Advanced Space Technologies in Space Science Missions
- Space VLBI Mission ASTRO-G Project as an Example -

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Space VLBI (very long baseline interferometry) mission, ASTRO-G, will be launched in 2013 by Japan Aerospace Exploration Agency (JAXA). ASTRO-G is a follow-on mission of HALCA (VSOP) mission in 1990s, which was the world first space VLBI mission. ASTRO-G will consists of a huge synthetic aperture with diameter of 35,000Km together with radio antennas in the ground. They will achieve the world highest angular resolution imaging by means of 43 GHz observation. This paper describes the advanced key technologies of ASTRO-G such as the 9m deployable antenna with very accurate surface, the fast rest - to - rest attitude maneuver, and the precision orbit determination above NAVSTAR’s orbits. These advance technologies lead ASTRO-G mission to the astronomical observation with the world highest angular resolution.

Key Words: Space VLBI, VLBI, Radio Astronomy, High Angular Resolution

1. Introduction

The Institute of Space and Astronautical Science (ISAS) started the VLBI Space Observatory Programme (VSOP) in 1989, and launched the first space VLBI satellite, HALCA, in 1997 1,2). Scientific observations were undertaken at 1.6 and 5 GHz, which provided the highest angular resolution images ever obtained in these frequency bands (0.36 micro-arcsecond at 5 GHz, and 1.1 mas at 1.6 GHz). VSOP observations yielded new results on topics such as the internal structure and motion of the active galactic nuclei jets, the highest brightness temperature sources, and the fine structure of the plasma shadow of free-free absorption. In total, 750 VSOP observations were successfully made. The HALCA satellite lost attitude in October, 2003, and satellite operations were finally terminated in November 2005, on the 3213th day after launch.

A next-generation space VLBI mission proposed the VSOP-2 mission in September 2005. The VSOP-2 mission was selected as the 25th scientific mission of JAXA in May 2006 and the VSOP-2 satellite was given the code name ASTRO-G. In April, 2007, ASTRO-G was approved to be a project in JAXA. A present (2009 May), ASTRO-G is in the basic design phase (so-called phase-B), aiming at launch in Japanese 2012 fiscal year 3). This paper describes the advanced key technologies of ASTRO-G such as the 9m deployable antenna with very accurate surface the fast rest - to - rest attitude maneuver, and the precision orbit determination above NAVSTAR’s orbits.

2. Overview of the ASTRO-G Satellite

The VSOP-2 spacecraft, ASTRO-G (Fig. 1), will have a deployable 9.3-m offaxis paraboloid antenna. Its surface accuracy will be less than 0.4 mm rms, and the pointing accuracy of less than 0.005 degree. Total mass is about 1,250 kg, and the total power supply is 2,000 W at EOL. ASTRO-G has 3 observing bands, 8 GHz, 22 GHz, and 43 GHz. It can observe both LHCP (left hand circular polarization), and RHCP (right hand circular polarization) to observe the polarization of the target sources. A target mission lifetime is 3 years.

The satellite will be placed in an elliptical orbit with an apogee height of 25,000km and a perigee height of 1,000 km, resulting in a period of 7.5 hours. The ASTRO-G and the ground radio telescope consist of the synthetic aperture with a diameter of about 35,000 Km, described in Fig.2. With an

Fig. 1. Schematic view of the ASTRO-G (VSOP-2) satellite.
apogee height of 25,000 km, 43 GHz observations can achieve an angular resolution of 38 micro-arcseconds. The launcher of ASTRO-G is H2A rocket of JAXA. It is not yet decided whether the launch will be single or shared, and the partner satellite in case of the shared launch.

To achieve an order of magnitude higher sensitivity for continuum sources than HALCA, VLBI data will be down-linked in real-time at 1 gigabit per second using the 37–38 GHz band. The on-board system is locked to a reference phase, derived from a H-maser at one of 3~4 tracking stations, and uplinked as a tone at 40 GHz. ASTRO-G has 2 IF channels with 2 sampling modes. One uses 256MHz bandwidth and 1-bit sampled channels, and the other has 128 MHz and 2-bit sampled channels.

