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SPACE VLBI SATELLITE HALCA AND ITS ENGINEERING ACCOMPLISHMENTS†

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Abstract—The Institute of Space and Astronautical Science (ISAS), Japan, launched a satellite named HALCA in February 1997 by the ISAS's new rocket M-V. It has become the first space Very Long Baseline Interferometry (VLBI) satellite of the world by accomplishing a series of engineering experiments, representative ones of which are deployment of 8 m diameter parabolic antenna, precise attitude control of spacecraft, transfer of phase reference signal, high data-rate telemetry, single dish telescope operation, and interferometry with ground radio telescopes. Following the successful engineering experiments, HALCA has been operated for science observations under the science program named "VSOP" (VLBI Space Observatory Programme) in cooperation with many organizations and radio telescopes around the world. © 2002 International Astronautical Federation. Published by Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

To extend the Earth-based Very Long Baseline Interferometry (VLBI) to space by orbiting a radio telescope around the Earth is called "space VLBI". It aims to generate images of celestial radio sources with extremely fine resolution by forming long baselines which are not limited by the diameter of the Earth. Expected objects of observations are active galactic nuclei, quasars, and maser sources.

The idea of space VLBI first appeared in the 1970s. In the 1980s, studies of the satellite for space VLBI were conducted in the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA), Intercosmos, and the Institute of Space and Astronautical Science (ISAS). In 1986–88, NASA demonstrated technical feasibility of space VLBI using the Tracking and Data Relay Satellite System (TDRSS) spacecraft, though the experiment was made under limited conditions [1]. Among the studies in the 1980s mentioned above, two programs, the Intercosmos's RadioAstron and the ISAS's MUSES-B [2] have become real projects. ISAS launched the satellite MUSES-B, giving it the name HALCA after the launch, on 12 February 1997 by the ISAS's new rocket M-V. HALCA has become the first satellite of the world to challenge space VLBI [3].

The program MUSES-B was originally defined as an engineering experiment because a large number of new engineering developments were necessary for realizing a space VLBI satellite [2,4]. After the launch, major engineering experiments: deployment of a large parabolic antenna with 8 m in effective diameter, transfer of stable phase reference signal to the satellite ("phase transfer"), transmission of a high data-rate signal (128 Mbps) from

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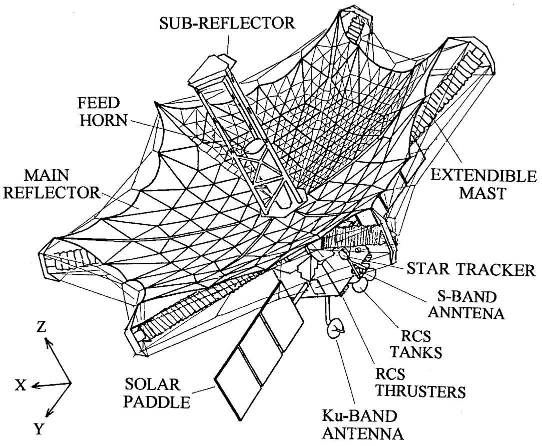

Fig. 1. The spacecraft HALCA.

the satellite to ground, control of the attitude of the spacecraft with a large parabolic antenna, confirmation of operation and performance of on-board radio-astronomy payload, precise orbit determination, formation of interferometer with ground radio telescopes, have successfully been conducted.

Based on the successful engineering accomplishments in orbit, HALCA generated high resolution images of quasars under internationally cooperated observations [5]. The angular resolutions achieved are really as expected from the orbit of the satellite HALCA.

Since the start of the satellite development at 1989, we have used, besides the name MUSES-B, another project name "VSOP" (VLBI Space Observatory Programme) when we stress science aspect of the program [6]. The project VSOP has been supported by NASA and the international radio astronomy community. Science observations by HALCA has become operational since mid 1997, and the observations have been conducted under VSOP in cooperation with many organizations and ground radio telescopes around the world [5].

In this paper we describe the features and the major engineering accomplishments of the satellite HALCA.

