Beyond Einstein: From the Big Bang to Black Holes

Self-gravity modeling for LISA

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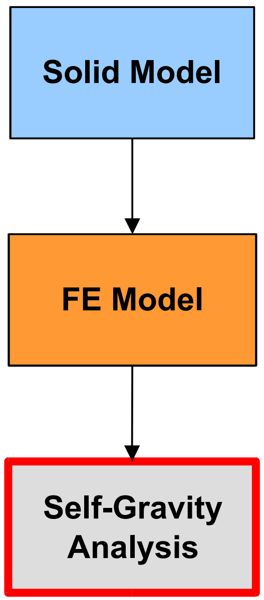
GSFC - JPL

Overview



- Mission level requirements:
  - Total Static Self-Gravity ≤ 5×10^{-10} m/s^2.
    - Equivalent to acceleration from 1 kg mass 36 cm away.
    - Acceleration of Mars on you is ~100×10^{-10} m/s^2 (20 x LISA budget).
  - Total Static Self-Gravity Gradient ≤ 3×10^{-8} s^{-2}.
    - Equivalent to gradient from 1 kg mass 16 cm away.
- Self-gravity analysis is a critical part of LISA Integrated Modeling.
- STOPG analysis used to analytically determine spacecraft distortions due to structural, thermal, and release of 1g loads.
  - Based on current practices used in integrated Structural, Thermal, OPtical (STOP) analysis
  - Addition of self-Gravity analysis leads to STOPG
- Self-Gravity tools accept distorted and undistorted cases.
- Outputs forces, moments, and their gradients on the proof masses.