Furthermore, a phase-referencing capability is being actively considered. The phase-referencing observations expect to have the orbit determination accuracy with the order of less than 10cm, and the fast-switching between 2 sources. This does not only increase the number of observable sources but will also allow state-of-art astrometric measurements to be undertaken. ASTRO-G should achieve an order of magnitude higher sensitivity than HALCA with these new capabilities.

Table 1. Specifications of the ASTRO-G satellite.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass at launch</td>
<td>1250 kg</td>
</tr>
<tr>
<td>Mean power</td>
<td>2.0 kW</td>
</tr>
<tr>
<td>S-band data transmission</td>
<td>S-band (command &amp; control operation, and telemetry transmission)</td>
</tr>
<tr>
<td>Science payload</td>
<td>Radio telescope antenna: 9.3 m diameter reflector</td>
</tr>
<tr>
<td>Observation frequencies</td>
<td>8, 22, 43 GHz</td>
</tr>
<tr>
<td>Frequency standard up-link</td>
<td>40.2 GHz</td>
</tr>
<tr>
<td>Science telemetry down-link</td>
<td>37.5 GHz</td>
</tr>
<tr>
<td>Science telemetry down-link rate</td>
<td>1024 Mbps</td>
</tr>
<tr>
<td>Orbit</td>
<td>Apogee altitude: 25000 km</td>
</tr>
<tr>
<td>Perigee altitude</td>
<td>1000 km</td>
</tr>
<tr>
<td>Inclination</td>
<td>31°</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.62</td>
</tr>
<tr>
<td>Precession of AOP</td>
<td>±128 deg/yr</td>
</tr>
<tr>
<td>Precession of LAN</td>
<td>±167 deg/yr</td>
</tr>
<tr>
<td>Orbital period</td>
<td>7.45 hr</td>
</tr>
<tr>
<td>Attitude control</td>
<td>Pointing: arbitrary celestial sources</td>
</tr>
<tr>
<td></td>
<td>Pointing precision: &lt; 0.005°</td>
</tr>
</tbody>
</table>

The design of the VSOP-2 instruments is intended to realize the following science goals:

1. The structures and magnetic field configurations of accretion disks in nearby active galactic nuclei (AGNs),
2. The mechanism of jet acceleration and collimation,
3. The motion of masers in galactic star forming regions,
4. The study of proto-stellar magnetospheres, and
5. The structures and magnetic fields of accretion disks in active galactic nuclei.

As a result, ASTRO-G will allow studies of regions where extreme physical conditions are encountered. Consequently the high-resolution imaging capability of VSOP-2 will enable new science in fundamental astrophysics to be undertaken. Table 1 summaries the main specification of ASTRO-G Project.

3. High-Accuracy Deployable Antenna

3.1 Basic design

The on-board radio astronomy antenna is one of the key parts of the spacecraft because of its size, mechanical complexity, and mass. The deployment structure is based on the ETS-VIII project antennas (S-band, 19 x 17 m size) which are successfully launched and deployed in December of 2006. The ASTRO-G antenna consists of 7 modules. To achieve a surface accuracy as high as 0.4mm rms for the observation up to 45 GHz, radial ribs and hoop cables will shape the surface of each module. Figure 3 is the photograph of the Engineering Model of one module.

The antenna has off-set Cassegrain optics with 3 different feeds for 3 frequency bands. The main reflector supporting boom is provided with 2 degrees of adjustability of the angels. The sub-reflector has a function to adjust focal length in addition to the adjustability of 2 angels. We adopt mesh as the surface for the main reflector. It is effective to make the antenna mass light and minimize the angular momentum torque due to solar radiation pressure.