2. THE SATELLITE

HALCA is orbiting with an apogee height of 21,400 km, a perigee height of 560 km, and an inclination angle of 31 deg. The orbital period is 6.3 h. Figure 1 shows the configuration of the spacecraft in orbit [4]. A Cassegrain type antenna composed of a mesh-surface main reflector with 8 m effective diameter and a sub-reflector with 1.1 m diameter is placed on a box-shaped main body with 1.5 m × 1.5 m cross-sectional area and 1.0 m height. The main reflector and the sub-reflector supporting structure were deployed in orbit. The solar paddles, with a total area of 7 m^2, generate about 700 W of power after one year in orbit. The attitude of the spacecraft is controlled by a zero-momentum, three-axis stabilized control system using reaction wheels as actuators. The solar panels are kept outside the shadow of the main reflector though the reflector is made of substantially transparent meshes. The reaction control system (RCS) attached at the bottom of the spacecraft was used for perigee-raising maneuver in the initial orbit injection, and since then has been used for the maneuver of the spacecraft to a safe-hold attitude. The Ku-band antenna seen in Fig. 1 is a parabolic one with 45 cm diameter and is used for phase transfer and science data transmission. A 1-m length boom, at the tip of which the Ku-band antenna is attached, was deployed in orbit. In Fig. 1 is shown the definition of the spacecraft coordinate; z: the direction of the central axis of the large parabolic antenna, y: the direction parallel to the rotating axis of the solar paddles, x: the direction orthogonal to y and z under the right-handed coordinate definition.

Fig. 2. HALCA before launch. The height is about 4 m and the total (wet) mass is 830 kg.

Figure 2 shows the photograph of the spacecraft before launch. The mass of the spacecraft at the launch was 830 kg including a mass of the liquid propellant for the RCS of 62 kg. The mass of the

