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ASTROD I: Mission concept and Venus flybys

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Abstract

ASTROD I is the first step of ASTROD (Astrodynamical Space Test of Relativity using Optical Devices). This mission concept has one spacecraft carrying a payload of a telescope, five lasers, and a clock together with ground stations (ODSN:

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Optical Deep Space Network) to test the optical scheme of interferometric and pulse ranging and yet give important scientific results. These scientific results include a better measurement of the relativistic parameters, a better sensitivity in using optical Doppler tracking method for detecting gravitational waves, and measurement of many solar system parameters more precisely. The weight of this spacecraft is estimated to be about 300–350 kg with a payload of about 100–120 kg. The spacecraft is to be launched with initial period about 290 days and to pass by Venus twice to receive gravity-assistance for achieving shorter periods. For a launch on August 4, 2010, after two encounters with Venus, the orbital period can be shortened to 165 days. After about 370 days from launch, the spacecraft will arrive at the other side of the Sun for the determination of relativistic parameters.

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 Astrodynamical Space Test of Relativity using Optical Devices (ASTROD) mission concept. An overview on ASTROD with references can be found in Ref. [4]. Alternate mission concepts, mini-ASTROD and super-ASTROD, were presented in the first TAMA Workshop in 1996 [5]. Mini-ASTROD is a downscaled 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. After a study workshop held in August 2002, it has been called ASTROD I. A summary of the ASTROD I mission concept is compiled in Table 1. The scientific goals of ASTROD I are threefold. The first goal is to test relativistic gravity and the fundamental laws of spacetime with three-order-of-magnitude improvement in sensitivity, specifically, to measure the parametrized post-Newtonian (PPN) 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 1–3 orders of magnitude. In this context, J_2 measurement will be improved by one order of magnitude, i.e., to 10^8.

2. Scheme and payload

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 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.

A schematic payload configuration of ASTROD I is shown in Fig. 1 [7]. The cylindrical spacecraft with diameter 2.5 m and height 2 m has its surface covered with solar panels. In orbit, the cylindrical axis is perpendicular to the orbit plane with the telescope

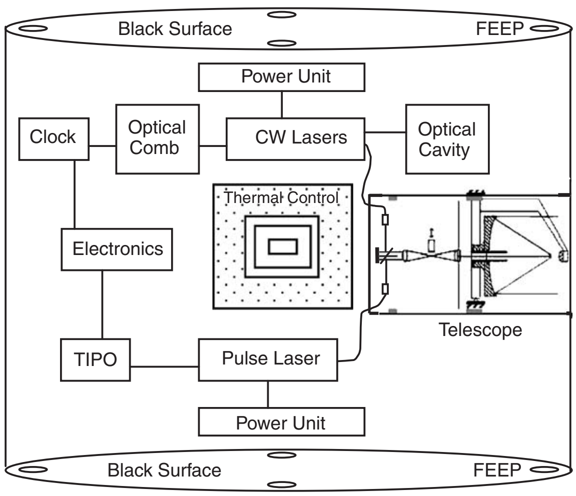

Fig. 1. A schematic diagram of payload configuration for ASTROD I.

Table 1
ASTROD I 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 1–3 orders of magnitude
Payload	*Laser systems for interferometric and pulse ranging* 2 (plus 1 spare) diode-pumped Nd:YAG lasers (wavelength 1.064 μm, output power 1 W) with 1 Fabry–Perot reference cavity: 1 laser locked to the Fabry–Perot cavity, the other laser pre-stabilized by one of them and 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): $50\times50\times35\,\mathrm{mm}^3$ rectangular parallelepiped; 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	Three-axis stabilized drag-free spacecraft
(total) mass	300–350 kg (including ion propeller)
(total) power	350 W
Drag-free performance	10^{-14}–$10^{-13}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$at 100 $\sim$ μHz (three-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 h in 2 days
Ground station	Deep Space Stations
Mission lifetime	3 years (nominal); 8 years (extended)

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 spacecraft is 300–350 kg. That of payload is 100–120 kg with science data rate 500 bps.

The spacecraft is three-axis stabilized. It contains a three-axis drag-free proof mass and the spacecraft is to follow this proof mass using micro-thrusters. The drag-free performance requirement is $10^{-13}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$ at 100 μHz to 1 mHz (three-axis). This performance is 30 times less stringent than the LISA drag-free system requirement. A $50\times50\times35\,\mathrm{mm}^3$ 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 SLR 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 [8]. 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 SLR and LLR. In the choice of interferometric ranging, 1–2 W diode-pumped continuous-wave (CW) 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 (Cs) 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 or more stable clock newly developed. For SLR and LLR, the timing technique has reached better than 5 ps accuracy. In the simulation in Section 4, we assume a timing accuracy of 10 ps.

