9th LISA Symposium, Paris
ASP Conference Series, Vol. 467
G. Auger, P. Binétruy and E. Plagnol, eds.
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LAGRANGE: LAser GRavitational-wave ANtenna in GEodetic Orbit

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Abstract.

We describe a new space gravitational wave observatory design called that maintains all important LISA science at about half the cost and with reduced technical risk. It consists of three drag-free spacecraft in a geocentric formation. Fixed antennas allow continuous contact with the Earth, solving the problem of communications bandwidth and latency. A 70 mm diameter sphere with a 35 mm gap to its enclosure serves as the single inertial reference per spacecraft, operating in "true" drag-free mode (no test mass forcing). Other advantages are: a simple caging design based on the DISCOS 1972 drag-free mission, an all optical read-out with pm fine and nm coarse sensors, and the extensive technology heritage from the Honeywell gyroscopes, and the DISCOS and Gravity Probe B drag-free sensors. An Interferometric Measurement System, designed with reflective optics and a highly stabilized frequency standard, performs the ranging between test masses and requires a single optical bench with one laser per spacecraft. Two 20 cm diameter telescopes per spacecraft, each with infield pointing, incorporate novel technology developed for advanced optical systems by Lockheed Martin, who also designed the spacecraft based on a multi-flight proven bus structure. Additional technological advancements include updated drag-free propulsion, thermal control, charge management systems, and materials. LAGRANGE subsystems are designed to be scalable and modular, making them interchangeable with those of LISA or other gravitational science missions. We plan to space qualify critical technologies on small and nano satellite flights, with the first launch (UV-LED Sat) in 2013.

1. Overview

Stanford University, NASA Ames Research Center, Lockheed Martin, the King Abdulaziz City for Science and Technology (KACST), and SRI International have formed a collabora-

tion (called SALKS) to develop a new space gravitational-wave observatory mission concept, named LAGRANGE, which maintains all important LISA science at reduced cost and with reduced technical risk. We achieve this goal by revisiting all aspects of LISA for possible improvements, while structuring the new elements to be modular and scalable, as well as interchangeable with baseline LISA systems. We incorporate both new technologies developed after the LISA and LISA pathfinder designs were base lined (UV-LEDs, non-transmissive optics, SRI thrusters, test mass (TM) coatings and others), as well as older space qualified technologies from Honeywell (1953), DISCOS (1972) (ref. Staffs Of The Space Dpt. and G&C Lab (1974)), GP-B (2004) (ref. Everitt, C. W. F., and others (2011)).

LAGRANGE comes close to meeting the LISA sensitivity at <10 mHz and exceeds it at higher frequencies (Fig. 1). A NASA cost analysis gives a cost of $950M, with 30% margin, significantly less than the current LISA cost, while including many technical advantages. The three elements of a gravitational-wave observatory are 1)the constellation and its orbit 2)the gravitational reference sensors, 3)the metrology system.

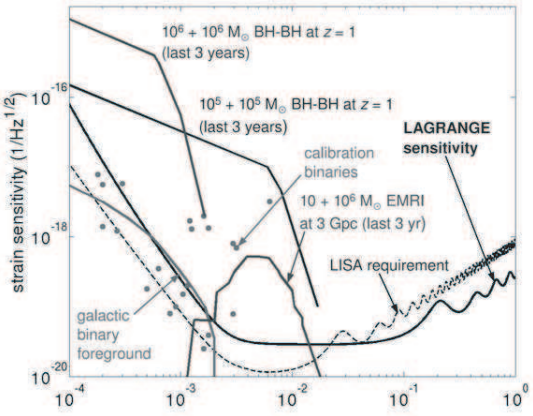

Figure 1. LAGRANGE strain sensitivity, and comparison with LISA requirements and gravitational wave sources, adapted from Stebbins et al. (2009)

Discriminating improvements of LAGRANGE are: 1. LAGRANGE consists of a triangular constellation of identical spacecraft (S/C) and payloads in one of three possible orbits: a) the Earth-Moon L3, L4, and L5 points, b) a retrograde lunar plane orbit, c) a halo orbit at the Sun-Earth L2 point (Table 1). Launch of the three spacecraft with one small propulsion module is possible on a Falcon 9 at a cost of $118M from NASA Launch Services. Earth-based receivers are continuously in the field of view of fixed transmitters on each spacecraft increasing the communication bandwidth by <100 from LISA and greatly reducing data latency (minutes instead of days). Experience with GP-B and LIGO, the closest analogs to date, make this bandwidth an absolute requirement for mission success (Table 2). This low estimate applies only to an antenna with 1 test mass per SC and does not address command and telemetry for the formation.