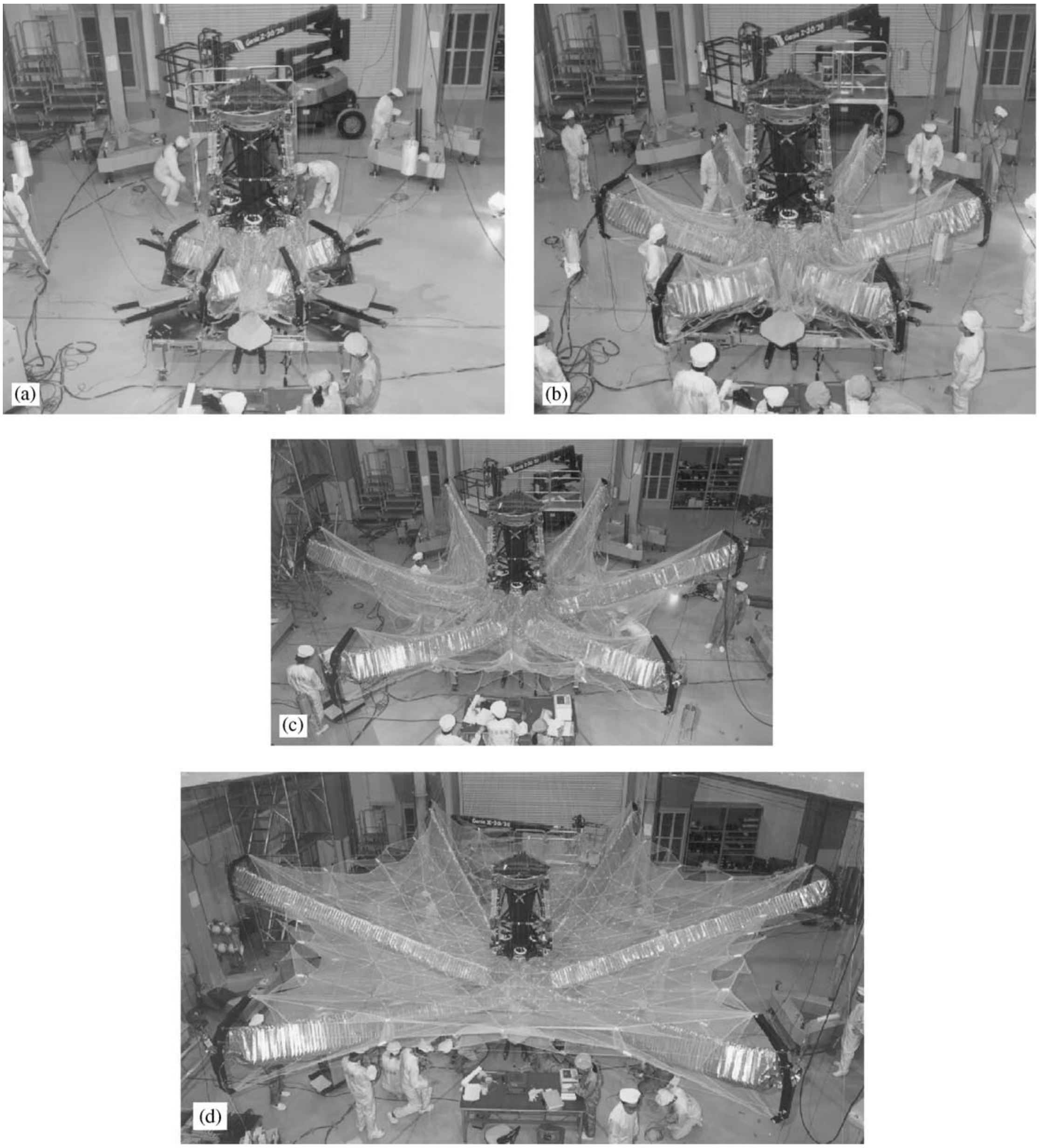

Fig. 3. Deployment test of the main reflector of the large antenna: (a) the start, (b) and (c) during deployment, (d) completely deployed.

large antenna is 246 kg, which is about one-third of the total mass of the spacecraft.

3. DEPLOYMENT OF LARGE PARABOLIC ANTENNA

The development of the large deployable antenna was the biggest engineering challenge of the MUSES-B (now HALCA) project. A light weight, high surface-accuracy antenna was developed based on the wire-tension-truss concept [7,8]. Great efforts were paid (1) to increase reliability of deployment of the antenna and (2) to increase surface accuracy of the main reflector.

The main reflector is composed of wire networks, meshes and six extendible masts. Extension of the six masts deploys the main reflector, and the same masts give tensions to the wire network and meshes such that the reflecting surface forms an accurate parabola. The wires are made of Kevlar core with Cornex envelope, and the meshes are made of gold-coated molybdenum wires. The effective aperture diameter of the antenna is 8 m, and the maximum structural diameter is 10 m. The focal length of the main reflector is 3.67 m. The antenna has a feed system operating at 1.6, 5, and 22 GHz. Among the antenna mass of 246 kg,

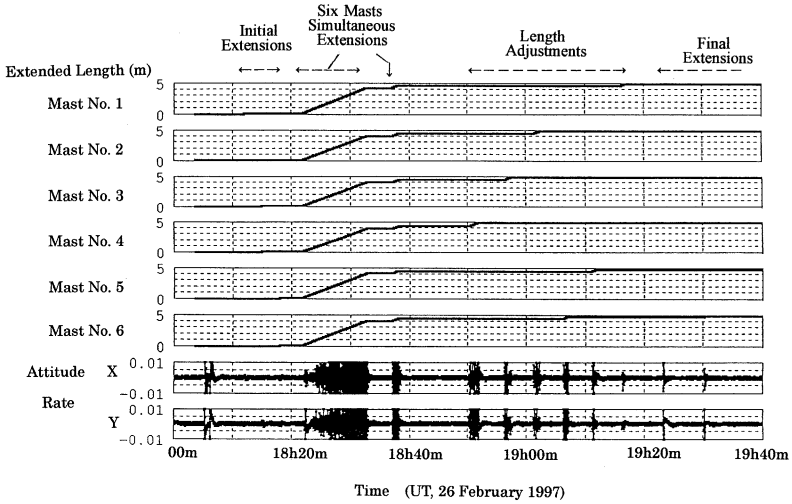

Fig. 4. The main reflector deployment: telemetry records of the extension of the six extendible masts (26 February 1997).

the mass of meshes and cables is about 11 kg and that of the six extendible masts is about 100 kg. Figure 3 shows the main reflector under a deployment test on the ground: (a) start of deployment, (b) and (c) during deployment, and (d) completely deployed. The surface of the main reflector was adjusted on the ground, and the final surface accuracy attained was 0.6 mm rms. The sub-reflector of the antenna is supported by three columns; the columns were folded during launch and extended in orbit.