3.2 Radial-rib/hoop-cable surface

Regular radial rib antennas can keep good accuracy in the radial direction. However, in the circumferential direction, undesirable dent deformation occurs due to the
effect of negative curvature, which is known as pillow effect. This dent curve line can be replaced by straight hoop cable lines in a concept of a radial rib and hoop cable (radial-rib/hoop-cable) reflector surface shown in Fig.4. Each of the seven deployable modules employs this idea of radial-rib/hoop-cable construction to stretch the knitted metal fabric surface as a mesh reflector, and to satisfy the required surface accuracy.

The characteristic of this surface construction is expected not only to suppress the pillow effect of convex curved surface, but also to avoid tangling of cables and to suppress errors due to catenary openings of inter-modules.

Figure 4 shows the differences between the two kinds of modular mesh reflectors, radial-rib/hoop cable construction in ASTRO-G and cable networks in ETS-VIII. All of these differences and improvements aim at the high frequency observation.

The mesh reflection loss is reduced by selecting fine stitch woven mesh and optimizing experimentally the tensile force of the mesh. Misalignment error is reduced by using low CTE materials, the alignment mechanisms of the main reflector and the subreflector, and thorough thermal design of the satellite structure.

3.3 Estimation of surface accuracy

There are many kinds of degradation cause of antenna performance, as shown in Table 2. Each of these causes is examined and is minimized in the design. To investigate and confirm an estimation of surface accuracy, some prototype models of a single module have been made, as shown in Fig.3.

Table 2 provides its quantitatively provisional allocation of surface error especially focusing on geometrical and structural aspects, although the final antenna performance should be evaluated by the RF (Radio Frequency) property. The degradation cause in surface accuracy should be controlled through design and test, as shown in Table 2 together with the corrective strategy. A single module surface with deployable back-truss structure of about 4m in diameter should be adjusted to 0.25mm-rms, and the total surface accuracy goal of 9.56m will be 0.4mm-rms.

Thermal deformation of the reflector surface depends on the satellite orbital elements and the angle of the reflector to the sunlight, the earth albedo, and so on, for astronomical observation purpose. Therefore, Table 2 does not include the causes that depend on the observation operation. However, the thermal deformation is suppressed to the utmost in principle by adopting low CTE(Coefficient of Thermal Expansion) materials for trusses and cables, and by adopting low interference design between reflector surface deformation and back-truss deformation. This is because the observation will be continued during an eclipse depending on the condition.

Thermal distortion of the reflector will be a main source of the mechanical and structural error in orbit. Thermal vacuum test data of an engineering model of a single module will be used to take correlation with the temperature analysis code and the thermal strain analysis code. Aged deterioration of the materials used as ribs and cables determines the degradation of observation in orbit. In order to estimate quantitatively the reflector error in orbit, aging of stiffness coefficient, CTE, and thermo-optical surface coefficient of the materials are under exam using ground-test facilities for the environment of thermal cycle, ultraviolet irradiation, electron irradiation, and creep.

The residual vibration of reflector, which is attributed to the swift switching attitude maneuver, is evaluated, and the accuracy depends on the flexible structure analysis, which includes all of the structure such as deployable booms, gimbal adjuster mechanism, deployable modular back-trusses, and reflector surface.

The RF performance and the design appropriateness of the proposed paraboloidal mesh reflector with quasi-trapezoidal facet should be verified in the high-frequency region used in the radio astronomy. A mesh reflector of 1.5m in diameter, which is a 3/8-scale model and has the same metal fabric mesh and CFRP ribs as the planned flight model, has been tested in a compact range test site with 43GHz feed horn. The compact range test site provides an approximately far-field condition. The obtained RF field patterns, when fed by vertically polarized wave and horizontally polarized wave, showed good correspondence with the EMF (Electro Magnetic Field) analysis, respectively. The obtained gain in the test also showed a reasonable value, when the photogram metrically measured surface shape and the previously measured sample mesh loss were taken in.

