# A non-drag-free gravitational-wave mission architecture

William Folkner
JPL

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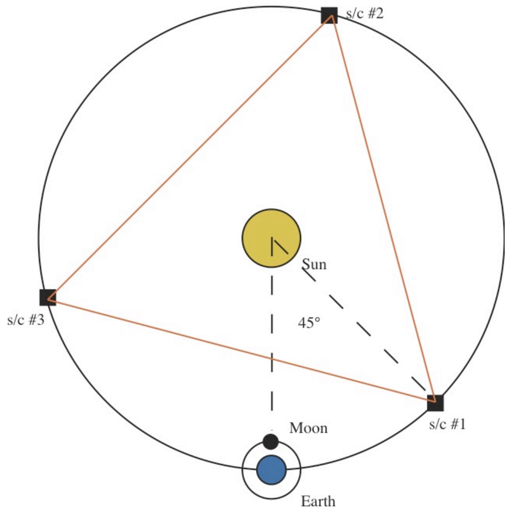
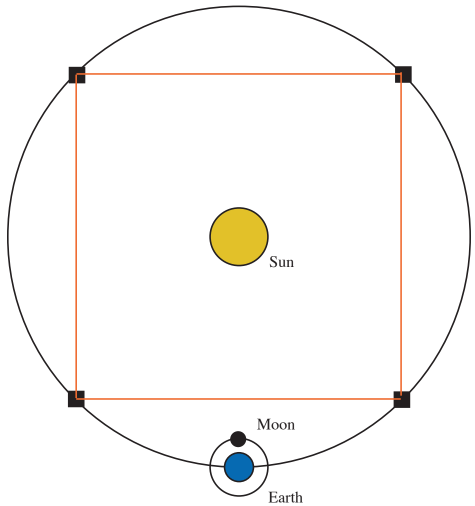
## #1: Which concept should be studied? Triangle or square?



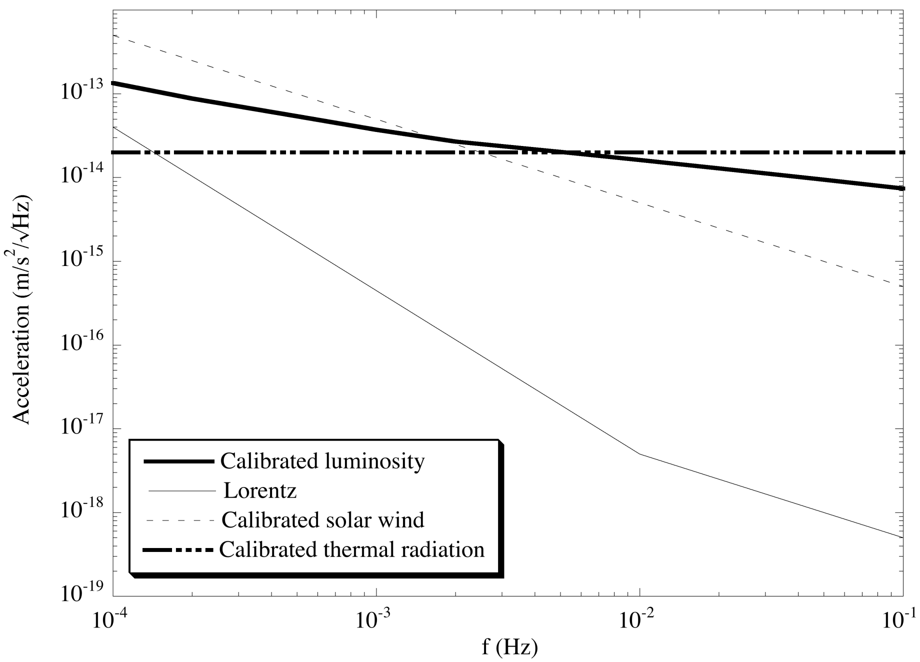

- The cost of 3 dual-string spacecraft with 6 telescopes/instruments should cost about the same as 4 single-string spacecraft with 8 telescopes/instruments
- For purposes of response to the RFI request for cost, mass, etc estimates based on on engineering work, analogies to the GRAIL mission with 2 single-string spacecraft recently launched will be more credible than creating a 3-spacecraft mission from thin air.
- Because the cost of the payload is the largest unknown, if a Team-X study is undertaken a study of the 3 spacecraft option is recommended

## #2: Would the Disturbance Free Payload described in the RFI By Shao, et al. be applicable to this concept?

- No. The Shao et al. concept includes a drag-free system, albeit with possibly coarser control, but that spacecraft positions control is counter to the non-drag-free approach where NO thrusting is used during science operations.

#3: Without drag-free, the noise budget is sensitive to noisy forces and mechanical disturbances on the spacecraft that are difficult to rule out on the ground and measure/model in space (e.g. Pioneer Anomaly). Are these controllable? What is the budget for unmodeled forces?