Solid Model

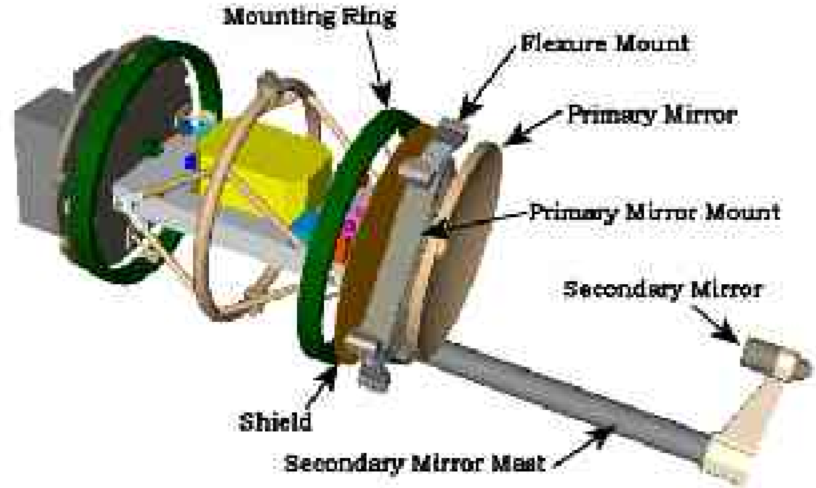
Solid Model

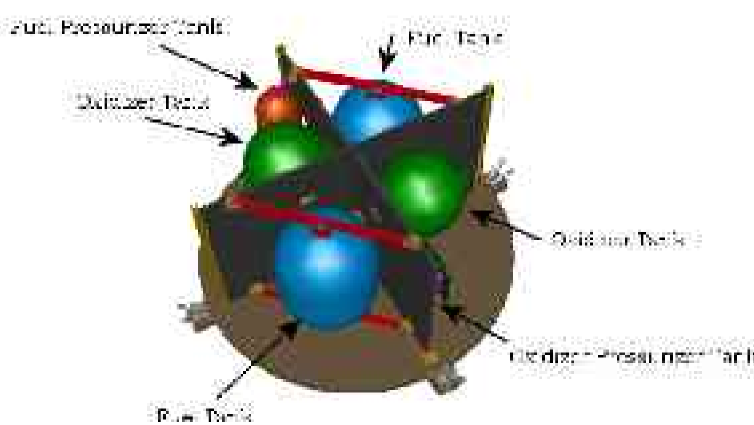
↓

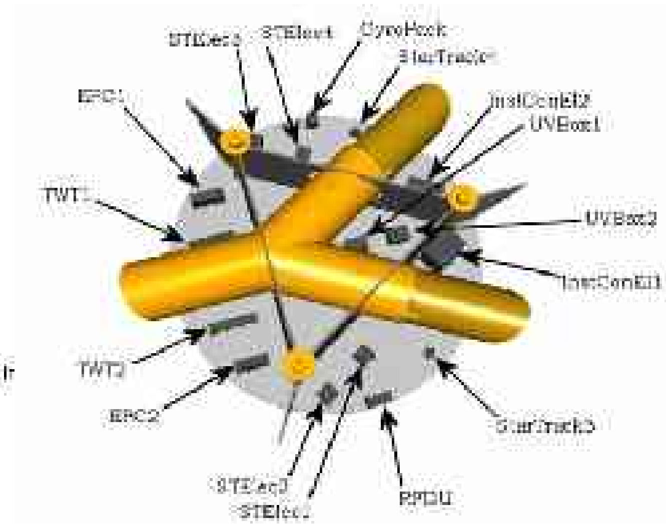
FE Model

↓

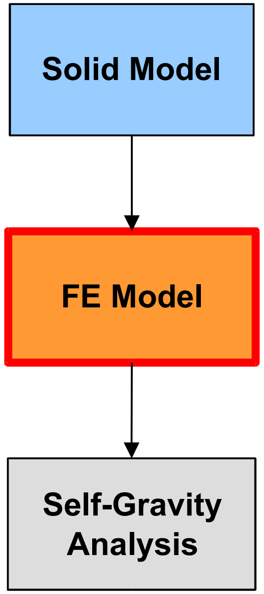
Self-Gravity Analysis

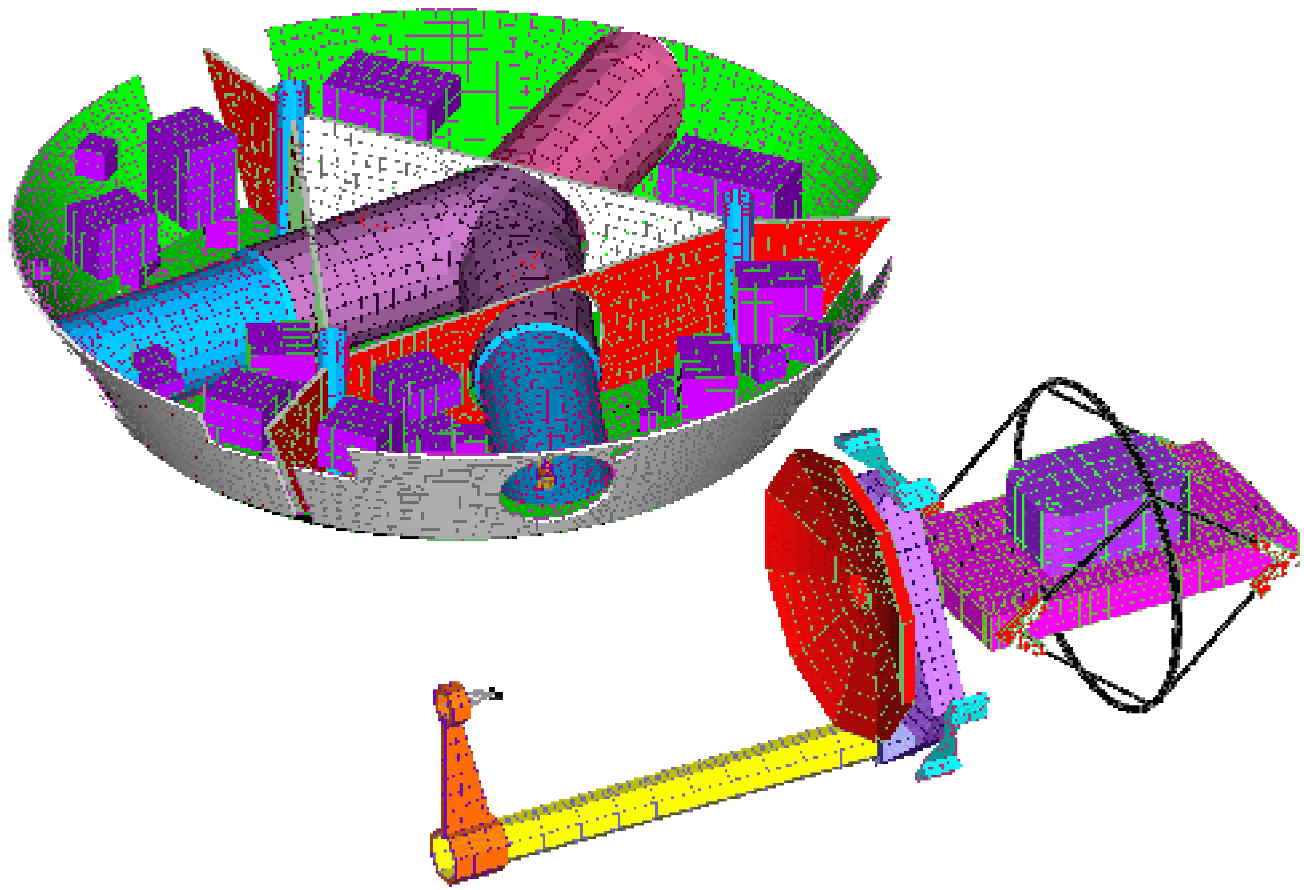






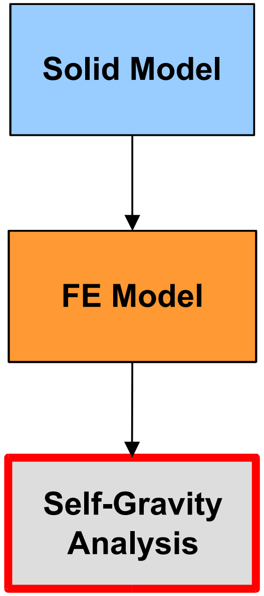
Structural FEM





- Meshing performed in FEMAP.
- A single mesh is used for all portions of the STOPG analysis.
- Current model has ~43,000 nodes