![Fig. 4. Differences between two modular mesh reflectors.](image)
4. On-board Observation Instruments

The low noise receivers are another key instruments for the high sensitivity of ASTRO-G. An uncooled receiver for 8 GHz band, and cryogenically cooled receivers for 22 GHz band and for 43 GHz band in both LHCP and RHCP, are installed. We use the Staring cycle refrigerator for 22 and 43 GHz band, which will be developed for AKARI (ASTRO-F: infrared astronomy) mission, and we can achieve the physical temperature of around 30 K.

The frequency of the amplified signal at 22 GHz and 43 GHz bands are down converted to the range of IF (intermediate frequency) signal of 6.6-8.8 GHz. The backend of ASTRO-G has 2 sampling channels, and 2 signals out of 6 signal source (3 bands and 2 polarizations) are selected. The IF signals are downconverted again to the baseband frequency of 1.1 GHz. ASTRO-G has 2 sampling modes, which are 2bit/sample, 256 Msps/channel (i.e. 128 MHz / channel), or 1 bit/sample, 512 Msps/channel. The former will be used for the normal observation, the latter is used for ground VLBI telescopes to record the data with 2 bit/sample, 512 Msps/channel for higher sensitivity. Total data rate is 1 Gbps for both modes.

5. Phase Transfer Uplink and Wide Band Data Downlink

The tone signal of 40 GHz refering to the highly stable atomic oscillator (Hydrogen Maser) is sent from the ground station to the satellite. The frequency conversion, A/D sampling, and the carrier of the down link signal are synchronized with referring to this uplink signal.

The observation data with the data rate of 1 Gbps is modulated with QPSK (Quadrature Phase-Shift Keying) scheme and send to the ground with the on-board 80- cm high gain antenna. The frequency band used for the 1 Gbps VLBI data link is 37–38 GHz band. Both up and downlink frequency are allocated for space research system. General description of the space VLBI system is also shown in the ITU recommendation SA.1344.

The link budget for downlink is satisfied with using 10-15 meter antenna of the link stations VLBI data. The wide bandwidth of the data and the usage of higher frequency make the link budget very severe in rainy condition. The data sent to the link station is demodulated. The receiver data is recorded on VLBI recording terminal, (or is sent to the wide band network system), and finally sent to the correlator. Total amount of data will be about 3 T bytes with the 7 hours tracking time.

ASTRO-G cannot store the VLBI data in the satellite. International network of the link station is required for the effective observation. Three or from link stations are required to obtain the 70 – 80 % of observation time. One of the tracking stations will be located in Usuda, Japan. The effort to obtain more tracking station is actively on – going.

6. Phase-Referencing Observation

Millimeter-wave Space VLBI observations will be a frontier in astrophysics. On the other hand, there is a difficulty in terms of the stability of terrestrial VLBI observables mainly due to the turbulent Earth’s atmosphere: all the errors included in VLBI cross-correlated phase, or fringe phase, except for due to the ionosphere is non-dispersive and proportional to the observing frequency. Although celestial radio waves received on ASTRO-G are not affected by the atmosphere, the fringe of a space baseline (a combination of orbiting and terrestrial telescopes) suffers from the atmospheric phase fluctuations because one of the elements is inevitably a terrestrial telescope.

To mitigate the fringe phase fluctuations in Space VLBI, phase referencing was proposed for ASTRO-G: a scientifically interesting celestial target source is observed with an adjacent strong celestial source as a reference calibrator with fast antenna pointing changes in order to compensate for any rapid phase fluctuations due to the atmosphere\(^5\). Figure 5 shows a schematic drawing of a phase referencing observation with ASTRO-G. One observation period from the beginning of the calibrator scan, then the

