Stanford, Space Gravity Research Group

Earth & Planetary Science: Geodesy, Aeronomy

Gravitational Science
Special & General Relativity

Gravity-Waves
Outline

➢ Small Sats Technology Program Collaboration
  ▪ ARC- KACST-Stanford University

➢ Ongoing projects
  ▪ UV-LED **Launch September 2013**
    • SAA (got update from BJ)
    • Payload delivery – October 2012
  ▪ Caging testing on parabolic flights proposal – **Flight 2013**
  ▪ Drag-free cube sat + DOSS (or Saudi sat) **Launch 2014**
    • **Follow up to UV-LED**
    • Stanford prototype, ARC environmental testing
    • KACST launch, MO, and possibly Saudi bus
    • SBIR from ARC for thrusters or $300,000 for VACCO
    • ~ $500,000 additional hardware and labor for Stanford
  ▪ Mini STAR – in lab (coordination with DLR October 2012) **launch 2015**
  ▪ Laser ranging – in lab **launch 2015**

➢ LISA this decade?
  ▪ Geocentric orbit – 1/4 LISA mass
  ▪ Relaxed performance - ~100-1000 – reduce risk and instrument cost
  ▪ Main science preserved – ultra massive black hole binaries
  ▪ STAR type consortium: Universities, KACST, NASA, Germany
    • 500 M$, < 10 years.

➢ Coordination meeting ARC-KACST-SU **TBD**
Gravitational & Planetary Research Program

- **Goals – Why?**
  - Relativity, Gravitational Waves, Geodesy, Aeronomy
  - Space Technology
  - Education and Training: STEM

- **Means – How?**
  - Technology Development
    - Nano & Small Satellites
      - 2 – 50 kg, 4 – 50 W
  - Science Missions
    - 5 – 500 kg, 6 – 500 W

- **Team – Who?**
  - NASA -ARC
  - Universities – Colorado, MIT, UF
  - Industry – SRI, Lockheed, other
  - Foreign Partners
    - Conventional & Unconventional
    - Germany, UK, Saudi Arabia

- **Schedule & Cost – When?**
  - 2012 – 2017
    - 6 technologies 1 – 4 M$ each
  - 2015 – 2025
    - NanoSat ‘GRACE II’ 10 M$
    - Relativity ‘STAR’ 30 M$
    - Gravitational Waves 1 G$
Science & Technology Implementation on Small Satellites

Education
- Grad, Undergrad
- 3-5 year projects
- Student led tasks

Science & Technology on Small Satellites
- Education driven
- International collaborations

Science
- Special/General Relativity
- Gravitational waves
- Earth Geodesy/Aeronomy

Technology
- Gravitational Reference Sensors
- Ultra-stable optics
  - Precision Navigation
  - formation flying

International collaborations

Grad, Undergrad
3-5 year projects
Student led tasks
Collaboration: Stanford – ARC – KACST

“Non Conventional Collaboration” on UV-LED SAT

- Basic research supports
  - Basic research at KACST
  - Flight program at ARC

≤ TRL 4
≥ TRL 5

Ames Research Center
Flight hardware, management
- TAA with KACST
- I&T, operations

KACST
S/C, Launch, basic res.
- TAA with ARC
- I&T, operations
- Basic research with SU
Space Gravity Technology Development

- **Technology Expertise**
  - Drag-free flight heritage
  - Gravitational reference sensors
  - Lasers & Frequency standards

- **Research & Development**
  - Advanced gravitational sensors
  - Flight frequency standards

- **GP-B gyroscope**
- **Triad I 1st drag-free**
- **UV-LED Satellite**
- **I₂ stabilized laser**
- **Drag-free Satellite**
Small Sats Technology Program

UV LED Sat - 2013

Shadow Sat - 2014 (partially-funded)

Drag-Free CubeSat - 2014 NEXT ARC-SU-KACST Flight

Optical Sat – 2015 (Lab development)

Mini STAR– 2015 (Lab development)

