DESIGN OF THE SPACE-VLBI SATELLITE MUSES-B *

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Abstract

The Institute of Space and Astronautical Science (ISAS) is developing a satellite named MUSES-B for conducting VLBI observations from space. The satellite is designed as an orbiting radio-telescope with a parabolic antenna of 8 m in effective diameter, forming long base-lines between ground radio-telescopes over the world. A deployable antenna, an on-board radio-astronomy system, phase transfer, high bit-rate science data transmission, antenna pointing control, and orbit determination, are the major technical features of the satellite. Compatibility to the ground VLBI systems is another feature considered in the satellite design.

Introduction

The Institute of Space and Astronautical Science (ISAS) is developing a satellite named MUSES-B for (1) conducting engineering experiments on the technologies necessary for space VLBI (Very long baseline interferometry) and (2) making radio-astronomical observations by VLBI in cooperation with ground radio-telescopes over the world. The radio-astronomical observations are being made under a program named VSOP (VLBI Space Observatory Programme) [1]. MUSES, which stands for Mu Space Engineering Satellite, is the name of the engineering satellite series of ISAS. The name "MUSES"-B indicates that technological developments are important for realizing a new kind of satellite: a satellite for radio astronomy. The development of MUSES-B started in 1989 [2], and presently, fabrication of the flight hardware of the satellite is being conducted. The satellite will be launched by the ISAS's M-V rocket in summer 1996 as the first space-VLBI-dedicated satellite in the world.

Since the start of the program, substantial progresses have been made in the development of the key technologies necessary for space VLBI. We have reached the final satellite design after detailed design studies, experiments, trade-offs, and international interactions, which continued during the three-year proto-type model (PM) development phase and the successive flight model

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(FM) development phase until today [3]. This paper describes the design of the space-VLBI satellite MUSES-B and discusses its engineering features.

Space VLBI Satellite

The maximum baseline length of VLBI on the earth is limited by the diameter of the earth. A natural idea for obtaining higher angular resolution is to put one radio telescope on an orbit with a substantially large apogee altitude, because the angular resolution of VLBI observations is inversely proportional to the baseline length. Both (1) the large baseline lengths between the orbiting radio telescope and ground radio telescopes and (2) continuously changing length and direction of the baselines make high-resolution and high-quality imaging of celestial radio sources possible.

The VLBI from space is a new technique, and the design of a space VLBI satellite requires new technologies and concepts, which are specifically related to the nature of VLBI observations.

Orbiting Radio Telescope

The satellite must have the complete function of the radio telescope for VLBI. Receiving signals from radio stars using a large antenna followed by low noise receivers, and converting and formatting signals by down converters, A/D converters and data formatters, are the same as the ground telescopes do. Differences are in data recording, reference frequency supply, and telescope position determination.

In the orbiting radio-telescope, we need a high-bit rate radio link between the satellite and ground stations for sending science data. We need another radio link which sends a stable reference frequency generated by a hydrogen maser (which is too heavy and too complicated to be on-board a satellite) from a ground station to the satellite. Sending a reference frequency this way is called "phase transfer". Further, we need accurate satellite orbit determination since the position of the telescopes forming a VLBI network must be known extremely accurately.

Science Objectives

(1) Selection of the frequency bands for science observations, (2) specifying a sensitivity of the interferometry system (which depends on the size of a radio astronomy antenna, system noise temperature, and frequency bandwidth), and (3) selection of the satellite's orbit satellite, are related to science objectives. We need trade-offs under constraints from an allowed launching rocket capability and satellite system capability.

International Cooperation

VLBI observations are performed by operating, simultaneously, both the satellite, and ground radio telescopes distributed on the earth. Without international cooperation, a space VLBI program does not work. Further, link stations that make contact with the satellite, hopefully continuously along its orbit, become important elements of a space VLBI system. These cooperative link stations can also be formed under international collaboration. Compatibility of such characteristics of the science data as frequency bandwidth, data format, and a number of data channels, to those of ground telescopes, are to be considered in the satellite system design.

Satellite operation

Because of the international nature of VLBI, the operation of a space VLBI satellite will become international.

MUSES-B Satellite Design Baseline

The satellite MUSES-B has been designed assuming a launch by the M-V rocket of ISAS. M-V is the ISAS's new satellite launching rocket [4], which development started in 1990; MUSES-B will be launched in the first flight of M-V.