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Target allocation [mmRMS]</th>
<th>Corrective Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear approximation error of facet</td>
<td>0.12</td>
<td>Analysis Reduction of facet size</td>
</tr>
<tr>
<td>Pillow deformation error of facet</td>
<td>0.05</td>
<td>Substantial proof Reduction of facet size, experimental proof based upon model</td>
</tr>
<tr>
<td>Assembly and adjustment error of a single module</td>
<td>0.25</td>
<td>Analysis Structural optimization of rib rigidity distribution and position of tie cable</td>
</tr>
<tr>
<td>Assembly and adjustment error due to module connection</td>
<td>0.20</td>
<td>Analysis Achievable by each module Adjustment and inter – module connecting method</td>
</tr>
<tr>
<td>Zero-G cancellation error</td>
<td>0.02</td>
<td>Analysis Nonlinear analysis at module</td>
</tr>
<tr>
<td>Repeatability of</td>
<td>0.15</td>
<td>Estimation Repletion test and module adjustment</td>
</tr>
<tr>
<td>Deformation due to</td>
<td>0.10</td>
<td>Analysis Analytical compensation</td>
</tr>
<tr>
<td>Measurement deviation</td>
<td>0.10</td>
<td>Substantial proof Measurement test</td>
</tr>
<tr>
<td>Total error</td>
<td>0.40</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Surface error causes and expected distribution at BOL.
target scan and return to the beginning of the calibrator scan, is referred to as the switching cycle time. In the phase referencing calibration, subtraction is made between fringe phases of the target and calibrator to cancel out the fringe phase errors when the switching cycle time is short enough and the calibrator is closely located to the target. Phase referencing can also remove long-term phase drifts due to geometrical errors and smoothly variable atmospheric delay errors, as well as any instability of the independent frequency standards.

The effectiveness of the ASTRO-G phase referencing is dependent on the separation angle between the celestial sources, switching cycle time, the orbit determination error of ASTRO-G, and so on. The typical parameters of the phase reference observation are the separation angle of $2^\circ$ and the switching cycle time of 60 s. It is noted that, if the orbit determination error is cm-order, the fringe phase error due to the Orbit determination error is comparable to the others. According to Space VLBI observation simulations, 10-cm orbit determination accuracy means the scientific full success to be achieved with ASTRO-G.

7. Fast Rest – To – Rest Attitude Maneuver

7.1 Configuration of attitude control actuators

To carry out the switching maneuver, some attitude control components must be selected carefully. A first unusual requirement is the amount of torque. Switching maneuver requires torque of more than 10[Nm]. However, such amount of torque cannot be generated by usual reaction wheels. The power to accelerate or decelerate the wheel is proportional to the product of rotor speed and the rotor torque.

For example, to generate rotor torque of 1[Nm] at 3000[rpm] requires power more than 300[W], and it is not acceptable from the view point of system configuration. For such large torque application, controlled momentum gyros (CMGs) are often used. The output torque vector $T$ of CMG can be calculated with

$$T = \omega \times H,$$

where $H$ is the angular momentum of the CMG rotor, and $\omega$ is the angular velocity of the gimbal. The advantage of the CMG is its relatively low power consumption compare to the wheel to output the same torque, and the disadvantage is that the direction of output torque vector varies with gimbal motion. Therefore, steering low typically using 4 CMGs is studied extensively, however, the ASTRO-G satellite takes another strategy.

As mentioned above, one of the main requirements for the ASTRO-G satellite is the switching maneuver capability. Basically this is a repetitive maneuver around one axis, therefore the gimbal axis of all CMGs on the ASTRO-G satellite can be parallel (Fig. 6). Since the z-body axis is the direction of the antenna directivity, the CMGs’ gimbal axis should be aligned to this axis. In this case, the axis of switching maneuver can be set on any direction in the $x$-$y$ plane. For this configuration, minimum number of CMGs is two, not four, thus the resources can be reduced.

Since CMGs’ output torque is always in some direction on the $x$-$y$ plane, z-axis torque should be generated deliberately to design a system using CMGs. Therefore, four reaction wheels are also equipped on the satellite, to provide usual attitude control capability and z-axis torque.