Deployment of the antenna was conducted over February 24–27, 1997, about 2 wk after the launch. First, on February 24, the sub-reflector supporting columns were extended successfully. On February 26–27, the main reflector was deployed also successfully. At $18^{h}00^{m}$ (UT) on February 26, the deployment started. Figure 4 shows how the six extendible masts extended up to their final extension length of 5 m. The most critical, concentrated operation was six masts simultaneous extension, lasted for about 11 min, from $18^{h}22^{m}$ to $18^{h}33^{m}$. By the followed operations, five masts were fully extended and were locked; and the remaining mast reached near the final lock state by the end of the allowed operation time ($21^{h}00^{m}$) of that day. The deployment was brought to completion in $21^{h}00^{m} \sim 21^{h}20^{m}$ (UT), February 27. Figure 5 shows the angle error of the attitude control of the spacecraft during the main reflector deployment in February 26. The definition of the coordinate axis has been given in Fig. 1. The figure indicates that the attitude of the spacecraft was kept stable under the large structural change of the whole spacecraft.

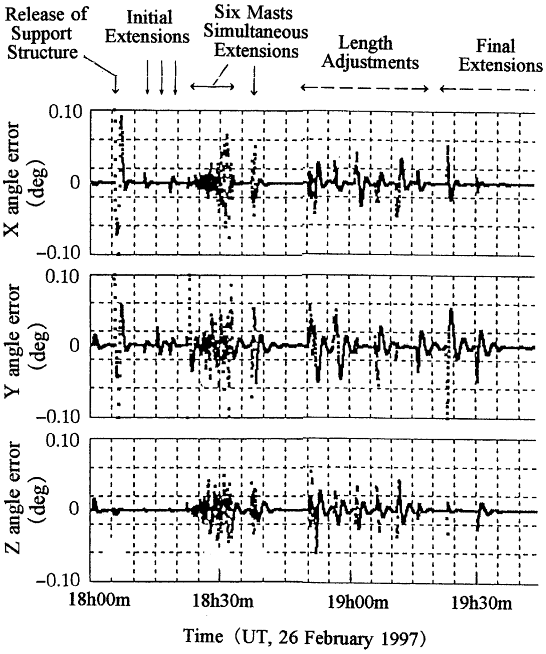

Fig. 5. The attitude of the spacecraft during the main reflector deployment: the angle errors of the three-axis stabilized control versus time (26 February 1997).

4. ATTITUDE CONTROL OF SPACECRAFT

The attitude control system is a zero-momentum, three-axis stabilized one, with four reaction wheels, an inertial reference unit (IRU), two star trackers (STT), magnetic torquers, and other attitude sensors [9]. The reaction wheels have a linear rotation range of ±3500 rpm and 6 N m s angular momentum. Unloading of the reaction wheels is performed by using the magnetic torquers. The spacecraft attitude is detected by the STTs and the

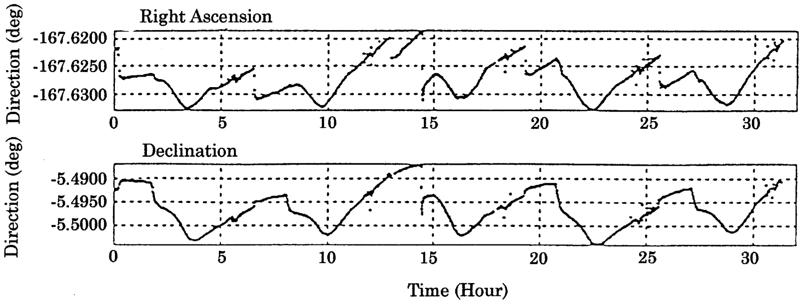

Fig. 6. An evaluation of the attitude (antenna pointing) control of the spacecraft: measured variation of the attitude measured for 32 h when the pointing direction was fixed.

