ASTROD and ASTROD I: Progress Report

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Abstract Over the next decade the gravitational physics community will benefit from dramatic improvements in many technologies critical to the tests of gravity and gravitational-wave detection. The highly accurate deep space navigation, interplanetary laser ranging and communication, interferometry and metrology, high precision frequency standards, precise pointing and attitude control, together with the drag-free technologies will revolutionize the field of the experimental gravitational physics. Deep-space laser ranging will be ideal for gravitational-wave detection, and testing relativity and measuring solar-system parameter to an unprecedented accuracy. ASTROD I is such a mission with single spacecraft; it is the first step of ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) with 3 spacecraft. In this paper, we will present the progress of ASTROD and ASTROD I with emphases on the acceleration noises, mission requirement, charging simulation, drag-free control and low-frequency gravitational-wave sensitivity.

1. Introduction

In this 6th Edoardo Amaldi Conference on Gravitational Waves, we have seen a lot of experimental progresses and developments on ground and space interferometry. On ground, all long-arm interferometers for gravitational-wave detection are in operation. For space interferometry missions, we see important research developments for LISA Mission and its technology demonstrator---LISA Pathfinder. In this short paper, we report on the progress for a deep-space mission concept, ASTROD /ASTROD I [1-6]. (ASTROD: ASTRODynamical Space Test of Relativity using Optical Devices)

During early nineties of the twentieth century, both pulse and interferometric deep-space laser ranging were proposed to map the solar-system gravity and to test relativistic gravity [1, 3, 6, 7 and references therein]. Owing to Geodesy Missions [8] and LISA [9] (Laser Interferometer Space Antenna) Program, improvements in many technologies critical to the tests of gravity are under development - the highly accurate deep space navigation, high precision frequency standards, precise pointing and attitude control, and the drag-free technologies. These will revolutionize the field of experimental gravitational physics. The Centennial of general theory of relativity in 2015 will motivate a significant number of experiments designed to test this theory to unprecedented accuracy. During the past 2 months, we had *2 consecutive meetings in Bremen, Germany on the deep-space laser ranging: (i) Lasers, Clocks, and Drag-Free: Key Technologies for Future Space Exploration and Testing Einstein's General Relativity in Space* [10]; *(ii) Second International ASTROD Symposium on Laser Astrodynamics, Space Test of Relativity and Gravitational-Wave Astronomy* [11], reporting and discussing on technologies and scientific developments related to deep-space laser ranging. In the following, we will introduce the space mission ASTROD and its precedent ASTROD I.

2. ASTROD

ASTROD (ASTRODynamical Space Test of Relativity using Optical Devices) consists of a fleet of drag-free spacecraft navigating in the solar system and ranging with one another using optical devices. ASTROD aims to map the solar-system gravity, to measure the related solar-system parameters, to test relativistic gravity and to detect gravitational waves.

A baseline implementation of ASTROD is to have two spacecraft in separate solar orbit carrying as payload, a proof mass, two telescopes, two 1-2 W lasers, a clock and a drag-free system, together with a similar L1/L2 spacecraft [1-4]. *The three spacecraft range coherently with one another using lasers* to map the solar-system gravity, to test relativistic gravity and to detect gravitational waves.

Distances among spacecraft depend critically on solar-system gravity, underlying gravitational theory and incoming gravitational waves. A precise measurement of these distances as a function of time will determine these causes. After 2.5 years, the inner spacecraft completes 3 rounds, the outer spacecraft 2 rounds, and the Earth 2.5 rounds. At this stage two spacecraft will be on the other side of the Sun, as viewed from the Earth, for conducting the Shapiro time delay experiment efficiently. The spacecraft configuration after 700 days from launch is shown in Fig. 1. Whenever there is no ambiguity, we denote this baseline implementation as ASTROD also.
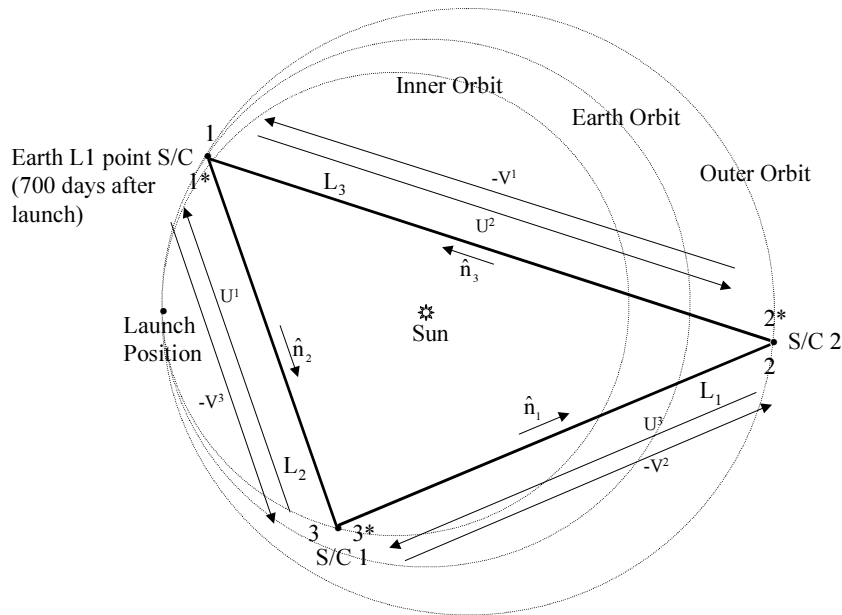

