MINI-ASTROD: MISSION CONCEPT AND STUDY PROGRESS

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ABSTRACT

The success of lunar laser ranging, the proposition of gravitational-wave detection in space using laser-interferometric techniques, together with a couple of mission proposals to test relativistic gravity using optical methods triggered the proposition of a systematic development of Laser Astrodynamics in the solar system in 1993. In this context, ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) mission concept was proposed. Mini-ASTROD is a down-scaled version of ASTROD. This mission concept has one spacecraft carrying a payload of a telescope, two (plus two spare) lasers, and a clock together with ground stations (ODSN: Optical Deep Space Network) to test the optical scheme and yet give important scientific results. These scientific goals include a better measurement of the relativistic parameters (γ, β to 10^{-7} and others with improvement), a better sensitivity (several times better) in using optical Doppler tracking method for detecting gravitational waves, a potential of measuring the solar angular momentum via Lense-Thirring effect and measurement of many solar system parameters more precisely. These will enable us to build a more precise ephemeris and astrodynamics. The weight of this spacecraft is estimated to be about 300-350 kg with a payload of about 100-120 kg. The present orbit option is to launch with an initial period about 290 days and to pass by Venus twice to receive gravity-assistance for achieving shorter periods. In this paper, we review the scientific goals and the mission scheme, and present the current study progress.

1. Introduction and Scientific Goals

In 1993, we have proposed to use laser astrodynamics to study the relativistic gravity and to explore the solar system [1]. With a multi-purpose astrodynamical mission proposed in 1994 [2,3], we reached the ASTROD (Astrodynamical Space Test of Relativity using Optical Devices) mission concept. An overview on ASTROD with references can be found in [4]. Alternate mission concepts, Mini-ASTROD and Super-ASTROD, were presented in the first TAMA Workshop in 1996 [5]. Mini-ASTROD is a down-scaled version of ASTROD with one spacecraft ranging with ground stations to test the optical scheme and yet give important scientific results. It was presented in more details in the First International ASTROD School and Symposium on Laser Astrodynamics, Space Test of Relativity and Gravitational-Wave Astronomy in 2001 [6], and has been under Phase A Study since then. A summary of the Mini-ASTROD mission concept is compiled in Table 1. The scientific goals of Mini-ASTROD are threefold. The first goal is to test relativistic gravity and the fundamental laws of spacetime

Table 1. Mini-ASTROD Mission Summary

Objective:	Testing relativistic gravity and the fundamental laws of spacetime with three-order-of-magnitude improvement in sensitivity; Improving the sensitivity in the 5 μHz - 5 mHz low frequency gravitational-wave detection by several times; Initiating the revolution of astrodynamics with laser ranging in the solar system, increasing the sensitivity of solar, planetary and asteroid parameter determination by 1 to 3 orders of magnitude.
Payload:	*Laser systems for interferometric and pulse ranging* 1 (plus 1 spare) diode-pumped Nd:YAG lasers (wavelength 1.064 μm, output power 1 W) pre-stabilized by a Fabry-Perot reference cavity and offset phase-locked to the incoming weak light. 1 (plus 1 spare) pulsed Nd:YAG laser with timing device for recording the transmitting time of space laser pulse and the receiving time of the incoming laser pulse from ground laser stations. Quadrant photodiode detector. 380-500 mm diameter f/1 Cassegrain telescope (transmit/receive), $\lambda/10$ outgoing wavefront quality. Drag-free proof mass (reference mirror as one face of it): 50×35×35 mm^3 rectangular parallelpiped; Au-Pt alloy of extremely low magnetic susceptibility ($< 10^{-6}$); Ti-housing at vacuum $< 10^{-6}$ Pa; six-degree-of-freedom capacitive sensing. Coronagraph; Cesium clock; Optical comb.
Ground laser stations:	1.2 m diameter telescopes with adaptive optics (transmit/receive)
Orbit:	Launch via low earth transfer orbit to solar orbit with orbit period 300 days. The initial orbit is corrected using a medium ion thruster. After two encounters with Venus to get gravity-assistance the orbit period of the spacecraft (S/C) can be decreased to 165 days. The apparent position of S/C reaches the opposite side of the Sun shortly after 400 days, 700 days and 1100 days from launch.
Launcher:	Long March IV B (CZ-4B)
Spacecraft:	3-axis stabilized drag-free spacecraft
(total) mass:	300-350 kg (including ion propeller)
(total) power:	350 W
Drag-free performance:	$10^{-14} - 10^{-13}\ \mathrm{ms}^{-2}/\sqrt{Hz}$ at ~ 100 μHz (3-axis)
Pointing accuracy:	2 μrad
Payload mass:	100-120 kg
Payload power:	100-120 W
Science data rate:	500 bps
Telemetry:	5 kbps, for about 9 hours in two days
Ground station:	Deep Space Stations
Mission lifetime	3 years (nominal); 8 years (extended)