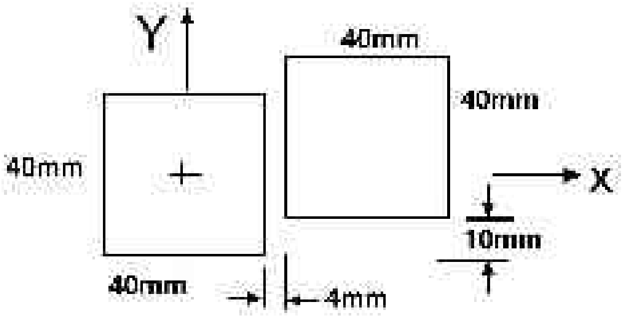
Self-Gravity Analysis



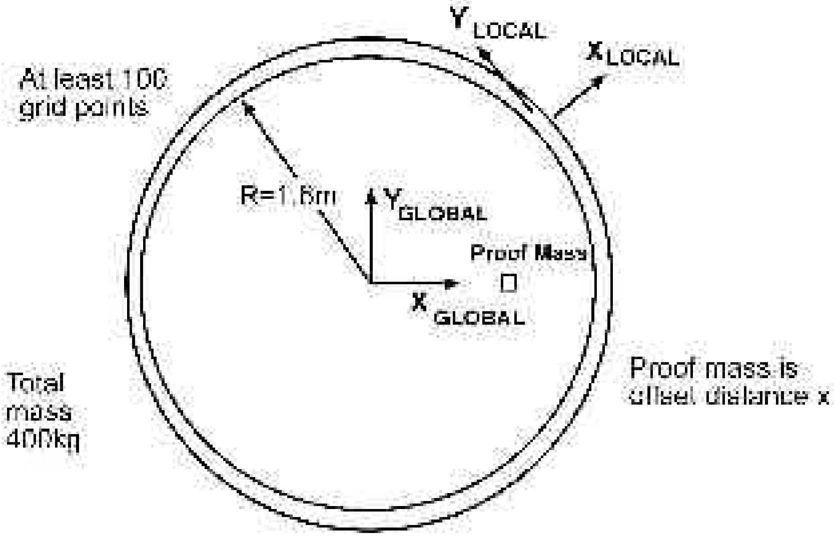
- Two independent self-gravity tools developed
  - Fortran 77 version (Swales developed)
  - Matlab version
- Point mass approximation used
- Inputs
  - FEM mass matrix and rigid body vectors
  - Spacecraft deformed node locations
- Outputs
  - Forces and moments on a proof mass (6 terms each)
  - Gradients on forces and moments (36 terms each)
  - Numerous checks on the accuracy of the inputs and calculations.
- Tools accept distorted and undistorted cases
  - Thermal distortions
  - One-g release distortions

Self-gravity Tool Verification

- Two independent tools developed and cross-checked
- Verified independently using analytically solvable problems
- Two examples:



Two cubes in proximity



Circular ring with proof mass

Mesh Requirements

- Conflicting mesh requirements:
  - Coarse mesh size for thermal (except in regions of high gradient)
  - Fine mesh size for structural analysis of deformed shapes
  - Very fine mesh size for self-gravity near the proof masses
- Self gravity guidelines for the FEM mesh size were developed:

	Maximum D/R for Grid Size	Maximum L/C for point mass approximation
Forces	0.9	0.3
Moments	0.5	0.1
Force gradients	0.4	0.2
Moment gradients	0.25	0.15

D = FEM gird spacing, the mesh size
R = Distance from the grid point to the surface of the proof mass
L = Largest dimension of the solid body
C = Distance from the center of the body to the surface of the proof mass

- Tool estimates errors caused by D/R ratios.
- A separate tool is used to remesh structure close to proof mass

Self-Gravity Division

Subdivision	# Grid Points	Mass (kg)
+Y housings with proof mass	2601	5.546
+Y optical block with mount and proof mass vacuum cover	4851	7.415
+Y telescope with primary mirror, mounts and sec. mirror assy.	1093	4.915
+Y OB cylindrical thermal shields, rings and flexures	1577	8.154
-Y housing with proof mass	2601	5.546
-Y optical block with mount and vacuum cover	4851	7.416
-Y telescope with primary mirror, mounts and sec. mirror assy.	1093	4.915
-Y OB cylindrical thermal shields rings and flexures	1577	8.157
Y tube with sun shade	1486	24.163
S/C structure top plate, bottom plate, bulkheads and support tubes	11842	93.037
S/C thermal shield, solar array and radiator panels	7832	36.490
E-boxes with their isolators	1922	68.243
Two HGAs	2	3.000
Total	43336	276.998

Self-Gravity Results

	For the +Y Test Mass	For the -Y Test Mass
Ax (m/s ^{2} x 10 $^{-10}$) =	–26.8925	–20.6873
Ay (m/s ^{2} x 10 $^{-10}$) =	–58.7772	58.1310
Az (m/s ^{2} x 10 $^{-10}$) =	–40.7371	–40.8112
αξ (ραδ/σ ^{2} ξ 10 $^{-10}$) =	1.2278	1.2652
αψ (ραδ/σ ^{2} ξ 10 $^{-10}$) =	0.0610	0.0486
αζ (ραδ/σ ^{2} ξ 10 $^{-10}$) =	0.1161	0.0205