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 incorporating OPTIS [9] 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 ASTROD I. Now, our baseline configuration is ILR–2PLR in Fig. 2. For a more detailed discussion on the implementation, please see Refs. [6,7].

The crucial technologies include: (i) 100 fW weak-light phase locking [10,11]; (ii) design and development of sunlight shield [6,7]; (iii) design and development of drag-free system. Optical phase locking of a 200 μW local oscillator to a 2 pW incoming beam of weaklight is achieved in [10]. Prospects and applications of femtowatt weaklight phase locking are discussed in [11]. The requirements for the drag-free system are very stringent, but less stringent than LISA. We will follow LISA development very closely. In the following section, we discuss the drag-free requirement.

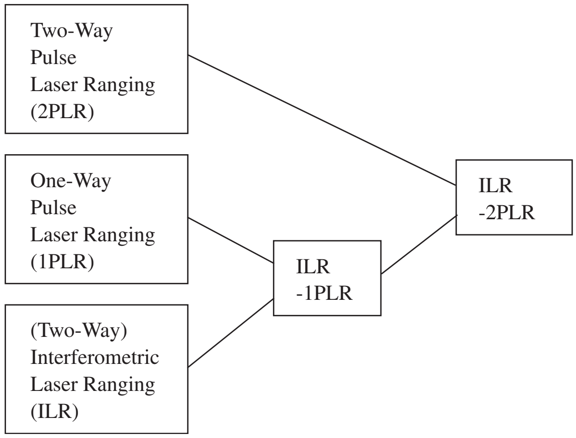

Fig. 2. Various alternatives of ASTROD I.

3. Drag-free requirement

In Table 2, we provide a summary of the parameter values that meet the accelerometer requirements for ASTROD I, in comparison with LISA. We use the notations and the LISA values of Schumaker [12]. The listed values are for the frequency at 0.1 mHz. The parameter values are largely relaxed for ASTROD I. The same values satisfy requirements for higher-frequency range, where frequency-dependent contributions to the acceleration noise become smaller.

We have estimated the magnitude of acceleration disturbances for the ASTROD I accelerometer by considering all estimable contributions in Table 2. In the estimation, we used the expressions, for the contributions, derived by Schumaker for LISA [12]. The acceleration disturbances can be classified into three categories: one related to the proof-mass (A_{np}), one to the spacecraft (A_{ns}) and one to PM–SC coupling (the coupling constant: K). More specifically, A_{np} is the root-sum-square (RSS) of the proof-mass environmental acceleration disturbance and the position sensor disturbance, and A_{ns} is the RSS of the spacecraft environmental acceleration disturbance and the control-loop disturbance. Estimated values for these acceleration disturbances at the frequency $f(\equiv \omega/(2\pi))$ of 0.1 mHz are given in section (c) of Table 1, in comparison with LISA. By using a general control model,

Table 2
Estimated acceleration disturbances and requirements for the ASTROD I accelerometer, in comparison with LISA

