)

Modelling of EMRI orbits and waveforms

The amount of interesting physics extractable from EMRI signals will depend on how well we can theoretically model the phase evolution of the inspiral orbits as predicted by General Relativity. Thanks to the extreme mass ratio, the underlying physical problem is relatively “clean”: The inspiralling compact object can be modelled by a point particle, and its motion can be studied within the relatively simple context of black hole perturbation theory. Yet, accounting for the effect of gravitational back-reaction for orbits deep in the strong field near the black hole presents a difficult theoretical and computational challenge. This talk will review the various methods used to tackle this problem and give an update on recent developments. This will cover (1) progress on developing approximate families of waveforms (post-Newtonian “Kludges” and adiabatic waveforms); and (2) progress on computing “exact” inspiral orbits via self-force calculations. The latter have now matured enough to allow comparison with post-Newtonian predictions in the weak-field regime.

JEAN CLAVEL  (ESA Astrophysics & Fundamental Physics Missions Division)

LISA and ESA’s Cosmic Vision 2015-2025

MONICA COLPI  (Department of Physics, University of Milano Bicocca)

Evolution of Massive Black Hole Binaries

Massive black holes are found to be ubiquitous in the nuclei of nearby galaxies, and their growth and evolution appear to be closely linked to that of their hosts. There is also growing observational evidence that binary black holes form when two galaxies collide. In the violently relaxed core of the merged system, they first pair and later bind under the action of gas-dynamical and gravitational torques. It is expected that further hardening would bring the binary to such a close orbit that gravitational waves drive their inspiral down to coalescence, in less than a Hubble time. In this talk, I will describe the evolution, i.e., the sequence and timing of events that lead to the formation of a massive black hole binary following a galaxy-galaxy collision and critically examine a number of open issues on their coalescence and observability.
Neil Cornish (Department of Physics, Montana State University Bozeman)

Advances in LISA data analysis techniques

The last two years have seen tremendous advances in LISA data analysis development, driven largely by an aggressive schedule of Mock LISA Data Challenges. All of the major LISA analysis problems now have at least partial solutions: the identification and regression of the galactic foreground has been convincingly demonstrated, as has the detection and characterization of non-spinning black hole binaries. Last year saw the first accurate recovery of a bright Extreme Mass Ratio Inspiral (EMRI) signal, and recent work has shown that spinning black hole binaries can also be faithfully recovered. I will describe the analysis techniques that have led to these advances, and discuss some of the outstanding problems that need to be addressed.

Curt Cutler (Jet Propulsion Laboratory)

Parameter estimation and implications for LISA Science

This talk has two main parts. The first part will be a general overview of the state of our knowledge concerning how accurately LISA can determine the physical parameters of its various sources, and the implications of this accuracy for doing science. The second part will focus on the work of the LISA Parameter Estimation Taskforce: its aims, results so far, and future plans.

Karsten Danzmann (Albert Einstein Institute Hannover)

LISA: The Science and the Mission

The joint ESA/NASA mission has been in the official Mission Formulation phase for over 2 years now and a lot of progress both on Science, Technology and Mission Planning has been made. We are now well prepared for a launch in 2018!

Sanjeev Dhurandhar (Inter University Centre for Astronomy and Astrophysics)

General Relativistic treatment of LISA optical links and TDI

In order to attain the requisite sensitivity for LISA, the laser frequency noise must be suppressed below the other secondary noises such as the optical path noise, acceleration noise etc. This is achieved by combining time-delayed data for which precise knowledge of time-delays is required. The gravitational field, mainly that of the Sun and the motion of LISA affect the time-delays and optical links. We also include the effect of the Earth on the orbits of spacecraft. This leads to additional flexing over and above that of the Sun. We have written a numerical code which computes the optical links, that is, the time-delays with great accuracy $\sim 10^{-2}$ metres (more than what is required) for most of the orbit (except possibly few hours) and with sufficient accuracy. Our analysis of the optical links is fully general relativistic and the numerical code takes into account effects such as the Sagnac, Shapiro delay, etc. self consistently. We show that with the deemed parameters in the design of LISA, there are symmetries inherent in the configuration of LISA, which may be used effectively in TDI analysis.

Jaume Garriga (Departament de Física Fonamental, Universitat de Barcelona)

Cosmology in the LISA era

I will review the prospects for GW signals from early universe cosmology, including those generated during preheating after inflation, or by a network of cosmic strings. Possible effects of theories where General Relativity is modified at short or long distances will be briefly discussed.

Catia Grimani (Istituto di Fisica, University of Urbino)

Solar physics with LISA

Galactic cosmic rays and solar energetic particles (SEPs) above 100 MeV(/n) penetrate and charge the test masses of the LISA missions. In order to control the charging process, a small telescope of silicon wafers will be placed on board the LISA PathFinder (LISA-PF) and, possibly, the three LISA spacecraft. These detectors are presently designed to monitor proton and helium nuclei above 100 MeV(/n). Spectral information will be provided up to energies of a few hundreds of MeV. Because of the peculiar topology of the LISA spacecraft formation, particle monitor measurements offer a unique chance to study evolving CMEs (Coronal Mass Ejections) near the ecliptic at small steps in longitude, twenty degrees behind the Earth. Variations and fluctuations of Galactic cosmic rays related to different levels of solar modulation and interplanetary processes will be studied as well. In particular, proper modelizations of solar activity and solar polarity allow us to estimate the most abundant components of the incident galactic cosmic-ray fluxes at
the time of LISA. Radiation monitor measurements on board LISA-PF will permit to verify our speculations. We point out that the detection of solar electrons on board the LISA mission would help in forecasting incoming SEP events.

**Gerhard Heinzel** (Albert Einstein Institute Hannover)

**LISA Breadboarding**

Not all experimental aspects of the LISA interferometry will be tested by LISA PathFinder, in particular not those that are related to the low received power, light travel time, orbital motion, and the extra function of ranging and data transfer between satellites. This talk will give an overview of those aspects and their possible tests on ground.

**Martin Hewitson** (Albert Einstein Institute Hannover)

**Data Analysis for LTP**

The LTP (LISA Technology Package) is the core part of the LISA PathFinder mission. The main goal of the mission is to study the sources of any disturbances that perturb the motion of the freely-falling test masses from their geodesic trajectories as well as to test various technologies needed for LISA. The LTP experiment is designed as a sequence of experimental runs in which the performance of the instrument is studied and characterised under different operating conditions. Each experiment will, to some extent, be optimised based on the results of previous experiments. That means that each experiment must be analysed promptly. The complexity of the LTP experiment demands a robust, reliable and flexible data analysis environment capable of performing close to real time analysis of the experiment being executed on board the spacecraft. The software developed for the LTP Data Analysis is a comprehensive data analysis tool based on MATLAB. The environment allows the user to design and run analyses to extract the key parameters measured in the several experiments using well tested and understood routines. The environment allows the users to gather the raw data from spacecraft telemetry, to employ pre-written analysis routines to extract the results, to control the data flow and to compose and redistribute new analysis algorithms. This talk introduces the analysis environment and how it fits in to the mission operations. In addition, the talk will touch upon the various test campaigns and mock data challenges being performed which will lead to a robust and mature data analysis package for the mission.

**Clovis Hopman** (Leiden Observatory)

**Extreme Mass Ratio Inspirals and Bursts**

Close interactions of stars with massive black holes lead to gravitational waves with frequencies in LISA’s observational window. Two different classes of such events are extreme mass ratio inspirals (EMRIs), and extreme mass ratio bursts (EMRBs). EMRIs are events where a star spirals into a massive black hole, until the orbital frequency is so high that it enters LISA’s frequency window. They are rare (∼ 1 per 100 Gyr per galaxy), but can be observed to large distances, so that LISA is expected to observe of order 10-100 sources. EMRBs are due to stars on relatively wide, highly eccentric orbits such that the frequency associated with periapse passage is in LISA’s frequency window. In contrast to EMRIs, EMRBs are frequent (∼ 1 per yr per galaxy), but very weak, so that they can only be observed directly in our own galaxy, and of order one EMRB is expected to be seen by LISA. Both classes lead to a stochastic background of gravitational waves that is comparable to LISA’s sensitivity. In this talk, I discuss the stellar dynamical phenomena that determine the event rates of both EMRIs and EMRBs.

**Andrew King** (Department of Physics and Astronomy, University of Leicester)

**On the Spin of Massive Black Holes**

It seems likely that AGN accrete mass in short events which are not aligned with the host galaxy or with each other. Accordingly their accretion discs are not initially aligned with the black hole spin. I discuss the resulting torques on the hole and disc, and the consequences for the evolution of their mass and spin.

**Alberto Lobo** (Institute of Space Sciences (CSIC-IEEC))

**LTP Diagnostics**

The Data and Diagnostics Subsystem of the LTP hardware and software are at present essentially ready for delivery. In this presentation I intend to describe the scientific and technical aspects of this subsystem, as well as the prospects for their integration within the rest of the LTP. I will also sketch a few lines of progress towards the more demanding diagnostics requirements which will be needed in LISA.
Piero Madau (Department of Astronomy and Astrophysics, University of California at Santa Cruz)

Impact on Astrophysics and Cosmology

The scientific motivations for the Laser Interferometer Space Antenna (LISA) encompass forefront problems in astrophysics ranging from the history of galaxies and their massive black holes to precision measurements of the cosmic expansion history. By working in tandem with other facilities LISA can address, to varying degree, many of the key astrophysical issues identified in the “Astronomy and Astrophysics in the New Millennium” and “Quarks to the Cosmos” reports.

Paul McNamara (European Space Agency)

The LISA PathFinder Mission

LISA PathFinder (formerly known as SMART-2) is an ESA mission designed to pave the way for the joint ESA/NASA LISA mission by testing in flight, to an unprecedented accuracy, one of the core assumptions of General Relativity: that free-particles follow geodesics. LISA PathFinder achieves this goal by putting two test masses in a near-perfect gravitational free-fall, and controlling and measuring their motion. 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 scheduled to be launched in the first half of 2010 to a Lissajous orbit around the first Sun-Earth Lagrange point, L1. In addition to a complete European technology package (the LISA Technology Package), LISA PathFinder will also carry thrusters and software, known as ST-7, a part of NASA’s New Millennium Program. Here I will give an introduction to, and current status of, the mission, followed by a more detailed discussion of the technologies to be tested.

Jay Marx (California Institute of Technology)

GWIC’s Gravitational Wave Global Roadmap

The Gravitational Wave International Committee (GWIC) was formed in 1997 as a sub-committee of IUPAP’s Particle and Nuclear Astrophysics and Gravitation International Committee (PaNAGIC) to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide. In the fall of 2007, GWIC chartered a subcommittee to develop a 30-year roadmap for the field of gravitational wave science. The goal of the roadmap is to develop a strategic plan that lays out the excitement of the field, the potential great discoveries, and the facilities and resources needed to exploit those scientific opportunities. From a perspective to optimize the global science in the field and taking account of known national and regional planned projects, the roadmap will address ground and space based capabilities, theory and numerical relativity, and the possible impact of new technologies and approaches. The roadmap will be submitted to GWIC in the fall of 2008. This talk will report the status of the roadmap process as well as the plan for completion of the roadmap during the next 4-6 months.

Cole Miller (University of Maryland, Department of Astronomy)

Intermediate-Mass Black Holes

Gravitational waves from black holes of hundreds to thousands of solar masses would carry unique information about star formation in the universe, as well as being tremendously strong probes of the spacetime around supermassive black holes. I will discuss the evidence that such objects exist as well as important frontiers to be explored about their gravitational radiation and astrophysical properties.

Gijs Nelemans (Radboud University Nijmegen)

The Galactic Gravitational wave foreground

I will review the expected Galactic binary star gravitational wave sources, binaries with compact objects such as white dwarfs, neutron stars and black holes. Many sources are expected to be detected individually. I will emphasize the recent developments in Astrophysics related to these sources and will discuss the exciting developments that are lying ahead with many wide field surveys starting in the next few years. This means that our knowledge of these objects will greatly improve before LISA will fly, providing good estimates of what can be expected and many high-quality verification sources. I will also discuss the specific Astrophysics problems that can be tackled with the LISA data, in particular the interactions in very short periods binary stars and binary evolution in dense stellar clusters.
The Status of the Terrestrial Gravitational Wave Detector Network

During the past year, the LIGO, GEO, and Virgo detectors completed their first major observational run and have begun to report on the results of astrophysical searches. Currently, ambitious plans are in place to upgrade all of the global detectors. LIGO is currently undergoing enhancements to improve its sensitivity by a factor of two during 2008, and Advanced LIGO, which will be 10 times more sensitive than LIGO, has received funding to begin construction in 2011. The Virgo interferometer is currently upgrading to an enhanced configuration in the near term, and plans are well underway to build Advanced Virgo, with sensitivity comparable to Advanced LIGO. The GEO600 detector will explore how to achieve increased sensitivities at high frequencies with GEO-HF. Plans are developing to construct the Large Cryogenic Gravitational-wave Telescope (LCGT), a third generation gravitational wave detector in Japan. In this talk, I’ll survey ground-based gravitational wave detectors, with an emphasis on the status of future intermediate and long term upgrades of the major projects. I’ll discuss the advanced detector research and development needed for future detectors as well as highlight some key astrophysics results obtained during the last year.

Numerical modelling of binary black-hole mergers

I will review the recent progress in the modelling of binary black-hole mergers, focussing in particular on the dynamics during the final few orbits, when general-relativistic effects are most prominent. Attention will be paid to the properties of the waveforms under different initial configurations, but also on how to use the numerical-relativity simulations to extract information on the recoil velocity and predict the spin of the final black hole under generic conditions.

LISA mission Design Review Highlights

Fundamental Physics and LISA

LISA and NASA’s Physics of the Cosmos Theme

In the past year, the LISA Project at NASA has completed a major review and has thoroughly reviewed its cost estimates. This talk will summarize the conclusions of the Beyond Einstein Program Assessment, and review the main conclusions of the cost estimation work done at NASA, including reduced mission concepts. Astro2010, the decadal review which sets priorities for astronomy and astrophysics projects in the U.S., is getting organized. Preparing for and participating in Astro2010 will be a crucial activity for the NASA side of the LISA Project in the next 18 months.

Rightsizing LISA

The LISA science requirements and conceptual design have been fairly stable for over a decade. In the interest of reducing costs, the LISA Project at NASA has looked for simplifications of the architecture, at downsizing of subsystems, and at descopes of the entire mission. This is a natural activity of the formulation phase, and one that is particularly timely in the current NASA budgetary context. There is, and will continue to be, enormous pressure for cost reduction from both ESA and NASA, reviewers and the broader research community. Here, we review the rationale for the baseline architecture, and report recent efforts to find simplifications and other reductions that might lead to savings. A few possible simplifications have been found in the LISA baseline architecture. In the interest of exploring cost sensitivity, one moderate and one aggressive descope have been evaluated; the cost savings are modest and the loss of science is not.

LISA and LISA PathFinder Charging

Charging of the isolated proof-masses which form the mirrors defining the path lengths for the LISA and LISAPF
interferometers turns out to be one of the limiting sources of spurious noise for both missions. An overview of the charging processes and effects will be given together with a discussion of the control hardware and operations to be used to keep the effects within budget.

Stefano Vitale (Dipartimento di Fisica, Università di Trento and INFN Gruppo di Trento)

LISA PathFinder: The experiment and the road to LISA

LISA PathFinder (LPF) main science goal is the quantitative verification of a few key parts of the noise model for LISA. Specifically LPF addresses the question of the physical limitations to the geodesic motion of LISA test-masses, by measuring the residual acceleration of a test-mass relative to a nearby reference one. It also addresses the ability to measure, by picometer laser interferometry, the separation between the centers of mass of extended bodies without mixing the motion of other degrees of freedom.

This program is performed by using hardware, (gravity reference sensor, local interferometric readout of test-mass motion, micro-thrusters etc.), nominally identical to that of LISA. In addition the program also tests some of the key environmental protocols to be used on LISA, like the suppression of the local gravitational field and of its fluctuation, and the basics of its dynamical control, the so called drag-free system.

After very briefly revising the project development status (that will be described in detail in the talk of P. McNamara) two years from is planned launch, the talk will describe the progress in the development of this experimental program that has taken place since the last LISA symposium. It will discuss the projected performance based on the hardware tests, the physical analysis activity, and the development of the data processing algorithms.

The talk will finally discuss the current understanding on how the resulting noise model may be used for LISA commissioning, optimization and data processing.

Henry Ward (Department of Physics and Astronomy, University of Glasgow)

High precision interferometry in space
4. Abstracts for Contributed Talks

MASAKI ANDO (Department of Physics, the University of Tokyo)

**DECIGO Pathfinder**

DECIGO pathfinder (DPF) is a milestone satellite mission for DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) which is a future space gravitational wave antenna. DECIGO is expected to provide us fruitful insights into the universe, in particular about dark energy, a formation mechanism of supermassive black holes, and the inflation of the universe. Since DECIGO will be an extremely large mission which will formed by three drag-free spacecraft with 1000m separation, it is significant to gain the technical feasibility of DECIGO before its planned launch in 2024. Thus, we are planning to launch two milestone missions: DPF and pre-DECIGO. The purposes of DPF are to test the key technologies and to make observations at 0.1-1Hz frequency band. DPF will be a small satellite with weight of about 300kg, orbiting the earth along a sun-synchronous orbit with an altitude of 500km. The mission part of DPF is designed to be a prototype of DECIGO, being comprised of a short Fabry-Perot (FP) cavity, a stabilized laser source, and a drag-free control system. The conceptual design and current status of the first milestone mission, DPF, will be reviewed in this talk.

STANISLAV BABAK (Albert Einstein Institute)

**Resolving Supermassive Black Holes with LISA**

It was shown that gravitational wave signals from inspiralling Massive Black Hole (MBH) binaries can be used for estimating the sky location and distance with an accuracy sufficient to conduct simultaneous electromagnetic and gravitational observations of the merger. This could be used to map the geometry of the Universe and measure the amount of the dark energy. For the higher mass binaries (Super Massive Black Holes) with a total mass above $10^7$ solar masses we do not to see much of the inspiral, but the merger and ring-down signals fall right in LISA’s band. We use numerical waveforms to study the sky resolution and the distance estimation. We have shown that the estimates could be as good (or even better) than those obtained from the inspiral alone and sufficient to conduct post-merger electromagnetic observations.

JOHN BAKER (NASA Goddard Space Flight Center)

**The Mock LISA Data Challenge Round 3: New and Improved Sources**

The Mock LISA Data Challenges are a program to demonstrate and encourage the development of data-analysis capabilities for LISA. Each round of challenges consists of several data sets containing simulated instrument noise and gravitational waves from sources of undisclosed parameters. Participants are asked to analyze the data sets and report the maximum information they can infer about the source parameters. The challenges are being released in rounds of increasing complexity and realism. Challenge 3, currently in progress, brings new source classes, now including cosmic-string cusps and primordial stochastic backgrounds, and more realistic signal models for supermassive black-hole inspirals and galactic double white dwarf binaries.

