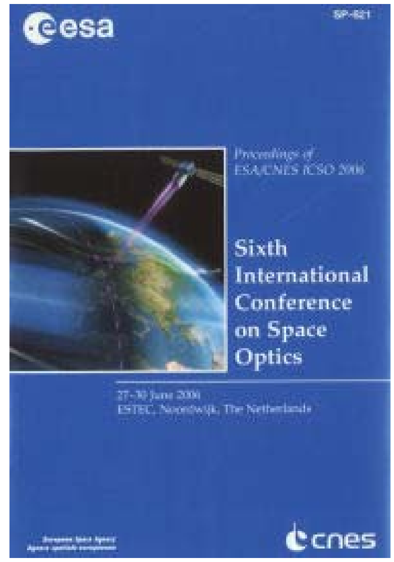
# International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

*Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas*




## *Drag-free deep-space laser ranging missions for fundamental physics*

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International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 1056748 · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2550487

# DRAG-FREE DEEP-SPACE LASER RANGING MISSIONS FOR FUNDAMENTAL PHYSICS

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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 drag-free satellite attitude control will revolutionize the field of experimental gravitational physics. Deep space laser ranging will be ideal for gravitational wave detection, and testing relativity and measuring solar system parameter to an unprecedentend accuracy. We use ASTROD (Astrondynamical Space Test of Relativity using Optical Devices) with three spacecraft and ASTROD I with a single spacecraft as examples for application those technologies. In this paper, we will present the scientific goals and optical requirements of the different mission scenarios, and will summarize the progress of ASTROD / ASTROD I mission studies with emphasis on optical interferometry, the acceleration noises, drag-free attitude control and low-frequency gravitational wave sensitivity.

## 1. INTRODUCTION

During the last 15 years, both pulse and interferometric deep-space laser ranging were proposed to map the solar-system gravity and to test relativistic gravity [1-4 and references therein]. Owing to Geodesy Missions [5] and the LISA [6] (Laser Interferometer Space Antenna) Program, improvements in many technologies critical to the tests of gravity are under development – i.e. highly accurate deep space navigation, high precision frequency standards, precise pointing and attitude control, and the drag-free satellite attitude and orbit control. 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. In the following, we will introduce the space mission ASTROD and its precedent ASTROD I.

## 2. MISSION GOALS

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 opti-

*Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)*

cal methods demonstrated the need of a systematic development of deep space laser tracking in the solar system. In this context, the ASTROD mission concept has been proposed. The modified ASTROD-I concept is a first and important step to realize ASTROD. This ASTROD-I concept has one spacecraft carrying a payload of a telescope, two (plus two spare) lasers, an optic comb and an atomic 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 ($\gamma$, $\beta$ 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 a measurement of many solar system parameters more precisely. These will enable us to build more precise ephemeris and astrodynamics. The weight of the ASTROD I spacecraft is estimated to be about 300-350 kg with a payload mass of about 100-120 kg. The present orbit option is to launch it in a heliocentric orbit with an initial period of about 290 days and to pass by Venus twice to receive gravity-assistance for achieving shorter periods.

| Effect/Quantity | Present accuracy | Projected accuracy |
|---|---|---|
| PPN parameters $\beta$ | $10^{-3}$ | $3 \times 10^{-9}$ |
| PPN parameters $\gamma$ | $5 \times 10^{-5}$ | $3 \times 10^{-9}$ |
| dG/dt | $10^{-12}$ | $1 \times 10^{-14}$ |
| Detection of gravitational waves in the range 0.1mHz to 10 mHz | $3 \times 10^{-15}$ - $5 \times 10^{-17}$ | 1-5 $\times 10^{-23}$ |
| Determination of solar quadrupole moment | 1 - $3 \times 10^{-7}$ | $1 \times 10^{-9}$ |
| Detection of solar g-modes | -- | Good chance of detection |
| Determination of planetary masses and orbit parameters | (depends on object) | 2 – 5 orders better |
| Determination of asteroid masses and density | (depends on object) | 2 - 3 orders better |

## 3. ASTROD – MISSION CONCEPTS

### 3.1 ASTROD

ASTROD (ASTRODynamical Space Test of Relativity using Optical Devices) consists of a fleet of spacecraft with drag-free attitude and orbit control navigating in the solar system. The satellites are interconnected via optical devices for ranging. 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 and one more in a Lagrangian (L1 or L2) orbit. The experiment includes an inertial proof mass, two telescopes, two 1 to 2 W lasers, an ultrastable clock and a drag-free attitude and orbit control system [1-3,7]. 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.