	ASTROD I	LISA
(a) *Acceleration noise goal*: A_P		
A_P ($\mathrm{m\,s^{-2}\,Hz^{-1/2}}$) (at 0.1 mHz)	10^{-13}	3×10^{-15}
($X_p \equiv A_p\omega^{-2}$ ($\mathrm{m\,Hz^{-1/2}}$))	(3×10^{-7})	(8×10^{-9}))
(b) *Parameter values for acceleration noise estimates*		
Proof Mass (PM)		
Magnetic susceptibility: χ_m	10^{-5}	10^{-6}
Maximum charge build-up: q (C)	10^{-12}	10^{-13}
Residual gas pressure: P (Pa)	10^{-5}	10^{-6}
Fluctuation of temperature difference across PM and housing: δT_d ($\mathrm{K\,Hz^{-1/2}}$) (at 0.1 mHz)	1.4×10^{-3}	2.2×10^{-5}
Spacecraft (SC)		
Thruster noise ($\mathrm{\mu N\,Hz^{-1/2}}$) (at 0.1 mHz)	0.5	0.1
Fluctuation of temperature in SC: δT_{sc} ($\mathrm{K\,Hz^{-1/2}}$) (at 0.1 mHz)	0.4	0.004
Capacitive sensing		
Voltage difference between average voltage across opposite faces and voltage to ground: V_{0g} (V)	1	0.1
Fluctuation of voltage difference across opposite faces: δV_d ($\mathrm{V\,Hz^{-1/2}}$) (at 0.1 mHz)	10^{-4}	10^{-5}
Asymmetry in gap across opposite sides of PM: Δd (μm)	10	1
Laser power		
Fluctuation of laser power: δI ($\mathrm{W\,Hz^{-1/2}}$) (at 0.1 mHz)	2×10^{-6}	2×10^{-8}
(c) *Estimated contribution to* A_P: $A_P \approx X_{nr}(-K) + A_{np} + A_{ns}K\omega^{-2}u^{-1}$		
PM environmental & sensor disturbances:		
A_{np} ($\mathrm{m\,s^{-2}\,Hz^{-1/2}}$) (at 0.1 mHz)	5.8×10^{-14}	1.1×10^{-15}
($X_{np} \equiv A_{np}\omega^{-2}$ ($\mathrm{m\,Hz^{-1/2}}$))	(1.5×10^{-7})	(3×10^{-9})
SC environmental & loop disturbances:		
A_{ns} ($\mathrm{m\,s^{-2}\,Hz^{-1/2}}$) (at 0.1 mHz)	1.5×10^{-9}	4.6×10^{-10}
($X_{ns} \equiv A_{ns}\omega^{-2}$($\mathrm{m\,Hz^{-1/2}}$))	(1.2×10^{-2})	(1.2×10^{-3})
Dimensionless PM–SC spring constant (at 0.1 mHz): $\Gamma \equiv K\omega^{-2}$ (theoretical limit)	8.6×10^{-2}	1.4×10^{-2}
(d) *Inferred requirements for sensors and control-loop performance at* 0.1 mHz		
PM–SC displacement sensor resolution: X_{nr} ($\mathrm{m\,Hz^{-1/2}}$)	1.7×10^{-6}	3.8×10^{-7}
SC open-loop gain: u	2.2×10^{3}	3.1×10^{3}

the contributions of these acceleration disturbances to the total acceleration noise A_p can be expressed as [12]: $A_P \approx X_{nr}(-K)+A_{np}+A_{ns}K\omega^{-2}u^{-1}$. By using this relation, we have inferred the requirements for the sensor readout resolution X_{nr} and the spacecraft open-loop gain u, as done by Schumaker for LISA. The inferred values are given in section (d) of Table 2. Section (b) of Table 1 lists the parameter values used for the estimation of the acceleration disturbances. One can see that those values are largely relaxed for ASTROD I in comparison with LISA.

4. 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 August 4, 2010, after two encounters with Venus around 112 days and 336 days after launch, the orbital period can be shortened to 165 days. After about 370 days from launch, the spacecraft will arrive at the other side of the Sun and relativistic parameter γ can be determined

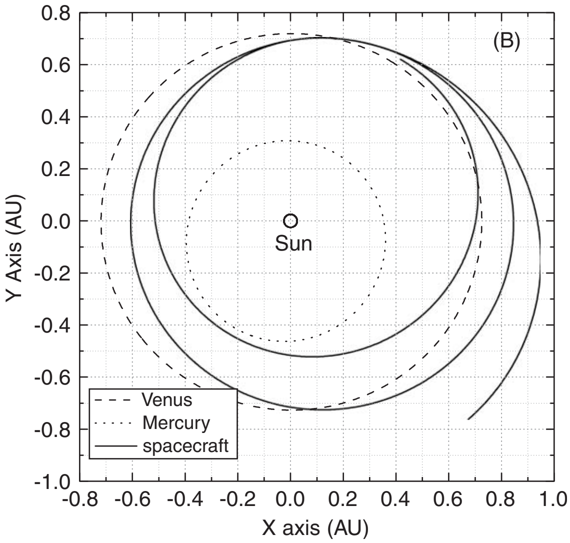

Fig. 3. An orbit design for the ASTROD I spacecraft for a launch on August 4, 2010.