Laser Ranging – 2016 (Lab development)

df/f ~ $10^{-12}$
1mm optical cavity
1 mm gas cell
25 cm$^3$, 25 g, <100 mW

Mini clock Sat – 2016 (Lab development)

GRACE follow-on With Cube-sats

STAR With miniSTAR

Geodesy, Aeronomy

Gravitational Science

LAGRANGE

10 years, 0.5G$, NASA< 0.2G$

Gravitational Waves
MGRS System Overview

**UV LED Charge Management**
- Solid state 255nm light source
- Charge control of proof mass and housing
- **September 2013 Launch**

**Differential Optical Shadow Sensor**
- Nanometer sensing for drag free signal
- Lower resolution, high dynamic range
- **2014 Launch**

**Full Drag-Free System**
- 70-30 Au-Pt sphere
- Silicone Carbide coating
- **2014 Launch**

**Proof Mass Caging**
- 700 g clamping of proof mass during launch
- No damage to proof mass surface
- **2014 Launch, 2013-0g flight**

**Grating Angular Sensor**
- Nanoradian level angular sensing
- Completed lab demo
- **In work**

**Grating Displacement Sensor**
- Picometer sensing for science signal
- High sensitivity, low dynamic range
- **In work**
# Applications of Drag-free Technology

<table>
<thead>
<tr>
<th>Category</th>
<th>Application</th>
<th>Drag-free Performance (m/sec^2Hz^{1/2}), frequency (Hz)</th>
<th>Metrology (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation</td>
<td>Autonomous, fuel efficient orbit maintenance</td>
<td>(\leq 10^{-10}), near zero frequency (^a,b)</td>
<td>(\leq 10) absolute</td>
</tr>
<tr>
<td></td>
<td>Precision real-time on-board navigation</td>
<td>(\leq 10^{-10}), near zero frequency (^a)</td>
<td>(\leq 10) absolute (^a)</td>
</tr>
<tr>
<td></td>
<td>Formation flying</td>
<td>(\leq 10^{-10}), near zero frequency (^a)</td>
<td>(\leq 10^{-9}) differential (^a)</td>
</tr>
<tr>
<td>Earth &amp; Planetary</td>
<td>Aeronomy</td>
<td>(\leq 10^{-10}, 10^{-2}) to 1 Hz (^a)</td>
<td>1 absolute (^a)</td>
</tr>
<tr>
<td></td>
<td>Geodesy, GRACE</td>
<td>(10^{-10}, 10^{-2}) to 1 Hz (^a, b, c)</td>
<td>(10^{-6}) differential (^a)</td>
</tr>
<tr>
<td>Science</td>
<td>Future Earth geodesy</td>
<td>(\leq 10^{-12}, 10^{-2}) to 1 Hz (^a)</td>
<td>(\leq 10^{-9}) differential (^a)</td>
</tr>
<tr>
<td>Fundamental Physics</td>
<td>Equivalence Principal tests</td>
<td>(\leq 10^{-10}, 10^{-2}) to 1 Hz (^a)</td>
<td>(\leq 10^{-10}) differential (^a)</td>
</tr>
<tr>
<td></td>
<td>Tests of general relativity</td>
<td>(\leq 10^{-10}), near zero frequency (^a)</td>
<td>(\leq 1) absolute (^a)</td>
</tr>
<tr>
<td>Astrophysics</td>
<td>Gravitational waves</td>
<td>(3 \times 10^{-15}, 10^{-4}) to 1 Hz</td>
<td>(\leq 10^{-11}) differential</td>
</tr>
</tbody>
</table>

Notes: \(^a\) Performance to be demonstrated by the drag-free CubeSat; \(^b\) demonstrated; \(^c\) non-drag-free
UV LED Small Satellite

**Technology Objectives**
- Raise TRL levels (4/5 → 8/9) for
  - Deep UV LEDs
  - ac charge control
- Beneficiaries:
  - LISA
  - GRACE follow-on
  - Drag-free CubeSat