In designing the satellite, the baseline assumptions were: (1) let the radio astronomy antenna to have a diameter of about 10 meters and (2) make observations at three frequency bands, 1.6, 5 and 22 GHz. Under these assumptions and based on the expected capability of M-V [4], the goal of the satellite mass was determined to be 800 kg, and an orbit with the apogee altitude of about 20,000 km, the perigee altitude of about 1,000 km and the inclination angle of 31° was selected. From a science observational point of view, this orbit lays a stress on high quality imaging of radio sources, because the U-V plane coverage becomes more uniform and dense compared to a case that the apogee height is several times larger or more [1]. Around the start of the MUSES-B program, discussions on international collaborations on space VLBI also started. The Inter Agency Consultative Group for Space Science (IACG) organized a panel in 1988 to promote international collaborations on space VLBI [5]; soon later, representatives from ground radio observatories participated in the panel. Almost the same time, NASA made a proposal to ISAS on VSOP collaboration, which consists of: (1) NASA operates the Deep Space Network (DSN) for science data reception, phase transfer, and orbit determination for VSOP, and (2) the National Radio Astronomical Observatory (NRAO) operates the Very Long Baseline Array (VLBA) and the VLBA correlator for VSOP. In the design of MUSES-B, the international collaborations have been taken into account, though there have been no collaborations on satellite flight hardware.

Satellite System

The development of MUSES-B have been conducted since 1989 through two development phases: the PM and the FM phases. At the start of the development, design goals were specified on the key subsystems, representatives of which were:

- A deployable antenna: to have a diameter of about 10 meters and operate at three frequency bands, 1.6, 5, and 22 GHz.
- On-board radio astronomy system: to operate at 1.6, 5, and 22 GHz with the maximum frequency bandwidth of 64 MHz.
- Phase transfer system: to satisfy a coherency requirement from VLBI.
- Science data transmission: capable of sending a signal with a rate of 128 Mbps.
- Attitude control system: to direct the antenna towards radio stars with a precision of 0.01°.
- Orbit determination: to achieve an accuracy required from the VLBI correlator operation.

The satellite design has been conducted on the basis of the ISAS's science satellite technology. Efforts have been made for the goals mentioned above to be satisfied. In the followings, features of the design of MUSES-B are described:

Spacecraft

Figure 1 shows the configuration of the satellite on orbit. The spacecraft main body is box-shaped, with 1.5 m x 1.5 m bottom area and 1.0 m height. A large parabolic antenna features the satellite; during the launch phase, the antenna is folded such that the whole spacecraft is contained inside of the nose fairing of the M-V rocket. Inside of the main body of the spacecraft is contained a cylindrical thrust tube, which works as a load path between the large parabolic antenna and the rocket. Outside of the bottom plate of the main body, a reaction control system (RCS) is attached. The present estimate of the satellite mass is 815 kg, an excess of which from the goal (800 kg) is in a range being managed until the launch. The estimate of the mass of satellite subsystems is shown in Table 1.

Large Deployable Antenna

A large dish antenna, deployed on orbit, is an essential element of the space VLBI satellite. A deployable antenna based on the "wire-tension-truss" concept [6] has been selected and is under development [7]. The main reflector is formed of wires and meshes supported by six extendible masts. The antenna has an effective aperture diameter of 8 m and a maximum structural diameter of 10 m. A current estimate of the weight of the antenna is 247 kg, which is about 30 The operating frequency bands of the antenna are 1.6, 5 and 22 GHz. Achieving the surface accuracy necessary for 22 GHz observations requires highly-sophisticated technologies on surface formation, surface adjustment, gravity compensation, material fabrication and extendible mast mechanics [7].

On-board Radio Astronomy System

As already mentioned, observations at three frequency bands, 1.6, 5 and 22 GHz, with the maximum frequency bandwidth of 64 MHz, are the baseline. The on-board hardware is composed of low-noise receivers, down converters, image rejection mixers, high speed sampler and formatter, two frequency synthesizers, calibrators and others. The tunable range of three frequency bands is 1.60–1.73 GHz, 4.7–5.0 GHz, and 22.0–22.3 GHz. Figure 2 shows the block diagram of the on-board radio astronomy system combined with telecommunications system for the data transmission and phase transfer.

The development of low noise amplifiers (LNA) has been one of the major research subjects, and presently, noise temperatures of less than 59 K at 1.6 GHz, less than 70 K at 5 GHz, and less than 180 K at 22 GHz, are attained by non-cooled LNAs. Treatment of the signal with 64 MHz bandwidth and the corresponding digital data with a rate of 128 Mbps, has required careful designs of analog and digital electronic equipments. Compatibility of the signal channel and the data format with the ground radio telescopes, especially with those of VLBA, has been an important subject of discussions in the international collaborative studies on VSOP. We have defined three observation modes: (1) two 32 MHz bandwidth channels and 1 bit A/D conversion, (2) two 16 MHz channels and 2 bit A/D, (3) one 32 MHz channel and 2 bit A/D. Among the three modes, (2) is a VLBA-compatible one. The on-board calibration system, composed of comb tone generators and noise diodes, is an important element of the radio-astronomy payload.

