VLBI Tracking of the Solar Sail Mission IKAROS

H. Takeuchi[1], S. Horiuchi[2], C. Phillips[3], P. Edwards[3], J. McCallum[4], S. Ellingsen[4], J. Dickey[4], R. Ichikawa[5], K. Takefuji[5], T. Yamaguchi[6], S. Kurihara[7], B. Ichikawa[1], M. Yoshikawa[1], A. Tomiki[1], H. Sawada[1], P. Jinsong[8]

[1]JAXA, 3-1-1 Yoshinodai, Chuou-ku, Sagamihara, Kanagawa 252-5210, Japan <takeuchi@isas.jaxa.jp>,
[2]DSN/NASA Canberra Deep Space Communication Complex, CSIRO Space Science & Astronomy, Australia,
[3]CSIRO Australia Telescope National Facility, Australia,[4]University of Tasmania, Hobart, Australia,
[5]NICT, Kashima Space Research Center, Japan,[6]Graduate University for Advanced Studies, Japan,
[7]Geospatial Information Authority of Japan, Japan, [8]Shanghai Astronomical Observatory, China

Abstract

IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) is the world's first spacecraft to successfully demonstrate solar-sail technology in interplanetary space. The spacecraft is made of square shape of very thin membrane, whose diagonal dimension is 20m. By changing its attitude toward Sun, radiation pressure of solar photons can be used as propulsive force of the spacecraft. To determine the orbit under the continuous big influence of the nongravitational perturbative force (i.e. solar radiation pressure), Very Long Baseline Interferometry (VLBI) observation is effective because sky plane position of the spacecraft can be directly and instantaneously measured by VLBI observables without (or with less dependence on) a priori assumption for solar radiation pressure model. In order to effectively perform VLBI measurements, a signal generator of Differential One-way Range (DOR) tones, which consist of multiple tones whose spanning bandwidth is about 28MHz, was developed and installed to the spacecraft. A digital backend system for the ground stations which has maximum output performance of 4-Gbps had also developed to sample wideband DOR tones. A total number of 24 international VLBI experiments were carried out by using totally 15 antennas among 8 agencies during July and August in 2010. As a result of initial analysis, measurement accuracy of VLBI delay was confirmed to be 50 pico second level, which is 20 times improved precision compared to the JAXA's conventional deep space spacecraft such as Hayabusa and Akatsuki.

1. Introduction

Solar sail is one of the future technologies which could greatly expand the flexibility of trajectory design for interplanetary missions, because the momentum of solar photons can be continuously used as the main propulsion of the spacecraft without consuming any propellant. A variety of unique and exciting missions such as outer solar system mission or solar polar trajectory mission are proposed by using solar-sail technology [1]. The idea of solar sail technology was born in the early 20th century, but it had lots of technical hurdles such as the appropriate material and deployment method for the sail. Japan Aerospace Exploration Agency (JAXA) had progressively developed and confirmed key technologies required for solar-sail from the early 2000s, and the first deep space solar-sail demonstrator IKAROS had developed and was launched together with Akatsuki (Venus Climate Orbiter) spacecraft on 21 May 2010.

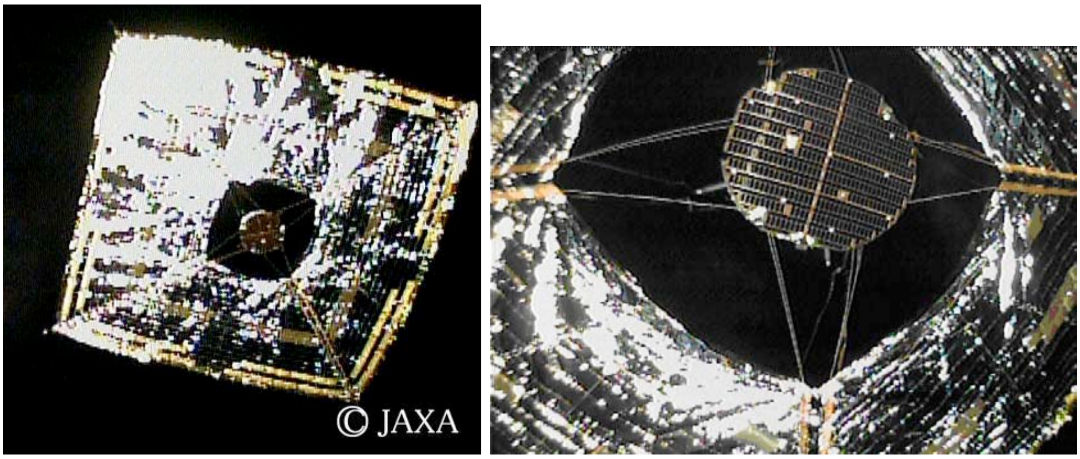

Figure 1. IKAROS's image taken by a deployed tiny subsatellite camera in deep space on June 14, 2010

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Deployment of the thin sail, which is made from 0.0075 mm width of polyimide, by means of centrifugal force produced by its spin went well [2] and large acceleration caused by solar photons were successfully confirmed on June 3, 2010 [Fig. 1]. Power generations by thin solar cell films on the surface and attitude control by changing reflection ratio of liquid crystal devices were also successfully demonstrated [Fig. 2]. On December 8, 2010, IKAROS passed by Venus at about 80,800 km distance, completing the planned mission period successfully.