Requirement = 5

Requirement = 300

	/δξ (μ)	/δψ(μ)	/δζ(μ)	/δξ (μ)	/δψ(μ)	/δζ(μ)
δAξ (1/σ ^{2} ξ 10 $^{-10}$) =	–1264.32	85.39	–25.74	–1258.04	–104.25	–24.69
δAψ (1/σ ^{2} ξ 10 $^{-10}$) =	85.39	1669.91	7.20	–104.25	1666.05	–26.13
δAζ (1/σ ^{2} ξ 10 $^{-10}$) =	–25.74	7.19	–405.60	–24.69	–26.13	–408.01
δαξ (ρσ ^{2}/μ ξ 10 $^{-10}$) =	1.81	1137.84	49.92	1.42	1138.13	50.69
δαψ (ρσ ^{2}/μ ξ 10 $^{-10}$) =	–300.77	–0.70	–9.01	–300.88	–0.45	–6.62
δαζ (ρσ ^{2}/μ ξ 10 $^{-10}$) =	–1.73	–8.19	–1.11	–0.16	–4.63	–0.97

	/δθξ (ρ)	/δθψ(ρ)	/δθζ (ρ)	/δθξ (ρ)	/δθψ(ρ)	/δθζ (ρ)
δAξ(μ/σ ^{2}/ρξ 10 $^{-10}$) =	0.00	40.66	–58.78	0.00	40.73	58.13
δAψ(μ/σ ^{2}/ρξ 10 $^{-10}$) =	–40.43	0.00	26.89	–40.51	0.00	20.69
δAζ(μ/σ ^{2}/ρξ 10 $^{-10}$) =	58.79	–26.89	0.00	–58.12	–20.69	0.00
δαξ (1/σ ^{2} ξ 10 $^{-10}$) =	1812.3	–0.171	–0.118	1812.23	–0.011	–0.019
δαψ (1/σ ^{2} ξ 10 $^{-10}$) =	–0.055	335.90	–1.260	0.009	335.90	–1.264
δαζ (1/σ ^{2} ξ 10 $^{-10}$) =	–0.178	–0.032	297.85	–0.068	0.001	297.84

Self-Gravity Breakdown

Results on +Y proof mass in local proof mass coordinates

Source	Ax ($m/s^2 \times 10^{-10}$)	Ay ($m/s^2 \times 10^{-10}$)	Az ($m/s^2 \times 10^{-10}$)	dAx/dx ($1/s^2 \times 10^{-10}$)	dAy/dy ($1/s^2 \times 10^{-10}$)	dAz/dz ($1/s^2 \times 10^{-10}$)
+ GRS housing	-0.43	-0.03	-0.39	-2274.9	1130.3	1144.7
+ Optical block	0.18	0.53	-43.24	600.8	676.8	-1277.5
+ Telescope	33.32	-0.25	-2.72	196.1	-105.1	-90.9
+ Thermal shield	-35.44	-0.30	-0.31	225.8	-145.7	-80.1
ÐProof mass	-1.26	-2.19	0.00	-1.1	5.4	-4.3
ÐGRS housing	-4.24	-7.25	0.01	-3.2	17.7	-14.5
ÐOptical block	-7.68	-12.53	-0.26	-3.3	29.7	-26.3
ÐTelescope	-0.78	-5.19	-0.17	-5.5	12.6	-7.1
ÐThermal shield	-12.94	-13.01	-0.44	19.8	14.9	-34.8
Y-tube	4.65	-7.67	-3.45	14.9	-0.4	-14.5
S/C structure	-7.39	-4.77	-3.52	-37.0	-7.2	44.2
S/C thermal	-1.02	-0.88	14.82	-4.8	-4.6	9.3
Electronic boxes	6.17	-5.74	-1.49	9.0	44.3	-53.3
High Gain Antennas	0.23	0.40	0.44	-0.4	1.1	-0.7

X-axis is telescope line-of-sight

Telescope Articulation

QuickTimeª and a
Video decompressor
are needed to see this picture.

Telescope Articulation

- Analysis completed for change in self-gravity due to telescope articulation.
- Nine models produced with the telescope articulation angle incremented
  - Expected articulation is ±0.5°
  - Linear change : -1.03×10^{-10} m/s²/degree for sensitive axis (x)

QuickTimeª and a
Video decompressor
are needed to see this picture.