with three-order-of-magnitude improvement in sensitivity, specifically, to measure the PPN (Parametrized Post-Newtonian) parameter γ to 10^{-7}, β to 10^{-7} and others with improvement. The second goal is to improve the sensitivity in the 5 μHz - 5 mHz low frequency gravitational-wave detection by several times. The third goal is to initiate a revolution of astrodynamics with laser ranging in the solar system, increasing the sensitivity of solar, planetary and asteroid parameter determination by 1 to 3 orders of magnitude. In this context, J_2 measurement will be improved by one order of magnitude, i.e., to a few parts of 10^8.

2. Scheme

The basic scheme of the Mini-ASTROD space mission concept is to use two-way laser interferometric ranging or laser pulse ranging between the Mini-ASTROD spacecraft in solar orbit and deep space laser stations on Earth to improve the precision of solar-system dynamics, solar-system constants and ephemeris, to measure the relativistic gravity effects and test the fundamental laws of spacetime more precisely, to improve the measurement of the time rate of change of the gravitational constant, and to detect low-frequency gravitational waves.

The spacecraft is 3-axis stabilized with a total mass 300-350 kg and a total power 350 W. It contains a 3-axis drag-free proof mass and the spacecraft is to follow this proof mass using micro-thrusters. The drag-free performance requirement is 10^{-14}-10^{-13} $\mathrm{ms}^{-2}/\mathrm{Hz}^{1/2}$ at 100 μHz to 1 mHz (3-axis). This performance will be met by a similar one as SMART2/LISA drag-free system. A 50×35×35 mm^3 rectangular parallelepiped proof mass using Au-Pt alloy of extremely low magnetic susceptibility ($<10^{-6}$) is initially planned. Titanium housing for the proof mass will remain at vacuum pressure less than 1 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 spacecraft can be the reference mirror, which can be one face of the proof mass or a separate entity which has a definite positional relation with respect to the proof mass. Incoming light will be collected using a 380-500 mm diameter f/1 Cassegrain telescope. This telescope will also transmit light from 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. At 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 to be used as a deep space laser station to transmit and receive deep space laser signals [7]. Adaptive optics is under consideration.

There are two methods for laser ranging between the spacecraft and ground laser stations: (i) interferometric ranging similar to radio Doppler tracking, LISA and ASTROD; (ii) pulse ranging similar to Satellite Laser Ranging and Lunar Laser Ranging. In the choice of interferometric ranging, 1-2 W diode-pumped CW (Continuous-Wave) Nd:YAG lasers will be used in the spacecraft. One laser is pre-stabilized and offset phase-locked to the incoming light. The light of this laser is transponding back to the ground laser station. In the choice of pulse ranging, a pulsed Nd: YAG laser will be used. The emitting times and receiving times of pulse will be recorded by the cesium clock or mercury clock on board the spacecraft. For the ground segment, the receiving times and emitting times will be recorded by the hydrogen maser clock. For SLR and LLR, the timing technique has reached better than 5 ps accuracy.

For the interferometric ranging, the frequency of the laser offset-phase-locked to the incoming light can be measured by comparison with a harmonic frequency generated by an optic comb using a standard input frequency from the Cs clock on spacecraft. We have considered to incorporate OPTIS [8] experiments --- Michelson-Morley experiment, Kennedy-Thorndike experiment and red shift comparison experiment. An analysis showed that only Michelson-Morley experiment could gain much sensitivity from a deep space mission like Mini-ASTROD. Now our baseline configuration is ILR-2PLR in the following diagram. For a more detailed discussion on the implementation, please see references [6].