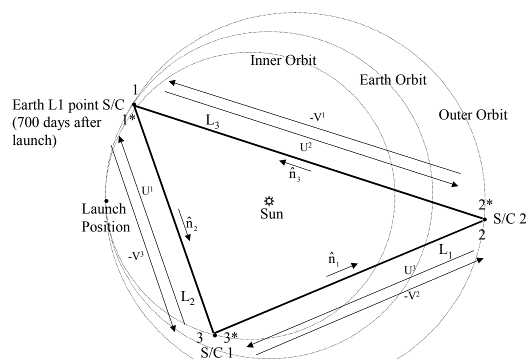


Fig. 1. A schematic ASTROD configuration (baseline ASTROD after 700 days of launch)

### 3.2 ASTROD I

ASTROD I is a down-scaled version of ASTROD. This mission concept consists of only one spacecraft. Its onboard experiment consists of a telescope, five lasers, and an ultrastable clock. In this concept, ranging and tracking will be done by ground stations (ODSN: Optical Deep Space Network) to test the optical scheme of interferometric and pulse ranging in order to give important scientific results [3, 9].

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 space-time 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 [9]. 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 to 350 kg.

The spacecraft is 3-axis stabilized. It contains a 3-axis drag-free inertial test mass and the spacecraft is to follow this proof mass using micro-thrusters. The drag-free performance requirement is $10^{-13}$ $ms^{-2}/Hz^{1/2}$ residual acceleration 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 × 50 × 35 $mm^3$ rectangular parallelepiped proof mass made from Au-Pt alloy of low magnetic susceptibility ($< 5 \cdot 10^{-5}$) 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 to 500 mm diameter f/1 Cassegrain telescope. This telescope will also transmit light from the spacecraft with λ/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.

The inertial 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

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

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. The strategy here is to have relatively moderate requirements compared to LISA 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 [10] with a torque resolution of $2 \cdot 10^{-11}$ Nm $Hz^{-1/2}$ from 1 mHz to 0.1 Hz.

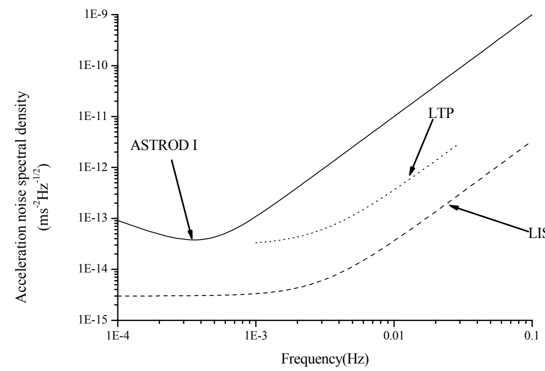


Fig.2. A comparison of the target acceleration noise curves of ASTROD I, the LTP and LISA.

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 [11]. 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 [12]; the noise requirement will be satisfied with a moderate discharging scheme.

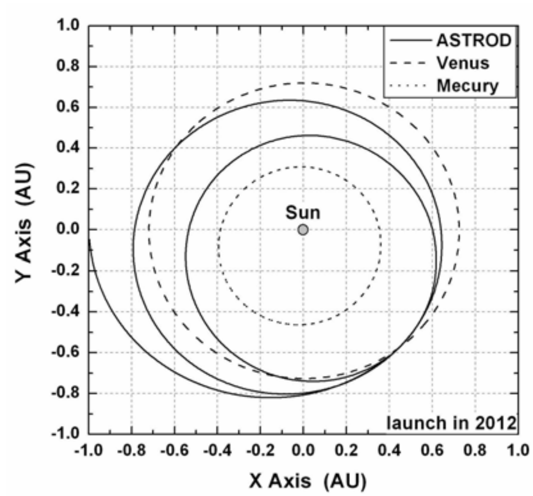


Fig. 3. The 2012 orbit in the heliocentric ecliptic coordinate system

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 [13], i.e. in 2012, 2013 and 2015. In Fig. 3, the 2012 orbit is shown starting at 2:09:36 on March 23, 2012. 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 [13].

