A Study on Medium Earth Orbit Utilization

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The Medium Earth Orbit (MEO) offers a greater width of satellite view than the Low Earth Orbit, and a greater proximity to the Earth’s surface than the Geostationary Earth Orbit. Global positioning systems and ionospheric sounding satellites have already operated in this orbit, and the MEO will appeal to satellite missions undertaking Earth observations, communications, positioning, and scientific explorations. The Sun-Synchronous Medium Earth Orbits (SS-MEOs) used in this study enable clear and daily observations of the Earth’s surface. However, problems such as severe radiation from the Van Allen radiation belt, and the inefficiency to launch a satellite in a southwest direction, need to be resolved. This paper presents the results of early studies on SS-MEO utilization: orbital characteristics and environments, candidates for Earth observation missions, and the feasibility of the development and launch of a satellite for operation within this orbit.

Key Words: Medium Earth Orbit, Sun-Synchronous, Van Allen Radiation Belt

1. Introduction

This paper describes the results of a study examining Medium Earth Orbit (MEO) utilization. Previous use of the MEO has been minimal, due to intense radiation emanating from the Van Allen radiation belt.

This study clarifies the orbital candidates, the mission candidates, and the system feasibility for the MEO. Although the previous studies on the usage of the MEO have adopted elliptical orbits or higher orbits without sun-synchronicity, this study focuses on the Sun-Synchronous Medium Earth Orbit (SS-MEO) which enables clear and daily observations of the Earth’s surface for the first time.

Two papers accompany this work. “Conceptual study on earth observation missions for Medium Earth Orbit Satellite,” describes the mission study for Earth observations using the SS-MEO, and the paper entitled “Study on effects of medium earth orbital environment on satellite system and their countermeasures,” describes the study of a satellite system used for the SS-MEO.

2. Outline of Study

2.1. Investigation strategy

JAXA develops satellite missions for Earth observations, communications, and positioning using the Earth’s orbits. Previously, the Low Earth Orbit (LEO; less than about 1,000 km altitude) and the Geostationary Earth Orbit (GEO; 36,000 km altitude) have been used for such missions. The super-low-altitude orbit lower than the LEO, and the MEO which lie between the LEO and the GEO, are rarely used except by certain missions. Figure 1 shows the heights of these orbits.

An atmospheric drag in the super-low-altitude orbit and a high radiation environment in the MEO present problems for satellite utilization. If these issues could be resolved through technical developments, these orbits could be utilized proficiently.

JAXA is developing the Super Low Altitude Test Satellite (SLATS) for exploitation of the super-low-altitude orbit. JAXA has now also initiated studies for the use of the MEO.

2.2. Features of MEO

The MEO has the following merits:

(1) Compared with the LEO, it is relatively easy to achieve a wide field of view from a satellite.

(2) Compared with the GEO, the performance requirements of the mission equipment are moderated by the use of a lower altitude.

Even if there is an expansion of the mission view of an Earth observation or communication satellite, the performance degradation of the side parts is minimal, because the angle of incidence of the MEO is less than that of the LEO, as shown in Figure 2. Due to this advantage, daily global observations...
would be possible using a single MEO satellite according to the preliminary analysis in this study.
Additionally, it would be possible to test experimental mission equipment used for the GEO in a MEO satellite.

However, the use of the MEO includes the following disadvantages:

(3) Depending on the orbital altitude, the satellite experiences a severe radiation environment.

(4) Depending on the orbital altitude and the orbital angle of inclination, the cost of the satellite launch increases.

A satellite operation that encounters the effects of severe radiation from the Van Allen radiation belt needs a design that can withstand high levels of radiation. This increases the weight and the cost of a MEO satellite.

The cost of the satellite launch increases because of the particularity of a launch to the MEO, (and in particular the SS-MEO), which tends to deteriorate the launch capability according to the preliminary analysis in this study.

Based on the above-mentioned advantages and disadvantages, a study for MEO utilization should involve the following:

(a) It is necessary to obtain a mission value that offsets the above-mentioned financial disadvantages.

(b) It is necessary to analyze the orbital environment and the practicality and efficiency of a radiation-proof design.

(c) An orbital design that achieves a good balance between (a) and (b) is required. (If an orbit is designed only for the advantages of the orbital environment, the mission values may be affected negatively.)

In order to optimize the scope of this first study of MEO utilization, the baseline and optional orbits that met the mission values of Earth observations were designed, and the system feasibility was studied based on these orbits.