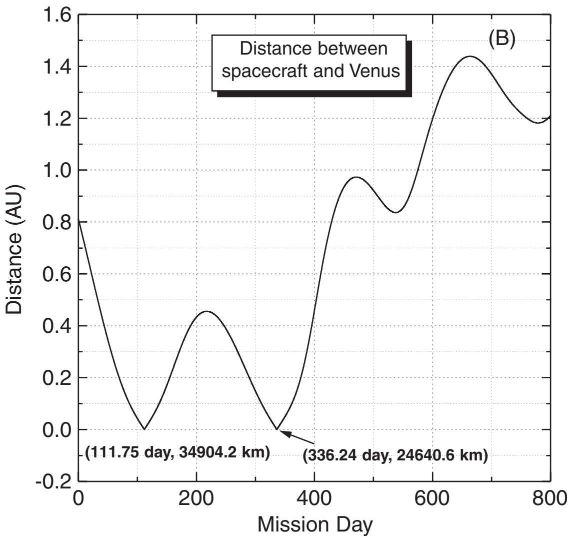

Fig. 4. Distance between spacecraft and Venus.

accurately. A specific orbit trajectory in the *X–Y* plane of the heliocentric equatorial coordinate system is shown in Fig. 3. The distance between spacecraft and Venus as a function of the mission day is shown in Fig. 4. If the second encounter with Venus is closer,

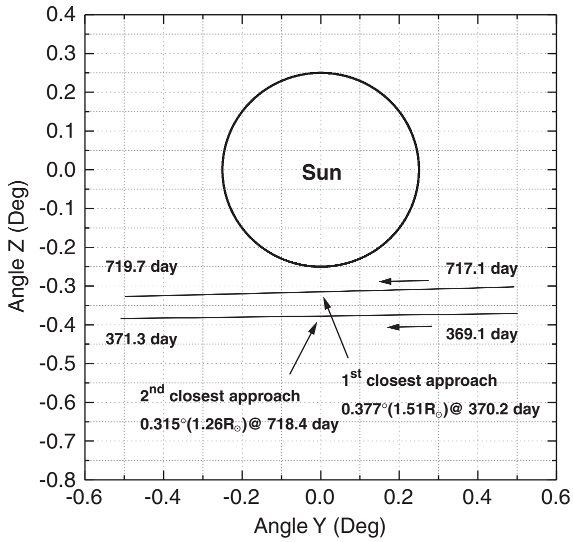

Fig. 5. Apparent angles during the two solar oppositions.

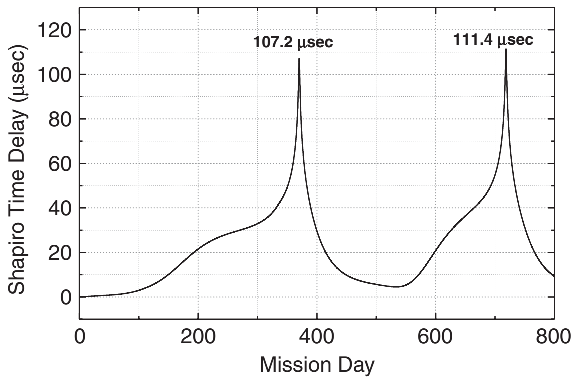

Fig. 6. Shapiro time delays.

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 around 370 days, 720 days and 1070 days from launch [13].

The apparent angles of the spacecraft during the two solar oppositions are shown in Fig. 5.

The one-way Shapiro time delays are shown in the Fig. 6. Near the two solar oppositions, the maximum Shapiro time delays are 107.2 and 111.4 μs, respectively [13]. During these two oppositions, from the laser range data, the relativistic post-Newtonian parameter γ can be measured precisely and separated from the determination of the relativistic parameter β. The precise determination of the relativistic parameters lays a firm foundation for relativistic ephemeris for the simultaneous determination of solar-system parameters.

To find out how precise one can determine these relativistic parameters and solar-system parameters, we have performed an orbit simulation [13]. 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 10 ps; 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 $10^{-15}\,\mathrm{m\,s^{-2}}$ and the direction of the unknown acceleration is changed randomly every 4 h; this is equivalent to $10^{-13}\,\mathrm{m\,s^{-2}\,Hz^{-1/2}}$ for $f \sim 10^{-4}$ Hz assumed as the requirement of the drag-free system. A simulation from 350 days after launch for 450 days with the orbit in Fig. 3 shows that both γ and β can be determined to 10^{-7}, and the solar quadrupole parameter J_2 to 10^{-8} [13].

For light propagation near the solar neighborhood, the post-post-Newtonian effects are about 5–6 orders of magnitude smaller than the post-Newtonian effects. For actual determination of γ and β to 10^{-7} from ranging data, post-post-Newtonian effects must be included. This means that we must have a parametrized post-post-Newtonian ephemeris framework to work on. We have started in this direction [14–16].