SIMON BARKE (Albert Einstein Institute Hannover)

**Phase Characterization of EOM Sidebands well within the Mission Requirements of the Laser Interferometer Space Antenna**

For measuring relative distance changes within the required accuracy of the LISA mission one must transfer the phase fluctuations induced by the on-board ultra stable oscillators (USOs) to the remote satellites. By that the noise can be cancelled from the scientific data in post-processing. For the noise transfer, sidebands at an integer multiple of the corresponding USO frequency are imprinted onto the outgoing laser beams by electro-optical modulators (EOMs). This scheme will only work if no significant excess noise is induced to the sidebands by any component in the noise transfer chain. We concentrate on the phase noise induced by the EOM itself. In our setup for testing the phase characteristics of EOM sidebands a polarization maintaining fiber coupled EOM by Jenoptik was used. The measurement results show an upper EOM phase noise limit which is within the required level of $0.6\text{mrad}/\sqrt{\text{Hz}}$ in the frequency range between $10^{-3}$ and 1Hz for EOM sideband frequencies of 2GHz. Additionally, we present requirements on temperature and laser power stability to ensure this EOM noise level on board the LISA spacecraft.
Matthew Benacquista (University of Texas at Brownsville)

**Contribution of disk, bulge, and halo white dwarf binaries to the LISA data stream**

A model of the white dwarf binary population of the Galaxy has been generated using the StarTrack binary evolution code. The population includes both detached and mass-transferring systems. We have separated out different evolutionary channels from disk, bulge, and halo populations and investigate their contributions to the resolvable and confusion-limited signals in the LISA data stream. The halo population is clearly less important than previously suggested, and distinct populations of the bulge and halo are seen to dominate the resolvable systems.

Peter L. Bender (JILA/University of Colorado)

**Other Possible Missions using LISA-Type Technology**

Among the many interesting possibilities for future missions that would benefit strongly from LISA and LISA Pathfinder technology development, three will be discussed. They are in the fields of fundamental physics, Earth science, and gravitational wave astronomy. The first is a mission to measure the gravitational time delay due to the Sun from a spacecraft near the L-1 point of the Earth-Sun system. It would require gravitational reference sensors with $10^{-13} m/s^2/\sqrt{Hz}$ performance at frequencies down to 0.4 $\mu$Hz. The target accuracy for determining the PPN parameter gamma is 1 or 2 $x$ $10^{-8}$. The second is a possible future mission to measure time variations in the Earth’s gravitational field, which is called the Dual-GRACE mission. A suggested geometry for it would use one pair of drag-free satellites in polar orbit with a 5 day repeat period and a second pair in a roughly 63 deg inclination orbit with a 22.7 day repeat period. Changes in the satellite separation of about 50 km would be measured with $10^{-14}$ or better accuracy, and there are interesting issues concerning how to correct for the effects of spurious accelerations at the orbital frequency and at very low frequencies. The third mission is a possible moderately improved LISA follow-on mission aimed at being able to detect mergers of 10 solar mass black holes with IMBHs out to redshifts of about 10 in order to investigate the formation and growth of IMBHs in more detail than LISA will be able to do.

Johanna Bogenstahl (University of Glasgow)

**Prototype LTP optical bench**

We present the development of a prototype LTP optical bench. This optical bench will be constructed using the same tooling and procedures as the flight model and to the same specifications. As part of its development it will be used in the qualification of the flight fibre injectors. This application and the use of the bench in further interferometric investigations will be presented.

Daniele Bortoluzzi (University of Trento)

**LISA Pathfinder test mass injection in geodesic: status of the on-ground testing**

The LISA Technology Package on board the LISA Pathfinder mission will realize the highest level of geodesic purity of an extended body, thus providing the in-flight testing of some of the key technologies needed for LISA. The tight requirements on the maximum allowed acceleration noise for the LISA Gravitational Reference Sensor drove its design towards a large test mass weight and large gaps to the surrounding electrodes. The first drawback of such a choice is the need to lock the test mass during the satellite launch against the high inertial accelerations, in order to avoid any impact against the electrode housing. The second drawback is the very low force authority of the capacitive actuation system on the test mass once it is in free-fall. The Caging Mechanism Assembly, designed to cage the test mass with a high force authority, must also provide its reliable and accurate injection in the geodesic. The criticality of this phase, that constitutes a potential single point of failure of the mission, is mainly related to adhesion of the test mass with the constraining device and the weak force authority of the capacitive actuation. The latter is able to capture and center the test mass after the detachment from the constraining device only if the transferred momentum is below a threshold. The on-ground testing of this phase is performed by measuring the transferred momentum between representative surfaces of the test mass and the release-dedicated device, reproducing the dynamics that will take place in flight. This paper reports on the testing activities performed at the Department of Mechanical and Structural Engineering of the University of Trento.

Francesca Cirillo (EADS Astrium GmbH)

**Control System Design for the Constellation Acquisition Phase of the LISA Mission**

The objective of the constellation acquisition phase for the LISA mission is to establish the three laser links between the three spacecrafts of the LISA constellation so that the interferometric measurements for the science experiment
can commence. The laser beam acquisition for LISA is extremely challenging given the 5 million km distance between the spacecrafts, the inherent limits of the attitude sensors accuracy, the orbit determination accuracy issues and the time required to phase-lock the incoming and outgoing laser signals. This paper presents the design of the control system for the acquisition phase of the LISA constellation: the acquisition operational procedure is outlined, guidance laws are defined together with the gyro-mode attitude control principle, which implements a Kalman filter for disturbances rejection purposes. Constellation-wide non-linear simulations demonstrate that the LISA constellation acquisition phase is feasible by means of the proposed control strategy.

JOHN CONKLIN (Stanford University)

Mass Center Measurement for Drag-free Test Masses

Space-borne gravitational wave observatories like the Laser Interferometer Space Antenna (LISA) and those beyond, which may utilize a Modular Gravitational Reference Sensor (MGRS), greatly benefit from precise knowledge of the mass center location of the test mass prior to launch. The motion of the mass center of a drag-free test mass, which follows a pure geodesic, must be inferred from measurements of the surface. Therefore, knowledge of the mass center is critical for calibration of the cross-coupling between rotational and translational degrees of freedom. Together with the moment of inertia tensor, the mass center also can provide an estimate of the density inhomogeneity distribution of the test mass material to quadratic order. The density inhomogeneity can be undesirably large in materials like AuPt, where spinodal decomposition can cause the two elements to separate as the material cools. Finally, the gravitational potential about the test mass can be estimated to third order from the measured mass, mass center and moment of inertia tensor, which improves modeling of the self gravitation forces applied to the test mass. These benefits, which are independent of the test mass shape, motivate improvements in mass center measurement beyond the current state of the art. A new technique, called velocity modulation, has been demonstrated to a precision of 150 nm for a sphere, a factor of \( \sim 20 \) improvement over the work presented at the LISA 6th symposium. This new technique involves rolling the sphere down a set of parallel rails to spectrally shift the mass center offset information to the rolling rate frequency, in order to avoid the 1/f noise that typically prevents other techniques from achieving precision below 1 \( \mu \mathrm{m} \). The velocity modulation technique uses a novel optical sensing system to measure the sphere’s trajectory and a nonlinear parameter search to recover the magnitude and phase of the mass center offset from the geometric center. The velocity modulation technique can also determine the mass center of a test mass of arbitrary shape (including a cube) to \( \sim 1 \mu \mathrm{m} \) by placing the test mass inside a spherical fixture. The measurement is repeated with the test mass in different orientations to separate the mass center of the fixture from that of the test mass. The measurement error for a test mass of arbitrary shape is limited by the repeatability of the placement of the test mass inside the spherical fixture.

JEFF CROWDER (Caltech / Jet Propulsion Laboratory)

The BAM algorithm, now with a dash of f-dot: Extending a solution to the LISA Galactic Foreground Problem

Tens of millions of galactic 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 discuss the Blocked-Annealed Metropolis Hastings (BAM) algorithm, a variant of a Markov Chain Monte Carlo (MCMC) approach, which has been extended to include searches for galactic systems with a small frequency derivative. The BAM algorithm was able to recover the source parameters for over 18,000 injected signals in each of the challenges of Round 2 of the Mock LISA Data Challenge (MLDC). The extension to the algorithm will be discussed, including projections for the performance of the algorithm in Round 3 of the MLDC, based on preliminary searches of the training data.

MARINA DEHNE (AEI Hannover)

Laser Interferometry for a future GRACE follow-on mission

The aim of a future GRACE follow-on mission is to map the gravitational field of the Earth with higher resolution. The proposed detector consists of two spacecraft carrying drag-free test masses in a Low-Earth Orbit, following each other with a separation of about 10 km. Distance variations in the frequency range from 1 to 100 mHz will be monitored by an interferometer with nanometer precision. In such a Low-Earth Orbit the atmospheric drag is significant and must be compensated. Hence, drag-free technology such as developed for the joint ESA-NASA space-based gravitational-wave detector “Laser Interferometer Space Antenna” (LISA) and its precursor mission LISA PathFinder could be
adapted for this purpose. Due to large distance variations between the two spacecraft, a heterodyne interferometer with a heterodyne frequency above the maximum induced Doppler shift is currently chosen as the baseline design. The estimated requirements on the interferometer sensitivity are 2.5 nm/√Hz from 100 mHz down to 10 mHz, increasing as 1/f between 10 and 1 mHz. The 10 km spacecraft separation causes a large pathlength difference between the two interfering beams which leads to a strong coupling of laser frequency noise to the interferometric phase readout. To meet the desired sensitivity the laser frequency stability needs to be approximately 30 Hz/√Hz at 1 mHz. In our proposed configuration the laser in the second spacecraft will be phase-locked to the incoming light with an offset frequency equal to the desired nominal heterodyne frequency. A possible measurement scheme for the interferometric phase readout is a digital PLL that tracks the signal frequency and phase. A similar approach is currently followed for LISA, and the experience gained from this work can be used to guide the design of this subsystem. These techniques have been demonstrated many times, for example at the AEI Hannover as part of the research for LISA and LISA PathFinder which can be adapted. Data analysis to be performed on ground will recover the information about the gravitational field from the interferometric phase measurements, in the form of the spherical harmonics from degree 6 to 240. After a brief overview of the overall mission concept, results of investigations on a possible interferometer configuration capable of fulfilling the requirements will be presented.

Steven Detweiler (University of Florida)

Gravitational self-force for an extreme mass ratio binary

A small mass m in orbit about a much more massive black hole M moves along a world line that deviates from a geodesic of the Schwarzschild geometry by $O(m/M)$. This deviation is said to be caused by the gravitational self-force of the metric perturbation $h_{ab}$ from m. For circular orbits, we numerically calculate the $O(m/M)$ effects upon the orbital frequency and upon the rate of passage of proper time on the worldline. These two effects are independent of the choice of gauge for $h_{ab}$ and are observable in principle. For distant orbits, our numerical results agree with a post-Newtonian analysis through terms of order $(v/c)^6$.

Luciano Di Fiore (INFN - Napoli)

Ground testing, with a Four-mass Torsion Pendulum Facility, of an Optical Read-Out for the LISA Gravitational Reference Sensor

In the last few years, the LISA group in Napoli has developed an Optical Read-Out (ORO) system based on optical levers as an auxiliary and backup readout for the Gravitational Reference Sensor (GRS) of LISA. Bench-top measurements, with a rigid set-up, have successfully proven that the ORO fits the requirements for sensitivity both in translational and rotational DOFs, exceeding the capacitive sensor performance in a wide range of frequencies. Last year an ORO system designed in Napoli in collaboration with the Trento LISA group, has been installed, as an auxiliary readout system, on the four mass torsion pendulum developed in Trento. In this paper we report on the results of the testing performed of this ORO device in comparison with the capacitive one and outline possible further improvements and their advantages for the torsion pendulum facility performances.

Christian Diekmann (Albert Einstein Institute Hannover)

Analog phase lock between two lasers at LISA power levels

Between the LISA satellites laser beams are sent in both directions and the relative phase contains the measurement signal. Because of the diffraction of the laser beams the detectable light power is only a few hundred pW. Direct reflection of the light is therefore not possible, but the frequency of the local laser is locked with a variable offset frequency of up to 20 MHz to the incoming laser beam. The development of the analog controller and the analog phase measurement system was done at mW laser power level and with this experimental setup the requirements for LISA could be reached. At LISA laser power levels the phase read out with different photodiode transimpedance amplifier could be tested. With a photodiode transimpedance amplifier consisting of transistors the noise spectrum of the phase read out is at 31 pW of the incoming laser and 1 mW of the local laser white down to 60 mHz and lays at $1.65 \times 10^{-4}$ rad/$\sqrt{\text{Hz}}$. Therefore it is on the order of the shot noise for this measurement, that was at $8.3 \times 10^{-5}$ rad/$\sqrt{\text{Hz}}$. The phase read out with the photodiode transimpedance amplifier was found to be limited by the power of the local laser and the phase measurement system. Electro-magnetic pick up has a significant influence in this power dimension. This pick up was reduced by shielding.
Steve Drasco (Jet Propulsion Laboratory, Caltech)

Verifying black hole orbits with EMRIs

When it occurs very near a black hole, generic bound test mass motion differs hugely from the familiar Keplerian ellipses. The motion is characterized by three fundamental frequencies instead of just one, and the corresponding radiation occurs only at frequencies that are integer linear combinations of those fundamental frequencies. Simulations of radiation from a wide range of generic orbit configurations exhibit simple rules for which combinations are significant. I describe a simple phenomenological template bank based on these rules which could be used to verify the existence of general relativity’s black hole orbits, and would recover the evolution of their three fundamental frequencies over the course of the inspiral. Though it may not rule out other theories of gravity, such verification would be a significant benchmark for gravitational wave observations.

Juan José Esteban Delgado (Max Planck Institut fuer Gravitationsphysik (Albert Einstein Institut))

Optical ranging and data transfer development for LISA

Ranging and data transfer between spacecraft is needed for LISA. For this purpose the carrier of the laser link is modulated by means of direct-sequence spread spectrum (DS/SS) and demodulated on the phase measurement system (PMS) as back end processing. This work describes the proposed receiver architecture which exploits the correlation properties of the signals in order to achieve the distance tracking with meters accuracy and successful data acquisition. In addition, simulation results that allow its efficient implementation within an FPGA (Field programmable gate array) are presented.

Marc Favata (Kavli Institute for Theoretical Physics)

Gravitational wave memory revisited

Certain classes of gravitational-wave sources can leave behind a “memory” of their waves’ passage. In an ideal gravitational-wave detector (a ring of freely floating test-masses) this memory manifests itself as a permanent displacement of the test masses. Inspiraling binaries produce a particularly interesting form of memory—the Christodoulou memory. Although arising from nonlinear interactions at 2.5 post-Newtonian order, the Christodoulou memory affects the gravitational wave amplitude at leading (Newtonian) order. Previous calculations have computed this amplitude correction during the inspiral phase of binary coalescence. Using an “effective-one-body” description calibrated with the results of numerical relativity simulations, I compute the evolution of the memory during the merger and ringdown phases and determine the memory’s final saturation value. Using this model for the memory, I reassess the prospects for its detection, particularly for supermassive black hole binary coalescences that LISA will detect with high signal-to-noise ratios. In addition to the memory effect, coalescing binary black holes also experience center-of-mass recoil due to the asymmetric emission of gravitational radiation. These recoils can manifest themselves in the gravitational wave signal in several waves. I will discuss LISA’s ability to detect these effects.

Luigi Ferraioli (University of Trento)

LTP Data Analysis Algorithms Development

The goal of the LTP (LISA Technology Package) experiment is focusing on the study of the sources of disturbance that perturb the motion of two test masses from their geodesic trajectory. This is achieved by measuring the fluctuations of the differential acceleration between the two Test Masses (TMs) that is reconstructed from the reading of the interferometer which is measuring the relative displacement of the TMs and the displacement of one TM with respect to the spacecraft. The short duration of the LISA PathFinder mission and the wide list of experiments to be performed during the flight forces the development of the data analysis environment well in advance. With this aim we are building LTPDA, a Matlab based data analysis tool, which will be used to implement the algorithms needed to analyze the individual experiments. These algorithms are tested in mock data challenge sessions, which are also very useful exercises allowing for more detailed definition of the experimental sequences to be performed in flight. One of the core algorithms is dedicated to the estimation of the differential acceleration noise between the two TMs. In particular the tool evaluates the TMs acceleration noise relative to the two interferometer channels, starting from the dynamical parameters (stiffness, cross-talk, . . . ) and control circuit continuous transfer functions. The tool separately calculates the total force and the commanded force and then subtracts each other in order to obtain the estimate of the acceleration noise of TM2 respect to TM1. At the same time, we are working on specific tools dedicated to analyzing single experiments devoted to measuring fundamental parameters characterizing individual contributions to the force noise, such as the measurements of the parasitic stiffness coupling TMs to the spacecraft, and the estimate of residual cross-talk among different degrees of freedom. In view of the application of the data analysis tools to the
signal parameters identification we are developing a noise whitening tool that can highly simplify the problem of their maximum likelihood estimation.

Ewan Fitzsimons (University of Glasgow)

Ultra-stable Interferometry Investigations for LISA

Polarising optics play a key role in the proposed LISA Optical Bench. It is therefore important to demonstrate that the picometer stability required for LISA can be achieved in an interferometer that uses polarising components for beam steering. The talk will describe the design and construction of, and initial results from, a hydroxide-catalysis bonded interferometer which incorporates polarising optics in a LISA-like way. Further optical experiments aimed at demonstrating key aspects of LISA metrology will also be outlined.

Roland Fleddermann (Albert Einstein Institute Hannover)

Measurement of the nonreciprocal phase noise of a single mode polarization maintaining optical fiber

In the current LISA baseline design a fiber link is foreseen to swap part of the laser light between the two optical benches on board each satellite. For this link it is currently planned to use a polarization maintaining single mode optical fiber. Such fibers are known to cause phase noise on the order of up to several rad/√Hz in the mHz frequency range. However, this phase noise can be subtracted from the measurement signal if the observed phase noise of the fiber is reciprocal. For this subtraction to work at the desired residual noise level, the nonreciprocal phase noise of the fiber needs to be below 6 µrad/√Hz, corresponding to nonreciprocal length fluctuations of less than 1 pm/√Hz. Currently there is no data available on the nonreciprocity of optical fibers in the LISA frequency range at this demanding level. We are giving an overview of experiments conducted in Hannover on the nonreciprocity of a fiber and their results. We report on first measurements with a sagnac interferometer as well as on experiments on a setup that is closer to the actual application on board the satellites which was built on a Zerodur® base plate using hydroxide-catalysis bonding technique. The current status of experiments and planned future improvements are discussed.

Ryuichi Fujita (Raman Research Institute)

An efficient numerical calculation of gravitational waves from extreme mass ratio inspirals

Gravitational waves from extreme mass ratio inspirals are one of the important source of LISA. We should calculate these waves so accurately that we can extract physical information of source by data analysis. Recently, we developed an efficient numerical method to compute gravitational waves from binary systems in which a point particle moves in circular orbits on the equatorial plane of the black hole. In this presentation, we apply this method to compute gravitational waves from binary systems in which a point particle moves in general bound geodesic orbits of the black hole. We check the accuracy of our code using spherical symmetry of Schwarzschild black hole such that energy flux radiated by a point particle is independent of the inclination angle from the equatorial plane of black hole. We find that the accuracy of our code may be limited by truncation of ℓ mode, degree of the spin-weighted spheroidal harmonics. In this work, we truncate ℓ up to 20. Then we evaluate gravitational waves from extreme mass ratio inspirals in the case of Kerr black hole. We also show that we can calculate gravitational waves accurately even in the case of high eccentric orbits. Our numerical code may be useful to make templates of extreme mass ratio inspirals.