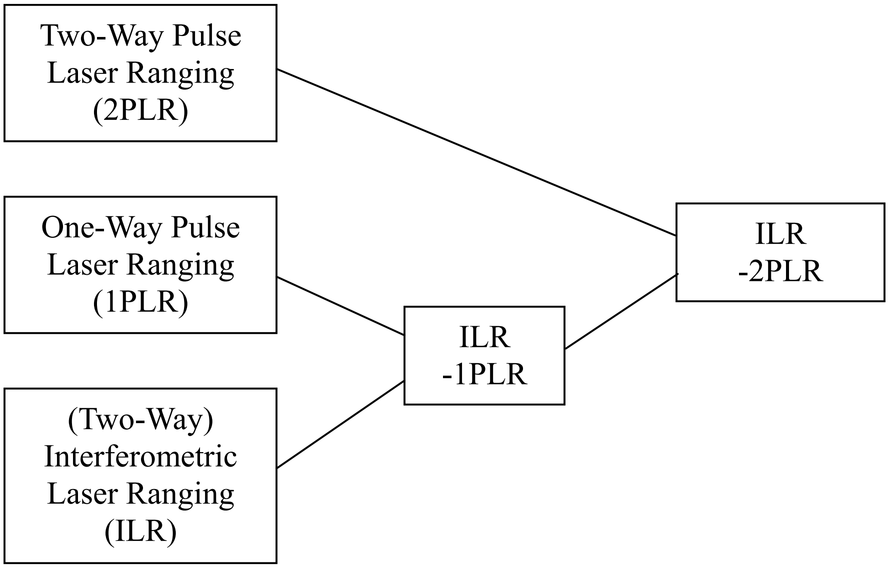


Fig. 1. Various alternatives of Mini-ASTROD.

3. Orbit Configuration and Simulation

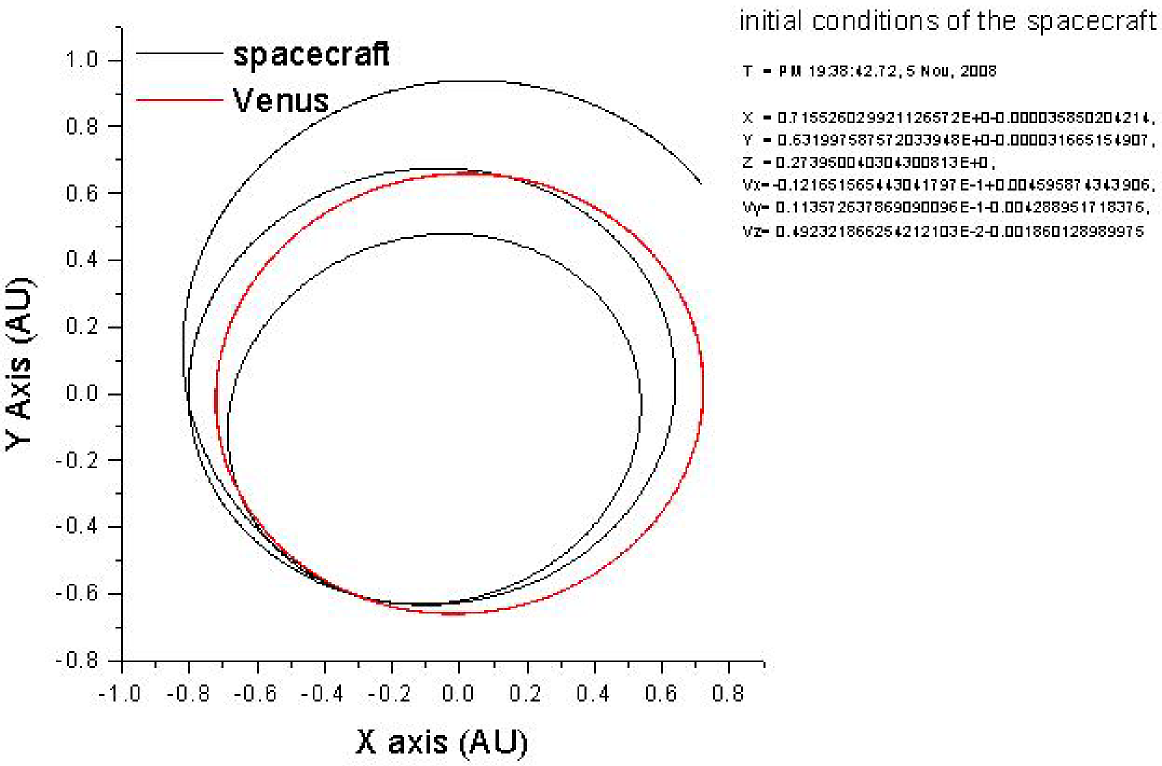
The orbit option now studied is to launch to solar orbit with initial period about 290 days and to pass by Venus twice to receive gravity-assistance for achieving shorter periods. For a launch on November 15, 2008, after two encounters with Venus, the orbital period can be shortened to 165 days. After about 400 days from launch, the spacecraft will arrive at the other side of the Sun and relativistic parameter γ can be determined accurately. A specific orbit trajectory in the X-Y plane of the heliocentric equatorial coordinate system is shown in Fig. 2. The distance between spacecraft and Venus as a function of mission day is shown in Fig. 3. If the second encounter with Venus is closer, orbit period can be shortened further. Launch via low earth transfer orbit to solar orbit using Long March IV B (CZ-4B) is under study. The initial orbit can be corrected using a medium ion thruster. The apparent position of S/C reaches the opposite side of the Sun shortly after 400 days, 700 days and 1100 days from launch.