5. Venus flybys

For the launch option in Fig. 3 on August 4, 2010, the ASTROD I spacecraft will have the first closest approach to the Venus at 111.75 day after launch with a distance of 34904.2 km to the center of Venus (Fig. 4). The approach in heliocentric frame is shown in the upper part of Fig. 7. The spacecraft crosses the Venus trajectory in front of Venus and gets a swing toward the Sun to achieve the Venus orbit period. This is transparent in the Venus comoving frame as shown in the lower part of Fig. 7. The trajectory in the Venus comoving frame is hyperbolic (the horizontal scale in the figure is larger) [13].

After the first encounter, the spacecraft has the same Venus orbit period and has a chance to encounter Venus again after 0.5 or 1 period (112.35 or 224.7 days). Active search for encounter after about 112 days is under way. In the present case, the second encounter occurs after about 1 period (224.49 days). The closest approach distance is 24640.6 km from the center of Venus. The second encounter is shown in Fig. 8. This time the spacecraft orbit period is changed to about 165 days.

In Figs. 7 and 8, the working inertial-frame means the inertial frame we use in our working ephemeris. It is very close to the solar barycentric frame, but have a very small velocity with respect to it.

We are working on the simulation of the determination of relativistic parameters together with lower multi-moments of Venus during two Venus flybys in a single fitting and will report the results when completed. The relevance of the improved moments to the structural models of Venus is clear.

6. Sensitivity to gravitational waves

Like the radio Doppler tracking of spacecraft [17], ASTROD I also has sensitivity to low-frequency gravitational-wave. Clock noise and the propagation noise are the dominant noise sources. Clock noise is the dominant instrumental noise. As clock stability improves, this noise becomes smaller. The propagation noise is due to fluctuations in the index of refraction of the troposphere, ionosphere and the interplanetary solar plasma. The fluctuations due to ionosphere and interplanetary plasma are not important for laser ranging. Tropospherical effect can be subtracted to a large extent by two-color (two-wavelength) laser ranging or by using artificial stars. The ASTROD I spacecraft noise is very small and negligible. With these improvements, ASTROD I will have a couple of times to several times better sensitivity to gravitational-wave for the same spacecraft-Earth configuration.