7.2 Appropriate gyroscopes for agile attitude maneuver

To achieve agile attitude maneuver, requirements for gyroscopes are as follows;

- the range of rate detection should be wide enough,
- the scale factor should be stable enough.

Several types of gyroscopes could have capability for these requirements. However, we expect that fiber optical gyroscopes (FOGs) have some advantages, especially its high scale factor stability. Table 3 shows the expected performance of a FOG under development.

<table>
<thead>
<tr>
<th>Random walk strength</th>
<th>$&lt; 0.0005 <a href="1%5Csigma">\text{deg} \sqrt{\text{h}}</a>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias instability</td>
<td><a href="1%5Csigma">$\text{deg/h}</a>$</td>
</tr>
<tr>
<td>Scale factor stability</td>
<td>[ppm] $(3\sigma)$</td>
</tr>
</tbody>
</table>
7.3 Attitude control law for agile and flexible satellite

7.3.1. Flexible structure of the satellite

There are several satellites with agile attitude maneuver capability, and usually the satellite configuration is rather rigid in such satellites. However, the ASTRO-G satellite must have large deployable reflector (LDR), and with no doubt it comes to be a flexible structure. Large solar array panel (SAP) is also another flexible structure. Therefore, the ASTRO-G satellite is required to achieve agile attitude maneuver against these flexible structures, and it is a challenging requirement. The detailed design of LDR and SAP is still ongoing, and now we assume that the lowest resonant frequency should be higher than 0.25 [Hz], in the fixed-free satellite dynamics. Figure 7 shows an example of the satellite dynamics. In the next section, our basic strategy for this issue is described.

7.3.2. Strategy for the flexible modes

One of the important parts of our strategy is not to excite flexible modes. The main issue on this aspect is how to prepare a plan or time profile of attitude maneuver, taking account of the flexible modes and maneuvering time. For example, if bung-bung type torque profile is applied, it minimizes the maneuvering time, however, flexible modes are excited at most. Some very conservative profile will not excite the flexible modes, but the maneuvering time will exceed the requirements.

Another important issue is the design of feedback controller. One possible approach is to design the feedback controller assuming that the plant is rigid. In this approach, the control bandwidth should be much lower than the lowest frequency of flexible modes. Advantage of this approach is its simplicity of the controller design and implementation, and disadvantage might be its relatively low robustness, against the parameter change or disturbance. Therefore, “rehearsal” switching maneuver will be carried out, in advance to the observation with switching maneuver. The parameters for maneuver profile or torque input will be adopted to achieve the appropriate switching maneuver. Another possible approach is to design a controller with taking account the flexible mode of the plant. In this case, even unpredictable disturbance could be suppressed with feedback controller.

The profiler design and the feedback controller design, could be merged into total control system. Figure 8 shows an example to combine some profiler and feedback controller in 2 degree-of-freedom (2 DOF) manner. In the following parts of this sections novel maneuver profile method proposed for the ASTRO-G satellite, is introduced. Then some studies about the feedback controller are also introduced.

7.3.3. NME Profiler: novel robust profile method

The NME profiler, or nil mode excitation profiler, is newly proposed for the ASTRO-G satellite \(^6\). There are so any studies on a profile or a input shaper, which do not excite flexible mode, such as input shaping, ZV shaping, ZVD shaping and so on \(^7-9\). One of the significant aspects of the NME profiler is its frequency components. In usual input shaper are designs its individual component at each specified frequency, typically each frequency of flexible mode. The concept of the NME profiler is, as its name indicates, to eliminate all components above some frequency. This characteristic is clearly shown in Fig. 9. Thus compared to other input shapers, the NME profiler is thought to be more robust to the uncertainty of the flexible modes’ frequency.