- Noise budget needs to be done for any GW mission
- Leading terms are discussed in paper, but more work needs to be done
- Unknown forces cannot be modeled, so there is always some risk;
  - A drag-free sensor has similar risks
- Note that there is good evidence that 'Pioneer anomaly' is well explained by spacecraft thermal model




Solar calibrated to voltage standard noise
Solar wind calibrated to 1%
Solar panel temperature controlled to 0.1 mK
(and assumes Earth environment (GRAC
Lorentz force based on 30 V potential

Not shown are:
Surface outgassing
Thruster leakage

## #4: Do you have an estimate of what delta-v is required for each spacecraft and how long the cruise phase will last?

- A simple calculation for a 3.5 year transit time to 180 degrees from Earth gives delta-v required = 2*1.43 km/s
  - one maneuver of 1.43 km/s at launch to reduce orbit period to 7/8 year, and similar maneuver to circularize
- Taking spacecraft mass of 350 kg, using Hall thruster (Busek BHT-600) with 42 mN thrust, Isp 1585 s, then 138 days of thrusting is required for each maneuver
- Total propellant mass is 65 kg
- GRAIL spacecraft dry mass is 200 kg, propellant mass is 100 kg
  - Assume non-drag-free spacecraft mass is 250 kg, 64 kg propellant mass, leaving 36 kg.
- GRAIL spacecraft peak power is 700 W

## #5: What comm. capability is required? What antenna sizes are required onboard and at the ground station? Would you consider lower sampling because of the lower frequency response?

- 1.25 m spacecraft antenna using X-band with 17 W transmitted power to a DSN 34m antenna gives a data rate > 15,000 bits/second
  - Antenna field of view is sufficient to see Earth at all times with no articulation
- Suggested data rate is 1500 bits/second, 130 Mb/day
  - 2.5 hours of contact per day (or 7.5 hours every third day) would get data down

- This data rate based on 2000 ESA Final Technical Report
  - LISA sensitivity might be achievable with larger telescope or shorter wavelength laser, so assume same interferometer data rate
    - Limited at low frequencies by binary confusion noise
  - No drag free sensor or control system, but similar data volume assumed for solar pressure, thermal, solar wind. etc. calibration data

# Simple telemetry link calculation

| | | | | |
|---|---|---|---|---|
| **Transmitter Parameters** | | | | |
| | RF Power, dBm | 42.30 | | |
| | *(Watts)* | | 17.00 | |
| | Transmit Circuit Loss, dB | -1.00 | | 1 is typical conservative value |
| | Antenna Circuit Loss, dB | -0.50 | | .5 is typical conservative value |
| | Antenna Gain, dBi | 38.24 | | |
| | *Antenna diameter, m* | | 1.25 | |
| | *Wavelength, cm* | | 3.40 | 3.4 cm is X-band |
| | *Efficiency* | | 0.50 | 0.5 is typical |
| | Pointing Error, dB | -1.00 | | related to how far off beam center |
| | Total : | 78.05 | | |
| | | | | |
| **Path Parameters:** | | | | |
| | Space Loss, dB | -280.90 | | |
| | *Range, km* | | 3.00E+08 | |
| | Atmospheric Atten, dB | -0.50 | | |
| | Total: | -281.40 | | |
| | | | | |
| **Receiver Parameters:** | | | | |
| | Polarization Loss, dB | -0.50 | | |
| | Antenna Gain, dBi | 68.39 | | |
| | *Antenna diameter, m* | | 34.00 | |
| | *Efficiency* | | 0.70 | |
| | Pointing Loss, dB | -1.00 | | |
| | Noise Spectral Dens, dBm/Hz | -183.83 | | |
| | *System Temp, K* | | 30.00 | |
| | | | | |
| **Power Summary:** | | | | |
| | Received Power, dBm | -136.46 | | |
| | Received Pt/N0, dB-Hz | 47.37 | | |
| | SNRV(1-sec) | 330.49 | | |
| | | | | |
| **Telemetry:** | | | | |
| | Bit Rate, dB-Hz | 44.77 | | |
| | *Bit Rate, bps* | 30000.00 | | Really Symbol rate, typically 2* (information rate) |
| | Data Power / Total Power, dE | 0.00 | | |
| | *Tlm Mod Index, deg* | 90.00 | | |
| | TLM Rcvr Losses, dB | 0.00 | | |
| | Eb/N0, dB | 2.60 | | Symbol margin, needs to be >2 typically |