2.3. Baseline orbits

Table 1 shows the specifications of the baseline and optional orbits for this study. The baseline and optional orbits were designed for samples of around 4,000 km and 3,000 km altitudes, respectively. These are SS-MEOs with sun-synchronicity, and each combination of the altitude and the inclination was adjusted for the recurrent orbit (the number of revs to repeat is an integer).

These two SS-MEOs with different altitudes were designed in order to compare their Earth observation performances and radiation environments. Figure 3(a) and (b) show the ground tracks and visible ranges from a Japanese ground station of them.

<table>
<thead>
<tr>
<th>Orbital candidates of SS-MEO</th>
<th>Orbital Parameters and Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Orbit</td>
<td>Altitude: 4,184 km</td>
</tr>
<tr>
<td></td>
<td>Inclination: 125 deg.</td>
</tr>
<tr>
<td></td>
<td>Number of Revs to Repeat: 8</td>
</tr>
<tr>
<td></td>
<td>Ground speed: 4.0 km/sec</td>
</tr>
<tr>
<td>Optional Orbit</td>
<td>Altitude: 2,720 km</td>
</tr>
<tr>
<td></td>
<td>Inclination: 110 deg.</td>
</tr>
<tr>
<td></td>
<td>Number of Revs to Repeat: 10</td>
</tr>
<tr>
<td></td>
<td>View angle for Japanese mainland Observing: ± 8.4 deg.</td>
</tr>
<tr>
<td></td>
<td>Ground speed: 4.8 km/sec</td>
</tr>
</tbody>
</table>

Fig. 3(a). Ground track of Baseline Orbit.

Fig. 3(b). Ground track of Optional Orbit.

3. Mission Study

3.1. Earth observation missions using SS-MEO

The outcome of this study suggests a number of applications for Earth observation missions and lists the following potential mission candidates for the SS-MEO:

- Agricultural observation
- Forest observation
- Ocean observation
- Air pollution observation
Table 2 shows a summary of the above mission candidates. Point 2.2.(1) above relates to agricultural, forest, and ocean observation missions, whereas 2.2.(2) above relates to mission candidates such as air pollution observations.

### Table 2. Summary of mission candidates for use of SS-MEO.

<table>
<thead>
<tr>
<th>Mission Category</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural observation</td>
<td>Survey of paddy fields and rice growing conditions.</td>
</tr>
<tr>
<td></td>
<td>• Repetition of observations: several times weekly</td>
</tr>
<tr>
<td></td>
<td>• Spatial resolution: 10 m</td>
</tr>
<tr>
<td>Forest observation</td>
<td>Detection of wildfires and estimate of global forestry biomass.</td>
</tr>
<tr>
<td></td>
<td>• Repetition of observations: daily</td>
</tr>
<tr>
<td></td>
<td>• Spatial resolution: 200 m (for forest fires)</td>
</tr>
<tr>
<td>Ocean observation</td>
<td>Forecasting and management of variation in fishery resources. Measurement of velocities and directions of ocean wind.</td>
</tr>
<tr>
<td></td>
<td>• Repetition of observations: daily</td>
</tr>
<tr>
<td></td>
<td>• Spatial resolution: 250 m</td>
</tr>
<tr>
<td>Air pollution observation</td>
<td>Technical development and demonstration of atmosphere and weather observations.</td>
</tr>
<tr>
<td></td>
<td>• Repetition of observations: once every few hours (original requirement; impossible without GEO)</td>
</tr>
<tr>
<td></td>
<td>• Spatial resolution: 10 km (horizontal)</td>
</tr>
</tbody>
</table>

In the case of agricultural observations, new design and manufacturing technologies may be required in order to incorporate both a wide-angle view and a high spatial resolution within the mission instruments.

This is described in detail in the paper entitled “Conceptual study on earth observation missions for Medium Earth Orbit Satellite.” 2)

### 3.2. Other satellite missions using MEO

As well as those mentioned in Section 3.1, other mission candidates with a potential for benefiting from the use of the MEO (including orbits other than that of the SS-MEO) include:

- Meteorological observations using a satellite constellation (under concept study by NOAA-JPL).
- Communication services using a satellite constellation (under deployment by O3b Networks).
- Arctic positioning interpolation services using two elliptical polar orbit satellites.
- Daily updates of the base map of Japanese land.
- Upper atmosphere Earth observations.