Jonathan Gair (University of Cambridge)

Probing black holes at low redshift through LISA EMRI observations

LISA observations of extreme mass ratio inspirals (EMRIs) will provide highly accurate information about low redshift galactic nuclei. The expected distribution of observed LISA EMRI events depends on the assumptions made about the population of massive black holes at low redshift. We will discuss how to estimate the rate of LISA events, how the number and parameter distribution of LISA events varies with the model assumptions and hence what we might learn from LISA observations. We will also briefly discuss the effect that a possible descope of the LISA mission would have on the EMRI rates and the consequences of this for the scientific payoff.

Antonio F. García Marín (Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute))

LISA Pathfinder experiment master plan

The LISA Pathfinder master plan (EMP) must describe precisely the experimental runs to be performed on orbit to test the three mission core technologies: drag-free test masses, picometre interferometry and microNewton thrusters. Their performance and real time coordination is essential to measure and suppress the disturbances affecting the test
masses, so that the virtually perfect free fall required for LISA can be demonstrated. We present an overview of the ongoing LTP-team work on the EMP, focusing on the most challenging runs and the science extraction for LISA: the initial alignment of the test masses with respect to the interferometer that will allow the first combined operation of these two LISA core systems, the acceleration measurements to demonstrate the drag-free performance and the characterisation of the different technologies in space for their direct application in LISA.

DOMENICO GERARDI (EADS Astrium Friedrichshafen)

**Advanced concepts for future space-based interferometers: design and performance considerations**

Future drag-free missions for space-based experiments in gravitational physics require a Gravitational Reference Sensor with extremely demanding sensing and disturbance reduction requirements. A configuration with two cubical sensors is the current baseline for the Laser Interferometer Space Antenna (LISA) and has reached a high level of maturity. Nevertheless, several promising concepts have been proposed with potential applications beyond LISA and are currently investigated at HEPL, Stanford, and EADS Astrium, Germany. The general motivation is to explore the possibility of achieving improved disturbance reduction, and ultimately understand how low acceleration noise can be pushed with a realistic design for future missions. In this paper, we describe different payload concepts for future space-based interferometers, compare expected low-frequency sensitivities, and discuss advantages and disadvantages of each of those concepts in achieving disturbance reduction for future missions.

RÜDIGER GERNDT (Astrium GmbH)

**LTP - Development Challenges of a Spaceborne Fundamental Physics Experiment**

The LISA Technology Package (LTP) is the main payload onboard the LISA PathFinder Spacecraft. The LTP Instrument together with the Drag-Free Attitude Control System (DFACS) and the respective LTP and DFACS operational Software forms the LTP Experiment. It is completed by the FEEPs of the LPF spacecraft that are controlled by DFACS in order to control the spacecraft’s attitude along with the experiment’s needs. This article concentrates on aspects of the Industrial development of the LTP Instrument items and on essential performance issues of LTP. The development currently is on the turn from existing engineering models to building the final flight items. Elements being critical during LTP development will be discussed and the pitfalls encountered will be addressed. Examples of investigations on specific issue - like electrostatic analyses and charge control issues being further detailed in separate presentations - will highlight the kind of special problems to be solved for LTP in close cooperation with the Scientific community. Key Words: LTP Instrument, electrostatic analyses, caging mechanism, charge control, optical performance, vibration testing of Structural Model

ADRIEN Grynagier (Universität Stuttgart)

**Drift Mode for the LISA Technology Experiment**

The basic feature of the Drift Mode of the LISA Technology Experiment is to put both test masses along the sensitive axis in true free flight, i.e. no suspension control at all is applied to both test masses along the sensitive axis. The aim is to investigate the force applied on both test masses as well as the measurement accuracy in the case of a reduced actuation force noise. There is an obvious time-limit to the drift phase, since the spacecraft cannot follow both test masses at the same time A first part of this article describes the run conditions in terms of sensing limitations, actuation limitations and disturbances on the LISA Technology Package. In particular it is discussed whether electrodes 1,2,3-4 should be completely switched off during the free flight, depending on noise spillover between the control around phi and the motion in the sensitive axis. These constraints are then used to define the experiment more precisely. Four possible control strategies are described with various sequences of commands, time based or event based mode switching. Consequences on control implementation are discussed and it is shown which option can be implemented realistically. Preliminary simulation results are shown, based on nonlinear simulations using the End-to-End simulator. Eventually, this will lead to an estimate of the duration of one drift mode cycle. From this it can be estimated to which extent the drift mode can serve as a backup for force noise estimation in case of exceeding electrostatic actuation noise.

FELIPE GUZMÁN CERVANTES (Albert Einstein Institute Hannover)

**Test facility for prototypes of the LISA point-ahead angle mechanism**

The motion of the LISA spacecraft over the light round trip time induces an angular misalignment in the vertical plane between the incoming and outgoing beams. This point-ahead angle (PAA) varies in approximately 6 urad in free space over 1 year. The magnification of the telescope amplifies this angle to the order of 1 mrad at the optical bench,
such that a pure angle active compensation mechanism is needed to provide for optimal beam overlap. Since this actuator is located in the main beam path at the optical bench, its noise contribution should not limit the sensitivity of the main longitudinal measurement. The current noise budget allocated is $1.4 \text{ pm/}\sqrt{\text{Hz}}$ with relaxed requirements below $3 \text{ mHz}$. The main measurement concept consists of a triangular cavity, where 2 mirrors are bonded onto a Zerodur baseplate, for high mechanical stability. The third mirror is located at a prototype PAA mechanism, operating at a 45 angle of incidence, which is the current LISA design nominal. The PAA mechanism will be placed onto the Zerodur baseplate. The frequency of a Nd:YAG laser is controlled to be on resonance with this cavity using the Pound-Drever-Hall technique. In the high-gain limit the laser frequency tracks the cavity resonance frequency, which is determined by the length of the cavity and thus sensitive to path length changes. An upper limit for the displacement noise is obtained by measuring the frequency of the beatnote produced by interfering this laser locked to this three mirror cavity with a reference laser of sufficient stability, that in this case is another laser locked to a stable ULE cavity. A detailed description of the test facility and results obtained from its characterization will be presented.

ZOLTAN HAIMAN (Columbia University)

Finding Electromagnetic Counterparts to Supermassive Black Hole Binaries

I will discuss several ideas that may be useful in locating electromagnetic counterparts to supermassive black hole (SMBH) binaries detected by LISA. In particular, the binary may produce a variable electromagnetic flux, such as a roughly periodic signal due to the orbital motion prior to coalescence, or a transient signal caused by shocks in the circumbinary disk when the SMBH recoils and “shakes” the disk. I will discuss whether these time-variable EM signatures may be detectable, and how they can help in identifying a unique counterpart, even with the relatively poor ($\sim 0.3 \text{deg}^2$) sky localization errors provided by LISA. I will also discuss the extra science that will be enabled if an EM counterpart is found, such as constraints on SMBH accretion physics, cosmology, and gravitational physics. References: (1) Kocsis, Haiman & Menou 2007, ApJ, submitted, arXiv:0712.1144 (2) Lippai, Frei & Haiman 2008, ApJL, submitted, arXiv:0801.0739

MARK HANNAM (University College Cork)

Production of full black-hole binary waveforms for LISA using numerical relativity

Gravitational waveforms from the late inspiral ($\sim 15$ cycles) and merger of black-hole binaries can now be calculated to high accuracy using numerical methods. These waveforms can in turn be connected to long early inspiral waveforms produced by analytic methods, and the final “full” waveforms will increasingly approach the accuracy requirements of LISA data analysis. We discuss the generation and accuracy of these waveforms, and their agreement with post-Newtonian equivalents, for the largest range of parameter space yet considered: equal- and unequal-mass binaries, with both non-precessing and precessing spins.

IAN HINDER (Penn State University)

Eccentric binary black holes in numerical relativity and post-Newtonian theory

Whilst the majority of binary black hole sources for gravitational wave astronomy are expected to have circularized by the time they enter the detector band, there have been suggested several astrophysical scenarios where waveforms with significant eccentricity can be detected by LISA. We present the first comparisons between post-Newtonian and numerical relativity waveforms for eccentric binary black hole inspirals, an important step on the road to constructing templates. We find that the agreement is not as good as in the circular case, presumably due to the reduced order of PN available for eccentric inspirals.

MARC HIRTH (Universitaet Stuttgart)

Optical Metrology Alignment and Impact on the Measurement Performance of the LISA Technology Package

Aside from LISA PathFinder’s top-level acceleration requirement, there is a stringent independent requirement for the accuracy of the optical metrology system. In case of a perfectly aligned metrology system (optical bench and test masses) it should rather be independent of residual displacement jitter due to control. However, this ideal case will not be achieved as mechanical tolerances and uncertainties lead to a direct impact of test mass and spacecraft displacement jitter on the optical measurement accuracy. In the first part of this paper, we present a simplified nonlinear geometrical model for the differential distance measurement of the test masses. From that a linearized measurement equation is derived and linked to the equations of motion for both the optical bench (i.e. the spacecraft) and the two test masses. This leads from test mass relative displacement to a formulation in terms of applied force/torque...
and thus allows to distinguish the absolute motion of each of the three bodies. It further shows how motions in each degree of freedom couple linearly into the optical measurement via DC misalignments of the laser beam and the test masses. By further apportioning the top-level requirement for these effects, the necessary alignment accuracy and the closed-loop acceleration requirements can be allocated at this point. In the second part, the verification of the applied simplified differential distance measurement model is presented. To this end, the driving alignments of the simple model are compared to sensitivities that are obtained from simulations of a complex optical model carried out at the Albert Einstein Institute. This comparison is done for each degree of freedom of the test masses and the spacecraft and it is presented to what extent the two models are in agreement. In the last part a budget for the measurement performance is compiled using data from Astrium’s end-to-end simulator and the results of a Monte Carlo simulation of the alignment and bonding procedure at the Albert Einstein Institute.

Sascha Husa (MPI for Gravitational Physics / Albert Einstein Institute)

**Toward LISA data analysis with full black-hole binary waveforms**

I give an overview on currently available complete black-hole binary waveforms, which connect inspiral, merger and ringdown, and of implementations in GW data analysis algorithms. I then discuss work in progress on the implications for LISA.

Bernard Kelly (NASA Goddard Space Flight Center)

**Gravitational Radiation Characteristics of Nonspinning Black-Hole Binaries**

We present a detailed descriptive analysis of the gravitational radiation from binary mergers of non-spinning black holes, based on numerical relativity simulations of systems varying from equal-mass to a 6:1 mass ratio. Our analysis covers amplitude and phase characteristics of the radiation, suggesting a unified picture of the waveforms’ dominant features in terms of an implicit rotating source, applying uniformly to the full wavetrain, from inspiral through ringdown. We construct a model of the late-stage frequency evolution that fits the $\ell = m$ modes, and identify late-time relationships between waveform frequency and amplitude. These relationships allow us to construct a predictive model for the late-time waveforms, an alternative to the common practice of modelling by a sum of quasinormal mode overtones. We demonstrate an application of this in a new effective-one-body-based analytic waveform model.

Joey Key (Montana State University)

**Characterizing the Gravitational Wave Signature from Cosmic String Cusps**

Cosmic strings are predicted to form cusps that propagate with velocities near the speed of light that will emit beamed bursts of gravitational radiation. The broad frequency spectrum of these bursts allows for possible detection by both ground and space based gravitational wave detectors. Round 3 of the Mock LISA Data Challenge includes simulated signals from cosmic string cusps. We have developed a Markov Chain Monte Carlo (MCMC) technique to detect and characterize these signals. Here we show results from the Challenge 3 training data, paying particular attention to how the high frequency detector response allows the sky location to be determined.

Pablo Laguna (Penn State)

**The issue of the final spin in hyperbolic black hole mergers**

The spin of the final black hole produced by the merger of a binary black hole system is approximately determined by the combination of orbital angular momentum, spins of the coalescing black holes and radiated angular momentum at the point when the binary enters the plunge. In circular or low eccentricity inspirals, numerical simulations have shown that, although there is a substantial amount ($\approx 20\%$) of angular momentum radiated, the spin of the final black hole is dominated by the orbital angular momentum. To further explore the role played by the orbital angular momentum, we present results from parabolic and hyperbolic encounters. Because the radiated angular momentum for these mergers is significantly lower, we are able to construct initial configurations that yield spin flipping as well as spinning-up of the final black hole significantly different from those in circular orbits.

Ryan Lang (Massachusetts Institute of Technology)

**Advanced localization of massive black hole coalescences with LISA**

The coalescence of massive black holes is one of the primary sources of gravitational waves (GWs) for LISA. Measurements of the GWs can localize the source on the sky to an ellipse with a major axis of a few tens of arcminutes to a few degrees, depending on source redshift, and a minor axis which is 2-4 times smaller. The distance (and thus an approximate redshift) can be determined to better than a percent for the closest sources, although weak lensing degrades
this performance. It will be interesting to search this three-dimensional “pixel” for an electromagnetic counterpart to the GW event. The presence of a counterpart allows unique studies which combine both electromagnetic and GW information, especially if the counterpart is found prior to the final merger of the holes. In order to understand the feasibility of early counterpart detection, we calculate the evolution of the GW pixel with time. We find that the pixel size changes the most in the final day before merger, when spin precession effects are maximal. The source can be localized to within 10 square degrees as early as a month before merger at \( z = 1 \); for higher redshifts, this accuracy is only possible in the last few days.

**JEFFREY LIVAS** (NASA Goddard Space Flight Center)

**Frequency-Tuneable pre-stabilized lasers for LISA via sideband locking**

Laser frequency noise mitigation is one of the most challenging aspects of the LISA interferometric measurement system. The unstabilized frequency fluctuations must be suppressed by roughly twelve orders of magnitude in order to achieve a stability sufficient for gravitational wave detection. This enormous suppression will be achieved through a combination of stabilization and common-mode rejection. The stabilization component will itself be achieved in two stages: pre-stabilization to a local optical cavity followed by arm-locking to some combination of the inter-spacecraft distances. In order for these two stabilization stages to work simultaneously, the lock-point of the prestabilization loop must be frequency tunable. The current baseline stabilization technique, locking to an optical cavity, does not provide tunability between cavity resonances, which are typically spaced by 100s of MHz. Here we present a modification to the traditional Pound-Drever-Hall cavity locking technique that allows the laser to be locked to a cavity resonance with an adjustable frequency offset. This technique requires no modifications to the optical cavity itself, thus preserving the stability of the frequency reference. We present measurements of the system stability, demonstrating that the pre-stabilization level satisfies LISA requirements. We also present a demonstration of a phase-lock loop which utilizes the tunable sideband locking technique as a pre-stabilization stage. The performance of the pre-stabilized phase-lock-loop indicates that the tunable sideband technique will meet the requirements as an actuator for arm-locking in LISA.

**ILYA MANDEL** (Northwestern University)

**Can we detect intermediate-mass-ratio inspirals?**

Gravitational waves emitted during intermediate-mass-ratio inspirals (IMRIs) of intermediate-mass black holes into supermassive black holes could represent a very interesting source for LISA. At present, however, it is not clear what waveforms could be used for IMRI detection, since the post-Newtonian waveform breaks down as an IMRI approaches the innermost stable circular orbit, and the perturbative waveform is only known to the lowest order in the mass ratio. We discuss the expected mismatches between approximate and true waveforms, and the choice of the best available waveform as a function of the mass ratio and the total mass of the system. We also comment on the systematic errors in parameter estimation that will arise due to the use of approximate IMRI waveforms.

**KIRK MCKENZIE** (Jet Propulsion Laboratory)

**Fiber noise measurements and photoreceiver development**

The two optical benches on each of the LISA space-craft will be linked optically using a fiber back-link, an optical fiber connection in which a fraction of the optical power of each of the local lasers is transmitted to the adjacent bench. The LISA measurement concept requires that these counter-propagating beams experience common optical path length fluctuations to the pm/√Hz level. Any differential path length fluctuations will directly enter the LISA measurement. We report on recent experiments to characterize the relative path length fluctuations made using the JPL LISA test-bed and the LISA prototype phasemeter. In addition, we will present results from prototype quadrant photoreceivers developed to meet the LISA requirements for noise and phase variation in support of the science interferometer as well as wavefront sensing. Efforts to adapt the laboratory prototypes for the photoreceiver and the LISA prototype phasemeter for spaceflight applications will be described.

**SEAN McWILLIAMS** (NASA Goddard Space Flight Center)

**Observing mergers of nonspinning black hole binaries with LISA**

Recent advances in the field of numerical relativity now make it possible to calculate the final, most powerful merger phase of binary black hole coalescence. We present the application of nonspinning numerical relativity waveforms to the search for and precision measurement of black hole binary coalescences using LISA. In particular, we focus on the advances made in moving beyond the equal mass, nonspinning case into other regions of parameter space, focusing
on the case of nonspinning holes with ever-increasing mass ratios. We analyze the available unequal mass merger waveforms from numerical relativity, and compare them to two models, both of which use an effective one body treatment of the inspiral, but which use fundamentally different approaches to the treatment of the merger-ringdown. We confirm the expected mass ratio scaling of the merger, and investigate the changes in waveform behavior and their observational impact with changing mass ratio. Finally, we investigate the potential contribution from the merger portion of the waveform to measurement uncertainties of the binary’s parameters for the unequal mass case.

Anneke Monsky (AEI Hannover)

The First LTP Mock Data Challenge

The data analysis of the LISA Technology Package (LTP) will comprise a series of discrete experiments, each focussing on a particular noise measurement or characterisation of the instrument in various operating modes. Each of these experiments must be analysed and planned in advance of the mission. As such, the data analysis team will develop and carry out a series of Mock Data Challenges (MDCs) with the aim of preparing the analysis tools and understanding the various planned analyses. This talk will focus on the first of these MDCs, which is a simplified treatment of the dynamics along the axis joining the two test-masses. In particular, it will discuss the motivation and aims, the generation of the data, the analysis carried out, and finally the results achieved and lessons learned.

Wei-Tou Ni (Center for Gravitation and Cosmology, Purple Mountain Observatory, Chinese Academy of Sciences)

SUPER-ASTROD: Probing Primordial Gravitational Waves and Mapping the Outer Solar System

The general concept of ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) is to have a constellation of drag-free spacecraft navigate through the solar system and range with one another using optical devices to map the solar-system gravitational field, to measure related solar-system parameters, to test relativistic gravity, to observe solar g-mode oscillations, and to detect gravitational waves. Distances between spacecraft depend critically on solar-system gravity (including gravity induced by solar oscillations), underlying gravitational theory and incoming gravitational waves. A precise measurement of these distances as a function of time will enable the cause of a variation to be determined. A baseline implementation (ASTROD II or simply ASTROD) of the general ASTROD mission concept is to have two spacecraft in separate solar orbits, each carrying a payload of a proof mass, two telescopes, two 1 - 2 W lasers, a clock and a drag-free system, together with a similar spacecraft near Earth at one of the Lagrange points L1/L2. The three spacecraft range coherently with one another using lasers to map solar-system gravity, to test relativistic gravity to 1 part per billion, to observe solar g-mode oscillations, and to detect gravitational waves in the frequency range 10 $\mu$Hz - 10 mHz. A simplified implementation (ASTROD I) of one spacecraft optical ranging with earth stations will be able to achieve significant part of goals in testing relativity and mapping the inner solar system, and yet provide an incremental technology demonstration. For detection of primordial gravitational waves in space. One may go to frequencies lower or higher than LISA/ASTROD bandwidth where there are potentially less foreground astrophysical sources to mask detection. DECIGO and Big Bang Observer look for gravitational waves in the higher range while Super-ASTROD look for gravitational waves in the lower range. In the third phase, Super-ASTROD (ASTROD III), 3-5 spacecraft with 5 AU orbits together with an earth-sun L1/L2 spacecraft can be implemented to probe primordial gravitational waves with frequencies 0.1 $\mu$Hz - 1 mHz and to map the outer solar system. In this paper we address to orbit selection, payload selection, sensitivity to gravitational waves, and scientific goals.