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 for the post-Newtonian parameters $\gamma$ and $\beta$ to be $0.9 \cdot 10^{-7}$ and $1.1 \cdot 10^{-7}$, respectively, and that for the solar quadrupole momentum $J_2$ to be $3.8 \cdot 10^{-9}$ [13]. 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 $3 \cdot 10^{11}$ m (2 AU), the laser/clock frequency needs to be known to one part in $10^{14}$.

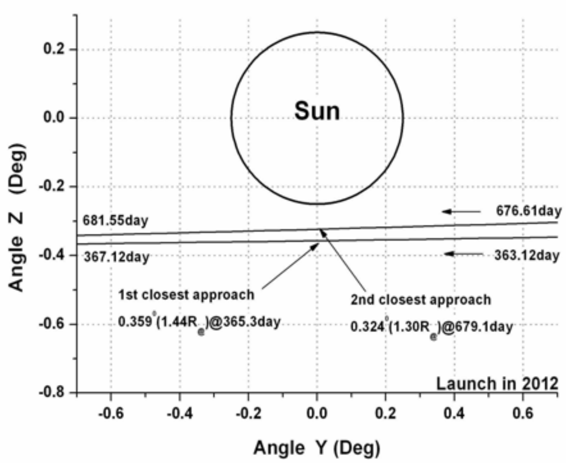


Fig. 4. Apparent angles during the two solar oppositions

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 the 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 [3, 8].

## 4. BACKGROUND LIGHT DISCUSSION AND OPTICAL ELEMENTS

The optical system should fulfil the tasks of sending CW laser light and pulsed laser light to the ground station, receiving and processing the weak light from the ground station received through the telescope in the spacecraft. The task of the optical system here will have the following functions: CW laser sending and receiving, pulsed laser sending and receiving, spacecraft pointing and tracing.

The optical arm made up of the spacecraft and the ground station is too close to the Sun, and thus the light energy it collects is far larger than that of LISA. Almost all of the light collected by the optical assembly in the ASTROD I is background light and the energy is powerful. It is more than a dozen powers of ten higher than the useful light information which is only some $10^2$ fW. It is needed to filter a large amount of useless background (Sun light) and attenuate it to the optical-electrical detector detection range.

There are different methods to deal with useless powerful background light according to different light information. In this optics design, we select a narrow band of 1nm using a multi-layer dielectric filter first. In certain places, we use shutters to attenuate the background light additionally. At this step, the pulsed counting method can be used to measure distance. As to the weak CW light information, we will select a Faraday Anomalous Dispersion Optical Filter (FADOF) [14] to further attenuate besides the narrow band filter and shutter. After this, we can pick up the useful information using the weak-light phase locking method. The FADOF which can be used has the advantages of ultra-narrow band (0.6~10GHz tunable), high transmissivity (higher than 90%) and no transmission wavelength drift. The FADOF work theory is shown in Fig. 5.

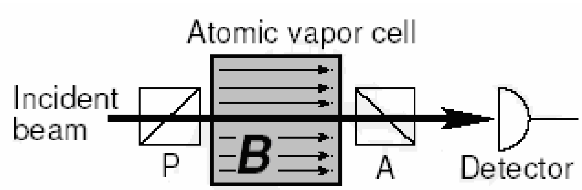


Fig. 5. FADOF work theory. P and A are crossed polarizing cube beam splitters (polarizer and analyzer)

Because we use two different laser wavelengths for the distance measurement, the optical layout must be able to send two different laser wavelengths and receive and separate the two different wavelengths, at the same time, it should also be able to point and trace for the spacecraft. According to the requirement of small volume, low weight and compact structure, we select the polarizing light modulation method for the optics design, that is to use components such as quarter wave plates (QW) and a polarizing cube beam splitter to accomplish the functions of sending and receiving laser light information in the same optical system.