IRU, and drifts of the attitude and the IRU are estimated on-board by a Karman filter. The attitude control system points the large parabolic antenna to celestial radio sources. The pointing accuracy aimed at the system design was 0.01 deg, the accuracy required in 22 GHz observations. Solar pressure and complex thermal effects are the main disturbances for precise pointing.

As described in the previous section, the attitude control system maintained the spacecraft stable during the large antenna deployment. After then the performance of the attitude control system was examined for the fully deployed configuration of the spacecraft, and was confirmed to be satisfactory. Figure 6 shows an evaluation result [10]: a variation of pointing direction (given in right ascension and declination) for a continuous 32 h when the *z*-axis of the spacecraft was directed towards a fixed direction. The variation was ±0.00715 deg in right ascension and ±0.00855 deg in declination. The nearly 6 h period variation seen in Fig. 6 is due to the STTs operation; the STTs are operated in some finite duration of the orbital period of 6.3 h and in the remaining time, the attitude is estimated by integrating the IRU data.

5. PHASE TRANSFER AND SCIENCE DATA TRANSMISSION

The spacecraft does not have an on-board hydrogen maser frequency standard, but receives a reference signal from a ground station, where the signal is generated from a hydrogen maser. The reference signal transfer by a radio wave to an orbiting spacecraft is one of the important techniques that had to be established for space VLBI. 15.3 GHz has been selected for the phase transfer of HALCA, since, at Ku-band, coherence is less affected by the ionospheric scintillation. The selection of the frequency was assisted by the Space Frequency Coordination Group (SFCG) [11].

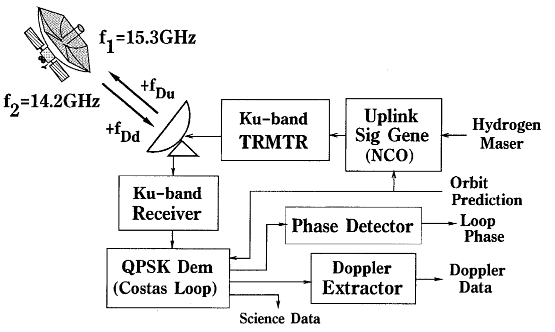

Fig. 7. Phase transfer to HALCA.

For sending the science data from HALCA to ground, a 14.2 GHz carrier is used. Data are quadrature phase shift keying (QPSK) encoded to the carrier, generating the down-link data rate of 128 Mbps.

As shown in Fig. 7, the up-link signal for the phase transfer is Doppler-compensated at the ground station such that the received frequency at the spacecraft becomes exactly 15.3 GHz. On the spacecraft, the 15.3 GHz signal is coherently translated to the 14.2 GHz down-link carrier. At the ground station, phase residuals in the two-way link signals and two-way Doppler shift are measured. ISAS built a new ground station with a 10 m diameter antenna at its Usuda Deep Space Center for the HALCA program. Besides the Usuda station of ISAS, three stations of NASA, and a station of the National Radio Astronomy Observatory (NRAO) of the USA, are tracking HALCA.

For the phase transfer and the science data down-link, the spacecraft has the 45 cm diameter parabolic antenna, which directs towards one of the ground stations successively. The half power beam-width of the antenna is about 3 deg. The angles that the antenna should be directed are calculated on-board using (1) satellite attitude data supplied in real time from the on-board attitude

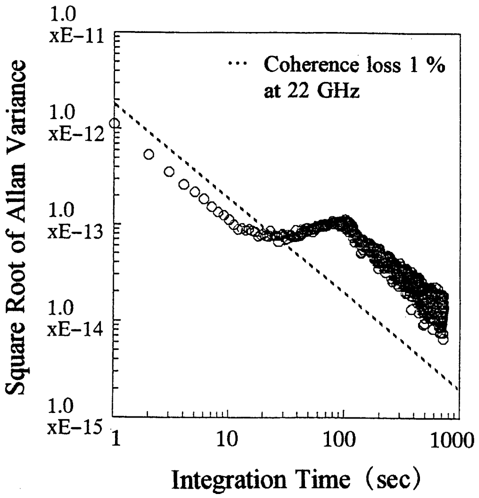

Fig. 8. An example of the measured two-way phase stability.

control system, (2) time, and (3) an initial value of the orbit sent from the ground and stored on the spacecraft (the initial value is sent once per 2 or 3 days). The angular deviation of the pointing is confirmed to be less than 0.02 deg.