Science Data Transmission and Phase Transfer

The satellite has Ku-band communications system for sending science data and receiving the phase transfer signal (See Fig. 2). The high bit rate (128 Mbps) of the science data and anticipated coherency degradation due to the ionospheric scintillation in the phase transfer were the reasons that the Ku-band was selected instead of X- or longer-wavelength bands. The frequencies we are using are 14.2 GHz for the science data transmission and 15.3 GHz for phase transfer. The 15.3 GHz signal is transmitted with no modulation to avoid coherency degradation due to such modulation as spectrum spreading. In determining the frequencies, we needed an international coordination among the Space Frequency Coordination Group (SFCG) [8], adding to a negotiation with the Telecommunications Bureau, the Ministry of Posts and Telecommunications, Japan. The phase transfer system, composed of on-board and ground equipments, has been designed extremely carefully with respect to phase stability and coherency. The on-board Ku-band antenna is a steerable parabolic one with a diameter of 45 cm and is attached to a deployable boom to increase its field of view. The ground stations are assumed to have a 10 m diameter class antenna. The Ku-band antenna tracks the ground station autonomously using orbit prediction data stored on the satellite and satellite attitude data supplied from the on-board attitude control system.

Attitude and Orbit Control

Observations at 22 GHz require an antenna pointing accuracy of 0.01° when the diameter of the antenna is around 8 m. A large solar pressure, complex thermal effects, and flexibility of the structure, are the major factors that have been considered in the design of the attitude control system for the antenna pointing.

Figure 3 shows the block diagram of the attitude and orbit control system of MUSES-B. The system consists of the Attitude and Orbit Control Electronics (AOCE), the Attitude and Orbit Control Processor (AOCP), four 6 Nms reaction wheels (RW), magnetic torquers (MTQ) for unloading, two Star Trackers (STT), an Inertial Reference Unit (IRU) composed of mechanical gyroscopes, another IRU using an optical fiber gyroscope (IRU-F), a geomagnetic aspect sensor (GAS), six Sun Aspect Sensors (CSAS), accelerometers (ACM), and the Reaction Control System (RCS). The antenna pointing control and re-targeting maneuver are performed by driving the four RWs, using IRU and two STTs as attitude sensors. A new method using a spectrometer at the Ku-band link station has been proposed to measure the angular accuracy of the antenna pointing [9]. The reaction control system (RCS) is mainly used for maneuvering in the initial orbit injection phase.

Electric Power System

The satellite has two solar paddles with a total area of 7 m^2 (See Fig. 1). About 700 W of power will be generated after one year on the orbit. The solar cells and the batteries are designed assuming three year operation.

Table 2 shows the power consumption of the satellite system in two typical operation modes.

Satellite Operation

Commanding and telemetry reception are made at the 20 m diameter antenna station of the Kagoshima Space Center (KSC) of ISAS, using S-band links. The Ku-band telecommunications for science data transmission and phase transfer are made at five stations; one is in the Usuda Deep Space Center of ISAS, where a new link station is being build, three in the DSN of NASA (Goldstone, Canberra and Madrid) , and the remaining one at Greenbank, NRAO. The DSN stations are under construction and the Greenbank station is near completion. Figure 4 schematically shows the earth stations for the MUSES-B operation.

Correlation of the science data will be carried out by a VSOP Correlator [10] and the NRAO's VLBA Correlator. The VSOP correlator will be placed at the National Astronomical Observatory, Mitaka. At Usuda, "near real-time fringe monitoring" is planned being used the 64 m diameter antenna as a radio-telescope.

Orbit Determination

The satellite orbit must be known accurately for correlating the science data obtained by the satellite with the data obtained at the ground telescopes. The accuracies the VSOP correlator requires are 3.2 km in position and 5.4 cm/s in velocity. For the near real-time fringe monitoring, accuracies of 800 m in position and 18 cm/s in velocity are required. The orbit is being determined by Doppler data from the Ku-band links, together with Doppler and range data obtained from the S-band links. Besides, an on-board orbit-determination experiment using GPS is being made.

Summary

The design of the space-VLBI satellite MUSES-B has been described. The satellite is formed as an orbiting radio-telescope with a parabolic antenna of 8 m in diameter. It will be launched by the ISAS's new rocket, M-V, in summer 1996. Manufacturing of the satellite hardware is progressing, and the integration and the system test of the satellite will start in 1995.

The MUSES-B satellite development is being carried out by the project team formed of a large number of scientists and engineers from ISAS, the National Astronomical Observatory (NAO), related universities and research institutes, and the companies participating as the contractors of ISAS.

The MUSES-B satellite design described in this paper is a product of cooperative works of these large number of people.

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Figures and tables not available in this format as yet

Fig. 1 MUSES-B satellite.

Fig. 2 Block diagram of the on-board system for radio-astronomy and Ku-band telecommunications.

Fig. 3 Attitude and orbit control system.

Fig. 4 MUSES-B satellite operation.