Ed Porter (Albert Einstein Institut)

Improving Parameter Estimation For Supermassive Black Hole Binaries Using Higher Harmonic Corrections.

We demonstrate how the use of higher harmonic corrections to the gravitational waveform can be used to improve parameter estimation for inspiralling Supermassive black hole binaries. In particular we focus on the improvement in sky resolution and mass estimation for the more massive systems. An important result is that we demonstrate, that with these extra corrections, LISA can continue to provide accurate parameter estimation in the event of two links failing and LISA essentially becoming a one channel detector.

Alix Preston (University of Florida)

Back Link Fiber Stability Measurements

The degree to which TDI will be effective depends on the correlation of the phase noise in several laser beat signals. One element that can degrade the correlation is the back link fiber that allows the laser beam from one optical bench to travel to the other optical bench, and vice-versa. The current design uses one fiber optic cable for both
laser beams. Both beams counter-propagate through this fiber. The fiber link is equivalent to the beamsplitter in a standard Michelson interferometer. Differential phase noise induced by the fiber acts like a noisy beam-splitter in an interferometer and reduces the overall sensitivity. We have set up an experiment to measure the differential phase noise in a fiber using a polarization Sagnac interferometer. Here we discuss the status of the experiment and present our latest results.

Miguel Preto (Astronomisches Rechen-Institut (ZAH), University of Heidelberg)

Merger of Massive Black Holes in Galactic Nuclei using N-Body Simulations with Post-Newtonian corrections

This work studies the formation and co-evolution of massive black hole binaries (MBHB) in axisymmetric, rotating models of galactic nuclei using self-consistent, high resolution direct N-body simulations including the full Post-Newtonian corrections (up to 2.5PN) to the equations of motion of the MBHB. The shrinkage of the MBHB’s orbit proceeds as follows: (i) initially, due to dynamical friction, the MBHs are funneled towards the center of the galaxy where they form a bound pair; (ii) after they reach the scale of a parsec, the evolution of the MBHB orbital elements is driven by super-elastic three-body interaction with field stars until the binary reaches a separation small enough where (iii) the relativistic inspiral obtains. We are thus able, for the first time, to follow the self-consistent evolution of MBHBs from the Kpc scale all the way down to relativistic inspiral and coalescence on a relevant astrophysical short time scale ranging from $10^8 - 10^9$ yr. This constitutes a possible, purely stellar-dynamical solution to the final parsec problem. The MBHBs, in our models, show the tendency to form with very high eccentricities (up to $e = 0.9, 0.99$) and, as a result, reach separations of $100 M$ with eccentricities which are clearly distinguishable from zero - even though gravitational wave emission damps the eccentricity during the inspiral. These deviations from exact circular orbits, at such small separations, will have important consequences for LISA data analysis. This work is done in the context of the LISA-Germany collaboration.

Surjeet Rajendran (Stanford University)

Gravitational Wave Detection with Atom Interferometry

We propose two distinct atom interferometer gravitational wave detectors, one terrestrial and another satellite-based, utilizing the core technology of the Stanford 10 m atom interferometer presently under construction. The terrestrial experiment can operate with strain sensitivity $h \sim 10^{-19}$ in the 1 Hz - 10 Hz band, inaccessible to LIGO, and can detect gravitational waves from solar mass binaries out to megaparsec distances. The satellite experiment probes the same frequency spectrum as LISA with comparable. Each configuration compares two widely separated atom interferometers run using common lasers. The effect of the gravitational waves on the propagating laser field produces the main effect in this configuration and enables a large enhancement in the gravitational wave signal while significantly suppressing many backgrounds. The use of ballistic atoms (instead of mirrors) as inertial test masses improves systematics coming from vibrations and acceleration noise, and significantly reduces spacecraft control requirements.

David Robertson (Glasgow University)

Fibre Injectors for LISA

In LISA laser light is brought to the optical bench through an optical fibre. At the optical bench a fibre injector matches the light from the $\sim 6 \mu m$ diameter fibre to the $\sim 1500 \mu m$ diameter on the optical bench. There are extremely tight requirements on the optical quality and alignment stability of the output beam from the fibre injector. In addition to these requirements the fibre injector must be physically robust enough to withstand handling, launch loads, and the space environment. We present the development of a fibre injector for LPF and the lessons for the LISA fibre injector.

Emma Robinson (University of Birmingham)

Analysis approaches for detecting isotropic stochastic GW signals with LISA

The analysis method proposed to search for isotropic stochastic gravitational wave radiation with LISA makes use of two (or more) channels, one of which must be insensitive to gravitational waves. We have developed a general approach in the framework of Bayesian inference, and an analysis algorithm based on Markov Chain Monte Carlo methods to compute the posterior probability distribution functions of the model parameters. For this method to work, it is essential to have some knowledge of the relationship between the instrumental noise power in the two channels. We present the method and discuss its performance for different levels of prior information about the instrumental noise, and for different parameterisations of the problem. We have also applied this method to selected sets of simulated data, and present the results of these analyses.
Norichika Sago (University of Southampton)

**Gravitational self-force effects on a point mass around a Schwarzschild black hole**

We consider the gravitational self-force exerted on a point mass moving in a generic (eccentric) orbit around a Schwarzschild black hole. We developed a numerical code to solve the metric perturbation equations in the time domain, under the Lorenz gauge condition, and to implement the so-called ‘mode sum’ scheme to obtain the self-force. We use our numerical results to investigate both dissipative and conservative self-force effects on the particle’s orbits. To check the consistency of our calculation, we (1) derive the energy flux of emitted gravitational waves and compare with results from standard Teukolsky-based calculations; (2) compare our results with independent calculations based on a different gauge, in the special case of a circular orbit (by considering gauge-invariant quantities); (3) test our results against post-Newtonian calculations.

Josep Sanjuán (Institute of Space Sciences (CSIC-IEEC))

**Extension of the LPF temperature diagnostics to the LISA band at 0.1 mHz: first results**

High-resolution temperature measurements are required in the LTP, i.e., $10 \mu K/\sqrt{Hz}$ from 1 mHz to 30 mHz. These needs have been already accomplished with thermistors and a suitable low noise electronics. However, the frequency range of interest for LISA stretches down to 0.1 mHz. No previous information of the sensors specifications at this frequencies has been published. Investigations on the performance of temperature sensors and the associated electronics at frequencies around 0.1 mHz have been performed. Theoretical limits of the temperature measurement system and the practical on-ground limitations to test them are shown, demonstrating that $1/f$ noise is not observed in thermistors even at frequencies around 0.1 mHz.

Shuichi Sato (Hosei University)

**The Japanese Space Gravitational Wave Antenna - DECIGO**

DECi-hertz Interferometer Gravitational wave Observatory (DECIGO) is the future Japanese space gravitational wave antenna. The goal of DECIGO is to detect gravitational waves from various kinds of sources mainly between 0.1 Hz and 10 Hz and thus to open a new window of observation for gravitational wave astronomy. DECIGO will consist of three drag-free spacecrafts, 1000 km apart from each other, whose relative displacements are measured by a Fabry-Perot Michelson interferometer. We plan to launch DECIGO pathfinder first to demonstrate the technologies required to realize DECIGO and, if possible, to detect gravitational waves from our galaxy or nearby galaxies.

Markus Schulte (Imperial College London)

**Inertial Sensor Surface Properties and their effect on Test Mass Discharging**

The performance and operation of the LISA PathFinder inertial sensor (LPF IS) depends strongly on the ability to remove electrostatic charge from the test masses. The charge management device (CMD) has been designed to remove charge either continuously with a low noise impact, or intermittently at high discharge rates. Recent measurements and simulations have highlighted the sensitivity of the discharge and noise performance to the surface properties of the test mass and the electrodes. In response to this Imperial College London (ICL) and UTN have started a series of very detailed surface characterization exercises to ensure that the surfaces installed in the flight inertial sensor are well understood and that the discharge simulations and pre-flight measurements are representative of the performance of the LTP IS. Results of initial measurements and the detailed modeling of the discharge, from emitting the light through the optical feedthroughs via generating electrons on the surfaces to the actually achieved discharge rates are now available. At the same time the team at ICL has incorporated the experience from the final stages of the LPF CMD development phase into the new proposed development for the LISA CMD. The result is a new concept to implement redundancy and ruggedness in a UV-LED based design ideally suited for the new optical harness design already used in LPF.

Mauro Sereno (University Zurich)

**Local dark matter/dark energy searches with LISA**

The LISA detector is expected to provide new constraints on cosmological dark mater/dark energy using standard gravitational wave sirens. Here we investigate two novel and more direct methods. First, the relative motion of the drag free satellites in the LISA constellation will be affected by the dark matter/energy in the Solar system in a peculiar way. The signal due to local dark matter comes close but does not actually reach the amplitude needed for detection. The main signal shows up at very low frequencies outside of the LISA range but the effect is carried also
by overtones of fundamental frequencies of the dynamics of the system and this opens the way to very promising possibilities. Second, a cosmological constant affects the propagation and detection of gravitational waves. Polarization states are not changed whereas amplitude and periodicity of the waveform get modified. Unfortunately, changes seem to be extremely tiny and well below the detectability threshold.

ALBERTO SESANA  (Penn State University)

The impact of seed black hole formation scenarios and of extreme GW recoil on LISA detections.

The nature and abundance of the first seed s of the massive black holes we see today in galactic nuclei leave a unique imprint on the detection of gravitational waves at mHz frequencies. I will discuss here the possibility of constraining different models of black hole formation and cosmic evolution using LISA, assessing its capability of providing unique high-redshift informations difficult to obtain by other means. I will also discuss the implications of extreme gravitational recoil for massive black hole binary demography, showing that this would not be a serious issue for LISA detections. In our worst (from the LISA detection point of view) scenario, we predict at least a dozen of sources to be safe LISA targets assuming a three year mission lifetime.

DEIRDRE SHOEMAKER  (The Pennsylvania State University)

Coupling Simulations with Data Analysis and Observations

The advent of gravitational-wave astronomy will allow us to observe dynamic, non-linear gravity at work in the Universe. Concurrently, theoretical research of non-linear relativity is progressing rapidly, leading to the development of computational tools that allow us to explore where and how gravitational wave observations can constrain or inform our understanding of astrophysical phenomena. The interaction of binary black holes may be one of the strongest sources for gravitational wave observatories such as LISA. We study how well ground and spaced based detectors can detect non-circular orbits and mergers of binary black holes and some of the implications of such detections.

XAVIER SIEMENS  (University of Wisconsin – Milwaukee)

Cosmic (super)string detection with LISA

I will discuss the detectability of cosmic strings using LISA through matched filter searches for bursts as well as the stochastic signal that a string network would produce. The cosmology is solved exactly and includes the effects of late time acceleration. I consider the case when the bursts originate from small short-lived loops as well as large near-horizon sized loops—a possibility suggested by recent numerical simulations of cosmic string networks.

CARLOS F. SOPUERTA  (Institute of Space Sciences (CSIC-IEEC))

On the construction of 'kludge' gravitational waveform templates for Extreme-Mass-Ratio Inspirals

Extreme-mass-ratio inspirals (EMRIs), stellar-mass compact objects inspiraling into a massive black hole, are one of the main sources of gravitational waves expected for the Laser Interferometer Space Antenna (LISA) observatory. To extract the EMRI signals from the LISA data stream we need very accurate theoretical templates of the gravitational waves that they produce. The estimated accuracy for these templates is very high and implies a big effort in the theoretical description of these sources. In particular, simulations of EMRIs involve the solution of (linear) partial differential equations. A parallel effort to obtain EMRI waveforms is to introduce extra simplifications in the description of EMRIs so that only ordinary differential equations are involved in the computations. That sort of waveforms have been denominated as ‘Kludge waveforms’ and were designed mainly for data analysis design purposes, but they have been found to approach the precision of waveforms obtained in the ‘adiabatic’ approximation. At the same time, a quick method to generate templates is required taking into account the EMRI parameter space and duration of these signals in the LISA data stream. In this talk, I will discuss a new framework for the construction of ‘Kludge waveforms’ in which we can assess some of the foundations of the simplifications involved in the constructions of these waveforms and, at the same time, it can be used to introduce, in a consistent way, backreaction effects that can improve the quality of these waveforms.

FRANK STEIER  (Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute))

The LISA PathFinder interferometry: experience for the LISA local readout

We present the results obtained with the LTP interferometry testbed at AEI. The LTP design has been tested, implemented, and the performance demonstrated using the engineering model optical bench. This has allowed to investigate on-board procedures, alignment, integration between test masses and interferometer and components stability at picometre level. In the next step we will together with the industrial partners test the engineering and flight models
of the different optical metrology subsystems: laser, modulator, phasemeter, optical bench and back-end processing hardware and software. In the first phase, each box will be integrated in the existing testbed to investigate any degradation of the overall performance. Finally, they will be assembled together to demonstrate the complete LTP optical metrology system at flight-hardware level.

Ke-Xun Sun (Stanford University)

**The First Year of Stanford Modular Gravitational Reference Sensor (MGRS) Program**

The Modular Gravitational Reference Sensor (MGRS) is a next generation core instrument for space gravitational wave detection and an array of precision experiments in space. NASA started to fund the MGRS program at Stanford University in Spring of 2007. The objectives in the first year are to gain a system perspective of the MGRS, to develop key component technologies, and to establish important test platforms. Our original program was very aggressive in proposing ten areas of research and development. Significant advancements have been made, and met or exceeded the goals for the first year program. Additionally, we have initiated research projects beyond the original plan, and have continued innovation in technologies. The Stanford MGRS program has made exceptional contribution to graduate education and public outreach. In this presentation we will give a balanced overview of the progress in system technologies, two layer sensing and control scheme, trade-off studies of GRS configurations, optical displacement and angle sensors, multiple optical sensor signal processing, diffractive optics, mass center determination, moment of inertia measurement, UV LED charge management, proof mass fabrication, thermal control and sensor development, differential optical shadow sensing, characterization for various proof mass shapes, alternative charge manage techniques, and potential tests using small satellites.

James Ira Thorpe (NASA Goddard Space Flight Center)

**LISA Parameter Estimation using Numerical Merger Waveforms**

LISA’s ability to detect the late inspiral and merger of super-massive black holes with extremely high signal-to-noise ratios provides an opportunity to make precision measurements of certain parameters of the generating systems. By comparing the observed waveforms with a family of parametrized template waveforms in a maximum-likelihood analysis, parameters such as the hole masses, hole spins, luminosity distance, orientation, and sky position can be extracted. To date, estimates of the accuracy of this parameter extraction only considered the inspiral portion of the signal and ignored the contribution of the final merger. This was in part due to a lack of a detailed description of the merger waveform. Recent advances in numerical relativity have now provided such a description. Here we present a preliminary analysis of the importance of the merger portion of the waveform to parameter estimation. A hybrid numerical/analytic waveform for equal-mass, non-spinning black holes is used as the source and the Synthetic LISA software package is used to simulate the instrument response. The Fisher information matrix method is used to estimate the errors in the waveform parameters (total redshifted mass, luminosity distance, orientation, sky position, orbital phase, and merger time) . The initial results indicate that inclusion of the merger signal can significantly improve the precision of some parameter estimates.

Massimo Tinto (Jet Propulsion Laboratory)

**Bayesian comparison of Post-Newtonian approximations of gravitational wave chirp signals**

We estimate the probability of detecting a gravitational wave signal from coalescing compact binaries in simulated data from an interferometer detector of gravitational radiation using Bayesian model selection. The simulated waveform of the chirp signal is assumed to be a spin-less Post-Newtonian (PN) waveform of a given expansion order, while the searching template is assumed to be either of the same Post-Newtonian family as the simulated signal or one level below its Post-Newtonian expansion order. Within the Bayesian framework, and by applying a reversible jump Markov Chain Monte Carlo simulation algorithm, we compare PN1.5 vs. PN2.0 and PN3.0 vs. PN3.5 wave forms by deriving the detection probabilities, the statistical uncertainties due to noise as a function of the SNR, and the posterior distributions of the parameters. Our analysis indicates that the detection probabilities are not compromised when simplified models are used for the comparison, while the accuracies in the determination of the parameters characterizing these signals can be significantly worsened, no matter what the considered Post-Newtonian order expansion comparison is. Reference: Richard Umstaetter and Massimo Tinto, Phys. Rev. D. In press (2008).

Christian Trenkel (Astrium Ltd)

**Ground-based self-gravity tests for LISA PathFinder and LISA**

Gravitational coupling between the free-falling test masses and the surrounding spacecraft is one of the dominant
noise sources for both LISA PathFinder and LISA. At present, there are no plans to verify any of the self-gravity
requirements by test, on the ground. Here, we explore the possibilities of conducting such tests, using a customised
torsion balance. We discuss the main sources of systematic and statistical uncertainty present in such a set-up.

CHRISTIAN TRENKEL (Astrium Ltd)

Gravitational Science with LISA PathFinder?

We investigate the potential of conducting interesting gravitational science experiments with LISA PathFinder, by
executing well defined de-orbiting manoeuvres following the nominal mission. Preliminary work suggests that the
residual control authority of the micropropulsion system may be sufficient to follow trajectories that include Earth
flybys and / or the crossing of the Sun-Earth saddle point. The former might be used to shed some light on the
so-called flyby anomaly, the latter, potentially, for a test of MOdified Newtonian Dynamics (MOND). We present
some sample trajectories, uncertainties in the current model, and opportunities for future work.

MICHAEL TROEBS (Albert Einstein Institute Hannover)

Laser systems for LISA: overview and phase characteristics

In comparison to LISA PathFinder, the laser system for LISA must emit at least 30 times more power and include an
electro-optical modulator for clock noise transfer between spacecraft. The integrated broadband optical modulators
we have studied so far can only handle a fraction of the 1 W laser power required for LISA and must hence be followed
by an optical amplifier. This amplifier must not change the phase of the sidetones imposed on the light by the EOM
for clock noise transfer. We present current options for a LISA laser system and report on phase characteristics
measurements for a number of optical amplifiers.

MICHELE VALLISNERI (Jet Propulsion Laboratory/Caltech)

A toolkit for evaluating LISA’s performance in alternate configurations

I describe a simple framework to assess the LISA scientific performance (more specifically, its sensitivity and expected
parameter-estimation precision for prescribed gravitational-wave signals) in its baseline configuration, with different
noises, and also under the assumption of failure of one or two inter-spacecraft laser measurements and of one to four
intra-spacecraft laser measurements. I show that the SNR and Fisher matrix for generic signals are invariant with
respect to the choice of a basis of TDI observables and instead depend only on which inter-spacecraft and intra-
spacecraft measurements are available.