**Payload**
- Isolated “test mass”
- 16 UV LEDs & photodiodes
- Charge amp
- Voltage bias plates
- ac charge control electronics

**Mission Design**
- Spacecraft: Saudi Sat
- Russian launch in 2013
- 2 month mission
- Fully funded ($1.5M)
  
  *Demonstrates unconventional international collaboration*

**Management**
- NASA ARC: Flight payload, PM, SE, SMA
- Stanford: Payload design, SOC
- KACST: Spacecraft, Launch, MOC

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**Saudi Sat 3**
- 55 kg
- 50 W
- 222×277×180 mm
- 6.5 kg
UV LED Small Sat Components

- Payload completion: May 2012
- Spacecraft CDR: Aug 2012
- Payload Integration: Dec 2012
- Russian launch: Sep 2013
UV LED Small Sat Integration and Test

Testing of engineering model ongoing at ARC, August, 2011

Thermovac chamber testing
The Drag-free CubeSat

Science
- Earth Aeronomy, space weather
- Demo < 10^{-12} m/sec^2 for future
  - Geodesy
  - Earth observation
  - Gravity science
  - Gravity-waves

Mission Design
- 3U CubeSat
- Secondary launch via P-POD
- Launch ~ 2015
- 1-2 month drag-free ops in LEO
- Target program: Franklin/Edison

Payload
- Drag-free sensor + micro-thrusters

Management
- NASA ARC: PM, SE, SMA, mission operations
- Stanford: Payload design, drag-free control, data analysis
The Drag-free CubeSat

4 kg
6 W
3U Cube

Thrust
Rate Gyro and GPS
Caging System
Payload with Test Mass Sensor
UV LED
Motherboard, CPU and Radio
Electrical Power System
ADACS
Differential Optical Shadow Sensor (DOSS)

**Technology Objectives**
- Raise TRL level for miniature high-sensitivity displacement sensor
  - nm/Hz\(^{1/2}\) sensitivity
- No forcing
- Non-contact

**Payload**
- Light source:
  - SLED, 1545 nm
- InGaAs quad-photodiode
- Ultra-low current Difet amp

**Mission Design**
- 2U CubeSat
- Any orbit
- Launch ~ 2014
- 1 month ops
- Payload funded

**Management**
- Stanford & KACST: Payload, CubeSat structure
- I&T & Launch: pending

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**2 kg**
**4 W**
**2U Cube**
Differential Optical Shadow Sensor (DOSS)

- **ADCS**
- **DOSS**
  - **DSP**
- **CubeSat Bus**
- **EPS**
- **C&DH**
  - **Battery**
  - **MCU**
  - **Memory**
- **COMM**
  - **Ground Station**

**Specifications:**
- **Weight:** 2 kg
- **Power:** 4 W
- **Size:** 2U Cube
The Drag-Free CubeSat

Drag-Free Concept
- Goal: Satellite in purely gravitational orbit
- Cancel all external disturbances
- Design for low internal disturbance

Applications
- Geodesy
- Aeronautics
- Autonomous orbit determination
- Fundamental Physics

Technology Evaluation
UV LED Satellite
- Goal: Raise TRL up to 8/9 for UV LEDs and AC charge control
- 16 UV LEDs & photo diodes
- Collaboration with KACST and NASA Ames
- Spacecraft: Saudi Sat 3 (55 kg)
- Launch: 2013

Differential Optical Shadow Sensor
- 2U CubeSat
- Raise TRL for Shadow Sensor
- Target sensitivity: 1 nm at 1 mHz
- Completion: 2013

Thruster Comparison
- SRI International
  - Thrust: 1 nN to 5 pN
  - ISP: up to 10,000 sec
- VACCO Industries
  - Thrust: 25 to 55 mN
  - ISP: 65 sec
- Advantages
  - Single unit produces forces and torques
  - High dynamic range
  - Low noise
  - Longer lifetime