## 6: Do you have an estimate of the total launch mass, and a candidate launch vehicle?

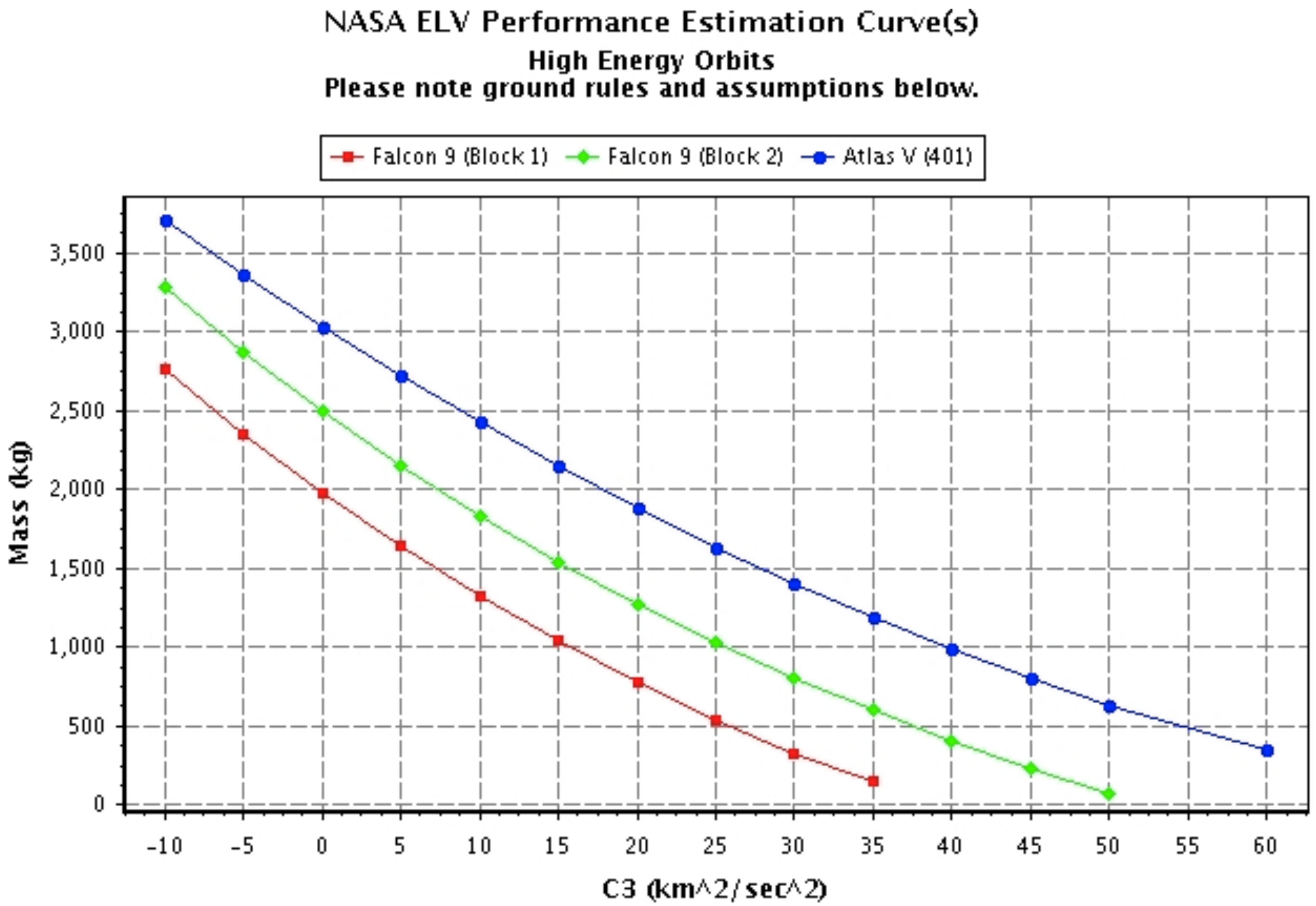
- Assume single-string spacecraft launch mass = 350 kg
  - GRAIL spacecraft dry mass = 200 kg
  - Additional payload mass = 35 kg
  - Propellant = 65 kg
  - Contingency = 50 kg
- Mass of 4 single-string spacecraft = 1400 kg
- Mass of launch adaptors (2x GRAIL) = 300 kg

- Launch mass 1700kg + margin

- For launch to C3 ~ 1 $km^2/s^2$, Falcon-9 block -2 or Atlas V-401 would work
  - Falcon 9 Block 2 launches ~2400 kg to C3 ~1
  - Atlas V 401 launces ~2900 kg to C3 ~1
- With 3 dual-string spacecraft Falcon-9 Block 1 might suffice
  - Falcon-9 block 1 launches ~1900 kg to C3 ~ 1

# Launch vehicle performance data

- From NASA launch services web site
- http://elvperf.ksc.nasa.gov




*This document has been reviewed and determined not to contain export controlled technical data.*

## 7: Where do the cost savings come over the SGO-Mid concept?

- SGO-Mid requires drag-free sensor and micro-newton thrusters
  - If LISA Pathfinder is successful, and NASA mission acquires GRS from Europe, GRS cost might cost $50M- $100M, and thruster development might cost >$10M
  - If NASA mission does not use Pathfinder contractors, or Pathfinder is not successful, then development of NASA drag-free system might require a flight demonstration, so cost could be very high.
- Other than GRS, the non-drag-free system reduces number of actuators, complexity of interferometry, demanding requirements on spacecraft
  - Team-X study not likely to correctly reflect cost of meeting drag-free requirements

| Assembly | SGO-Mid | Non-Drag-Free |
|---|---|---|
| Point ahead actuator | Yes | No |
| IFO back-link | Yes | No |
| Stablity requirement | 50 pm > | 1 nm |
| S/C Mass balance | Yes | No |
| Telecon steering | Yes | No |
| GRS | Yes | No |
| ¨N thrusters | Yes | No |