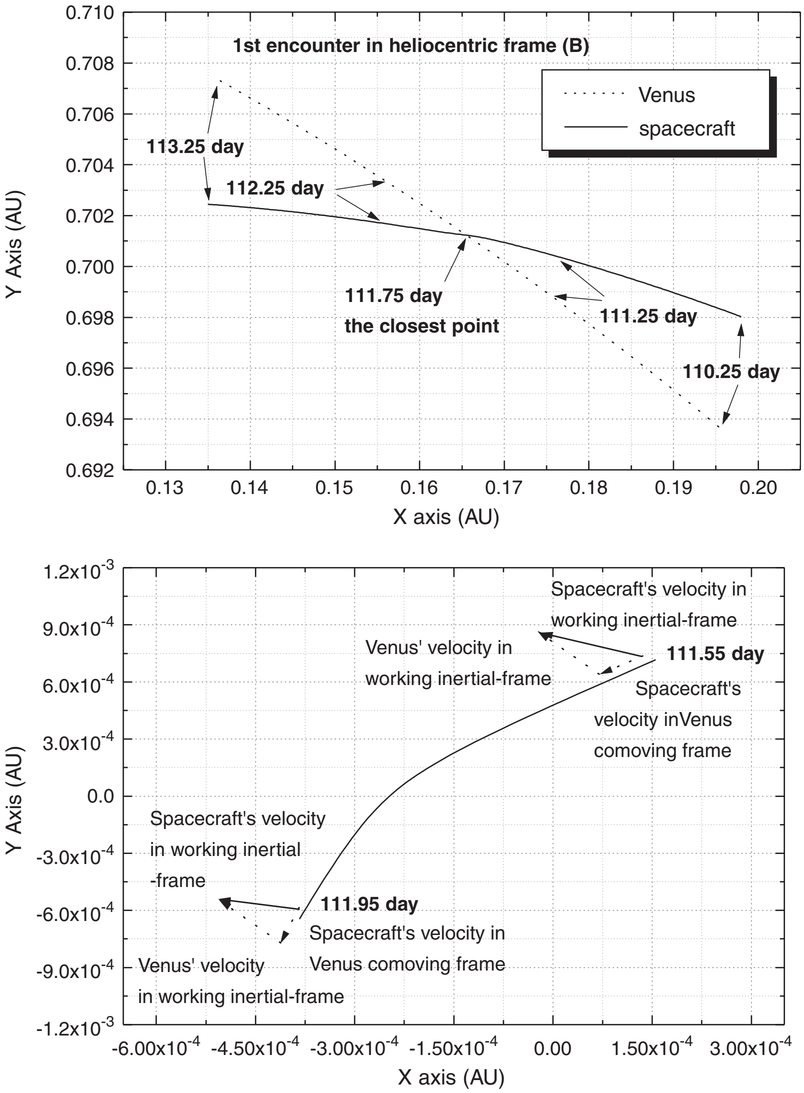

Fig. 7. First spacecraft—Venus encounter in heliocentric frame and in Venus comoving frame.

Detailed analysis will be presented in a forthcoming publication.

7. Outlook

ASTROD I and ASTROD using techniques of fundamental physics missions and with goals across all three disciplines of science in space—fundamental physics, solar exploration and astrophysics are currently under mission studies. ASTROD I with important scientific goals and using demanding but readily achievable techniques will open a new era in precision astrodynamics and in the exploration of the fundamental laws of spacetime. The ongoing Pre-Phase A Study for ASTROD I will set the schemes for the developments in key demonstrations and key scientific works needed to meet the scientific goals.

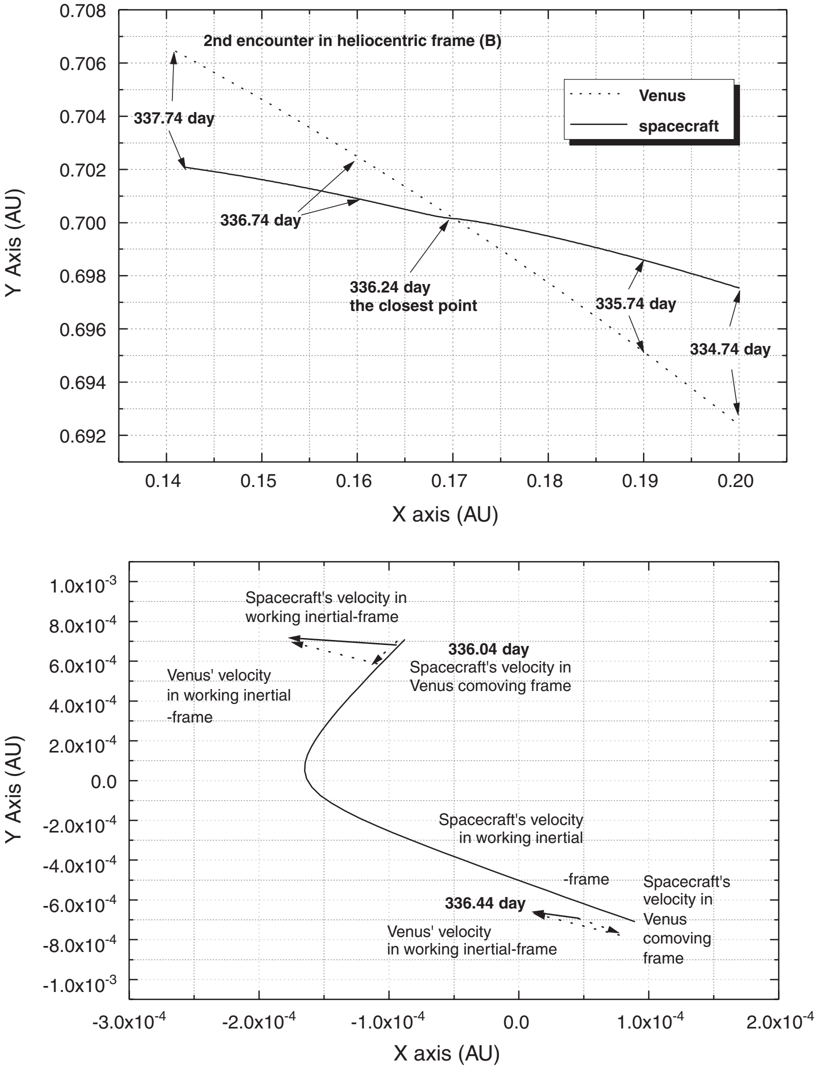

Fig. 8. Second spacecraft—Venus encounter in heliocentric frame and in Venus comoving frame.

A more detailed study of ASTROD I mission concept will appear in the Phase A Study Report [7].

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