The DRS Interferometric Displacement Sensor

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Disturbance Reduction System

- Technology validation of sensor and thrust-producing technologies to control a space vehicles flight path so the payload responds only to gravitational forces.

Sensor: Stanford University, Stanford, CA

- Launch 2006 as NASA’s Space Technology 7 project (ST7)
  - Piggy-backing on ESA’s SMART-2 Mission
DRS Technology Objectives

• Validate that a test mass follows a trajectory determined by gravitational forces only within $3 \times 10^{-14} \, \text{m/s}^2/\sqrt{\text{Hz}}$
  - Low acceleration noise is needed for study of general relativity, planetary gravity, gravitational waves

• Validate spacecraft position control to an accuracy of $<10 \, \text{nm}/\sqrt{\text{Hz}}$
  - Spacecraft position control is required for separated-spacecraft interferometers which do not use internal delay lines
The DRS Instrument package consists of:

- Interferometer to measure the distance between the two test masses.
- Micromotors for spacecraft position control.
- Two gravitational reference sensors.

DRS Concept
**DRS Technologies**

- **Gravitational Reference Sensors**
  - Test mass noise $< 3 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}$, 1 mHz to 10 mHz
  - Measurement of position to $< 3 \text{ nm/}\sqrt{\text{Hz}}$, 1 mHz to 10 mHz
  - Accelerometer mode
    - Validation of thrusters
  - Force noise diagnostics
    - Validate noise models

- **Micro-Newton Thrusters**
  - 1-20 $\mu$N range
  - Control precision adjustment $< 0.1 \mu$N
  - Noise $< 0.1 \mu$N/\sqrt{Hz}, 1 mHz to 10 mHz

- **Interferometer is not a new technology**
  - Can be completely tested on ground
  - Is used in DRS for validation only - I.e. independent (out-of-loop) detector
Flight Validation Rationale

- Must be validated in space
  - 1 g environment on Earth makes ground testing impossible
- Must be in orbit far from Earth
  - Difference in gravitational force on two test masses must be small to validate instrument performance
    - Requires orbit at GEO altitude or higher
- Must have mechanically, thermally stable environment
  -- Spacecraft must be in constant orientation during DRS tests
  -- Thermal isolation system needed for DRS
    - Spacecraft eclipses need to be avoided
- ESA SMART-2 spacecraft suitable host
  -- Will operate ~ 0.1 AU from Earth
Flight Activities

- DRS operations will take 90 days
  - DRS operates only at specific times
  - Spacecraft needs to be in quiet state
    - No maneuvers
    - No moving parts
    - No changes in power dissipation
  - Spacecraft will establish a nominal orientation and dead band
    - DRS should maintain orientation
    - If orientation dead band exceeded, DRS will be shut off
  - DRS tests will consist of a series of experiments of 1-3 days each
    - Experiments can be scheduled non-consecutively
    - Experiments can be repeated if necessary
Flight Validation Measurements

- GRS in accelerometer mode validate thruster performance
  - Can use two GRS to compare calibrations
  - Initial thruster calibration to be used for setting spacecraft control parameters
  - Calibration will be repeated several times over 6 months to check stability
- Fire thrusters to center spacecraft on one GRS test mass
  - GRS position measurements used for control and validation
  - Interferometer readout cross-checks GRS in one direction
- Fire thrusters to orient spacecraft around two test masses
  - GRS position measurements used for control and validation
- Verify acceleration noise on test masses
  - Laser interferometer compares acceleration of two test masses
- Verify force noise model verification
  - Apply known perturbations to see that response is as predicted
GRS Description

- GRS consists of:
  - A freely-floating test mass within a housing,
  - Position measurement of the test mass w.r.t. housing
  - Control of test mass orientation
  - Charge control subsystem

- The proof mass must be isolated from:
  - Solar magnetic field
  - Solar radiation pressure
  - Residual gas pressure
  - Thermal radiation pressure
  - Charging by cosmic rays
  - Spacecraft self-gravity
  - Spacecraft magnetic fields
  - Spacecraft electric fields
## GRS Requirements