Table 1. The three LAGRANGE candidate orbits

Orbit	**Type**	**Arm Length**	**To Earth**
a) EM - L3, L4, L5		0.67 Gm	0.4 Gm
b) Lunar retrograde	OMEGA	1.0 Gm	0.58 Gm
c) SE - L2 Halo	JWST	1.39 Gm	1.5 Gm

Table 2. Data rate estimates for LAGRANGE compared to GP-B

	GP-B	1 × LGR SC	3 × LGR SC vs GP-B
Planned	0.35 GB/day (actual)	0.004 GB/day (ESA)	0.013 GB/day (ESA)
System			
SC	GPB 6 deg ctrl.	LGR 7 deg ctrl.	≈(GPB)×3
Temperature	Cryogenics	μK control	≈(GPB)×3
Activation	He thrusters	μN thrusters	≈(GPB)×3
Pointing	1 telescope	2 telescopes	≈(GPB)×3
Test Masses	4 TM × 3 deg ctrl.	2 TM × 6 deg ctrl.	≈(GPB)×3
Read-out	4 SQUID systems	4 pm interferometers	≈(GPB)×3
BW	BW 12.9 mHz	BW 0.1-100 mHz	≥(GPB)×3

LISA data rate ≥3× GP-B data rate ≥ 1 GB/day
Estimated LISA data rate/Planned LISA data rate (ESA) ≥77

2. The single Gravitational Reference Sensor (GRS) is based on the Modular Gravitational Reference Sensor concept (MGRS) developed by SALKS and consists of a spherical test mass spinning at 3-10 Hz thus providing frequency separation from the 1 mHz to 1 Hz primary LAGRANGE bandwidth. Similar TMs have been successfully flown on DISCOS, and GP-B. The MGRS is true drag-free with no forcing in any direction, and has a 35 mm gap that can be increased if necessary. Caging by a single screw mechanism was demonstrated on the DISCOS flight and is critical to the risk reduction in LAGRANGE versus LISA. Magnetic spin-up and polhode damping were demonstrated thoroughly in Honeywell gyroscopes.

3. The Interferometric Measurement System (IMS) consists of a single laser and optics bench that incorporates only reflecting elements in the critical locations: gratings and mirrors, while laser frequency stabilization is enhanced by high finesse optical cavities and/or iodine molecular clocks. Two telescopes per S/C with in-field pointing are designed to minimize path-length errors.

Significant cost reduction for LAGRANGE over LISA was achieved principally in two ways: (a) by decreasing the per spacecraft mass and power by reducing payload components (2 lasers, 2 GRSs, and 2 optics benches for LISA was reduced to 1 of each for LAGRANGE), and (b) by using a geocentric orbit, which requires only one propulsion module for all three spacecraft and reduces mission operations complexity by increasing communications bandwidth. There is incremental risk reduction in LAGRANGE due to an emphasis on simplicity. In addition, the SALKS collaboration is implementing flight demonstrations of critical technologies on small satellites and CubeSats (ref. Worden et al. (2008)). These include charge management, laser frequency stabilization, shadow and interferometric position measurement, thrusters and caging mechanisms. The charge management flight (UV LED Sat) (ref. Sun et al. (2011)) is scheduled for 2013.

2. The LAGRANGE Observatory

The primary measurement band for LAGRANGE is 1 mHz to 1 Hz, where the strain sensitivity is 3×10^{-20}. The target astrophysical sources include: (1) Massive black hole mergers in the range of 10^4 (MBH) to 10^7 (SMBH) solar masses with orbit periods of 10^2 to 10^4 s, giving signal-to-noise ratios (SNR) up to several thousand out to z ∼ 15; (2) Stellar mass compact objects orbiting MBH (EMRI) with periods of 10^2 to 10^3 s; (3) Stellar mass binaries within the Milky Way with orbital periods of 10^2 to 10^3 s.

Fig. 1 shows the estimated LAGRANGE strain sensitivity (solid black curve) in units of $Hz^{-1/2}$, compared to the LISA requirement (dashed curve). Other curves and points represent the various known sources within the LAGRANGE bandwidth. Sensitivity normal to the ecliptic plane is less than that of LISA due to the reduced out-of-plane motion of the observatory.