The meteorological observation concept of NOAA-JPL (orbital altitude candidate: 10,400 km) 1) and the communication service of O3b Networks (orbital altitude: 8,062 km) have adopted the orbital altitudes which avoided the inner and the outer Van Allen radiation belts, differently from the SS-MEO of this study.

### 4. System Study

#### 4.1. Geometric features of SS-MEO

In order to analyze the features of Earth observations that use the SS-MEO, the baseline orbit, the optional orbit, and a typical Sun-Synchronous Low Earth Orbit (SS-LEO) were compared in this study, using “Systems Tool Kit (STK)” supplied by Analytical Graphics, Inc.

(a) Baseline Orbit of SS-MEO (shown in Table 1)
(b) Optional Orbit of SS-MEO (shown in Table 1)
(c) Typical SS-LEO (altitude: 803 km, inclination: 99 deg., number of Revs to Repeat: 57)

(1) Advantages compared to SS-LEO

The essential advantage of the SS-MEO is the possibility of observation conditions near the nadir view at both ends, (e.g., the optical characteristics of observed objects, and the degradation of horizontal resolution), even if a wide view angle is taken.

Figure 4(a) and (b) show the sight analysis results of the relationships between observation swaths and angles of incidence (AOIs; shown in Figure 2) in this study. Each additional vertical line of Figure 4(a) and (b) shows the full-coverage condition of the observation swath in a day for each orbit.

In the case of daily global observations, the AOI of each orbit is derived from Figure 4(a) and (b) as follows:

- Baseline Orbit (altitude: 4,184 km)  AOI: 39 deg.
- Optional Orbit (altitude: 2,720 km) AOI: 47 deg.
- Typical SS-LEO (altitude: 803 km)  AOI: 68 deg.

(in descending order of advantage)
(2) Disadvantages compared to SS-LEO

One of the disadvantages of the SS-MEO is the inability to observe the polar regions. This is because the orbital inclination of the SS-MEO is larger than that of the SS-LEO’s, in order to maintain sun-synchronicity.

According to the orbital inclination, the observation bound of latitude for each orbit is as follows:

- Baseline Orbit (altitude: 4,184 km)  Bound of Lat.: ± 55 deg.
- Optional Orbit (altitude: 2,720 km)  Bound of Lat.: ± 70 deg.
- Typical SS-LEO (altitude: 803 km)  Bound of Lat.: ± 81 deg.

( in descending order of the disadvantage)

Another disadvantage of the SS-MEO is an increase in the local time gap between observed objects. For example, when an orbit is designed for the local sun time (LST) 10:30 on the equator, the LST of Tokyo for each orbit is as follows:

- Baseline Orbit (altitude: 4,184 km)  LST on Tokyo: 12:32.
- Optional Orbit (altitude: 2,720 km)  LST on Tokyo: 11:31.
- Typical SS-LEO (altitude: 803 km)  LST on Tokyo: 10:55.

( in descending order of disadvantage)

A mission that can exploit the advantages, and is not compromised by the disadvantages listed above, is considered to be a suitable candidate for the SS-MEO.

4.2. Feasibility of orbital injection for SS-MEO

Table 3 shows the flight analysis result of the injection capabilities of the Japanese launch vehicle H-IIA into the SS-MEO. Since JAXA has not launched into an orbital altitude with an inclination such as the SS-MEO, the values of Table 3 were estimated based on the following conditions in this study:

- Flight path: Direct injection into the SS-MEO.
- Launch faring: 4 m diameter.
- Launch season: Summer.
- Launch range: Tanegashima Space Center Osaki Range (the restrictions of an initial azimuth angle and visibility of downrange stations are not included).

Table 3. Estimated injection capabilities of H-IIA into SS-MEO.

<table>
<thead>
<tr>
<th>Orbital candidates of SS-MEO</th>
<th>Estimated injection capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Orbit</td>
<td>H-IIA202: approx. 1.0 tons</td>
</tr>
<tr>
<td>Altitude: 4,184 km</td>
<td>H-IIA204: approx. 1.5 tons</td>
</tr>
<tr>
<td>Inclination: 125 deg.</td>
<td></td>
</tr>
<tr>
<td>Optional Orbit</td>
<td>H-IIA202: approx. 3.3 tons</td>
</tr>
<tr>
<td>Altitude: 2,720 km</td>
<td></td>
</tr>
<tr>
<td>Inclination: 110 deg.</td>
<td></td>
</tr>
</tbody>
</table>

A launch method involving the injection of the H-IIA into an elliptical orbit followed by the injection of the satellite into the SS-MEO could possibly improve the net mass of the satellite. However, in this study, the only conditions of a direct injection by the H-IIA into the SS-MEO were estimated.