<table>
<thead>
<tr>
<th>ITEM</th>
<th>REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive Axis Acceleration Noise</td>
<td>$3 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>Trans. Axis Acceleration Noise</td>
<td>None</td>
</tr>
<tr>
<td>Sensitive Axis Position Sensitivity</td>
<td>$10 \times 10^{-9} \text{ m/} \sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>Trans. Axis Position Sensitivity</td>
<td>$2.5 \times 10^{-6} \text{ m/} \sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>Orientation Control Noise</td>
<td>$1 \times 10^{-6} \text{ rad/} \sqrt{\text{Hz}}$</td>
</tr>
</tbody>
</table>
DRS Performance Limits

- **LISA requirement @ 1 mHz:** \(3 \times 10^{-15} \text{ m/s}^2/\sqrt{\text{Hz}}\)
- **Proof mass sensor noise:** 1 nm/\(\sqrt{\text{Hz}}\)
- **Interferometer noise @ 1 mHz:** 500 pm/\(\sqrt{\text{Hz}}\)
- **DRS goal @ 1 mHz:** \(3 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}\)

- **LISA requirement @ 10 mHz:** \(1.5 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}\)
- **Interferometer noise @ 10 mHz:** 50 pm/\(\sqrt{\text{Hz}}\)
- **DRS goal @ 10 mHz:** \(1.5 \times 10^{-13} \text{ m/s}^2/\sqrt{\text{Hz}}\)

- \(a = (2\pi f)^2 \times 5 \times 10^{-10} \text{ m/} \sqrt{\text{Hz}} \sim 2 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}} @ 1 \text{ mHz}\)
- \(a = (2\pi f)^2 \times 1 \times 10^{-9} \text{ m/} \sqrt{\text{Hz}} \sim 4 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}} @ 1 \text{ mHz}\)
- \(4 \times 10^{-12} \text{ m/s}^2/\sqrt{\text{Hz}} @ 10 \text{ mHz}\)
- \(a = (2\pi f)^2 \times 5 \times 10^{-11} \text{ m/} \sqrt{\text{Hz}} \sim 2 \times 10^{-13} \text{ m/s}^2/\sqrt{\text{Hz}} @ 10 \text{ mHz}\)
DRS Performance Limits

- Extrapolation from DRS by x10
- DRS Capacitor Readout Limit; $10^{-9}$ m/$\sqrt{\text{Hz}}$
- DRS Acceleration Noise Goal = 10 x LISA goal
- LISA Sensitivity for SNR=5 and 1 year Integration
- LISA Acceleration Noise Goal
- DRS Homodyne Interferometer Limit; $2 \times 10^{-14}$ m/s²/$\sqrt{\text{Hz}}$

Frequency (Hz)

Strain Amplitude h

$10^{-20}$ $10^{-21}$ $10^{-22}$ $10^{-23}$ $10^{-24}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$
Laser Requirements

- Average unstabilized laser noise seen: \( \approx 5.5 \text{ MHz/}\sqrt{\text{Hz}} \) @ 10 mHz
- \( \approx 30 \text{ MHz/}\sqrt{\text{Hz}} \) @ 1 mHz
- Interferometer pathlength mismatch: \( \Delta L < 1 \text{ mm} \)

- Laser noise -> path noise: \( \Delta x = \Delta L \times \Delta v / v \)
  - @ 10 mHz \( < 20 \text{ pm/}\sqrt{\text{Hz}} \) (avg.)
  - @ 1 mHz \( < 100 \text{ pm/}\sqrt{\text{Hz}} \) (avg.)

Compare to:
- Interferometer noise req’d: \( 50 \text{ pm/}\sqrt{\text{Hz}} \) @ 10 mHz
- Interferometer noise req’d: \( 500 \text{ pm/}\sqrt{\text{Hz}} \) @ 1 mHz
• Proof mass pointing stability: 1 μrad/√Hz @ 1 mHz
  - associated displacement error: TBD
OPD error vs. Fringe Visibility/wavefront tilt

- OPD error due to changing fringe contrast @ max. slope of fringe signal (e.g due to proof mass tip/tilt):

Fringe signal: \( I = I_0 * (1 + V \sin(4\pi x / \lambda)) \)

\[
dI/I_0 = 4\pi V/\lambda \cos(4\pi x / \lambda) dx + \sin(4\pi x / \lambda) dV
\]

=> @ \( x = n*\lambda/4 \) w/ \( n = 1, 2, 3, \ldots \) (the max. slope of the fringe) \( \sin(4\pi x / \lambda) = 0 \),
i.e. no sensitivity to visibility change \( dV \). Q: How close can we get to that?