The test of the phase transfer and the science data transmission between HALCA and the Usuda station started in the middle of March 1997, and the links were soon established. The 128 Mbps data transmission is performed with sufficient margin even under rainy conditions. The performance of phase transfer has been confirmed to be perfectly suitable for interferometry. Figure 8 shows an example of the measured two-way phase stability: square root of the Allan variance of two-way phase versus integration time; in the figure, the dotted line corresponds to the coherence loss of 1% at 22 GHz. Following the Usuda station, three stations of NASA, located at Goldstone, Canberra and Madrid, and the NRAO station at Green Bank, established the links with HALCA.

6. SINGLE DISH TELESCOPE PERFORMANCE

The on-board radio astronomy subsystem is composed of low-noise amplifiers for three frequency bands, 1.6, 5 and 22 GHz, down-converters, two video converters, two high speed samplers, a formatter, two frequency-synthesizers, and a calibration signal generator. The frequency ranges of three observing bands are 1.60–1.73, 4.7–5.0 and 22.0–22.3 GHz. Figure 9 shows the block diagram of the subsystem, including the equipment for the phase transfer and the high data-rate telemetry [4]. At the standard observing mode, two 16 MHz bandwidth channels cover 32 MHz observing bandwidth, and each channel is sampled in 2-bit. The generated data has a rate of 128 Mbps.

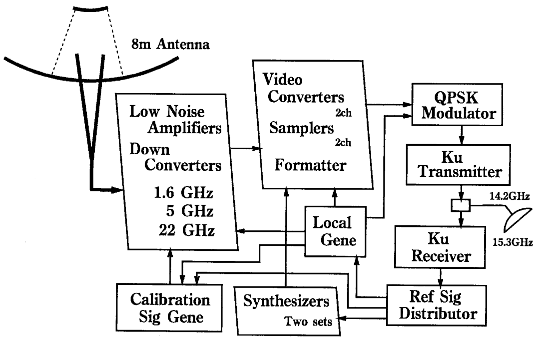

Fig. 9. On-board science subsystem including equipment for phase transfer and science data transmission.

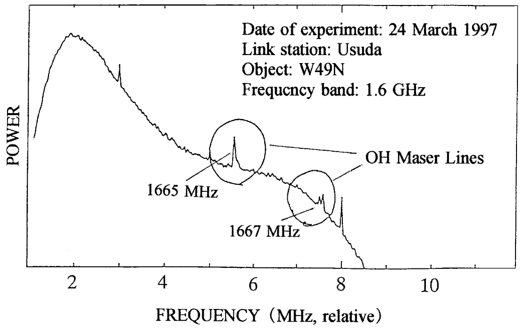

Fig. 10. The first celestial signal that HALCA received; HALCA was directed to the OH maser W49N on 24 March 1997 and detected the signal at 1.6 GHz.

The first single dish experiment of HALCA was conducted on 24 March 1997. Under the spacecraft being linked to the Usuda station, the large parabolic antenna of HALCA was directed to the hydroxyl (OH) maser source, W49N. The down-linked signal was analyzed by a spectrometer at the Usuda station in nearly real time and the maser lines at 1665 and 1667 MHz were clearly detected. Figure 10 shows the spectrum of the signal detected in this HALCA's first observation at 1.6 GHz.

During about 4 months following the first single dish operation, the performance of the radio telescope HALCA was evaluated. Summarizing them, (1) typical values of the system noise temperature are 75 K at 1.6 GHz and 95 K at 5 GHz, (2) the antenna efficiency is about 30% at 1.6 GHz and about 40% at 5 GHz, and (3) the antenna beam-width is about 50 arcmin at 1.6 GHz and about 20 arcmin at 5 GHz. Concerning 22 GHz, it was discovered that the system noise temperature was unexpectedly high (larger than 400 K), and is thought that the 22 GHz waveguide connecting the feed horn