CHRIS VAN DEN BROECK (Cardiff University)

LISA as a dark energy probe

Pre-merger localization of supermassive binary black holes using LISA is very important in following up the possible
electromagnetic event coincident with the binary black hole merger. An improved angular resolution would help in
localizing the host galaxy of the source, in which case one could obtain redshift via electromagnetic observations. This
would then allow us to verify the relationship between luminosity distance and redshift, which depends sensitively on
cosmological parameters. We argue that using templates based on non-restricted post-Newtonian waveforms, which
include higher harmonics of the orbital frequency of the binary, increases the angular resolution quite dramatically.
This has profound implications for the cosmological information LISA can provide. In particular, we examine the
accuracy with which LISA can measure the dark energy equation of state. We also study the importance of having
a better low frequency sensitivity for cosmological parameter estimation. We use the 3PN accurate polarizations
recently derived by Blanchet et al. as our waveform model and our noise model for LISA follows that of the Mock
LISA Data Challenge.

GLENE DE VINE (Jet Propulsion Laboratory)

First experimental demonstration of clock-noise cancellation for LISA

We report on the first experimental demonstration of post-processed, time-delay interferometry with USO noise can-
cellation. The demonstration used simplified optical benches constructed from ultra-low expansion glass and the
LISA phasemeter prototype. Each bench was incorporated into an end station, consisting of two NPRO lasers, and
three phase measurements (two inter-bench measurements and one local measurement). The interferometer has been
designed to provide signals representative of LISA interferometry. The laser frequency noise-free combination, alpha,
was formed by combining the six phase measurements from the two end stations, each of which contained a clock
which was used as the master reference for that bench’s three phase measurements. The phase measurements were
interpolated in post-processing to correct for the errors in sampling times caused by the relative drift of the end stations’ clocks. After interpolation, the laser frequency noise in alpha was reduced by almost 4 orders of magnitude (relative to the noise level in the individual phase measurements) down to the performance limit of the interferometer. As expected, the independent clocks’ phase fluctuations also caused a large increase in the measured noise. This clock phase noise was removed by phase modulating the clock frequencies onto the laser beams exchanged between spacecraft in the manner planned for LISA. The clock noise was suppressed by almost 5 orders of magnitude. Notably, both the laser frequency noise and clock noise were suppressed down to our interferometer displacement noise level of 20 pm/√Hz at 0.1 Hz. Although this noise meets the LISA minimum mission requirement, work is ongoing to reduce the pathlength noise low enough to demonstrate laser frequency noise and clock noise suppression to below the error allocation of approximately 13 pm/√Hz. The current results validate both the expected performance of TDI as well as the performance of the LISA phasemeter prototype.

Vinzenz Wand (University of Florida)

The UF LISA Interferometry Simulator (UFLIS)

UF LISA Interferometry Simulator (UFLIS) is aiming for a hardware simulation of LISA interferometry under conditions as realistic as possible. This involves long time delays of the order of seconds and realistic noise sources such as laser frequency noise. LISA relies on three strategies to suppress laser frequency noise. Pre-stabilization to a cavity and arm-locking are intended to actively suppress initial frequency noise by several orders of magnitude. Data post-processing (TDI) suppresses the remaining noise down to 1 µHz/√Hz at 1 mHz. UFLIS provides an excellent testbench for the implementation and investigation of Armlocking and TDI. This presentation places particular emphasis on our Armlocking implementation and its current performance providing 5 orders of magnitude suppression @1 mHz. An unique feature of our armlocking implementation is the specific consideration of Doppler shifts. We discuss their impact on the design of our armlocking controller and its performance.

Peter Wass (University of Trento)

Direct-force measurements for testing the LISA PathFinder gravitational reference sensor

We present results of testing of the LISA PathFinder gravitational reference sensor (GRS) using a 4-test mass torsion pendulum facility aimed at measuring low-frequency acceleration-noise sources in the LISA and LISA PathFinder frequency band. Using this pendulum, for the first time, we have been able to make measurements sensitive to all forces acting along the sensitive axis of the test-mass. We will report on a campaign of testing using the LISA PathFinder engineering model GRS which has set upper limits on the overall force-noise acting on the test-mass contributed by surface effects within the sensor at a level below 100 fN/√Hz at 1 mHz and measured specific sources of unwanted disturbances. These sources include forces arising from the electrostatic coupling between the sensor and test-mass motion, electrostatic-fields due to surface-potential variations and thermal-gradient effects within the sensor.

David Wealthy (Astrium Limited)

Gravitational Modelling & Mass Control on LISA PathFinder

Accurate knowledge of the spacecraft gravitational field is crucial to the success of the LISA PathFinder mission. In high resolution mode the capacitive actuation system controlling the test masses is only able to generate a force one order of magnitude less than the natural gravitational force that arises from the spacecraft environment. Self gravity is also the major source of force gradient on the spacecraft and thus a major source of force coupling between axes. To have a working system, this natural gravitational field must be compensated to a high precision. This requires extremely accurate knowledge of the distribution of mass as well as a thorough estimate of the source of errors. This paper will describe the activities carried out by the LISA PathFinder team to model the spacecraft level mass distribution; assess the knowledge accuracy; and the plans for mass control during the spacecraft integration phase.

William Weber (Università di Trento and INFN)

Experimental tests of low frequency acceleration noise for free-falling LISA test masses

We report on experimental efforts to investigate the limits of geodesic motion for the LISA test masses, which must be in perfect free-fall to within an acceleration noise of 3 fm/s²/√Hz at 0.1 mHz. We will present an overview of the acceleration noise budget, incorporating recent results from torsion pendulum measurements of the interaction between a suspended LISA-like test mass and a surrounding prototype LISA capacitive sensor. Specific attention will be given to low frequency force noise from thermal gradient and stray electrostatic field effects. Finally, we will discuss what we can hope to learn from future improved torsion pendulum tests and from the LISA PathFinder mission.
Dennis Weise (EADS Astrium GmbH)

Alternative Opto-Mechanical Architectures for the LISA Instrument

As part of the on-going LISA Mission Formulation study funded by ESA, EADS Astrium GmbH has recently suggested and investigated a variety of novel LISA payload architectures utilizing so-called “In-Field Pointing” for accommodation of seasonal constellation dynamics. Here, the annual variation in the angle between the interferometer arms of roughly +/-1 is compensated by steering the lines of sight of the individual telescopes with a small actuated mirror located in an intermediate pupil plane inside the telescopes. This introduces a certain flexibility for the overall payload configuration and allows for very compact designs. In particular, it enables a “single active proof mass” mode with a true cold redundancy between the nominal and a backup GRS system on board each spacecraft, and thus potentially enhances mission robustness. We discuss challenges and realizations of LISA instrument architectures with In-Field Pointing, and compare their optical metrology and design features to those of the latest baseline configuration.

John Whelan (Albert Einstein Institute Potsdam)

F-Statistic Searches for White Dwarf Binaries in the Mock LISA Data Challenges

The F-statistic is an optimal detection statistic for continuous gravitational waves, i.e. long-duration (quasi-)monochromatic signals with slowly-varying intrinsic frequency. This method was originally developed in the context of ground-based detectors, but has also been applied to LISA data, in particular the search for galactic white-dwarf binaries (WDBs). A collaboration consisting of Reinhard Prix (AEI) and myself, with help from Deepak Khurana (Indian Institute of Technology and AEI), has generalized the open-source LALApps software suite developed by the LIGO Scientific Collaboration, and used it to perform searches for WDBs in the Mock LISA Data Challenges (MLDCs). I will summarize our previous results and describe the status of our ongoing program.

Bernard Whiting (University of Florida)

Post-Newtonian and self force calculations for EMRI sources

EMRI sources are currently outside the domain of full numerical general relativity, but they are amenable to perturbation analysis. For more than three decades we have known how to use energy loss from such systems to estimate the waveform generated. Using perturbation analysis, moves are now afoot to employ knowledge of the changed orbit to improve those waveform estimates. Far from coalescence, post-Newtonian methods have long been known to provide waveforms, depending upon the order of the calculations invoked, but their accuracy near coalescence is uncertain. Perturbation methods now give a way of demonstrating the range of applicability of post-Newtonian calculations, and provide a means to go beyond them.

Nicolás Yunes (Penn State University)

Constraining string theory with LISA

The low-energy limit of all string theories and quantum gravity requires the enhancement of the Einstein-Hilbert action by a parity-violating, Pontryagin term. Such a modified action defines an effective theory, Chern-Simons gravity, that has already been successfully employed to resolve the leptogenesis problem and anisotropies in the CMB. In this talk, I shall discuss gravitational-wave probes of this effective theory, focusing on LISA. A weak-field expansion of the modified theory reveals an “amplitude birefringence” correction to the propagation of gravitational radiation. Such a correction could be detected by LISA, thus gravitationally probing for the first time the quantum structure of spacetime on local and cosmological scales.

Ze-Bing Zhou (Huazhong University of Science and Technology)

Progress of performance measurements of the inertial sensor with an electrostatic-controlled torsion pendulum

The torsion pendulum, as a high sensitive probe of the torque in laboratory, not only can be used to investigate the residual acceleration disturbances on the space inertial mass, such as effects of the temperature and its gradient, the electromagnetic fields and so on, but also can be used to simulate operation of the inertial sensor in flight. To test the performance of the electrostatic actuators for the non-sensitive axes motions, and to measure the cross coupling between the sensitive axis and electrostatic servo axes of the inertial sensor, an electrostatic-controlled torsion pendulum have been constructed in our laboratory. In our experimental setup, the gaps between the proof mass and electrodes are much smaller than that used in Trento group, and the torsion pendulum is unstable without the feedback control torques because the amplitude of the negative parasitic stiffness of the capacitance transducers is much lager than the restorative stiffness of the suspension fiber. The parasitic stiffness due to the capacitance transducer was measured,
which agreed well with the theoretic analysis. The effects of the magnetic field and temperature on the proof mass were measured. The experimental setup to measure the coupling effects between the sensitive and non-sensitive axes of the proof mass are constructing.

Tobias Ziegler (Astrium GmbH)

Principles, Operations, and Expected Performance of the LISA PathFinder Charge Management System

The test masses of LISA PathFinder are free flying and therefore not grounded to the spacecraft by a wire. Because of galactic cosmic rays, solar energetic particles, and unknown microscopic surface effects during initial test mass release, an unacceptable level of absolute charge might be present on the test masses. A charged test mass can endanger the transition to high accuracy control modes which are required for the science experiments. Furthermore, charged test masses can introduce unwanted disturbance accelerations due to Lorentz interactions with magnetic fields and Coulomb interactions with conducting surfaces surrounding the test mass. The charge management system (CMS) is designed to discharge the test masses up to a tolerable level of absolute charge such that the mission goal can be achieved. It is therefore an essential part of the experiments to be performed with the LISA Technology Package (LTP). The paper describes the tasks to be performed on board the spacecraft and summarizes the principles of charge measurement and discharge control actuation. An overview of the experiment operations is given where the interconnection of the charge management system and the operational modes of the drag-free, suspension and attitude control system (DFACS) are taken into account. Performance results of the individual charge management modes of operation are presented. The performance results are obtained with simulated telemetry data.
**5. Abstracts for Posters**

**PAU AMARO SEOANE** (Institute of Space Sciences (CSIC-IEEC))

**Why eccentricity could play a role in IMBHs binaries**

If binary massive black holes (with masses ranging between 100 and $10^4 M_\odot$) form in dense stellar clusters, their inspiral will be detectable with the planned Laser Interferometer Space Antenna (LISA). We present a detailed study of the dynamical evolution of different models of binaries of massive black holes in stellar clusters. We find that the eccentricity of the fiducial model of the binary at the LISA bandwidth is large enough to induce a measurable phase difference. The inspiral signals can be characterized accurately enough that they can be removed from the data stream and in the process. This has an obvious impact in the detection of these sources, since it is usually assumed that a massive binary (with no mass ratio) will have a zero eccentricity when entering the LISA band. Our results prove that in our scenario eccentricity will play a non-negligible role.

**Michele Armano** (European Space Agency, ESTEC)

**SW Acceptance Testing for the LISA Technology Package**

The peculiar nature of the LISA Path-finder makes it unique and cornerstone a mission for risk assessment in view of LISA. The credible detection of Gravity Waves in space in the frame of ESA Cosmic Vision Plan and ESA/NASA Beyond Einstein program stands on the shoulders of LISA Path-finder. The high level demand of accuracy and the short operational time of the mission constitute evidence for the need of a reliable Data Analysis (DA) Framework as part of the Ground Segment. Unlike standard astrophysics missions, LISA PathFinder will have a more flexible operations schedule: the Science and Technology Operation Centre (STOC) will largely employ DA for decision-making during the operational phase. Is this tool ready for that demanding purpose? Are the standard procedures of Software Testing for such a package applicable? The scientific demand of reliability and that of ease of use are higher than for pure off-line data analyses. We report on the effort of planning and performing of acceptance testing of the LTPDA toolbox at ESAC.

**Michele Armano** (European Space Agency, ESTEC)

**Writing operational procedures for the LISA Technology Package**

The peculiar nature of the LISA Path-finder makes it unique and cornerstone a mission for risk assessment in view of LISA. The credible detection of Gravity Waves in space in the frame of ESA Cosmic Vision Plan and ESA/NASA Beyond Einstein program stands on the shoulders of LISA Path-finder. The effectiveness of the mission in the relatively short lifetime of the PathFinder satellite strongly relies on a carefully written set of operational procedure. LISA PathFinder will have a tight schedule to prove a list of technology goals. The link between pre-mission scientific analysis and operational phase is of paramount importance in this scenario. Moreover, the ability to tune measurement procedures and finely adjust the space experiment in turn relies on the flexibility of the measurement master plan. We report on the activity of writing operational procedures as a way to bridge the mission into reality. We will mainly consider the roadmaps for the measurement of acceleration difference and cross-talk evaluation, but provide insights on the main method.

**Peter L. Bender** (JILA/University of Colorado)

**LISA studies at the University of Colorado**

Coauthors: Michael J. Nickerson and Ellery B. Ames. The main experimental study for LISA being carried out at the University of Colorado is the design and testing of a new type of dual-cylinder laser reference cavity. The objective is to demonstrate laser locking to Fabry-Perot resonant cavities that have substantially reduced sensitivity to temperature fluctuations and to vibrations. The inner cylinder is the spacer for a Fabry-Perot interferometer, and the outer concentric cylinder provides support and a stable environment for the inner one. Both cylinders are made from a single piece of ULE glass, with a 5 mm thick disk connecting them near their midpoint. This design evolved from experiments by Nottcutt, Ma, Ye and Hall [Opt. Lett. 30, 1815 (2005)] and by Nottcutt et al. [Phys. Rev. A 73, 031804(R) (2006)] demonstrating high performance by vertical Fabry Perot cavities supported by disks near their centers. Estimates of the reduced sensitivity of the dual-cylinder cavities and their mountings to thermal fluctuations and to vertical vibration will be presented. In addition, some tests of the stability of reference voltage sources and a limit on their temperature sensitivity will be reported. These tests support earlier results obtained by Heinzel et al. at the Max-Planck-Institut fur Gravitationsphysik in Hannover [see paper in “Laser Interferometer Space Antenna”, Proc. 6th Int. LISA Symp., AIP Conf. Proc. 873 (2006), p. 291].
Daniel Bindel (ZARM - University of Bremen)

Optimized Thruster Control Algorithm for Drag-Free Spacecraft

Several space missions for fundamental physics research require a disturbance-free environment for their demanding science experiments. The concepts of these missions incorporate a drag-free technology for the spacecraft in order to counteract any external forces and torques. With a disturbance force, originated by the solar radiation pressure and other effects in the range of several MicroNewton, micro-propulsion systems are necessary for the spacecraft AOCS. Today, electrical and cold gas engines are available or in development to provide a continuous and controlled thrust in the MicroNewton range. Though, the different technologies for the thrust production have different advantages and disadvantages. An ideal thruster control algorithm should be able to deal with these different attributes in an optimal manner. The content of this paper is the analysis of the currently used methods to control the spacecraft thrusters of a drag-free mission like MICROSCOPE, LISA PathFinder or LISA and an introduction of a more advanced method. It shows the basic equations and problems of a Thruster Actuation System (TAS) for a simultaneous control of six degrees of freedom. The focus is on the modification of the standard linear programming algorithm SIMPLEX to meet robustness requirements for the application on a satellite onboard system. This new method takes care of the thrust range limitations (Control Authority) and the dynamics (change of thrust level) of the engines. As a true optimization algorithm, it also provides suitable control strategies for different types of thrusters. In comparison to the standard optimization method, the required memory and computational effort could also be decreased by a special modification, called “Solution Range Placement”. The algorithm that is developed is finally applied in a closed-loop, nonlinear simulation environment for the LISA mission. In this context, the science mode performance is demonstrated in which two proof masses on board of the LISA spacecraft are isolated from external disturbances along a sensitive axis down to a level of $3 \times 10^{-15} \, \text{m/s}^2/\sqrt{\text{Hz}}$. At the end of the paper, a small overview is given, how numerical instabilities in the original optimization algorithm can be avoided.

Arkadiusz Blaut (Institute of Theoretical Physics University of Wroclaw)

Grids for efficient all sky search of white dwarf binaries

Coauthors: Andrzej Królak and Maciej Pietka. We present construction of the 3 and 4 dimensional grids in the parameter space for all sky-search of gravitational wave signals from white dwarf binaries with LISA data. The 3 dimensional grid is for search of frequency and the sky position of the source and the 4 dimensional grid includes the spin down parameter. The grid solves the covering problem in the parameter space with the constraint that nodes of the grid coincide with Fourier frequencies (multiples of the inverse of the observation time). This allows the use of the FFT in the evaluation of the optimal statistic and greatly speeds up the search.

Nico Brandt (Astrium GmbH)

Electrostatic Model Revisited: Results and Consequences of the LISA PathFinder Inertial Sensor Finite-Element Analysis

Coauthor: Walter Fichter. A comprehensive finite-element (FE) electrostatic analysis of the LISA PathFinder Inertial Sensor (IS) has been carried out at Astrium GmbH. First, the results are used to verify the approximations of the IS electrostatic modeling applied by performance analysis, simulations and on-board algorithms. Second, operational scenarios, such as the test mass (TM) release strategy, are confirmed by analyzing the impact of the retractable caging plunger in the housing in close vicinity of the TM. Third, caging finger and TM interface design trades are supported and patch effects due to non-coated surfaces are analyzed. Starting with a detailed geometrical model of the IS housing and TM flight units, FE results are derived from multiple analyses runs applying the MAXWELL 3D field simulation software for different realistic actuation and sensing voltage settings. A significant amount of time was spent on assessing the solution specific software settings in order to find the best compromise between accuracy and computation time and to enable quantification of the accuracy of each solution. The electrostatic forces and torques on the TM in 6DoF, as well as all non-negligible capacitances between the TM, the 18 electrodes, the caging features, and the housing, are extracted for different TM translations and rotations. By fitting least-squares polynomials to the force and torque data, the according electrostatic stiffness is estimated. Thus, allowing for an accurate prediction, within the model accuracies, of the electrostatic actuation forces and torques, and the stiffness caused by the actuation scheme and sensing. The results of the FE analysis were expected to confirm the existing model used for performance analysis, simulations, and on-board algorithms. However, major discrepancies were found between the results and the model used so far. In general, FE results give considerably higher capacitance values than the equivalent infinite non-parallel plate estimates. In contrast, the FE derived forces and torques are in general significantly lower compared to the analytical IS electrostatic model predictions. The stiffness values, however, match quite well the model estimates. These differences are attributable to the fact that the analytical IS electrostatic model approximations
ignore fringing field effects and further neglect the additional capacitance between each electrode and its surrounding housing. In the paper, the FE analyses results are discussed in detail and reasons for deviations from the current analytical IS electrostatic model predictions are elaborated. Based on these results, an adapted electrostatic IS model is proposed that reflects the electrostatic forces, torques, and stiffness values in the LISA PathFinder IS significantly more accurate.