- With \( V^2 = [2J_1(\pi\theta D/\lambda)/(\pi\theta D/\lambda)]^2 \) w/ \( \theta \) angle between wave fronts, \( D = 1 \) mm, \( \lambda = 1064 \) nm we get a \( dV \sim 10^{-5} \) (10 ppm) with the 1 µrad/√Hz @ 1 mHz proof mass pointing stability.
OPD error vs. Signal (laser) Intensity

- OPD error due to changing laser intensity $I_0$:
  \[ \frac{dI}{dI_0} = 1 + \sin(4\pi x/\lambda) \text{ w/ } \sin(4\pi x/\lambda) = 0 \]
  @ $x = n*\lambda/4$

  \[ dI = dI_0 \]

  using $dI/I_0 = 4\pi V/\lambda \ast \cos(4\pi x/\lambda)*dx$

  we get an error of $dx = V*20 \text{ pm}$ for a signal (laser) intensity change $dI_0 \sim 2*10^{-4}$ @ $x \sim n*\lambda/4$. 
Instrument Configuration

- Two gravitational reference sensors.
- Individual vacuum housings (not shown).
- Sensors integrated with interferometer.
Microthruster Concept

- Colloidal thrusters
  - Fluid fed through fine needle
  - High voltage extracts charged droplets
  - Droplets accelerated by high voltage
  - Thrust control of 0.1 $\mu$N through change of voltage or flow rate
  - Many needles can be combined to develop necessary thrust
  - Proportional thrust control allows precision position control
    - (displacement to thrust feedback loop)
# Microthruster Requirements

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Specification</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thrust</td>
<td>1–20(\mu)N</td>
<td>Smoothly variable between end point values within 0.1(\mu)N</td>
</tr>
<tr>
<td>2</td>
<td>Thrust controllability/resolution</td>
<td>0.1(\mu)N</td>
<td>Must be within (\pm0.1\mu)N from set point</td>
</tr>
<tr>
<td>3</td>
<td>Thrust noise</td>
<td>(0.1 \mu N/\sqrt{Hz}) from (10^{-3}) Hz to (10^{-2}) Hz</td>
<td>Stable over given period</td>
</tr>
<tr>
<td>4</td>
<td>Specific impulse</td>
<td>(\sim 500) sec</td>
<td>May vary depending on thrust</td>
</tr>
<tr>
<td>5</td>
<td>Thrust slew rate</td>
<td>(&lt; 0.5 \mu N/sec)</td>
<td>Over voltage range/slower with flow</td>
</tr>
<tr>
<td>6</td>
<td>System mass</td>
<td>(\leq 2) kg</td>
<td>Includes all thruster subsystem</td>
</tr>
<tr>
<td>7</td>
<td>Total system power</td>
<td>(&lt; 6.2) W</td>
<td>Average/thruster zeolite heater major consumer</td>
</tr>
<tr>
<td>8</td>
<td>Total operating time</td>
<td>(\geq 2000) hours</td>
<td>90 days mission</td>
</tr>
</tbody>
</table>

## Propulsion System Package

- 8 thrusters in 4 clusters
- Continuous/differential operation, authority over 6 DOF
Performance can be characterized in ground tests

- Thrust levels inferred from beam current (time of flight spectrometry)
- Torsional thrust stand verifies thrust to sub-\( \mu \)N levels (also at JPL)
- Lifetime tests (emitter/electrochemistry and extractor/sputtering)
- Mission profile simulation tests, life and dynamic response demonstration (thrust commands from simulated spacecraft computer)
- Beam neutralization and beam profile measurements
  - Input to models to predict behavior in space
- Contamination tests
  - Limited by back-scatter from test chambers (JPL)
Microthruster Flight/Validation Experiments

- Upon final orbit acquisition place GRS’s in accelerometer mode
- Fire one thruster at a time
- Sweep 1 to 20 μN, compute calibration factors
- Hold steady \( t \geq 1000 \text{ sec.} \) and record thrust noise at 3 levels of thrust
- Validate ground tests (thrust, noise, beam/neutralization)
- Repeat at middle and end of DRS operations

3 Thrusters Cluster concept
2 Thrusters Cluster baselined