The basis of the NME profiler is the combination of two sinc functions, or two sampling functions,

\[
y(t) = A \left( \frac{\sin(\omega(t - t_1))}{\omega(t - t_1)} - \frac{\sin(\omega(t - t_2))}{\omega(t - t_2)} \right). \tag{2}
\]

The frequency characteristic of this \(y(t)\) is plotted in Fig. 9 as "combined sampling function", and the time response is also plotted in Fig. 10. These graphs indicate that if this \(y(t)\) is used as a profile of the maneuver torque, smooth acceleration and deceleration will be achieved. The remaining problem is the residual oscillation as shown in Fig. 10, which continues forever. Thus a window function is applied to Eq. (2), to

![Fig. 7. Example of plant dynamics (singular values).](image7)

![Fig. 8. Block diagram of 2-DOF control scheme.](image8)

![Fig. 9. Sample function (frequency characteristic).](image9)
terminate the acceleration or deceleration.

One major drawback of the NME profiler is its relatively slow slew motion. Robustness and agility are always in trade-off, generally speaking, and the NME profiler pays much attention on the robustness.

7.3.4. Robust feedback control approach

The discussion in the previous subsection was about input shaper, or a block indicated with $R(s)$ in the block diagram of Fig.8. Then this subsection follows the discussion on the block $C(s)$, a feedback controller. One of possible approaches is to design $C(s)$ with Hinf method. To balance the robustness and the agility, lower flexible modes should be included in the nominal plant model. Another possible approach is use PD or PID controller with profiler, such as lead-lag filter. These two types of controllers or another one \cite{11} are now designed, evaluated, and compared. Also other approaches are considered.

8. Precision Orbit Determination (POD)

8.1 POD strategy

The Orbit determination error with conventional Range & range-rate measurements will exceed the required level here by two to three orders of magnitude. The typical orbit determination accuracy of the HALCA satellite was 2 to 5 m by use of Doppler measurements of phase-transfer data-link at Ku-band. In the ASTRO-G mission, GPS navigation technique was proposed for ASTRO-G’s POD \cite{12,13}. ASTRO-G will be equipped with a GPS receiver system to acquire GPS observables (pseudorange and carrier phase). GPS navigation for low-Earth-orbit satellites has been widely studied. The POD with a few cm accuracy has been reported for GRACE (Gravity Recovery And Climate Experiment), and CHAMP (CHAllenging Minisatellite Payload). For ASTRO-G, however, the GPS navigation has some difficulties. One of them is the attitude control. The main purpose of the ASTRO-G satellite is to observe celestial radio sources together with terrestrial VLBI telescopes, so that there is not a specific plane on ASTRO-G directing to the GNSS constellations, and the attitude fixed in the inertial frame lasts for longer than several hours. Therefore ASTRO-G onboards four GPS antennas to receiver GPS signals from all the direction. Another difficulty comes from its HEO: when the altitude is higher than 3500 km, the satellite will be outside of the illumination of the main beam of a given GPS Space Veficle (SV), so that it is hard to receive the GPS signals at the higher altitudes. Therefore, we introduce the SLR system to strengthen the POD together with the GPS navigation.

8.2 Space laser ranging (SLR)

The visibility simulations \cite{13} showed that the number of tracked GPS SVs is not enough to obtain GPS bservables at the higher altitudes. To strengthen the POD, the ASTRO-G satellite will be equipped with SLR array to measure the round trip time of a laser beam from an SLR station to ASTRO-G. Figure 11 shows a preliminary design of SLR array. The SLR will assist the POD when the GPS observables are unable to provide stable navigation data. The accumulated SLR measurements will be used for the POD together with the GPS observables, although SLR has hardly ever used for an HEO.

Since there is no specific plane on the ASTRO-G body directing to the Earth, SLR array will be installed aside Ka ANT parabola dish. Since the SLR stations will not be constructed close to an SLR station, rather large distributed incident angles to SLR array must be taken into consideration. SLR array has a three-dimensional design mainly consisting of two regions: an inner region with the center 6 tilted retroreflectors is designed for the low altitudes and large distributed incident angles, and an outer region with 28 retroreflectors to form a flat and large aperture is designed in order that laser photons will be returned for the higher altitudes in small distributed incident angles. SLR will be used as a complement to the GPS at the middle-to-high altitude. SLR operational supports in a global network of observation stations under International Laser Ranging Service (ILRS) is very essential for ASTRO-G’s POD.