Fig. 1. A schematic ASTROD configuration (baseline ASTROD after 700 days of launch)

The accuracy and the precision of the measurement depend on the timing accuracy, the inertial sensor/accelerometer noise and the laser/clock stability. As for the timing accuracy, an event timer has been designed at OCA (Observatoire de la Côte D'Azur) in the framework of both T2L2 (Time Transfer by Laser Link) project and the laser ranging activities [12]. At present, the prototype of the OCA timer is fully operational having a precision less than 3 ps, a linearity error of 1 ps rms and a time stability less than 0.01 ps over 1000 s with dead time less than 10 µs. For a mission within the next 10-20 years, a timing accuracy better than 1 ps (300 µm in terms of ranging) can be anticipated. In coherent interferometric ranging, timing events need to be generated by modulation/encoding technique or by superposing timing pulses on the CW laser light. The interference fringes serve as consecutive time marks. With timing events aggregated to a normal point using an orbit model, the precision can reach 30 µm in range. The effective range precision for parameter determination could be better, reaching 3-10 µm using orbit models. Since ASTROD range is typically of the order of 1-2 AU ($1.5\text{-}3 \times 10^{11}$ m), a range precision of 3 µm would give a fractional precision of distance determination of 10^{-17}. Therefore, the desired clock accuracy/stability is 10^{-17} over 1000 s travel time. Optical clocks with this accuracy/stability are under research development, having been a hot discussion topic in the First ESA Optical Clock Workshop, June, 2005. Space optical clock is under development for the Galileo project. This development would pave the road for ASTROD to use optical clocks [13]. The present range precision for radio tracking is a couple of meters. The improvement of ASTROD would be 5 orders of magnitude, allowing to test relativistic gravity in the solar system to the 1 ppb (part per billion) realm.

To achieve the 1 ppb realm, high precision drag-free performance is a must to guarantee that the test masses of the ASTROD spacecraft follow geodesics in the solar system. In terms of drag-free performance, the ASTROD test mass is aimed at residual acceleration noise

$$S_{\Delta a}^{1/2}(f) = (0.3\text{-}1) \times 10^{-15} [1 + 10 \times (f/3 \text{ mHz})^2] \text{ ms}^{-2}\text{Hz}^{-1/2}, \qquad (1)$$

in the frequency range 0.1 mHz $< f <$ 100 mHz. This is a factor of 3-10 improvement over the LISA residual acceleration noise goal at 0.1 mHz. This improvement will be achieved by using capacitive sensing with larger gaps or by going to optical method [2]. In our preliminary orbit simulation, with the improved accelerometer noise and with 1 ps timing error, we obtain that the uncertainties of measuring γ and β are in the $(1\text{-}3) \times 10^{-9}$ range, and that for J_2 in the 10^{-10} range [1]. This result demands post-post-Newtonian ephemeris framework to be established for the analysis and simulation of data. Efforts have been started towards this direction [14-18].

The algorithms for unequal-arm noise cancellation of Armstrong, Estabrook and Tinto are applicable to ASTROD (Fig. 1). Recently, a nice review has come out with many references [19]. The gravitational-wave sensitivity of ASTROD is shifted to lower frequency as compared to LISA because of ASTROD's longer armlengths [2, 20]. Moreover, because of its orbit modulation, ASTROD could be able to separate the effects due to g-mode oscillation of the Sun and gravitational waves coming from outside the solar system. Among all experiments and proposals, ASTROD has the highest sensitivity to solar g-mode oscillation [20, 21]. By measuring the Lense-Thirring effect of the Sun, ASTROD can also measure the solar angular momentum precisely [20].