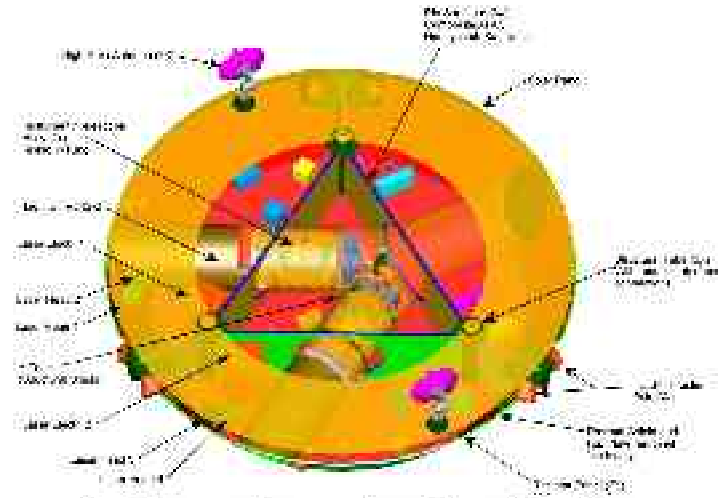
Change In Translational Accelerations and Gradients on the +Y Proof Mass

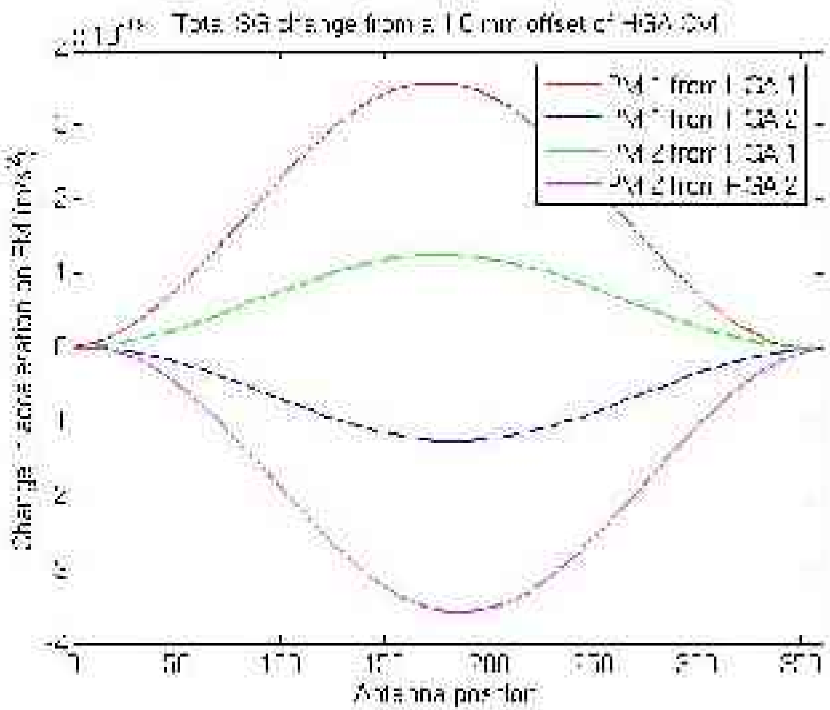
Articulation Angle θz	$\Delta A\xi$ $(\mu/\sigma^2\ \xi\ 10^{-10})$	$\Delta A\psi$ $(\mu/\sigma^2\ \xi\ 10^{-10})$	$\Delta A\zeta$ $(\mu/\sigma^2\ \xi\ 10^{-10})$	$\Delta\delta A\xi/\delta\xi$ $(1/\sigma^2\ \xi\ 10^{-10})$	$\Delta\delta A\psi\delta\psi$ $(1/\sigma^2\ \xi\ 10^{-10})$	$\Delta\delta A\zeta/\delta\zeta$ $(1/\sigma^2\ \xi\ 10^{-10})$
$+0.8^0$	−0.824	0.351	2ε−6	2.32	−2.32	2ε−4
$+0.6^0$	−0.619	0.262	2ε−6	1.74	−1.74	1ε−4
$+0.4^0$	−0.413	0.174	1ε−6	1.15	−1.15	7ε−5
$+0.2^0$	−0.207	0.087	4ε−7	0.58	−0.58	4ε−5
0	0	0	0	0	0	0
-0.2^0	0.207	−0.086	−5ε−7	−0.58	0.57	−4ε−5
-0.4^0	0.414	−0.171	−1ε−6	−1.14	1.14	−8ε−5
-0.6^0	0.622	−0.256	−2ε−6	−1.71	1.71	−1ε−4
-0.8^0	0.829	−0.339	−2ε−6	−2.27	2.27	−2ε−4