In the orbit simulation, we assume two types of errors:

(i) the uncertainty due to the imprecision of the ranging devices,

(ii) unknown accelerations due to the imperfections of the spacecraft drag-free system.

The first type of error is modelled as a Gaussian random noise with zero mean and with standard deviation 1×10^{-11} s; for the second type of error, the magnitude of the unknown acceleration is treated as a Gaussian random noise with zero mean and with standard deviation 10^{-15} m/s^2 and the direction of the unknown acceleration is changed randomly every four hours (equivalent to



initial conditions of the spacecraft

T = PM 19:38:42.72, 5 Nou, 2008

X = 0.715526029921126572E+0-0.000035850204214,
Y = 0.631997587572033948E+0-0.000031665154907,
Z = 0.273950040304300813E+0,
Vx=-0.121651565443041797E-1+0.004595874343906,
Vy= 0.113572637869090096E-1-0.004288951718376,
Vz= 0.492321866254212103E-2-0.001860128989975

Fig. 2. A specific orbit trajectory in the X-Y plane of the heliocentric equatorial coordinate system.

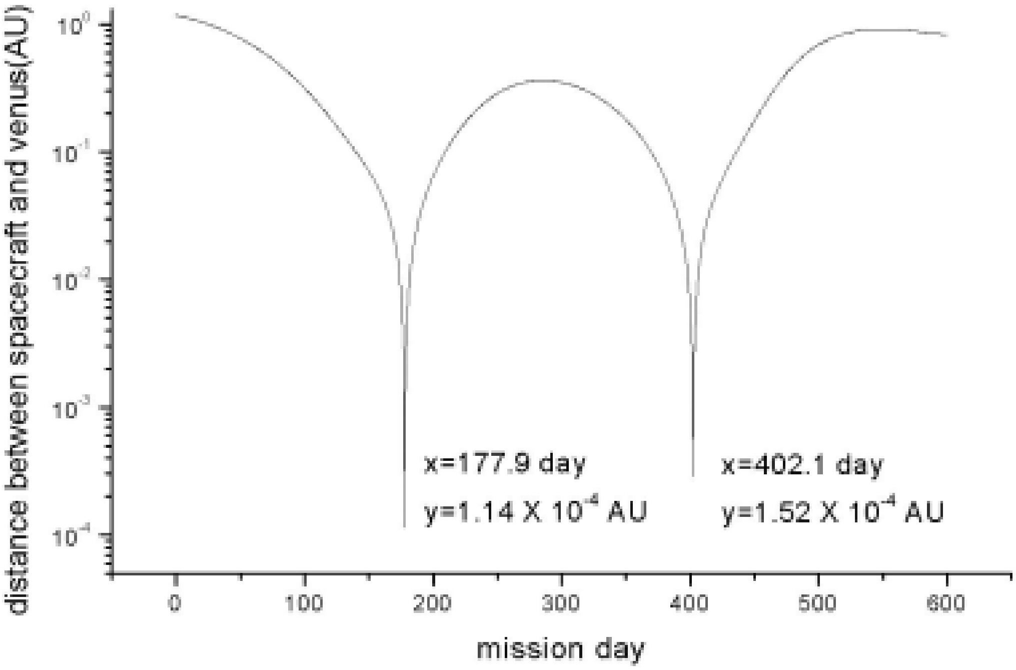


Fig.3. Distance between spacecraft and Venus as a function of mission day.

10^{-13} ms^{-2} / (Hz)$^{1/2}$ for f ~10^{-4} Hz). A simulation from 405 days after launch for 300 days with the orbit in Fig. 2 shows that both γ and β can be determined to 10^{-7}. Details of simulation will be presented in [9].

For a discussion of payload configuration, please see reference [10]. *A more detailed study of Mini-ASTROD mission concept will appear in the Phase A Study Report.*

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