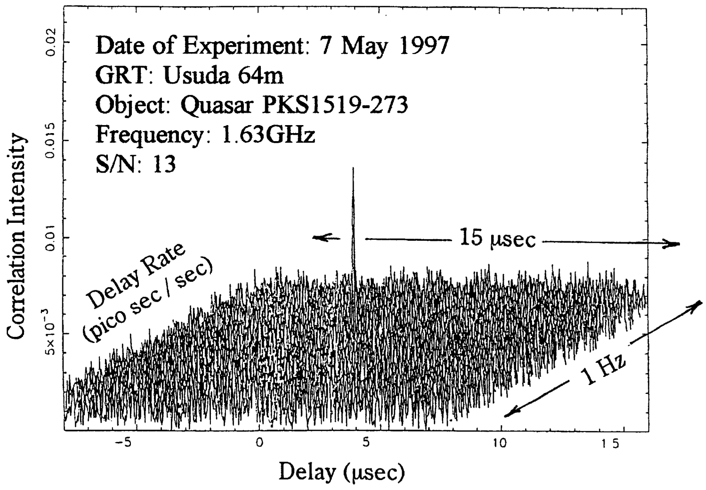

Fig. 11. The first fringes detection: a three-dimensional representation of the correlation intensity versus delay and delay rate, detected on the HALCA–Usuda 64 m telescope baseline.

and the front-end may have been impaired due to vibrations during launch. Nevertheless, a signal from the water maser source W49N was detected at 22 GHz in July 1997. The efficiency of the antenna at 22 GHz is not yet determined.

7. FIRST FRINGE DETECTION

HALCA succeeded to operate as a radio telescope for interferometry in May 1997, about three months after the launch. On May 7, HALCA and the 64 m diameter telescope of Usuda observed the quasar PKS1519-273 at 1.6 GHz. The Usuda 10 m station linked with HALCA. The data from the two radio telescopes were processed at the National Astronomical Observatory (NAO), Mitaka, where a new correlator [12] developed for the VSOP program was operated. Reconstructed orbit information, derived using the Doppler data of the Ku-band links and the range and range-rate data of the two-way S-band links for commanding and spacecraft status monitoring, was supplied to the correlator [13]. On May 13, fringes were first detected. Figure 11 shows a three-dimensional representation of the correlation intensity as a function of delay and delay rate. In the experiments followed, three station interferometry with HALCA, the Usuda 64 m telescope and the 34 m diameter telescope of the Communications Research Laboratory at Kashima was conducted. Figure 12 shows the correlation amplitudes and the closure phase under 60 s integration, obtained at an observation made on May 21, where the quasar PKS1519-273 was observed at 1.6 GHz for about 1 h and 20 min. The baseline lengths formed by HALCA and the ground telescopes were 8000–12, 000 km. Figure 13 shows the correlation amplitude versus integration time on the HALCA–Usuda 64 m baseline. The figure indicates that coherence is well maintained up to the integration time of 1000 s (at 1000 s, coherence is about 92% of that at 32 s).

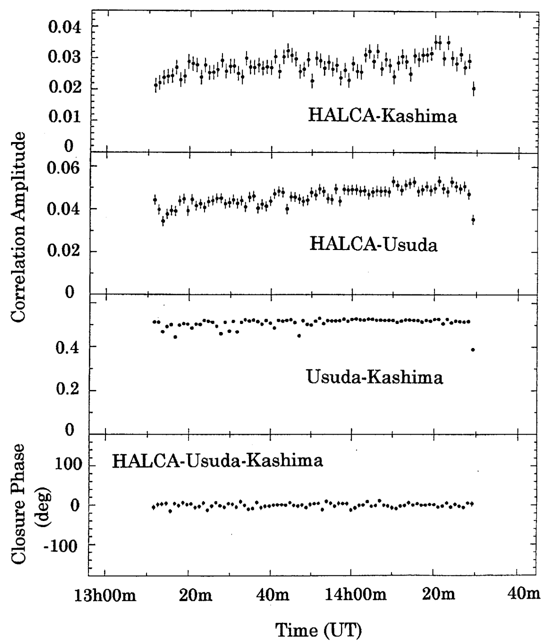

Fig. 12. Three telescopes interferometry. The correlation amplitudes and closure phase among HALCA, the Usuda 64 m telescope and the Kashima 34 m telescope.