Error Budget
- Follows LISA error budget
- Assumptions:
  - 25 mm AuPt Sphere
  - Temperature stability: 20 K at orbit rate
  - 1 K at other frequencies
  - Thermal noise limited below 0.3 mHz
- Limited by S/C-to-TM stiffness above 0.3 mHz

Conclusion
State of the art drag-free performance can be demonstrated on CubeSat
DOSS & Drag-free CubeSat Lab Models

DOSS prototype on air bearing

Laboratory DOSS CubeSat

Vacuum TM levitation system

Caging adhesion testing
Fiber-coupled Optical Cavity Small Sat

**Technology Objectives**

- Raise TRL levels for:
  - Frequency stabilized laser
  - Fiber coupled optical train
- Beneficiaries:
  - STAR, GRACE follow-on, LISA

**Mission Design**

- Saudi-sat compatible secondary
- Any orbit, slow tumble OK
- Launch ~ 2015
- 1 month mission lifetime

**Payload**

- High-finesse Optical cavity
- Optical fiber coupling
- Low-cost laser
- Modulator
- photodiodes

**Management**

- NASA ARC: PM, SE, SMA, ops
- Stanford: Payload design, science
- KACST: Spacecraft

**Specifications**

- 55 kg
- 50 W
- Saudi Sat 3
Fiber-coupled Optical Cavity Small Sat

- **Mass**: 9 kg
- **Power**: 50 W
- **Name**: Saudi Sat 3
MiniSTAR Concept

STAR – KT experiment $10^{-15}$
Laser Ranging Concept

Detector
- Photo detector
- Corner Cube
- LED

Source
- Laser
- Beat Detector

3cm ULE cavity
- Primary mirror
- Secondary mirror

$dl \sim 10-100 \text{ nm}$
Differential Laser Ranging Source

- Primary mirror
- Secondary mirror
- 3cm ULE cavity
- Laser
- Beat Detector
Differential Laser Ranging Reflector

Cube corner

LED

Photo detector
Differential Laser Ranging Concept
# Space-Time Asymmetry Research (STAR)

## In Re-Design to Reduce Complexity and Cost

### Science

“Deviations from Einstein's predictions would cause us to rethink one of the foundational pillars of all of physical science” – Astro2010 decadal

- STAR will measure:
  - Isotropy of speed of light to $10^{-17}$
  - The direction of anisotropy
  - Dependence on boost velocity

### Payload

- Molecular clocks
- Orthogonal optical cavities
- Low-noise comparator
- Multi-layer thermal enclosure

### Mission Design

- ESPA compatible on EELV
- Circular sun-sync 650 km orbit
- Launch ~ TBD
- 2-year lifetime
- Class D mission

### Management

- NASA ARC: PM, SE, SMA, ops
- Stanford: Payload design, science
- KACST: Spacecraft & Launch
- DLR: molecular clocks
NASA Gravity-wave Concept Study

- Stanford experience led to LAGRANGE concept (LISA, ST-7, GP-B, STAR)
  - 3 drag-free spacecraft in geocentric orbit
  - Minimized payload: 1 test-mass (sphere), 1 laser, 2 telescopes

- Science ≈ LISA; Cost: $0.6-0.9 G, Com-link: >100 LISA

- Small sat approach to tech demonstrations

- Trade-space study

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Inertial Ref</th>
<th>Metrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliocentric</td>
<td>LPF Cubes</td>
<td>Reflective</td>
</tr>
<tr>
<td>(4-5 options)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geocentric</td>
<td>Cold atoms</td>
<td>Arm locking</td>
</tr>
<tr>
<td>(3 options)</td>
<td>None</td>
<td>Cavity, ...</td>
</tr>
</tbody>
</table>

Space Gravity Group’s LAGRANGE
NASA Gravity-wave Observatory

- Geocentric Orbit ~ 50% Heliocentric cost
- Simplified Robust Inertial Sensor (LPF back-up)
  - Spherical, fully drag-free, optical sensing
- Metrology
  - Optical Reflective with Gratings
- Small sat approach to tech demonstrations
  - 2013-2017 technology (LISA is older than 2000 technology)
  - Parallel, low cost, low risk, on small and cube satellites
  - ~6 technologies at 1 M$ - 4 M$ each
  - Multiple institutions and international partners