8.3 Expected POD accuracy

POD simulations for ASTRO-G based on the above strategy were reported for the following two cases: by use of the GPS observables, and by use of both the GPS observables and SLR measurements \cite{14}. The simulation conditions reported in \cite{10} are as follows:
- In the simulations, GPS SVs’ visibility has a simple
criteria whether ASTRO-G passes in the main beam of a
given GPS SV (except for ones which are hidden by the
Earth),
- the accuracy of the pseudorange and carrier phase is 3
m and 10 cm, respectively;
- 30-min SLR pass segments are repeated three times at
around the mid altitudes per one orbit;
- the accuracy of the SLR measurements is 6 cm.;
- the covariance analyses were made to estimate the orbit
determination accuracy.

The reconstructed orbits were generated for continuous
two orbits, and 1- s error ellipsoids in a satellite fixed
coordinate with radial, along track, and cross track
components were estimated. The simulation results show a
tendency that, the higher the altitude is, the larger the error
ellipsoid is. In the OD simulate
on only with the GPS observables the error ellipsoid at
the perigee is 1 to 3 cm for all the components, while the
ellipsoid at the apogee is 1 to-2 cm for the radial, 4 to 5 cm for
the cross track, and 12 cm for the along track component. On
the other hand, if the SLR observations are included in the OD
as well, the along track component was significantly improved
and shortened to-7 cm. The combined method using the GPS
navigation and the SLR is promising for ASTRO-G’s POD
even if full-time tracks of the GPS observables and/or the SLR
pass segments are not expected.

The above simulation results encourage
us. However, we have to note that, in the simulations,
perturbations related to non-gravitational accelerations are
considered to be involved in the GPS observables and SLR
measurements. Since an area-mass ratio of the ASTRO-G
satellite is enormously large due mainly to LDR and SAP, the
perturbations are no longer negligible, and the incomplete
dynamical models will cause erroneous reconstructed orbit.
To achieve the required POD, the non-gravitational
accelerations shall be modeled with an accuracy of $10^{-7}$
to $10^{-10}$ m/s². Solar Radiation Pressure (SRP) causes one of the
most significant accelerations, and it is estimated to be the
order of $10^{-7}$ m/s². Its model uncertainty considerably affects
the POD accuracy because it always accelerates the satellite
for all the trajectory unless ASTRO-G goes into the Earth
down. Note that Earth Radiation Pressure (ERP) and
atmospheric drag significantly perturb the orbit at around the
perigee, although the effects are not so severe because those
are effective only in a short period. The order of the
accelerations caused by such perturbations listed in Table 4. A
satellite shape model has been developed by using 256-
polygons in order to estimate the effects of the SRP and ERP
with a ray tracing technique. It is hard but important to
develop the dynamical model of the ASTRO-G body for the
POD to meet the mission requirements.

9. Summary

Space VLBI (very long baseline interferometry) mission,
ASTRO-G, will be launched in 2013 by Japan Aerospace
Exploration Agency (JAXA). ASTRO-G is a follow-on
mission of HALCA (VSOP) mission in 1990s, which was the
world first space VLBI mission. ASTRO-G will consists of a
huge synthetic aperture with diameter of 35,000Km together
with radio antennas in the ground. They will achieve the world
highest angular resolution by means of 43 GHz observation.

This paper describes the advanced key technologies of
ASTRO-G such as the 9m deployable antenna with very
accurate surface the fast rest – to - rest attitude maneuver, and
the precision orbit determination about NAVSTARs’ orbit.
These advance technologies will lead ASTRO-G mission to
the astronomical observation with the world highest angular
resolution.

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