In June 1997, international partners succeeded in detecting fringes; the Canadian correlator at the Dominion Radio Astrophysical Observatory (DRAO), Penticton, and the Very Long Baseline Array (VLBA) correlator of NRAO, Socorro, detected fringes at 1.6 GHz, where the co-observed

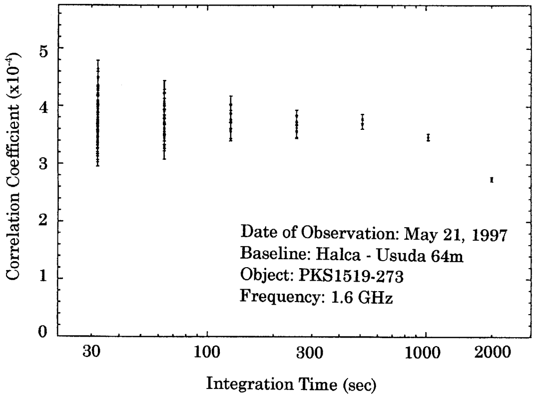

Fig. 13. Correlation amplitude versus integration time obtained on the HALCA–Usuda 64 m telescope baseline.

ground radio telescopes were the 70 m radio telescope at Tidbinbilla, VLBA and VLA (Very Large Array) of NRAO, and the link stations were the Green Bank and Goldstone ones.

In July 1997, fringes at 5 GHz were first detected at Socorro, then Penticton and Mitaka. In April 1998, fringes at 22 GHz were first detected in an observation of the bursting water maser in the Orion-KL nebula; correlation was made at NRAO, Socorro.

8. IMAGING BY SPACE VLBI

After interferometry between the satellite and ground radio telescopes was established, imaging was attempted using procedures similar to those for ground-based VLBI. Under the orbit of HALCA, with the apogee altitude of about 21,000 km, the maximum baseline length formed by HALCA and the radio telescopes on the Earth becomes about 3 times that formed by the ground radio telescopes on the Earth. When observing at the frequencies, 1.6, 5, and 22 GHz, expected angular resolutions of VLBI images become 1, 0.3, and 0.07 milli-arc-seconds(mas), respectively.

In mid-June of 1997, the first image was generated from an observation of the quasar PKS1519-273 at 1.6 GHz, conducted by HALCA, the ten-element VLBA and VLA on May 22. The image was constructed at NRAO, Socorro, on June 16. The image indicated the quasar as a compact radio source, with an angular resolution of 3 × 1 mas. The second image, observed by HALCA and VLBA and synthesized also at Socorro, of the quasar 1156+295, has shown a structure of the object, a compact bright core and an extended jet on one side of the core [5]. Images at 5 GHz were first generated in July 1997, where the angular resolution of about 0.3 mas was achieved. Imaging at 22 GHz has not yet succeeded.

9. CONCLUSIONS

The engineering accomplishments of the space VLBI satellite HALCA have been described. The series of the experiments: deployment of 8 m diameter parabolic antenna, precise attitude control of spacecraft with a large structure, transfer of phase reference signal, high data-rate telemetry, single dish telescope operation, and interferometry with ground radio telescopes, have established HALCA as a satellite for space VLBI. The major functions as an orbiting radio telescope have been confirmed until about 3 months from the launch.

Since June 1997, images of quasars, with high angular resolution, have been generated under international cooperation [5]. Science observations have been conducted under the VSOP, where scientists from ISAS, NAO, the Jet Propulsion Laboratory (JPL), NRAO, the Australia Telescope National Facility (ATNF), DRAO, the Joint Institute for VLBI in Europe (JIVE), and other organizations, are closely cooperated and many facilities around the world, including the VLBA, the European VLBI Network (EVN), the Australia Telescope Compact Array, the five tracking stations, and the three correlators, have been working with HALCA.

The development of the satellite, the engineering experiments in orbit, and the operation of the satellite, have been carried out by the project team composed of a large number of personnel from ISAS, NAO, related research institutes and the contractors of ISAS. The authors have presented this paper representing this large number of people.

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