Generally, orbit determination of deep-space spacecrafts should be performed under ballistic flight conditions during which spacecraft's thruster is switched off, to avoid the model error of propulsion forces. Usually at least a few days of ballistic flight is required to determine the sky plane components of the spacecraft's position because those components are estimated from diurnal variations of Doppler observable produced by Earth's daily rotation [3]. On the other hand, ballistic flight is impossible for solar sail because continuous solar radiation pressure acting on the surface cannot be turned off. Therefore high precision solar radiation pressure modeling with a priori knowledge of surface optical parameters such as reflectivity or absorption coefficients and detailed modeling of membrane shape is important for orbit determination of solar sail. However developing such a precision model is difficult work because surface optical parameters may be gradually changed in the space due to material degradation, and the shape of membrane can be changed affected by its spin rate. In order to deal with the problem, VLBI is an effective way because sky plane components of the spacecraft position can be directly measured by a VLBI observation, the typical duration time of which is about one hour or less. Because a few days of multiple observations are not necessary to determine sky plane components of the spacecraft position unlike the case of Doppler measurements, position error originated from the imperfectness of the solar radiation pressure model can be minimized by VLBI measurements. In order to effectively perform VLBI measurements, wideband DOR tones [4] which consist of multiple tones whose spanning bandwidth is about 28MHz was developed and installed to IKAROS.

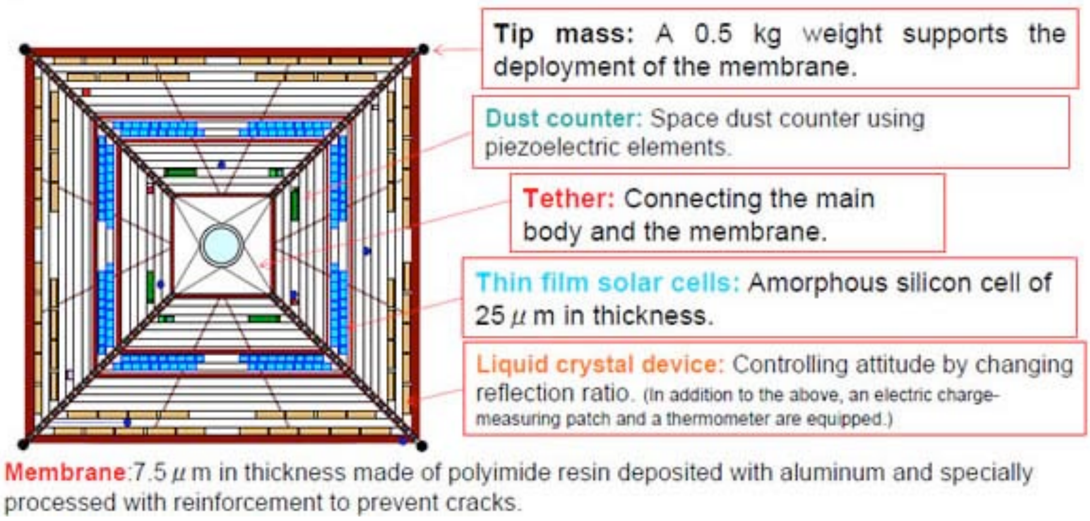

Figure 2. IKAROS's structure and installed instruments

2. VLBI Measurements

A total number of 24 international VLBI experiments were carried out by using totally 15 antennas among 8 agencies [Fig.3] during July and August in 2010. Because each agency has different receiver system, sampling parameters for raw radio signals (such as baseband frequency, real/IQ sampling, bandwidth or number of bits) were not identical among agencies. For the purpose of changing center frequency and recording bandwidth of the sampled data in order to adjust signal forms for data correlation, digital down-conversion software which has a function to extract arbitral frequency range from each sampled data was developed and used for the observations. While I/Q sampling is traditionally used in the recording system of space agencies (NASA,ESA), real sampling is used in the conventional astronomical or geodetic VLBI stations. A software-based Hilbert transformer was used to translate between I/Q and real sampling raw data. In order to detect the phase of a DOR tone a short-time FFT software, of which tipical resolution bandwidth is 0.1Hz, was applied to the spacecraft raw data. By differencing measured phases of a DOR tone received at both stations and also calculating the difference of those differenced phases between two separate tones, a DOR observable can be calculated (see eq.13-132 of [5]). Because a DOR observable contains bias errors such as clock bias, atmospheric delay bias, or ionosphere delay bias, it should be calibrated with VLBI delay observables of angularly near-by quasars. Akatsuki spacecraft could be also used as a calibrator source, when it was inside the half power beamwidth of the boresight direction of IKAROS during this period.