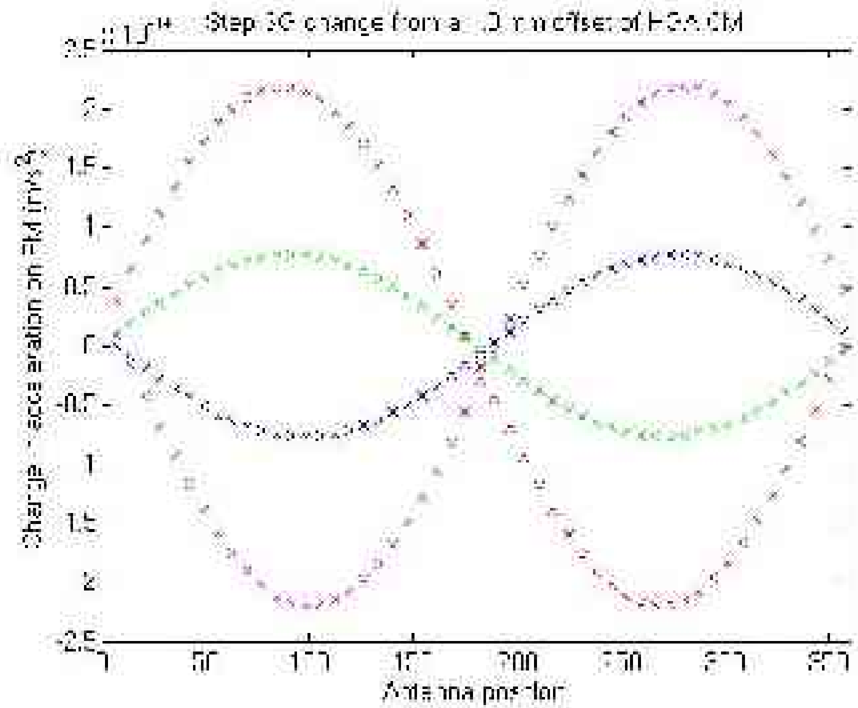
~20 % of requirement

HGA Rotation

- Two high gain antennas rotate ~7° once per week.
- For a 1 mm CM offset of 1 antenna:
  - 3.6×10^{-13} m/s² pp over 1 year.
  - 2.2×10^{-14} m/s² max step

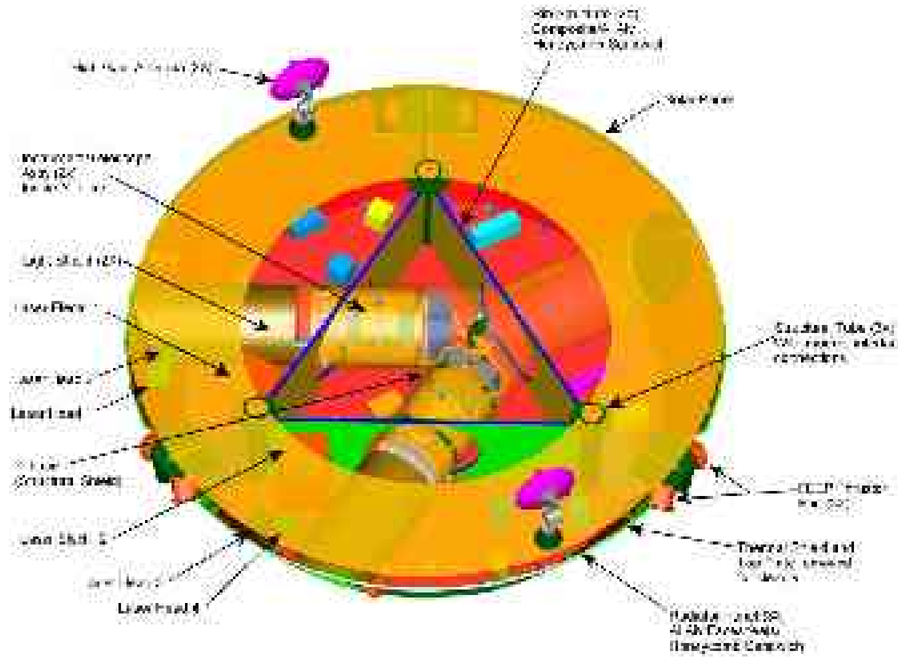


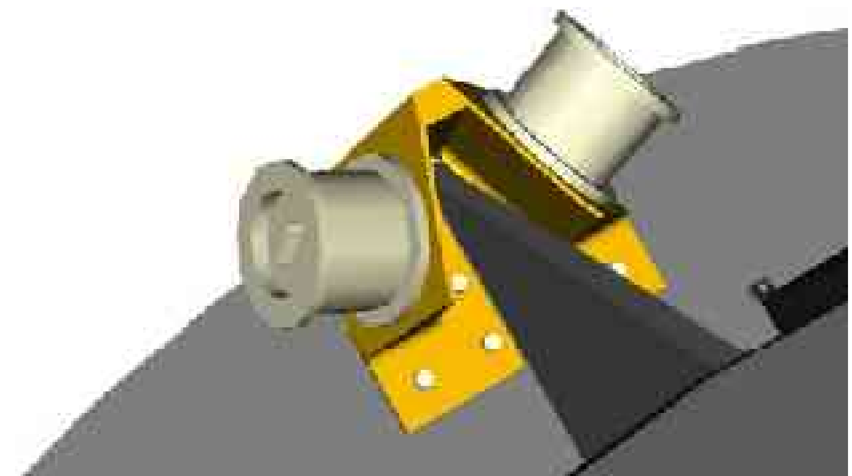




Thruster Propellant Use

- Change in self-gravity from μN-thrusters propellant loss is out of band.
- Over life of mission, worst case total change is:
  - 0.7×10^{-10} m/s^2 (14% of requirement) for colloid thruster with I_{sp}=1000s, total mass = 8 kg.
  - 12×10^{-10} m/s^2 (240% of requirement) for cold gas with I_{sp}=60s, total mass = 20 kg.