Cost
Reduce 50%

Complexity
Reduce 50%

Comm Link
Increase >10²
LAGRANGE Performance
Gravity-wave Observatory This Decade

- ‘Small’ Geocentric Orbit
- Relaxed performance on GRS and laser interferometer
- Reduced technical Risk – Maintain main science
- STAR type consortium

LISA 2020

- 1.0-1.5 t launch
- SmlSat Technol.
- 0.5 G$ Total cost
- <0.2 G$ @ NASA
- 2020-2022 launch

<table>
<thead>
<tr>
<th>LISA 2020</th>
<th>Orbit</th>
<th>Inertial Ref</th>
<th>Metrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geocentric</td>
<td>Sphere</td>
<td>$10^{-13}$ ms$^{-2}$Hz$^{-1/2}$</td>
<td>Reflective $\sim100$ pm Hz$^{-1/2}$</td>
</tr>
</tbody>
</table>
LAGRANGE Cost Estimate

Total Flight System Cost vs. Size (mass, power)

Cost = \((0.0125 \times P \times M)^{0.655}\)

M = 500 kg \times 3 \text{ SC}
P = 500 W \times 3 \text{ SC}

3 \times \text{Cost} (500 \text{ kg} \times 500 \text{ W}) = 584 \text{ M$ (FY07)} = 637 \text{ M$ (FY11)}

\text{Cost} (1,500 \text{ kg} \times 1,500 \text{ W}) = 821 \text{ M$ (FY07)} = 895 \text{ M$ (FY11)}

1.00 (FY07'M$) = 1.09 (FY12'M$)
### Data Rate Estimate for Space Antenna

<table>
<thead>
<tr>
<th></th>
<th>GP-B</th>
<th>1 LAGRANGE SC</th>
<th>3 LAGR. SC vs GPB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plan</strong></td>
<td>0.35 GB/day (actual data)</td>
<td>0.004 GB/day (ESA)</td>
<td>0.013 GB/day (ESA)</td>
</tr>
</tbody>
</table>

#### System

<table>
<thead>
<tr>
<th></th>
<th>GPB SC 6 deg ctrl.</th>
<th>LAGR. SC 7 deg ctrl.</th>
<th>LISA SC 16 deg ctrl.</th>
<th>≈ (GPB) 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>Cryogenics</td>
<td>µK control</td>
<td></td>
<td>≈ (GPB) 3</td>
</tr>
<tr>
<td><strong>Activation</strong></td>
<td>He thrusters</td>
<td>µN thrusters</td>
<td></td>
<td>≈ (GPB) 3</td>
</tr>
<tr>
<td><strong>Pointing</strong></td>
<td>1 telescope</td>
<td>2 telescopes</td>
<td></td>
<td>≈ (GPB) 3 2</td>
</tr>
<tr>
<td><strong>Test Masses</strong></td>
<td>4 TM 3 deg ctrl.</td>
<td>2 TM 6 deg control</td>
<td></td>
<td>≈ (GPB) 3</td>
</tr>
<tr>
<td><strong>Read-out</strong></td>
<td>4 SQUID systems</td>
<td>4 pm interferometers</td>
<td></td>
<td>≈ (GPB) 3</td>
</tr>
<tr>
<td><strong>BW</strong></td>
<td>Meas. BW 12.9 mHz</td>
<td>Meas. BW 0.1-100 mHz</td>
<td></td>
<td>≥ (GPB) 3</td>
</tr>
</tbody>
</table>

GPB data rate ≤ 1 LAGRANGE SC data rate

**LAGRANGE data rate ≥ 3**  **GP-B data rate ≥ 1 GB/day**

Estimated LAGR. data rate / Planned LISA data rate (ESA)* ≥ 77

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*7 kbit/s for 8 hours every 2 days = 0.013 MB/day | ESA web site