Via measuring the distance between the ground station and the spacecraft flying at the other side of the Sun to test many scientific research objects, the laser beams sent by the spacecraft or the ground station will pass through the outer space vacuum and the atmosphere. It cannot determine the distance with a single laser wavelength. The 'air column', the total integrated air density over the beam paths, is not known, but with the knowledge of the refractive indices of the air at two different wavelengths this unknown variable can be computed and then appropriately taken into account in the data analysis. In the optics design, two different wavelength for a CW laser are selected and a pulsed laser to measure the distance with laser interference tracing and pulsed counting method. As to the optics of the ASTROD I, it will contain the optical systems not only on the Optical Bench (OB) and the telescope sending and receiving light that are on the spacecraft, but also on the ground station.

In order to make the optical layout compact and the optical energy maximally used, the same optical path to send and receive light will be adopted. The polarizing light modulation method is used to pick up the CW light information. In the CW light receiving optical path, after the useful light pass through the telescope (or coronagraph), the background light is still dominating after the selection by the 1 nm optical filter. To provide even further attenuation, it is made to pass through a FADOF. And even then it needs to use a shutter again to eliminate the background light.

The useful light information received by the telescope in the spacecraft contains two parts, one part is CW laser light (wavelength $\lambda_1$), the other part is pulsed laser light (wavelength $\lambda_2$). For convenience in laser wavelength selection, we use wavelength 1064 nm for the CW laser and select the pulse laser wavelength 532 nm. A detailed description of the ASTROD I optical system is given in [15].

## 5. DISTURBANCE EFFECTS ON SPACECRAFT AND INERTIAL TEST MASS

The spacecraft would be affected by various environmental disturbances, e.g. solar radiation pressure, solar wind and micro-meteorite impacts. Among these sources, solar radiation pressure is considered to be the major contributor. By assuming a perfectly reflecting surface of the spacecraft, it can be shown with data from the VIRGO experiment [16] on SOHO, that the acceleration noise caused by fluctuation in solar irradiancies in the order of less than $10^{-9}$ m/s$^{-2}$ Hz$^{-1/2}$.

The impact rate of a 1 ng- micro-meteorite on the ASTROD I spacecraft can be estimated to about 7 events per day. An impact of 1 ng-meteroites with an average velocity of 18 km/s on the spacecraft surface without reflection would produce a linear velocity increment of about $5 \cdot 10^{-11}$ m/s. Smaller meteorites have larger flux, but even smaller impacts, wherefore the contribution to the acceleration disturbances at 0.1 mHz seems to be insignificant.

In addition to the acceleration noise from environmental effects, the spacecraft would suffer from thruster noise. A thruster force fluctuation of only 10 μN Hz$^{-1/2}$ corresponds to an acceleration disturbance of 2.8 ms$^{-2}$ Hz$^{-1/2}$. Therefore thruster noise is a dominating effect. However, recent studies for the LISA Pathfinder indicate that force noise up to 0.1 mN Hz$^{-1/2}$ can be tolerated by increasing the gain [17].

Disturbances acting on the inertial test mass can be classified into two categories depending on their origin: environmental disturbances and test mass sensor back action acceleration. The former includes disturbances related to magnetic fields, impact effects by cosmic rays and residual gas molecules, temperature dependent effects (like radiometric and outgassing effects and thermal radiation pressure) as well as tidal effects caused by thermal distortion. Back action effects in the capacitive sensing system are caused by voltage fluctuation, charge fluctuations, thermal noise of the readout electronics, patch field voltages and thermal voltage noise by dielectric losses. A detailed and comprehensive analysis of all effects listed above is given in [18].

The total direct acceleration disturbance of the inertial test mass at 0.1 mHz has been estimated to be nearly a factor of 2 smaller than required. This 50 % margin may be allocated for unknown or unestimated disturbances, like cross-talks in the capacitive sensor and magnetic damping of the inertial test mass. The sensor back action acceleration disturbances can be reduced by increasing the space gap between electrodes and test mass, but must be further discussed based on results from laboratory torsion balance experiments.

## 6. 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*<br>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.<br>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.<br>Quadrant photodiode detector.<br>380-500 mm diameter f/1 Cassegrain telescope (transmit/receive), λ/10 outgoing wavefront quality.<br>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.<br>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: | $10^{-14}$-$10^{-13}$ $ms^{-2}/\sqrt{Hz}$ 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) |

## 7. ACKNOWLEDGEMENTS

We thank the National Natural Science Foundation (Grant No's: 10343001 and 10475114), the Foundation of Minor Planets of Purple Mountain Observatory, as well as the German Aerospace Agency DLR for financial supports.

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