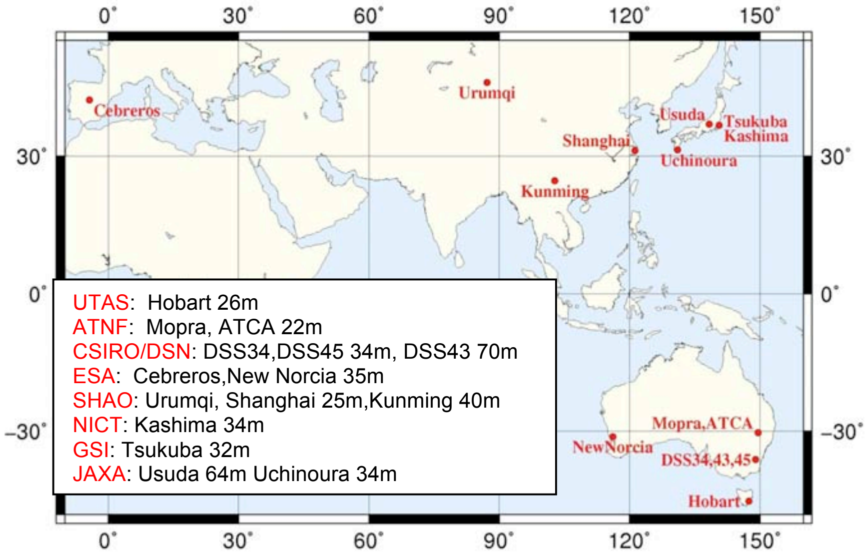

Figure 3. VLBI stations participated in the IKAROS VLBI sessions

3. Observation results

Measurement accuracy of IKAROS VLBI delay observables was confirmed to be typically 50-pico second level during this observation period. This is 20 times improved precision compared to the JAXA's conventional deep space spacecraft such as Hayabusa and Akatsuki. Because JAXA's former spacecrafts did not have wideband DOR tone generator unlike IKAROS, Delta-DOR measurements should be performed by using two-way range tones or one-way sub-carrier signals. In these cases, achieved precision was only 1 nano second level because the pass bandwidth of onboard transponder was limited to only 1-2 MHz aiming to suppress unexpected thermal noise, which prevented the use of wideband multiple tones. Figure 4 shows the VLBI delay residuals observed on the Usuda-Canberra baseline on July 29 2010. Two radio quasars were used as calibrators (second quasar is weaker than first quasar but angularly nearer than the first one) to validate the delay bias cancelation effects by quasars. VLBI delay residuals are gradually changed and those trends are consistent for both quasars but a 7.8 nano seconds of systematic delay bias is clearly seen between quasar and IKAROS observables. This bias is the Delta-DOR observable, which reflects on the error of IKAROS's reference orbit which is determined by Range and Doppler observables only. Results of combined orbit solution in which all of Rage, Doppler and VLBI observables are included will be introduced in the oral presentation and described in detail in another paper.

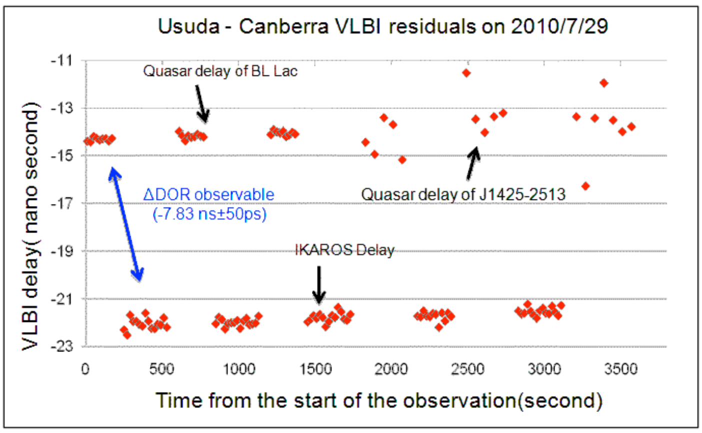

Figure 4. Measured Delta-DOR observables on the Usuda-Canberra baseline

5. Conclusion and Future plan

By the use of a newly developed wideband on-board DOR multi-tone generator for IKAROS and a newly developed digital backend system for ground stations which has maximum output performance of 4-Gbps, 50-pico second level of VLBI measurement accuracy was achieved. This is 20 times improved precision compared to the JAXA's conventional deep space spacecraft such as Hayabusa and Akatsuki. This system will be operationally used for Hayabusa-2 which will be launched on 2014 and the future 50-m diameter solar sail mission to Jupiter which is planned to be launched around 2020. A standardization process for VLBI tracking of deep-space mission is on-going in Consultative Committee for Space Data Systems (CCSDS) [6]. IKAROS tracking data will be expected to be used for interoperability tests required for the standardization process. This standardization product will be applied to the VLBI tracking of BepiColombo, joint mission of JAXA and ESA, in which many times of gravity assists with Venus and Mercury are planned during its cursing phase to Mercury.

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