**Ernst-Jan Buis** (cosine Science & Computing BV)

**Simulation of the cosmological stochastic background in LISA**

One of the most striking observables from the early universe that has been measured up to now, is most probably the cosmic microwave background radiation (CMB). The CMB provides us with an astonishing picture of the early universe at the period of photon decoupling. In this paper we examine the feasibility of detecting the state of the universe in an even earlier phase. A possible source can be the first order phase transitions induced by symmetry breaking in the primordial plasma. While the upcoming start of the LHC might provide us crucial knowledge on the nature of symmetry breaking in the early universe, the red shifted gravitational waves originating from phase transitions may lie within the sensitivity of the proposed LISA mission. Expected spectra from such events are well motivated and quantified in literature. We report on the simulation of the stochastic background originating from phase transitions in the early universe. We use the expressions for stochastic background together with the LISA transfer functions to determine the expected signal in LISA. One of the largest source that might obscure the signal is the foreground that originates from galactic white dwarf binaries. The signal from these white dwarf binaries have been well simulated and are available through the Mock LISA Data Challenge. To study the feasibility to detect signals from an early universe we have carried out an analysis of the foreground signal an space in order to determine the reach of the LISA mission. In addition we draw the conclusion of the reach in view of the sensitivities of the experiments at the Large Hadron Collider.

**Priscilla Cañizares Martínez** (Institute of Space Sciences (CSIC-IEEC))

**Simulations of Extreme-Mass-Ratio Inspirals using Pseudospectral Methods**

Extreme-mass-ratio inspirals (EMRIs), stellar-mass compact objects inspiraling into a massive black hole, are one of the main sources of gravitational waves expected for the Laser Interferometer Space Antenna (LISA) observatory. To extract the EMRI signals from the LISA data stream we need very accurate theoretical templates of the gravitational waves that they produce. In order to do so we need to consider the gravitational backreaction, that is, how the gravitational field of the stellar-mass compact object affects its own trajectory. In general relativity, the backreaction is described in terms of a gravitational 'self-force', and the foundations to compute it have been laid several years ago. However, parts of the calculation of the self-force have to be performed numerically. In this poster we describe an effort towards the computation of the self-force based on time-domain pseudospectral methods, in which we try to take advantage of the high precision that this method provides.

**Giacomo Ciani** (University of Trento/INFN)

**A 4-TestMass torsion pendulum for direct force measurements in preparation for LISA and LISA PathFinder gravitational reference sensor ground testing**

We present the concept and experimental implementation of a 4-TM (Test Mass) torsion pendulum built to directly measure forces acting on a hollow, LISA-like Test Mass suspended inside a representative LISA PathFinder GRS (Gravitational Reference Sensor). Thanks to its geometry the pendulum is directly sensitive to forces acting on the TM along its translational degree of freedom, thus allowing for a representative investigation of known and unknown surface force noise sources arising inside the GRS. We will also describe measurement techniques used for a preliminary testing campaign using the LISA *PathFinder* GRS Engineering Model. The same techniques will be employed soon for an in-depth characterization of a GRS Flight Model Replica and its related force noise. Tests to be performed include electrostatic-model verification, characterization of stray surface-potential fluctuations, investigation of thermal gradient related effects and setting upper limits on unknown force-noise sources.

**Aleix Conchillo** (Institute of Space Sciences (CSIC-IEEC))

**Software components in the LTP Data Management Unit**

Over the last three years, the development of the Data Management Unit software has seen major enhancements, the Boot Software Unit is almost in its final state and the Application Software is already being used to perform tests with real hardware, mostly, the diagnostic items: coils, magnetometers, heaters and temperature sensors. Some other
parts of the software, such as the LTP devices, are still to be tested, but most of the hard work has already been done. In this poster, we present the current DMU software scenario, as well as its future, without forgetting how did we get to this point through this three-year long trip.

JEFF CROWDER (Caltech / JPL)

**A Four-Stage Search for Massive–Black-Hole Binaries in Mock LISA Data**

This talk will present the data analysis pipeline being developed by the JPL/Caltech group to search for the signals of inspiraling massive–black-hole–binary in synthetic LISA data. The pipeline consists of four stages. The first searches for tracks in the time-frequency plane, returning an estimate of the two mass parameters and the coalescence time. The second stage is a grid search over $M_1$, $M_2$, and $t_c$, narrowing the range of these parameters through an iterative sequence of ever finer grids. The third stage is another grid search over the sky position, which also narrows the search range using a sequence of increasingly fine grids. The final stage is a Markov Chain Monte Carlo search, which produces the best fit for all nine physical parameters, using the results from the previous stages to substantially shorten the burn-in time. I will discuss the reasons underlying this pipeline’s construction, and give results show how the pipeline fared in extracting source parameters from data sets released as part of the Mock LISA Data Challenge, and we briefly discuss our plans for future work.

ODYLIO D. AGUIAR (National Institute for Space Research (INPE))

**Perspectives to Testing Quantum Gravity Theories with LISA**

The spacing for the imaginary part of $\omega_n$ of high overtones of the Dirac quasinormal spectrum for the Schwarzschild black hole is equidistant and equals to $3\omega_{n+1} - 3\omega_n = i/8M$ ($M$ is the black hole mass), which is twice less than that for fields of integer spin. LISA should be able to detect QNM ringdown gravitational waves emitted by oscillating newly formed supermassive black holes. Here we discuss the possibility to distinguish the correct quantum gravity theory by observing high overtones of these highly excited supermassive black holes.

JUAN JOSÉ ESTEBAN DELGADO (Max Planck Institut fuer Gravitationsphysik (Albert Einstein Institut))

**LISA Phasemeter Development: Advanced Prototyping**

One of the most important key technology development issues of the LISA-mission is the interferometric readout of the main science measurement. We present the status of our work on the LISA phasemeter hardware, based on a custom designed board with fast AD converters and an FPGA processor. The performance of this phase measurement system (PMS) is demonstrated in laboratory conditions. We also discuss the architecture of the next PMS breadboard under construction which includes a DSP.

GUILLAUME FAYE (Institut d’Astrophysique de Paris - CNRS)

**Third post-Newtonian gravitational wave polarisations from inspiraling compact binaries in quasi-circular orbits**

The gravitational waveform of inspiraling compact binary systems is obtained at the third post-Newtonian approximation (3PN) with the twofold motivation of: (i) providing accurate templates for data analysis in the context of interferometric detection experiments and (ii) allowing future comparison, through the mode decomposition of polarisations, with waveforms produced in numerical relativity. Previous computations based on the multipolar post-Minkowskian formalism are extended by one half post-Newtonian order. Notably, the link between the radiative and source moments is found at the 3PN approximation, as well as the explicit expression of the source moments and hereditary terms for compact binaries in quasi-circular orbits.

NOEMI FINETTI (Dipartimento di Fisica dell’Università degli Studi dell’Aquila)

**Study of test-mass charging process in the LISA missions due to diffuse Gamma-rays**

Charging of the LISA test-masses due to exposure of the spacecraft to cosmic radiation and energetic solar particles affects operation of gravitational inertial sensors. In this paper we report on the role of diffuse gamma-rays (undetected by on board radiation monitors) in charging the LISA and LISA-PF test-masses with respect to protons and helium nuclei. The diffuse gamma-ray flux in the Galaxy was interpolated taking into account the outcomes of recent calculations. A comparison with gamma-ray observations gathered by different experiments (COMPTEL and EGRET, Milagro, Whipple, HEGRA, Tibet) was carried out. Simulations of the test-mass charging process were performed by means of the FLUKA2006.3b package. Results concerning the average steady-state charging rate and the single-sided power spectrum of the charge rate noise are discussed in this paper.
Zsolt Frei (Eotvos University)

Black Holes in High-Redshift Dark Matter Halos: The LISA Perspective

It is well known that an initial population of seed black holes (BHs), formed in the nuclei of low-mass galaxies at high-redshift, can simultaneously explain, through their subsequent growth by mergers and accretion, both the observed evolution of the quasar luminosity function (LF) and the distribution of remnant supermassive black masses (SMBHs) measured in local galactic nuclei. Here we consider three very different initial conditions for this scenario: models in which initial seed BHs form in either all, or only a small fraction ($f_{bh} = 0.1$ or 0.01) of high-redshift dark matter halos (with $M_{halo} = 5 \times 10^9 M_\odot$ at $z=6-10$). We show that with a suitable, and relatively minor adjustment of two global physical parameters (the radiative efficiency and mass accretion time-scale of quasar episodes), all three models can reproduce the remnant SMBH mass function, as well as the observed quasar LF at redshifts $0 < z < 6$. However, the merger histories of SMBHs in these models differ significantly, and as long as $f_{bh} \geq 0.01$, the future LISA instrument will be able to distinguish these models by directly measuring the SMBH merger rate using gravitational waves.

Peter Gath (EADS Astrium GmbH)

LISA Mission and System Architectures and Performances

In the context of the LISA Mission Formulation Study, the LISA System was studied in detail and a new baseline architecture for the whole mission was established. This new baseline is the result of trade-offs on both, mission and system level. The talk gives an overview of the different mission scenarios and configurations that were studied in connection with their corresponding advantages and disadvantages as well as performance estimates. Differences in the required technologies and their influence on the overall performance budgets are highlighted for all configurations. For the selected baseline concept, a more detailed description of the configuration is given and open issues in the technologies involved are discussed.

Domenico Gerardi (EADS Astrium Friedrichshafen)

LISA Pathfinder interferometer acquisition: design and analysis

The Optical Metrology Subsystem (OMS), i.e. laser assembly, heterodyne Mach-Zender interferometer, phase-meter, and data processing unit, is one of the key instrument for the test runs to be performed with the LISA Technology Package (LTP). Before science measurements are taken in a drag-free mode aboard the LISA Pathfinder spacecraft, optical signals have to be successfully acquired. In this paper, an optimized design of the optical acquisition phase in accelerometer mode is outlined with emphasis on the operational interconnection among OMS, Drag-Free and Attitude Control System (DFACS), and Experiment Control software. The design is demonstrated with a non-linear, fully coupled, 18 degree-of-freedom End-to-End simulator of spacecraft and payload.

Domenico Gerardi (EADS Astrium Friedrichshafen)

Estimation of the motion of a spherical proof mass with applications to future space-based detectors

A concept for a reference sensor with potential applications to future space-based detectors beyond LISA is presented; the sensor features a free-floating (unsupported) spherical proof mass whose center of mass is read out by means of high-precision heterodyne interferometry. We illustrate the status of our work on the design of the sensor (with emphasis on the optical design, and data acquisition/processing), present required calibration runs, describe a data processing strategy to estimate the motion of the center of mass of the sphere, and discuss expected measurement performance with reference to future space-based detectors. Sensor calibration and data processing algorithms are validated with a non-linear model of optics and processing hardware; results from non-linear optical sensing simulations are presented.

Martin Gohlke (EADS Astrium)

A High Sensitivity Heterodyne Interferometer as a possible Optical Readout for the LISA Inertial Sensor and its Application to Technology Verification

In the LISA spacecraft the relative motion between the inertial reference (i.e. the proof mass) and the spacecraft will be measured by use of an optical readout (ORO). Depending on the LISA optical bench design, this position sensor must have up to pm/√Hz sensitivity for translation measurement and up to nrad/√Hz sensitivity for tilt measurement. In collaboration with the Humboldt University Berlin and the HTWG Konstanz, a prototype ORO has been realized over the past years, which meanwhile is close to achieving the required picometer sensitivity in translation and nanorad sensitivity in attitude metrology. The polarizing heterodyne interferometer is characterized.
by a highly symmetric design and employs differential wavefront sensing for determination of the proof mass tilt in 2 degrees of freedom. We will present the experimental setup and its latest performance, as well as its application to first verification of critical LISA subsystems as e.g. the characterization of the CTE of various CFRP samples with ultra-high sensitivity, including “near-zero-CTE” tubes.

ACHAMVEEDU GOPAKUMAR (Theoretisch-Physikalisches Institut (Friedrich-Schiller University))

The TaylorEt approximant and its implications for LISA

GW polarizations relevant for inspiralling compact binaries under the TaylorEt approximant is introduced and its salient features are explained. The implications of the TaylorEt templates for doing astrophysics with massive binary black hole inspiral and testing General Relativity are briefly discussed.

FELIPE GUZMÁN CERVANTES (Albert Einstein Institute Hannover)

LISA test mass optical read out: deep phase modulation scheme

The need for monitoring the LISA test mass motion with sub-nanometer sensitivity in many degrees of freedom is currently under study. We present an optical readout scheme based on the deep phase modulation of a laser beam at one arm of a Mach-Zehnder interferometer. A discrete Fourier Transform is applied to the measured photocurrent, where the harmonic components of the first ten multiples of the modulation frequency are used to assemble a complex system of equations. The interferometric phase, yielding the test mass displacement, can be extracted by solving this system of equations via a Levenberg-Marquardt fit algorithm. The real-time phase readout system reaches a longitudinal sensitivity of the order of few 10 pm/√Hz. By using quadrant photodetectors, the test mass angular motion can also be measured to better than 10 nrad/√Hz, applying a differential wavefront sensing technique.

HUBERT HALLOIN (APC (AstroParticule et Cosmologie))

Iodine laser stabilization for LISA

In a nutshell, the expected performance of LISA relies on two main technical challenges: the ability for the spacecrafts to precisely follow the free-flying masses and the outstanding precision of the phase shift measurement. This latter constraint requires frequency stabilized lasers and efficient numerical algorithms to account for the redundant, delayed noise propagation, thus canceling laser phase noise by many orders of magnitude (TDI methods). Recently involved in the technical developments for LISA, the goal of our team at APC (France) is to contribute on these two subjects: frequency reference for laser stabilization and benchtop simulation of the interferometer. In the present design of LISA, two stages of laser stabilization are used (not accounting for the “post-processed” TDI algorithm): laser pre-stabilization on a frequency reference and lock on the ultra stable distance between spacecrafts (arm-locking). While the foreseen (and deeply studied) laser reference consists of a Fabry-Perot cavity, other techniques may be suitable for LISA or future metrology missions. In particular, locking to a molecular reference (namely iodine in the case of the LISA Nd:YAG laser) is an interesting alternative. It offers the required performance with very good long-term stability (absolute frequency reference) though the reference can be slightly tuned to account for arm-locking. This technique is currently being investigated by our team and optimized for LISA (compactness, vacuum compatibility, ease of use and initialization, etc.). Ongoing results and prospects to increase the performance of the system will be presented at this session. Beyond the laser pre-stabilization, it is also desirable to test interferometric algorithms and devices, such as Time Delay Interferometry, arm-locking and phasemeters. To achieve this goal, we are currently designing an optical benchtop experiment representative of LISA measurements, that will be implemented in the near future. The main problem of LISA “hardware” simulation is the propagation delay between spacecrafts (about 16 s). Obviously, light cannot be delayed accordingly in the lab. Nevertheless, only the phase (or frequency shift) of the wave is of interest for the LISA measurements. The limited bandwidth of this information (less than 1 Hz) makes it easy to digitally store and delay. These noises (and Doppler effects) are then imprinted on the laser beams using acoustic- or electro-optics modulators. Ultimately, this experiment is expected to be a facility opened to the whole LISA community.

ANNA HEFFERNAN (University College Dublin)

Detecting a Stochastic Gravitational Background

We construct a general formula for the signal-noise ratio of an anisotropic stochastic background that can be broken down to agree with both the spherical harmonic and pixel basis approaches. We use this formula to investigate a wavelet inspired basis.
Simulating the UV Discharge System for LISA PathFinder.

Following tests of the UV discharge system performed using the torsion pendulum facility at the University of Trento, a simulation is being developed at Imperial College London in order to characterise the relevant surface properties of the inertial sensor. In addition, it will model the effects of various combinations of applied voltages and their effect on the test-mass equilibrium voltage. We describe the model details and preliminary results.

Precision alignment of optical components for LISA PathFinder and LISA

An enabling technology for the LISA PathFinder and LISA missions is the precision location and flight-worthy jointing of optical components to baseplates made of low expansion materials. A method of aligning and hydroxide-catalysis bonding these components has been developed and tested. Results showing component positioning and bonding at sub-micron level will be presented and the technique described. This process is being used in the LISA PathFinder optical bench build and it is envisaged that it will also be used in the LISA optical bench construction.

Harmonic correlation for eccentric binaries in gravitational wave observations

Binary systems will be among the most numerous sources detected by interferometric gravitational wave detectors. In many instances, the binaries will have non-zero orbital eccentricities, producing power in the Fourier spectrum at the fundamental orbital frequency and its higher harmonics. This talk describes a binary search technique called “harmonic correlation” which exploits the harmonic structure of the signal to identify binaries in gravitational wave data streams, even at low signal-to-noise ratios.

Determining the neutron star structure using narrow-band gravitational wave detector

The direct detection of gravitational waves (GWs) will provide valuable astrophysical information about many celestial objects. The most promising sources for detection of GWs are neutron stars (NSs) and black holes. These objects emit waves in a very wide spectrum of frequencies determined by their quasi-normal modes oscillations. In this work we are concerned with the information we can extract from quasi-normal modes of the NSs when a candidate leaves its signature in a detector of resonant mass. With this goal we have verified the mass-radii relations and some informations about nuclear structure of NSs using the resonance frequencies of these detectors.

Gravitational wave radiation from white dwarf close encounters in globular clusters

In the dense central regions of globular clusters close encounters of two white dwarfs are relatively frequent (one or more strong encounters per star in the lifetime of the cluster). Such encounters should be potential sources of gravitational wave emission. Thus, it is foreseeable that these collisions could be either detected by LISA or they could contribute significantly to the background noise of the detectors. We compute the gravitational wave pattern resulting from these encounters for a broad range of system parameters, which include the masses and the relative distances of the white dwarfs involved in the encounter.

TEPO project with similar technologies used in LISA PathFinder

The Equivalence principle (EP), as one fundamental hypotheses of Einstein’s general relativity, has been tested by many experiments. Several space projects such as STEP, MiniSTEP, GeoSTEP, GG, and MicroSCOPE, were proposed to test the EP at the level of from 10-15 to 10-18. We propose the TEPO project (Test of Equivalence Principle with Optical readout in space) to test of Equivalence Principle for the differential composition bodies at the relative level of 10-16, and for the rotating extended bodies at the relative level of 10-14. The payload used in the TEPO mission is similar to that used in LISA PathFinder, which consists of the two proof mass, capacitance transducers and electrostatic actuators for the non-sensitive axes of the both test masses, a heterodyne interferometer to measure the differential motion along the sensitive axis, a charge management unit based on the ultra-violent light discharge techniques to discharge the proof mass, and a drag-free and attitude control system (DFACS) combined with the micro-Newton thrusters to obtain an ultra-low disturbance satellite platform. The main difference between...
the TEPO and LISA PathFinder is that the centre of mass offset between the proof masses is changed from a few tens of centimeter to nanometer accuracy, and corresponding shape of the proof masses are changed from the cubic block to the cylinder. The TEPO project could test the technologies for LISA with a scientific objective to test the Equivalence principle. In this paper, the feasibility of the TEPO project is briefly described, and the requirements of key technologies are discussed.