However, higher gravitational-wave harmonics provide a significant improvement in the position determination of MBH binaries (ref. Wainwright & Moore (2009)). LAGRANGE will achieve the three most important science goals of LISA listed in the 2010 astrophysics decadal survey, "New Worlds, New Horizons" (ref. Comm. for a Decadal Survey of Astronomy (2010)) and will deliver excellent science, little reduced from LISA.

LAGRANGE consists of a triangular constellation of three identical spacecraft in one of the orbits of Table 1. Detection and observation of gravitational waves is performed using laser interferometry to measure the distances between inertial references in each spacecraft as in LISA (ref. Bender et al. (1998)). Each spacecraft contains a single spherical test mass as the inertial reference and a single optical bench serving as a metrology reference. The light source is a 1 W laser, while two 20 cm aperture telescopes send and receive laser light to and from the remote spacecraft. The fundamental measurement scheme is based on the LISA approach. The interferometric science measurement is made in two steps. The first is the short- arm interferometer, which measures the optical bench position with respect to the TM center of mass. The second is the long-arm interferometer that measures the distance from the local optical bench to the optical bench on the remote spacecraft. Time delay interferometry (ref. Armstrong et al. (1999)) combines phase measurements made on-board each spacecraft, accounting for the light travel time between spacecraft to cancel laser noise while retaining the gravitational wave signal.

Based on experience with the successful drag-free satellites Triad I (ref. Staffs Of The Space Dpt. and G&C Lab (1974)) and Gravity Probe B (ref. Bencze et al. (2006)), a spherical geometry was chosen for the LAGRANGE GRS. A spherical GRS for LISA was proposed as early as 1998 (refs. DeBra (1998), Keiser et al. (2000)), and has advantages that outweigh its disadvantages: (a) no TM forcing, torquing, electrostatic support or capacitive sensing is required, reducing disturbances and complexity; (b) large TM-to-housing gap (35 mm): disturbances are reduced and spacecraft requirements are relaxed, (c) a long flight heritage (ref. DeBra & Conklin (2011)): Honeywell gyroscopes, Triad I and GP-B; (d) scalability: performance can be scaled up or down by adjusting TM and gap size; (e) simplicity: no cross coupling of degrees of freedom; (f) a simple flight-proven caging mechanism.

This GRS concept, now called the Modular Gravitational Reference Sensor (MGRS) has been under development for a wide range of applications since 2004 (refs. Buchman et al. (2004), Sun et al. (2006)).

Two interferometer configurations have been studied. The primary configuration utilizes a double-sided diffraction grating to act as the main reference surface and as a beam splitter. A finesse-enhanced Fabry- Perot cavity allows a direct measurement of the distance between the grating and the TM, without the use of a reference arm of a Michelson interferometer. The PDH technique allows the measurement to be made at frequencies where the laser is quantum-noise-limited. A short-arm interferometer using a Littrow mounted grating has been demonstrated in the lab at Stanford (ref. Allen (2009)). The secondary configuration is similar to the LISA optical bench (refs. Livas et al. (2009), Shaddock et al. (2006), Pijnenburg et al. (2010)).

The LAGRANGE mission is divided into four phases: (a) launch plus 6 month cruise to the science orbits, (b) Initial Orbit Checkout, which includes starting drag-free operations and acquisition of the signal from the spacecraft, (c) 5-year science observations, and (d) decommissioning. Existing LISA data analysis methodologies (ref. Babak et al. (2008)) would directly apply to the LAGRANGE data. The main difference would be the change of antenna pattern due to the different orbit. The total mass of the spacecraft and payload is 2,070 kg, including 30% margin for payload and propulsion module, 14% margin for > TRL 6 Lockheed spacecraft. The total power consumption of the spacecraft is 500 W, including 30% margin for the payload and 8% margin for spacecraft, while transmitting.

LAGRANGE cost is estimated in the medium range of $600M to $1B. A detailed and conservative joint ARC and Lockheed Martin cost analysis puts the mission ROM cost at $950M FY12, including 30% reserves. All major sub-systems are >TRL 5.

3. Acknowledgments

We thank L. Hollberg (Stanford), K. X. Sun (UNLV), S. Vitale (U. Trento), R. Hellings (MSU), C. Ocampo (UTA), V. Hruby (Busek) for their support.

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