3. ASTROD I

ASTROD I is the first step toward ASTROD. This mission concept consists of one spacecraft carrying as payload a telescope, five lasers, and a clock, together with ground stations (ODSN: Optical Deep Space Network) to test the optical scheme of interferometric and pulse ranging in order to give important scientific results [5, 6].

The basic scheme of the ASTROD I space mission concept is to use two-way laser interferometric ranging and laser pulse ranging between the ASTROD I spacecraft in solar orbit and deep space laser stations on Earth. ASTROD I aims at improving the precision of solar-system dynamics, solar-system constants and ephemeris, and measuring relativistic gravity effects and testing the fundamental laws of spacetime more precisely. ASTROD I also aims at improving the measurement of the time rate of change of the gravitational constant, and detecting low-frequency gravitational waves.

A schematic payload configuration of ASTROD I is shown in [5]. The cylindrical spacecraft with diameter 2.5 m and height 2 m has its cylindrical surface covered with solar panels. In orbit, the cylindrical axis will be perpendicular to the orbit plane with the telescope pointing toward the ground laser station. The effective area to receive sunlight is about 5 m^2 and can generate over 500 W of power. The total mass of the spacecraft is 300-350 kg. That of payload is 100-120 kg with science data rate 500 bps.

The spacecraft is 3-axis stabilized. It contains a 3-axis drag-free proof (test) mass and the spacecraft is to follow this proof mass using micro-thrusters. The drag-free performance requirement is 10^{-13} ms^{-2}/Hz$^{1/2}$ between 0.1 mHz and 1 mHz (3-axis). This performance is 30 times less stringent than the LISA drag-free system requirement. In the range measurement, both timing noise and spurious acceleration noise contribute to the uncertainties of parameter determination; the timing noise does not accumulate while the acceleration noise accumulates. The drag-free requirement here would give an error comparable to 10 ps timing error in about one year. A $50 \times 50 \times 35$ mm^3 rectangular parallelepiped proof mass made from Au-Pt alloy of low magnetic susceptibility ($< 5 \times 10^{-5}$) is planned to be used. Titanium housing for the proof mass will remain at a vacuum pressure below 10 μPa.. Six-degree-of-freedom capacity sensing for the proof mass will be implemented. The laser ranging is between a fiducial point in the spacecraft and a fiducial point in the ground laser station.

The fiducial point in the spacecraft can be a reference mirror with a defined position with respect to the proof mass housing. Incoming light will be collected using a 380-500 mm diameter f/1 Cassegrain telescope. This telescope will also transmit light from the spacecraft with $\lambda/10$ outgoing wavefront quality to Earth. Ground laser stations will be similar to the present lunar laser ranging (LLR) stations or large satellite laser ranging (SLR) stations. In the Yunnan Astronomical Observatory in Kunming, there is a large satellite laser ranging station with a 1.2 m azimuth-elevation reflection telescope. This station is under study in order to be used as a deep space laser station to transmit and receive deep space laser signals [22]. Adaptive optics is also under consideration. Weak light phase locking reached 2 pW [23].

The test mass will be surrounded by electrodes on all six sides to capacitively sense its motion relative to the spacecraft. Micro-thrusters on the spacecraft will then be used to force it to follow the test mass. The ASTROD I residual acceleration noise target is

$$S_{\Delta a}^{1/2}(f) = 3 \times 10^{-14} \,[(0.3 \text{ mHz} / f) + 30 \times (f / 3 \text{ mHz})^2] \text{ ms}^{-2}\text{Hz}^{-1/2}, \qquad (2)$$

in the frequency range of 0.1 mHz $< f <$ 100 mHz. This residual acceleration target is compared to noise curves of the LISA-Pathfinder LISA Technology Package (LTP) and LISA [9] in Fig. 1. The strategy here is to have relatively moderate requirements compared to LISA [5, 24], and yet to have important scientific goals in astrodynamics and relativity. A torsion pendulum study for prototype inertial sensor for ASTROD I is reported in [25] with a torque resolution of 2×10^{-11} N m Hz$^{-1/2}$ from 1 mHz to 0.1 Hz.
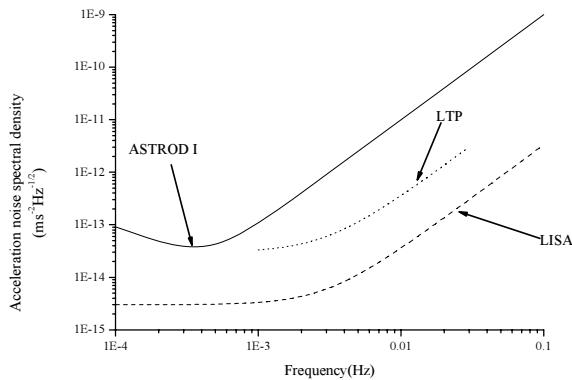

Figure 2. A comparison of the target acceleration noise curves of ASTROD I, the LTP and LISA.