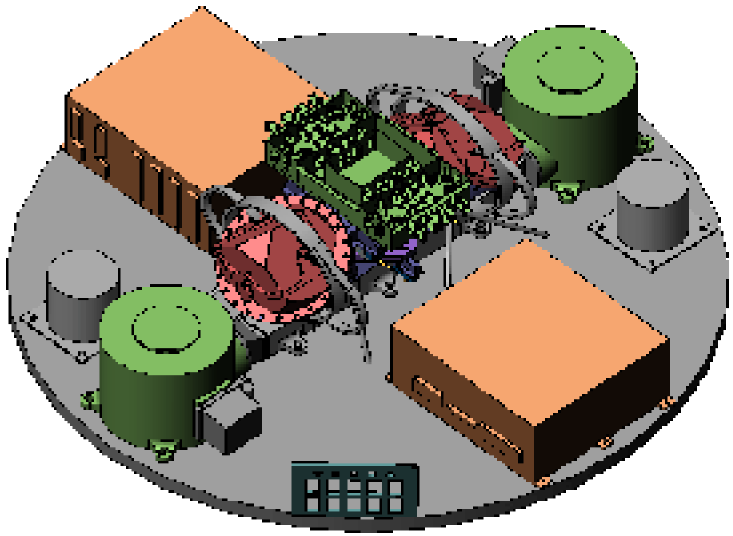


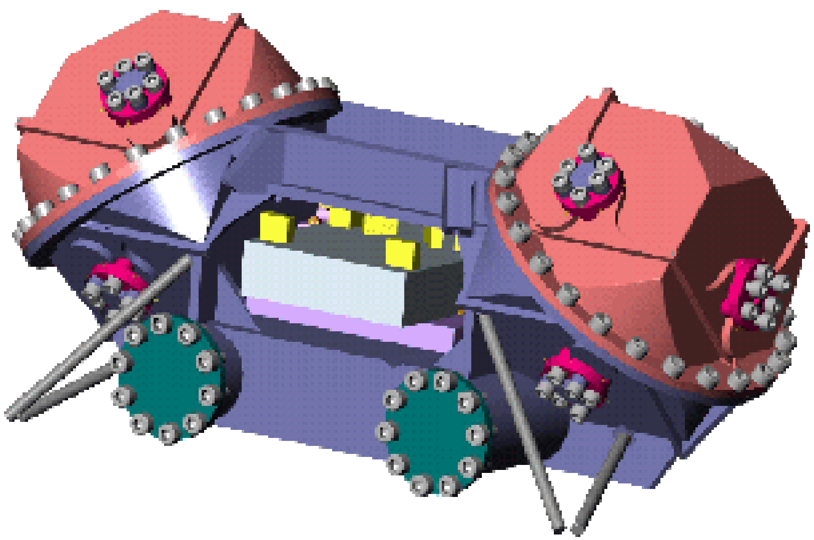


ST-7 Self-Gravity

- ST-7 DRS flies on the ESA LISA Pathfinder spacecraft
- L1 orbit
- Launch date: late 2007
- Operational life: 3 months
- The key new technologies are gravitational reference sensors and microthrusters.
  - DRS validate spacecraft position control to an accuracy of <10nm/√Hz over frequency range 1 mHz to 10 mHz
  - DRS validates that a test mass follows trajectory determined by gravitational forces only within 3×10^{-14} m/s²/√Hz over frequency range 1 mHz to 10 mHz
- Self-Gravity Requirements:

Type	Allowed Max. Acceleration
DC acceleration	1.0×10^{-9} m/s ^{2}
DC acceleration gradient	80.0×10^{-9} 1/s ^{2}
AC fluctuations	5.0×10^{-15} m/s ^{2}/√Hζ



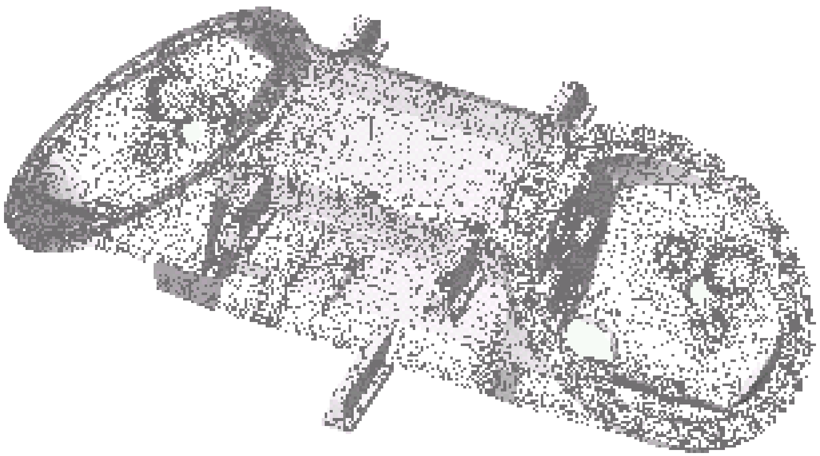


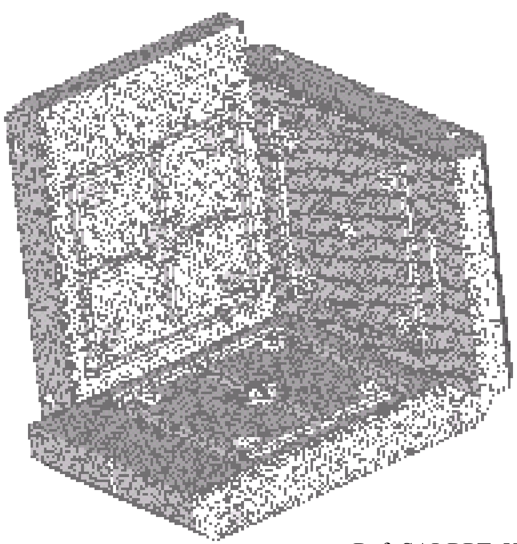
ST-7 Self-Gravity

- The FEM consisted of 39 sub-assembly models
- Overall – 1,266,463 grid points (7,598,778 DOF)
- Mathematical errors estimated to be less than 0.1%
- Results in the sensing direction:

	Ax ($m/s^2 \times 10^{-9}$)	dAx/dx ($1/s^2 \times 10^{-9}$)
From the other proof mass	-1.3	10.0
From housing walls alone	-0.4	8.7
From chassis alone	-9.1	50.7
From GRS assembly	-15.6	174.8
Complete assembly	-21.7	124.8
Budget	1.0	80.0

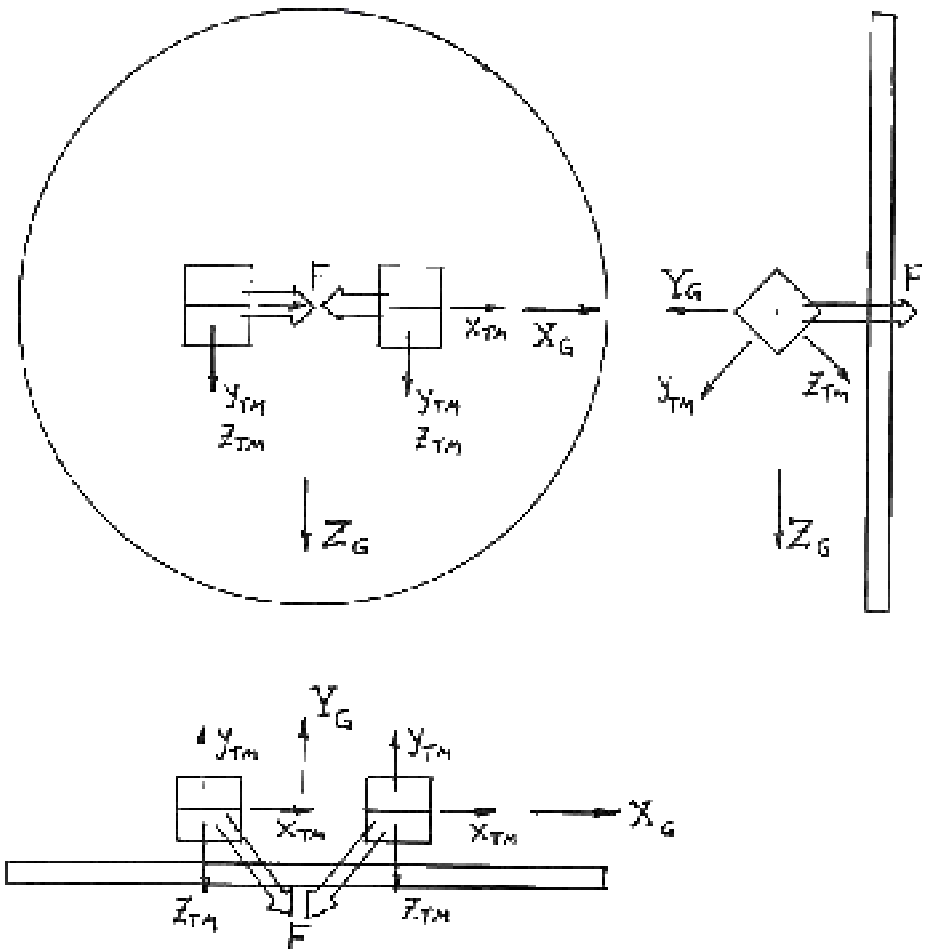
- ST-7 flight provides a self-gravity anchor point.





Ref: SAI-RPT-570, “Preliminary Self-Gravity of the ST7 DRS”, by William Haile, 10Feb’04

ST-7 Self-Gravity



	+X PM	-X PM	Budget
Ax (m/s² x 10^{-9})	-21.7	22.0	1.0
Ay (m/s² x 10^{-9})	-21.6	-21.5	
Az (m/s² x 10^{-9})	21.2	21.2	
α_X (rad/² x 10^{-9})	-0.01	-0.03	
α_Y (rad/s² x 10^{-9})	0.14	-0.15	
α_Z (rad/s² x 10^{-9})	0.04	-0.05	
dAx/dx (1/s² x 10^{-9})	124.8	124.8	80.0
dAy/dy (1/s² x 10^{-9})	-60.7	-62.0	
dAz/dz (1/s² x 10^{-9})	-64.2	-62.8	

Future Work

- Complete thermal distortion study (in progress).
- Repeat analysis on evolving LISA design as necessary.
- Update ST-7 analysis after CDR.
- Study effects of non-uniform proof mass density.
- Develop self-gravity balancing techniques and tools.