LORENZO MARCONI (Università di Firenze & INFN Firenze)

Ground Based Test for LISA and LISA PathFinder

We present the first results of the measurement with the roto-translational pendulum for the characterization of the GRS (Gravitational Reference Sensor) for LISA and LISA PF. In the roto-translational pendulum, a mock test mass will be in quasi free fall motion on two DoFs (Degree of freedom). With our facility we will have a better simulation of the flight conditions, where test masses are free in all 6 DoFs. We will be able to study the couplings between the rotational and the translational DoF of the test mass. In particular, we will measure the residual disturbance along one DoF when we close the control loop on the other one, with a sensitivity limited by the thermal noise.

JOSÉ IGNACIO MATEOS MARTÍN (Institute of Space Sciences (CSIC-IEEC))

Towards an improved magnetic diagnostic system for LISA

The current design, and material implementation of the magnetic field sensing in the LTP is based on a set of 4 high-precision 3-axis fluxgate magnetometers. In order to avoid magnetic disturbances on the TMs, originated by the sensors themselves, these are placed somewhat far from the TMs, which results in partial losses of valuable field information. We are currently investigating alternative magnetic sensing techniques, based on AMR devices (magneto-resistors). These are much smaller in size than fluxgates, therefore a more numerous array can be thought of for flight. In addition, there is a chance that they may be attached closer to the TM, thereby enhancing magnetic field sensing spacial resolution. Several issues need to be addressed, such as real sensitivity (including electronics noise) and set/reset trigger procedures. This presentation will show the latest results of our research.

STEPHEN MERKOWITZ (NASA Goddard Space Flight Center)

Current LISA Spacecraft Design

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 spacecraft. LISA is unique from a mission design perspective in that three spacecraft and their associated operations form one distributed science instrument, unlike more conventional missions where an instrument is a component of an individual spacecraft. The design of the LISA spacecraft is also tightly coupled to the design and requirements of the scientific payload; for this reason it is often referred to as a “sciencecraft.” A detailed discussion will be presented that describes the current spacecraft design and mission architecture needed to meet the LISA science requirements.

JOACHIM NAEF (Institute for Theoretical Physics, University of Zurich)

On the Effect of a Nonvanishing Cosmological Constant on Gravitational Waves

We investigate the linearised Einstein’s equations with a cosmological term. We consider a de Sitter and an anti-de Sitter background spacetime and focus upon the part of the equations which is linear in the metric perturbation. These contributions are then expanded up to linear order in $\Lambda$. The resulting equations can be interpreted as a wave equation in Minkowski spacetime which is perturbed by a linear hyperbolic differential operator of second order proportional to $\Lambda$. When taking into account this perturbation the polarization states of the wave solutions remain unchanged, whereas the amplitude as well as the frequency as measured by a distant observer get modified with terms depending on $\Lambda$. These effects are, however, below the detectability threshold of future planned gravitational wave detectors such as LISA or present ones such as LIGO by more than twenty orders of magnitude.

WEI-TOU NI (Center for Gravitation and Cosmology, Purple Mountain Observatory, Chinese Academy of Sciences)

Sensitivities to Scalar Gravitational Waves for LISA, ASTROD

In general relativity, a spherically symmetric gravitational collapse does not radiate gravitational wave. However, scalar-tensor (or dilaton-tensor) theories of gravity predict gravitational radiation for such collapse. Since scalar-tensor (or dilaton-tensor) theories of gravity are prevalent in cosmology, we address to the possibility of detecting scalar gravitational waves for space detectors. The signal to noise ratio of LISA can reach $10^{576}$ for coalescence of massive black holes from galaxy mergers. For a galactic supermassive collapse to a black hole, the magnitude for the
tensor component of gravitational radiation is similar to that of merger times the nonsphericity of the collapse, while the magnitude of the scalar component is of the order of that of the merger times the scalar coupling strength. In this paper, we obtain the sensitivities to scalar gravitational waves for LISA, ASTROD, DECIGO, Big Bang Observer, and look into configurations more sensitive to the scalar gravitational waves. For ASTROD, the sensitivity to scalar gravitational waves would be large enough to detect scalar gravitational waves from a galactic supermassive collapse to a black hole even the strength of scalar coupling is of the order of $10^{5/6}$.

**Daniele Nicolodi** (Università di Trento / INFN)

**An improved torsion pendulum for on-ground verification of the LISA gravitational reference sensor**

We report on the progress towards an advanced torsion pendulum for on-ground verification of the LISA gravitational reference sensor, that will lead to improved force sensitivity and thus bring ground testing closer to the LISA requirements. These enhancements consist of the employment of a fused silica torsion fibre which promises a much higher mechanical quality factor and thus much lower mechanical thermal noise, and in the development of an interferometer that will drastically reduce the angular readout noise. We present our progress with the first integration of a fused silica fibre into the Trento single mass torsion pendulum facility and discuss the design of the interferometer. Those improvements should lead us to a force noise sensitivity of $10 \text{fN/}\sqrt{\text{Hz}}$ in the mHz frequency region, gaining more than a factor 10 over our current force sensitivity.

**Miquel Nofrarias** (Institute of Space Sciences (CSIC-IEEC))

**Thermal coupling within LTP dynamics control loop: diagnostics and data analysis**

The Diagnostics Subsystem in the LISA Technology Package (LTP) on board the LISA PathFinder mission (LPF) will characterise those external disturbances with a potential impact on the performance of the experiment coming from either thermal, magnetic or charged particle perturbations. In this talk we will focus our attention in the thermal diagnostic case, where 24 sensors will be monitoring the high stable LTP environment, and 14 heaters will be used to induce controlled perturbations. Based on ground experiments and thermal simulations, we analyse how temperature perturbations will couple into the LTP dynamics control loop and describe the experiments designed to estimate the parameters driving this interaction during flight operations. We develop this analysis in the framework of the LTPDA Toolbox, the Matlab data analysis toolbox being developed by the LPF collaboration specifically to deal with LTP data.

**Kenji Numata** (NASA Goddard Space Flight Center and University of Maryland)

**Stabilized interferometry platform for LISA ground testing**

The LISA interferometer must be able to measure a 10pm level of relative displacement between spacecrafts over 1000 seconds. The ground verification of this requirement is very significant and critical. However, the verification measurement is very difficult, because it is 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. This is done by interferometric sensing and an active feedback control. We have implemented optical setup similar to LISA — distance variation between two all-glass optical benches is measured by a frequency-stabilized heterodyne interferometer. The stabilized level is about 10 times larger than LISA requirement, and the limiting noise is identified as cross coupling from uncontrolled degree of freedom.

**Kenji Numata** (NASA Goddard Space Flight Center and University of Maryland)

**Coated fused silica fibers for enhanced sensitivity torsion pendulum for LISA**

In order to investigate the fundamental thermal noise limit of a torsion pendulum using a fused silica fiber, we systematically measured and modeled the mechanical losses of thin fused silica fibers coated by electrically conductive thin metal films. Our results indicate that it is possible for coated silica to achieve a thermal noise limit lower than obtained with the tungsten fiber used in recent LISA torsion pendulum studies. This will allow a corresponding increase in sensitivity of torsion pendula used for small force measurements.

**Satoshi Okuzumi** (Kyoto University)

**Possible discovery of nonlinear tail and quasinormal modes in black hole ringdown**

We discuss the nonlinear evolution of black hole ringdown in the framework of higher-order metric perturbation theory. By solving the initial-value problem of a simplified nonlinear field model analytically as well as numerically, we find that (i) second-order quasinormal modes (QNMs) are indeed excited at frequencies different from those of
first-order QNMs, as predicted recently. We also find serendipitously that (ii) late-time evolution is dominated by a new type of power-law tail. This “second-order power-law tail” decays more slowly than any late-time tails known in the first-order (i.e., linear) perturbation theory, and is generated at the wavefront of the first-order perturbation by an essentially nonlinear mechanism. These nonlinear components should be particularly significant for binary black hole coalescences, and could open a new precision science in gravitational wave studies.

ERIC PLAGNOL (APC (Paris))

LISACode and the Stochastic Background (MLDC 3.5)

LISACode has been used to generate the simulated data for the Stochastic Background corresponding to the MLDC 3.5. The hypothesis adopted is that this background has a $f^{-3}$ slope. At 2 mHz, where the background is of the same order as the instrumental noise, the sensitivity to the background will be tested at the level of $\Omega_{gw} \approx 10^{-12}$. The poster will show how the background has been generated and how the response of LISA, at the phasemeter level and at the TDI level influences the slope of the detected background. Some indications on the methods that will be used to analyse the data will be presented.

ERIC PLAGNOL (APC (Paris))

A study of the angular resolution of LISA for monochromatic GW

The angular resolution of LISA for monochromatic GW has been studied using an analytic formula reproducing the modulation of the amplitude of LISA for different TDI combinations. The data has been generated by using LISACode and the study is performed as a function of the position of the source in the sky, of its polarisation and on the Signal/Noise ratio.

LARRY PRICE (University of Wisconsin-Milwaukee)

Stochastic Background of Gravitational Waves from Cosmological Sources

Several mechanisms exist for generating a stochastic background of gravitational waves in the early universe. These mechanisms are generally classical in nature, with the gravitational waves being produced from inhomogeneities and not quantum fluctuations. The resulting stochastic backgrounds could be accessible to the next generation of gravitational wave detectors. In this talk I’ll discuss a general framework for computing such a background and provide examples of sources.

ANTONIO PULIDO PATÓN (Purple Mountain Observatory, CAS)

Gravitational disturbances in drag-free sensors

The performance of drag-free satellites is ultimately limited by the uncompensated self-gravitational field and gravity field gradient of the spacecraft structure and payload. These residual fields constitute an important source of acceleration noise for the proof mass in free fall motion. We will identify critical aspects for the design of the spacecraft and distribution of the payload constituents to minimize disturbances of gravitational origin. We will explore new ideas for diagnostic and compensation of gravitational fields in the vicinity of the proof mass. The benefits of these diagnostic tools for future missions like ASTROD, will be discussed.

JOSEP SANJUÁN (Institute of Space Sciences (CSIC-IEEC))

Magnetic polarization effects of temperature sensors and heaters in LISA PathFinder

Temperature sensors and heaters belong in the diagnostics subsystem of the LISA Technology Package (LTP) on board LISA PathFinder, the technology demonstrator for LISA. A number of these diagnostics items are placed at short distances from the LTP proof masses, and are NTC thermistors. By design, these devices have tiny amounts of ferromagnetic materials which therefore constitute a potential source of disturbance to the performance of the LTP. We will present a detailed magnetic characterization of the NTC’s, and use the data to evaluate their impact on the acceleration noise budget of the LTP. The effect is seen to be small if the NTC’s are submitted to a de-magnetization process before they are attached. Re-magnetization is unlikely, as rather strong fields ($\sim$ mili-Tesla) are required to produce potentially dangerous NTC magnetic polarization.

FABIO SCARDIGLII (Yukawa Institute for Theoretical Physics)

Glimpses on the micro black hole Planck phase

Mass thresholds and lifetimes of micro black holes are computed using different generalized uncertainty principles.
Results are compared with previous analog approaches.

**Alberto Sesana** (Penn State University)

**LISA and Pulsar Timing Arrays: orthogonal tools to constrain Massive Black Hole cosmic history**

Future Pulsar Timing Arrays (PTAs) will be sensitive to gravitational wave backgrounds at nHz frequencies, a domain where the signal is expected to be dominated by supermassive ($M > 10^8 M_\odot$) nearby ($z < 2$) black hole binaries. On the other hand, LISA is sensitive to lighter binaries ($10^3 < M < 10^7 M_\odot$) up to higher redshift ($z > 10$). Observation with LISA and PTAs are thus orthogonal, and together will constrain the evolution of massive black holes during cosmic history, from the first seeds in protogalaxies at $z > 10$ to the local supermassive black holes we see in giant ellipticals today.

**Alberto Sesana** (Penn State University)

**Observing white dwarfs orbiting massive black holes in the gravitational wave and electro-magnetic window**

We present a potential new class of sources consisting of a white dwarf and a massive black hole in the mass range $\sim 10^4 - 10^5 M_\odot$ producing a gravitational wave signal detectable with the Laser Interferometer Space Antenna (LISA) and electro-magnetic flares due to the white dwarf tidal disruption. We investigate the depth of surveys, the associated detection rate and discuss the implications for precise cosmography. This class of sources could also provide insights on e.g. the demographics of black holes in the mass range $\sim 10^4 - 10^5 M_\odot$, the dynamical interactions and white dwarf populations in the core of dwarf galaxies, and the structure and equation of state of white dwarfs.

**Diana Shaul** (Imperial College London)

**How to use a radiation monitor to reduce LISA noise levels**

High energy cosmic ray and solar particle fluxes will charge up the LISA test masses. This charge will result in spurious electromagnetic forces acting on the test masses, disturbing their geodesic motion. The primary approach to minimise the impact of these forces is to discharge the test masses using the photoelectric effect. Unfortunately, the flux and energy spectrum of these high energy charged particles varies over time and therefore it is not easy to match charging and discharging rates, which would minimise the disturbances induced by charging. The gravitational reference sensor can be used to measure the average charge accumulated over the measurement period, but not the shorter term variations in the charging rate. A radiation monitor can enable tracking of these changes. We discuss how a radiation monitor could be used to reduce the charging disturbances for LISA and the plans for use of the radiation monitor on LISA PathFinder, including an approach that could enable acceleration noise associated with charging to be effectively subtracted.

**Frank Steier** (Albert Einstein Institute Hannover)

**Processing of interferometric data on board LISA PathFinder**

On board LISA PathFinder the interferometer data is calculated inside the Data Management Unit (DMU). A lot of calculations are performed on the interferometer data before the main science channels – one longitudinal and two angular signals for each test mass – are transferred to the on board computer (OBC). Usually only these science channels are transferred to ground. In this talk the DMU internal data processing is introduced and an experimental demonstration of interferometer performance is presented. In the data processing software important features are included, which were not needed in prior breadboard performance tests. These new features are: averaging of redundant photodiode channels, DMU internal error handling, down-sampling of the output channels and simulations of the asynchronous data transfer between DMU and OBC. Additionally a digital controller was implemented to control the piezo actuated dummy mirrors, which are used instead of the real test masses for the performance tests. This way it was possible to simulate the on-orbit test mass alignment.

**Frank Steier** (Albert Einstein Institute Hannover)

**Coupling of test mass jitter into the longitudinal measurement**

On board LISA PathFinder the alignment of the frames defined by the optical bench and the inertial sensor is very critical. The inertial sensor has the highest sensitivity around its centre and the interferometric angular test mass read out – derived by Differential Wavefront Sensing – is most sensitive around its zero. In order to operate both, inertial sensor and interferometer, at high sensitivity the required relative alignment of the optical bench and inertial sensor frame must have an accuracy in the order of $\pm 50$ micron in x-direction and $\pm 100$ micro radian in two angles. In this talk simulation results of the optical bench alignment are presented. The simulation includes ray tracing, interference
of curved wavefronts on quadrant photodiodes with slits and realistic misalignment of optical components on the optical bench. It is used to derive coupling factors of the angular test mass jitter into the longitudinal measurement. Additionally experimental results of this coupling and a subtraction method are presented.

**Ke-Xun Sun** (Stanford University)

**Design of a highly stable and uniform thermal test facility for MGRS development**

The LISA mission requires extremely tight temperature control, which is as low as $30 \mu K/\sqrt{\text{Hz}}$ over 0.1 mHz to 1 Hz. Both temporal stability and spatial uniformity in temperature must be achieved. Optical path length variations on optical bench must be kept below 40 pm/\sqrt{\text{Hz}} over 0.1 mHz to 1 Hz. Temperature gradient across the proof mass housing must be to reduce differential pressure. Thermal disturbances due to, for example, solar irradiation, is expected to be significant disturbance source to the LISA sensitivity requirements. The Modular Gravitational Reference Sensor (MGRS) will alleviate the thermal requirement. However, a stable and uniform thermal environment is desirable to achieve higher science measurement precision in future missions. We have designed combined passive and active thermal control system with the goal of achieving sub micro-Kelvin temperature stability and uniformity over an optics bench size enclosure, which has an analogous structure to the LISA spacecraft. For the active control, we have developed a model predictive control scheme, which will provide temperature controllability down to sub-microkelvin over the LISA science band. For the passive control, we are designing a new thermal enclosure that has a multilayer structure with alternative conducting and insulating layers, which enables the temperature uniformity and ease the burden of the active control. The thermal enclosure will be an important test facility for MGRS development.

**Ke-Xun Sun** (Stanford University)

**UV LED Qualification for Space Instrumentation**

**Coauthors:** Nick Leindecker, Sei Higuchi, Saps Buchman, and Robert L. Byer. UV LED Qualification for Space Instrumentation Ke-Xun Sun, Nick Leindecker, Sei Higuchi, Saps Buchman, Robert L. Byer We have continued UV LED power and spectral lifetime tests. The UV LED has now been operated more than 12,500 hours without significant power drop at time of this abstract submission. At 10,000 hour mark, the UV LED spectral shift is measured to be $\sim 1nm$ towards shorter wavelengths, which actually enhances photoelectric effects. To fully simulate the space environment, we have initiated another UV LED lifetime test in $1 \times 10^{-7}$ tor vacuum chamber since January 2008. Thus far the UV LED output has been stable without noticeable degradation. We will conduct radiation hardness tests using an accelerator proton source and a radioactive gamma ray source. When concluded, these tests will provide important support for deploying UV LED based charge management system in space.

**Ke-Xun Sun** (Stanford University)

**Differential Optical Shadow Sensing**

**Coauthors:** Martin Trittler, John Conklin, and Robert L. Byer. We have proposed and demonstrated differential optical shadow sensing scheme, in which the laser intensity noise is cancelled, whereas the proof mass displacement signal is doubled. We have designed and constructed an optical shadow sensing test platform comprised of a step motor driven actuator for large range actuation and a piezo driven flexure structure for fine adjustment. The proof mass placed on the platform can be displaced for several millimeters with a precision of nanometers in each step. Additionally we investigated signal formation and methods of signal to noise ratio enhancement. We reduced the noise effects of electronics, electromagnetic interference, air flow and temperature. Currently we have achieved a sensitivity of $\sim 2 \text{ nm/}\sqrt{\text{Hz}}$ at 2 Hz, currently limited by air flow. The dynamic range is $\sim 0.3 \text{ mm}$, limited only by the detector diameter. We applied the differential optical sensing technique to mass center determination measurement and improved the mass center precision to $\sim 200 \text{ nm}$. More importantly, differential optical shadow sensing can be used to measure proof mass position in the modular gravitational reference sensor (MGRS) to generate the primary signal for spacecraft drag-free control.

**Ke-Xun Sun** (Stanford University)

**Improved Grating Angular Sensor for LISA and MGRS Applications**

**Coauthors:** Patrick Lu and Robert L. Byer. We have improved the grating angular sensor by lowering noise and expanding the dynamic range. We have constructed a vacuum enclosure for the entire grating angular sensor assembly. The photodetector and amplifier circuits now can receive higher laser power without saturation. With an input laser power of 14 mW, we have observed an angular sensitivity of $\sim 0.2 \text{ nrad/}\sqrt{\text{Hz}}$ using the symmetric grating angular sensor. At low frequencies, we have achieved $1 - 2 \text{ nrad/}\sqrt{\text{Hz}}$ at 1 Hz. The angular sensor will be applicable...
for both modular gravitational reference sensor (MGRS) and LISA telescope steering, which requires a precision of $0.5 - 1 \text{ nrad/} \sqrt{\text{Hz}}$.