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High-energy cosmic rays and solar energetic particles (SEPs) easily penetrate the light structure of spacecraft transferring heat, momentum and electrical charge to the test mass [26]. Electrical charging is the most significant of these disturbances. Any charge accrued by the test mass will interact with the surrounding conducting surfaces through Coulomb forces. Further, motion of the charged test mass through magnetic fields will give rise to Lorentz forces. To limit the acceleration noise associated with these forces and meet the residual noise requirement, the test mass must be discharged in orbit. A charging simulation is reported in [27]; the noise requirement will be satisfied with a moderate discharging scheme.
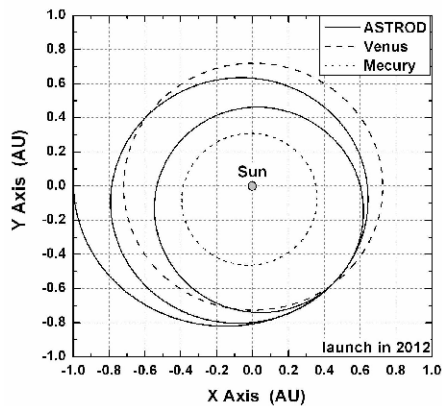
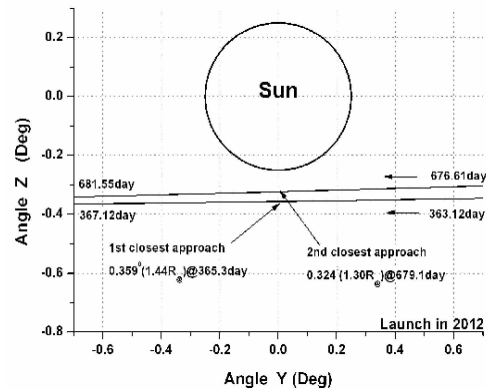Fig. 3. The 2012 orbit in heliocentric ecliptic coordinate system

Fig. 4. Apparent angles during the two solar oppositions

During the orbit design and orbit simulation for ASTROD I, we noted that for Venus swing-by to obtain gravity assistance to reach the other side of the sun sooner, there is a launch window about every 584 days [28]. There is a launch window in 2012, 2013 and 2015. As an example we report the 2012 orbit. This orbit would start at 2:09:36 on March 23, 2012, and it is shown in Fig. 3 in the X-Y plane of the heliocentric ecliptic coordinate system. Two Venus swing-bys are around 107.8 days and 332.3 days after launch. The apparent position of the spacecraft reaches the opposite side of the Sun 365.3 days and 679.1 days after launch. The apparent angles of the spacecraft during the two solar oppositions are shown in Fig. 4. The maximum one-way Shapiro time delays near the two solar oppositions are 0.1172 ms (at 365.3 day) and 0.1196 ms (at 679.1 days) respectively [28].

Assuming a timing error of 10 ps (3 mm ranging accuracy) and an accelerometer noise of 10^{-13} $m/s^2(Hz)^{1/2}$ at frequency $f \sim 100$ µHz, and fitting simulated data from the 350th to the 750th day after launch, we obtain the uncertainties of determining relativistic parameters γ and β to be 0.9×10^{-7} and 1.1×10^{-7}, respectively, and that for the solar quadrupole parameter J_2 to be 3.8×10^{-9} [28]. This simulation supports our original goals. The timing uncertainty of event timer reaches 3 ps (0.9 mm in ranging) in satellite laser ranging at present. Space qualified versions of similar accuracy are under development. For a ranging uncertainty of 3 mm in a distance of 3×10^{11} m (2 AU), the laser/clock frequency needs to be known to one part in 10^{14}. This can be set as a requirement of the space laser/clock or a requirement for laser frequency monitoring through ground clock and modelling. As to ground station jitter, monitoring to an accuracy of 3 mm is required and can be achieved. The atmospheric effects on laser propagation will be monitored and subtracted to mm-level by using 2-color (2-wavelength) ranging (one color for pulse ranging and one for interferometric ranging). These measurement uncertainties are not cumulative in the range determination while the acceleration disturbances accumulate in time in the geodesic deviations. Our acceleration disturbance requirement is consistent with the above requirements. During the Shapiro time measurement, sunlight shield system is important; its basic design is reported in [6, 20].

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