4.3. Radiation environment in SS-MEO

A satellite that moves within the SS-MEO is exposed to a high radiation environment, mainly from high-energy protons, because the orbit is located within the inner belt (2,000 - 5,000 km above the equator) of the Van Allen radiation belts.

Figure 5 shows the Integral Linear Energy Transfer (LET) spectra of the SS-MEOs calculated with CREME96 5,6) model. In this calculation, the “solar minimum phase” and the “stormy” geomagnetic conditions were applied as the worst case calculation.

According to this analysis result, a SS-MEO satellite would be affected by more than ten times the amount of radiation that affects the SS-LEO.

Figure 6 shows the relationships between the aluminum shield thickness and the total radiation dose from within the SS-MEOs obtained by SHIELDOSE-2 7) calculation code. In this calculation, the shield geometry was assumed as full sphere. According to this analysis result, a SS-MEO satellite will need more than ten times the amount of shield thickness than a SS-LEO satellite.
When considering countermeasures against the radiation environment in the design of electronic components for a SS-MEO satellite, it is necessary to consider not only the total dose effect, but also the single event effect and the displacement damage.

4.4. Feasibility of satellite design for SS-MEO

This study of the systems discovered that most of the electronic components, photovoltaic cells, power harnesses, and optical attitude sensors of the satellite system, together with the detectors and optical lenses used in the Earth observing instrument, will be negatively affected by the high radiation environment of the SS-MEO. However, it was also discovered that countermeasures for the adverse effects would be possible with the use of radiation shields and radiation-proof parts. Such radiological countermeasures adversely influence the costs of the satellite development and launch.

No other disadvantages of operating in this orbit were found, except for a degradation of the GPS positioning accuracy.

The paper entitled “Study on effects of medium earth orbital environment on satellite system and their countermeasures,” 3) describes the satellite system study in detail.

4.5. Additional study: elliptical SS-MEO

The “Elliptical SS-MEO” shown in Table 4 and Figure 7 was designed as an additional radiological countermeasure in this study. The combination of the semi-major axis, the inclination, and the eccentricity of this orbit was adjusted for the sun-synchronous, recurrent, and fixed “Argument of Perige” orbit.

By using this orbit, the estimated effects of the orbital radiation environment could be approximately halved, because the Elliptical SS-MEO avoids the centers of the inner and the outer Van Allen radiation belts.

Table 4. Elliptical SS-MEO designed in this study.

<table>
<thead>
<tr>
<th>Orbital candidates of SS-MEO</th>
<th>Orbital Parameters and Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elliptical SS-MEO</td>
<td>Altitude at Apogee: 7,839 km</td>
</tr>
<tr>
<td>• Sun-Synchronous recurrent orbit</td>
<td>Altitude at Perige: 523 km</td>
</tr>
<tr>
<td></td>
<td>Inclination: 117 deg.</td>
</tr>
<tr>
<td></td>
<td>Eccentricity: 0.35</td>
</tr>
<tr>
<td></td>
<td>Number of Revs to Repeat: 8</td>
</tr>
</tbody>
</table>

5. Conclusion

This study clarified the orbital candidates, the mission candidates, and the system feasibility for the MEO as follows:

• Earth observation mission candidates for use of the SS-MEO, together with other mission candidates were determined, and the outlines of mission coverage and characteristics of the MEO were clarified.

• The MEO with sun-synchronicity (SS-MEO) orbital candidate was examined and the observing conditions and the feasibility of a satellite launch were clarified. The Elliptical SS-MEO was developed as a suitable alternative to the SS-MEO.

• The adverse effects of the orbital radiation environment on a SS-MEO satellite and the corresponding countermeasures were clarified.

The utilization and the technical feasibility of the MEO missions were clarified based on the above-mentioned results. However, in order to clarify the mission feasibility and the project feasibility, the following additional studies are required:

• A mission demand survey and requirement analysis.

• A redesign of the orbital candidates for mitigation of the radiation environment.

• A physical design study of the mission instruments and the satellite system.

In the above-mentioned physical design study, it would be possible to minimize the volume of electronic components by adopting active heat transfer technologies, as a weight saving method for the radiation shield.

Acknowledgments

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References


6) https://creme.isde.vanderbilt.edu/