**Ke-Xun Sun** (Stanford University)

**Characterization of High Efficiency Dielectric Gratings for Formation Flight Interferometry**

Coauthors: Patrick Lu and Robert L. Byer. External interferometry for formation flights using the modular gravitational reference sensor (MGRS) calls for gratings with high diffraction efficiency. We have characterized dielectric gratings fabricated at Lawrence Livermore National Laboratory. We have constructed grating cavities with extensive work in improving mechanical stability, calibrating the PZT actuation, and mode matching. So far we have observed a finesse of 806, or a grating diffraction efficiency of 99.26%. We have tested the thermal characteristics of the dielectric gratings by illuminating a sample with up to 34.5 W of 1064nm light in a 1.5mm diameter spot without observing significant wavefront distortion. Our measurements may qualify these dielectric gratings for use in a LISA class interferometer using a 2W laser. We plan to further develop and test gratings for higher power use in the Big Bang Observatory (BBO), which may use MGRS as a core instrument.

**Dylan Sweeney** (University of Florida)

**Laser Communication and Ranging for LISA**

In order for LISA to be successful the spacecraft must be able to share information, transfer clock noise, and measure the distance between the spacecraft. All of these will be done using the laser link between the spacecraft. The clock noise is modulated onto the laser beam creating sidebands while a pseudo random noise (PRN) code is modulated onto the carrier in order to measure the distance between spacecraft. We modified our phasemeter to correlate the received PRN code with a locally generated code. We perform each of these tasks individually and simultaneously using synthetic and optical signals. We also investigate the effects of our modulation scheme on the main interferometry.

**Nicola Alex Tateo** (Università di Trento)

**Design and development of the LTPDA Infrastructure**

Coauthors: Ingo Diepholz, Luigi Ferraioli, Gerhard Heinzel, Martin Hewiston, Mauro Hueller, Anneke Monsky, and Gudrun Wanner. The peculiar nature of the LTP experiment, to be performed aboard LISA PathFinder, with an expected lifetime of 6 months and a precise pre-defined set of experimental runs to be executed on track, demanded the development of an equally peculiar infrastructure. The primary driving requirements in the design process were introduced by the need for a common ground for data analysis, ensuring highest usability while providing a complete traceability of results, together with the need for a tool capable of assisting decision making and analysis revising even in the frantic short lifetime of the mission. The LTP Data Analysis (LTPDA) toolbox was therefore developed based on a user-defined set of classes, the most important of which are the Analysis Objects (AOs), containing a 'history' field edited by the functions in the toolbox, allowing to keep track of the operations computed over the data. Other additional classes, such as parameters lists, filters and pole-zero models were also developed to meet the demands of simple and involved analysis procedures. The data objects are then wrapped into a graphic interface (based on MATLAB Simulink), in order to make analyses easier to read and to edit, so that the entire functions toolbox is converted into a blockset library. The drawing of an analysis thus becomes as easy as the composition of different blocks on a Simulink model, while all the settings and parameters are clearly gathered together on a multi panned GUI. The infrastructure for LTPDA is completed with a ground segment where downlinked data are automatically converted into AOs and stored inside redundant repository servers: these are deeply implemented in the interface, enabling the user to search, submit and retrieve both space data and previously performed analyses and results.

**Manuel Tessmer** (Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universitaet Jena)

**Compact binaries in inspiralling eccentric orbits: implications for GW data analysis**

Stellar mass compact binaries in eccentric orbits are almost guaranteed sources for LISA. We present a prescription to compute accurate and efficient gravitational-wave polarizations associated with bound compact binaries of arbitrary eccentricity and mass ratio inspiralling along slowly precessing orbits. We briefly discuss advantages and implications of our prescription.

**David Tombolato** (University of Trento/INFN)
First study of force noise with the LISA-PathFinder G.R.S. with sapphire

LISA-PathFinder aims to verify immunity of the test-masses from forces due to non gravitational origin, by measuring fluctuations of their relative acceleration within $30 \text{ fm/s}^2/\sqrt{\text{Hz}}$ at 1 mHz. In order to perform the first study of force noise caused by the LISA-PathFinder gravitational reference sensor (G.R.S.) with sapphire electrodes, we have used a torsion pendulum facility working very close to its mechanical thermal noise limit. In addition to verifying the G.R.S. as a nm-level displacement sensor, we have characterized several key force noise sources for LISA-PathFinder and LISA itself, including residual springlike coupling and electrostatic DC potentials. Finally, we have used torsion pendulum force measurements to establish upper limits on G.R.S. related surfaces disturbances with a sensitivity of $100 \text{ fm/s}^2/\sqrt{\text{Hz}}$ at 1 mHz.

BARRY WARDELL  (University College Dublin)

Quasilocal Contribution to the Self-Force

One of the primary candidate sources of gravitational wave signals falls under the category of large mass binary systems. In particular, extreme mass ratio inspiral (EMRI) systems such as that of a compact solar mass object (mass $m$) inspiraling into a black hole of 1,000 to 100,000,000 solar masses (mass $M$) are expected to be detectable by LISA out to Gpc distances. In modeling such a system, the smaller mass is seen to exert a force on itself which we call the self-force. The computation of this self-force is of fundamental importance to the accurate calculation of the orbital evolution of such binary systems and hence to the prediction of the gravitational radiation waveform. We present a matched expansion approach to calculating the self-force, whereby it is divided into a contribution from the recent past (the quasi-local region) and a contribution from the more distant past. In particular, we focus on calculating the contribution from the quasi-local region.

PETER WASS  (University of Trento)

Testing the LTP Data Analysis environment with torsion pendulum data

The LTP experiment to be flown aboard LISA PathFinder is designed as a sequence of experimental runs, in which the external conditions (such for instance the level of compensation of residual dc voltages on the surfaces facing the test masses) are adjusted on daily scale based on the outcomes of the previous experiments, in order to exploit the instrument performance. The decision making must then be performed promptly. The LTP measurements show a very strict analogy with the experiments which are being performed with the two torsion pendulum (TP) facilities of the Trento labs, that were built with the aim of characterizing the small stray forces exerted by the Gravitational Reference Sensor on free falling test masses. Additionally, the design of the LTP individual runs, which will focus on the characterization of individual noise sources, is taking advantage of the heritage of the very similar experiments which are performed with the torsion pendulums. This suggests to employ the TP data as a crucial test bed for the data analysis infrastructure which is being developed by the LTP team. This allows testing of the toolbox and the algorithms with “real” data, in a significant environment and time-frame, with a wider set of users contributing to the development of the toolbox itself. The development of the algorithms can then proceed in parallel with a better understanding of the individual experiments for the flight, allowing for their detailed definition, in terms of commands to be uploaded to the spacecraft. We present here the application of the LTP Data Analysis tools to the task of processing the data produced by the TP facilities, either to estimate the residual acceleration of the suspended test masses, either to discriminate the results of the individual experiments which are performed in order to characterize individual disturbance sources.
6. List of Participants

1. Odylvio D. Aguiar (INPE, Brazil) <odylio@das.inpe.br>
2. Mansoor Ahmed (NASA Goddard Space Flight Center, USA) <mahmed@hst.nasa.gov>
3. Tal Alexander (Weizmann Institute of Science, Israel) <tal.alexander@weizmann.ac.il>
4. Bruce Allen (Max-Planck-Institut für Gravitationsphysik Hannover, Germany) <bruce.alexander@aip.de>
5. Pau Amaro Seoane (Instituto de Ciencias del Espacio (CSIC-IEEC), Spain) <pau@aei.mpg.de>
6. Masaki Ando (The University of Tokyo, Japan) <ando@granite.phys.s.u-toyko.ac.jp>
7. Bérengère Argence (APC, France) <argence@apc.univ-paris7.fr>
8. Michele Armano (European Space Agency ESTEC, Netherlands) <armano@rssd.esa.int>
9. Stuart Aston (University of Birmingham, UK) <sma@star.sr.bham.ac.uk>
10. Gérard Auger (APC, France) <auger@apc.univ-paris7.fr>
11. Stanislav Babak (Albert Einstein Institute, Germany) <stba@aei.mpg.de>
12. John Baker (NASA Goddard Space Flight Center, USA) <john.g.baker@nasa.gov>
13. Leor Barack (University of Southampton, UK) <leor@soton.ac.uk>
14. Simon Barke (Albert Einstein Institute, Germany) <simon.barke@aei.mpg.de>
15. Massimo Bassan (Università Tor Vergata & INFN, Italy) <bassan@fisica.uniroma2.it>
16. Matthew Benacquista (University of Texas at Brownsville, USA) <benacquista@phys.utb.edu>
17. Peter L. Bender (JILA/University of Colorado, USA) <pbender@jila.colorado.edu>
18. Daniel Bindel (ZARM - University of Bremen, Germany) <bindel@zarm.uni-bremen.de>
19. Arkadiusz Baut (University of Wrocław, Poland) <abaut@ift.uni.wroc.pl>
20. César Boatella Polo (CNES, France) <cesar.boatella-polo@cnes.fr>
21. Johanna Bogenstahl (University of Glasgow, UK) <j.bogenstahl@physics.gla.ac.uk>
22. Daniele Bortoluzzi (University of Trento, Italy) <daniele.bortoluzzi@ing.unitn.it>
23. Nico Brandt (Astrium GmbH, Germany) <nico.brandt@astrium.eads.net>
24. Grazia Branduardi-Raymont (University College London, UK) <gbr@mssl.ucl.ac.uk>
25. Sasha Buchanan (Stanford University, USA) <sbuchman@stanford.edu>
26. Ernst-Jan Buis (cosine Science & Computing BV, Netherlands) <ebuis@cosine.nl>
27. Robert Byer (Stanford University, USA) <vbivre@stanford.edu>
28. Ruben Martín Cabezón Gómez (Universitat Politècnica de Catalunya, Spain) <ruben.cabezon@upc.edu>
29. Jordan Camp (NASA Goddard Space Flight Center, USA) <jordan.camp@nasa.gov>
30. Umberto Cannella (University of Geneva, Switzerland) <umberto.cannella@physics.unige.ch>
31. Priscilla Cañizares Martínez (Instituto de Ciencias del Espacio (CSIC-IEEC), Spain) <pcm@ieec.uab.es>
32. Massimo Cerdonio (Università degli Studi di Padova, Italy) <cerdonio@pd.infn.it>
33. Sempagala Chris (Uganda Christian University, Uganda) <ppete764@yahoo.com>
34. Giacomo Ciani (University of Trento & INFN, Italy) <ciani@science.unitn.it>
35. Francesca Cirillo (EADS Astrium GmbH, Germany) <francesca.cirillo@astrium.eads.net>
36. Jean Clavel (ESA Astrophysics & Fundamental Physics Missions Division, Netherlands) <Jean.Clavel@esa.int>
37. Carlo Nicola Colacino (ELTE Budapest, Hungary) <cn.colacino@gmail.com>
38. Monica Colpi (University of Milano Bicocca, Italy) <colpi@mib.infn.it>
39. Alice Conchillo (Instituto de Ciencias del Espacio (CSIC-IEEC), Spain) <aconchillo@ieec.cat>
40. John Conklin (Stanford University, USA) <johnwc@stanford.edu>
41. Neil Cornish (Montana State University, USA) <cornish@physics.montana.edu>
42. Jeff Crowder (Caltech/JPL, USA) <crowder@caltech.edu>
43. Mike Cruise (University of Birmingham, UK) <a.m.cruise@bham.ac.uk>
44. Curt Cutler (Jet Propulsion Laboratory, USA) <Curt.J.Cutler@jpl.nasa.gov>
45. Karsten Danzmann (Albert Einstein Institute Hannover, Germany) <danzmann@aei.mpg.de>
46. Luigi D'Arcio (European Space Agency ESTEC, Netherlands) <luigi.darcio@esa.int>
47. Glenn de Vine (Jet Propulsion Laboratory, USA) <glenn.devine@jpl.nasa.gov>
48. Marina Dehne (Albert Einstein Institute Hannover, Germany) <marina.dehne@aei.mpg.de>
49. Steven Detweiler (University of Florida, USA) <det@phys.ufl.edu>
50. Sanjeev Dhurandhar (Inter University Centre for Astronomy & Astrophysics, India) <sanjeev@iucaa.ernet.in>
51. Luciano Di Fiore (INFN - Napoli, Italy) <difiore@na.infn.it>
52. Christian Diekmann (Albert Einstein Institute Hannover, Germany) <christian.diekmann@aei.mpg.de>
53. Nicolas Douillet (ARTEMIS (CNRS), France) <douillet@oca.eu>
54. Steve Drasco (JPL/Caltech, USA) <sdrasco@jpl.nasa.gov>
55. Emilio Elizalde (Instituto de Ciencias del Espacio (CSIC-IEEC), Spain) <elizalde@ieec.uab.es>
56. Juan José Esteban Delgado (Albert Einstein Institute, Germany) <juan.jose.esteban@aei.mpg.de>
57. Jorge Fauste (European Space Agency, Spain) <jorge.fauste@esa.int>
58. Marc Favata (Kavli Institute for Theoretical Physics, USA) <favata@kitp.ucsb.edu>
179. Shuichi Sato (Hosei University, Japan) <sato.shuichi@k.hosei.ac.jp>
180. Fabio Scardigli (Yukawa Institute for Theoretical Physics, Japan) <fabio@yukawa.kyoto-u.ac.jp>
181. Patricia Schmidt (University of Vienna, Austria) <icetea@vienna.at>
182. Markus Schulte (Imperial College London, UK) <m.schulte@imperial.ac.uk>
183. Bernhard Schutz (Albert Einstein Institute, Germany) <Bernhard.Schutz@aei.mpg.de>
184. José M. M. Senovilla (Universidad del País Vasco, Spain) <josemm.senovilla@ehu.es>
185. Mauro Sereno (University Zurich, Switzerland) <sereno@physik.unizh.ch>
186. Alberto Sesana (Penn State University, USA) <alberto@gravity.psu.edu>
187. Daniel Shaddock (Jet Propulsion Laboratory, USA) <Daniel.Shaddock@jpl.nasa.gov>
188. Deirdre Shoemaker (Penn State University, USA) <deirdre@gravity.psu.edu>
189. Xavier Siemens (University of Wisconsin-Milwaukee, USA) <siemens@gravity.phys.uwm.edu>
190. Robert Silverberg (NASA Goddard Space Flight Center, USA) <Robert.Silverberg@nasa.gov>
191. Daniel Shaddock (University of Florida, USA) <diana.shaull@imperial.ac.uk>
192. Robert Spero (Jet Propulsion Laboratory, USA) <spero@jpl.nasa.gov>
193. Xavier Siemens (University of Wisconsin-Milwaukee, USA) <xi@physics.gla.ac.uk>
194. Ruggiero Stanga (Università di Firenze and INFN, Italy) <stanga@arcetri.astro.it>
195. Robin Stebbins (NASA Goddard Space Flight Center, USA) <Robin.T.Stebbins@nasa.gov>
196. Frank Steier (Albert Einstein Institute Hannover, Germany) <frank.steier@aei.mpg.de>
197. Timothy Sumner (Imperial College London, UK) <t.sumner@imperial.ac.uk>
198. Ke-Xun Sun (Stanford University, USA) <kxsun@stanford.edu>
199. Dylan Sweeney (University Florida, USA) <dsweeney@ufl.edu>
200. Nicola Alex Tateo (Università di Trento, Italy) <tateo@science.unitn.it>
201. J. Taylor (ORISE, USA) <greenlel@orau.gov>
202. Manuel Tesserer (Friedrich-Schiller-Universitaet Jena, Germany) <m.tesserer@uni-jena.de>
203. Damien Texier (European Space Agency, Spain) <damien.texier@esa.int>
204. Jonathan Thornburg (University of Southampton, UK) <J.Thornburg@soton.ac.uk>
205. James Ira Thorpe (NASA Goddard Space Flight Center, USA) <James.I.Thorpe@nasa.gov>
206. Massimo Tinto (Jet Propulsion Laboratory, USA) <Massimo.Tinto@jpl.nasa.gov>
207. David Tombolt (University of Trento & INFN, Italy) <tdavid@science.unitn.it>
208. Christian Trenkel (Astrium Ltd, UK) <christian.trenkel@astrium.eads.net>
209. Miquel Trias Cornellana (Universitat de les Illes Balears, Spain) <miquel.trias@uib.es>
210. Michael Troebs (Albert Einstein Institute Hannover, Germany) <michael.troebs@aei.mpg.de>
211. Oscar Turazza (APC, France) <turazza@apc.univ-paris7.fr>
212. Michèle Vallisneri (Jet Propulsion Laboratory/Caltech, USA) <Michele.Vallisneri@jpl.nasa.gov>
213. Chris Van Den Broeck (Cardiff University, UK) <Chris.van-den-Broeck@astro.cf.ac.uk>
214. Jakob van Zyl (Jet Propulsion Laboratory, USA) <jakob.j.vanzyl@jpl.nasa.gov>
215. John Veitch (University of Birmingham, UK) <jveitch@star.sr.bham.ac.uk>
216. Jean-Yves Vinet (CNRS, France) <vinet@oca.eu>
217. Stefano Vitale (University of Trento, Italy) <vitale@science.unitn.it>
218. Vinzenz Wand (University of Florida, USA) <vwand@physics.ufl.edu>
219. Henry Ward (University of Glasgow, UK) <h.ward@physics.gla.ac.uk>
220. Barry Wardell (University College Dublin, Ireland) <barry.wardell@ucd.ie>
221. Brent Ware (Jet Propulsion Laboratory/California Institute of Technology, USA) <brent.ware@jpl.nasa.gov>
222. Carl Warren (Astrium Ltd, UK) <carl.warren@astrium.eads.net>
223. Peter Wass (University of Trento, Italy) <wass@science.unitn.it>
224. Günther Waxenegger (University of Vienna, Austria) <guenther.waxenegger@gmx.at>
225. David Wealthy (Astrium Limited, UK) <dave.wealthy@astrium.eads.net>
226. William Weber (Università di Trento / INFN, Italy) <weber@science.unitn.it>
227. Dennis Weise (EADS Astrium GmbH, Germany) <dennis.weise@astrium.eads.net>
228. John Whelan (AEI Potsdam, Germany) <whelan@aei.mpg.de>
229. Bernard Whiting (University of Florida, USA) <bernard@phys.ufl.edu>
230. Clifford Will (Washington University, USA) <cww@wuphys.wustl.edu>
231. Xavier Xirgu Aleixandre (Instituto de Ciencias del Espacio (CSIC-IEEC), Spain) <xxirgu@infonegocio.com>
232. Yinan Yu (University of Florida, USA) <yinan@phys.ufl.edu>
233. Nicolás Yunes (Penn State University, USA) <yunes@gravity.psu.edu>
234. Ze-Bing Zhou (Huazhong University of Science & Technology, China) <zhouzb@mail.hust.edu.cn>
235. Tobias Ziegler (Astrium GmbH, Germany) <tobias.ziegler@astrium.eads.net>

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