ORBIT OPTIONS FOR AN INTERFEROMETRIC ASTROMETRY MISSION

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ABSTRACT

In this paper the following orbit options for an interferometric astrometry mission are described: (a) a geostationary orbit, (b) a triangular libration point in the Earth-Moon system, and (c) a colinear libration point L1 in the Earth-Sun system. The considerations presented here are of a preliminary nature. The final choice of the orbit can only be made after a careful trade-off among the many parameters and aspects involved addressing scientific, technical and cost issues.

Key words: space astrometry, GAIA, orbit selection, geostationary orbit, libration point orbits

1. INTRODUCTION

The objective of the interferometric astrometry mission is to measure with 10 microarcsec accuracy the position and parallax of more than 50 million stars up to magnitude 15. Similarly, the proper motion should be determined with an accuracy of 10 microarcsec per year. In comparison with the successful Hipparcos mission the accuracy requirements have been increased by a factor of 100.

This mission has been proposed as one of the candidates for Horizon 2000+ under the name GAIA (Global Astrometric Interferometer for Astrophysics, Lindegren & Perryman 1994, 1995). Similar to Hipparcos, the celestial sphere should be several times completely scanned in a uniform manner during the nominal mission lifetime. While in Hipparcos the rotation axis was kept at a fixed angle of 43°, for GAIA a slightly larger value (53°) has been proposed. The period of rotation is about three hours, corresponding to about 120 arcsec/s for the motion of the star images across the field.

The stringent attitude requirements will impose constraints on the design of the spacecraft. Movable parts or liquids within or on the spacecraft are excluded (e.g., no fuel sloshing). As consequence, orbit manoeuvering capability in the operational orbit will be very limited, since only cold gas systems can be envisaged.

Also, the shape of the spacecraft should, as far as possible, be symmetrical with respect to the direction to the sun in order to minimize attitude torques caused by solar radiation pressure. In order to avoid disturbing torques caused by solar radiation pressure, Høg (1995) suggests placing the spacecraft behind a sun-shield. This idea is intriguing, but it poses some formidable engineering challenges, since the spacecraft is slowly rotating, and spacecraft and sun-shield have to be somehow mechanically connected. The mechanical connection, however, must not disturb the attitude motion of the spacecraft. A simpler solution, but still of considerable complexity, could be a free-flying sun-shield controlled with field emission electric propulsion (FEEP).

2. REQUIREMENTS AND ASSUMPTIONS

The orbital requirements are as follows:

(1) atmospheric and terrestrial interference should be avoided as far as possible (radiation belts, atomic and molecular contamination, atmospheric torques, etc.);

(2) stable thermal environment, with minimum eclipses;

(3) low cost: the major cost elements to be considered are (a) launch vehicle, (b) spacecraft, and (c) operations including ground facilities;

(4) orbit control in the operational orbit should not require large Δv manoeuvres;

(5) the nominal mission lifetime is five years;

(6) the spacecraft velocity should be known with respect to the solar system barycenter with an accuracy better than about 0.002 m/s.

From the above requirements it is clear that any low-altitude orbit is not acceptable.

In order to keep the launch costs small, dual launch with Ariane 5 into a geostationary transfer orbit is foreseen. The Ariane 5 dual-launch performance is 5900 kg. Deducting launch adaptor and SPELTRA mass, a maximum launch mass for GAIA of 2600 kg is assumed. The following Ariane 5 geostationary transfer orbit is considered: perigee altitude 620 km, apogee altitude 35786 km, inclination 7°, argument of perigee 180°. The longitude of the first descending node is near 10° W. Velocity at perigee is 9.890 km/s and at apogee 1.640 km/s.

For GAIA, data rates of several hundreds of kbits per second are foreseen. In the following a continuous data rate of 500 kbps is assumed (250 kbps each for the coherent and incoherent parts of GAIA).

In the following three orbit options are considered. All avoid passing through near-Earth space in the operational phase.

Figure 1 (left): Libration points in the restricted problem of three bodies (synodical coordinates). Figure 2 (right): Libration points near the Earth

Figure 3 (left): Example of five-impulse transfer to L4 in the Earth-Moon system. Figure 4 (right): Small-size quasi-periodic orbits near L4. A rotating coordinate system is used. Projection into lunar orbit plane. The y-axis is parallel to the Earth-Moon direction

Figure 5 (left): Station visibility near L4 from Villafranca and Perth. Figure 6 (right): Lissajous orbits near L1 (Earth-Sun system).

Figure 7 (left): Transfer trajectory from geostationary transfer orbit to L1 (Earth-Sun system). Projection into ecliptic. Figure 8 (right): Transfer trajectory from geostationary transfer orbit to L1 (Earth-Sun system). Projection into plane perpendicular to ecliptic.

3. GEOSTATIONARY ORBIT

The geostationary orbit offers several advantages: (a) a single ground-station is sufficient for support during the operational phase (however, during the 'launch and early orbit phase', several ground-stations have to be used), (b) distance ground-station to spacecraft is about 40 000 km, (c) eclipses occur around the equinoxes and do not exceed 72 minutes.

A significant simplification will result if some limited spacecraft motion in the north-south direction is acceptable, and in this case, north-south station-keeping will not needed. The annual costs for station-keeping are: 40–50 m/s for north-south; 2 m/s for east-west. The varying cost for north-south station-keeping is caused by the varying inclination of the lunar orbit with respect to the Earth equator.

For the telemetry transmission typical ESA ground station performance is assumed. The 500 kbps data rate can be handled in S-band with two low-gain antennae providing omnidirectional coverage. The required power is about 10 W. Ranging accuracy is typically 3–5 m, and range-rate is measured to better than 0.001 m/s. Both figures assume calibration and modeling of major error sources. Two options are considered:

(a) Ordinary Geostationary Orbit: the spacecraft will be positioned in the geostationary arc at a certain geographical longitude above Europe. The initial inclination and ascending node of the orbit will be selected such, that the inclination will initially decrease and later increase, but never assume an inclination above the initial value. For a five-year lifetime, the inclination can be kept below about 2.5°. The transfer from geostationary transfer orbit to geostationary orbit will require a velocity change of 1.461 km/s (by means of an apogee boost motor burn), assuming an inclination change of 7°. An additional 60–70 m/s are needed for station acquisition and correction of the apogee boost motor burn.

(b) Stable Geostationary Orbit: here, the spacecraft will be positioned in the geostationary arc at a certain geographical longitude above Europe. If the initial inclination is selected at about 7.3° and the longitude of the ascending node as 0°, then the orbital plane will remain fixed, apart from some periodic perturbations. This is the so-called Laplace plane at the geostationary distance. The spacecraft will thus not be in a truly geostationary orbit, and it will carry out a daily motion between 7.3° north and 7.3° south. The transfer geostationary transfer orbit to geostationary orbit requires a velocity change of 1.434 km/s (zero inclination change).

4. TRIANGULAR LIBRATION POINTS L4 AND L5 (EARTH-MOON)

The libration points in the restricted problem of three bodies were discovered by Euler and Lagrange in the eighteenth century. With the two primaries P1 (Earth) and P2 (Moon), there are five equilibrium positions (Fig. 1). Three colinear libration points L1, L2, L3 are located on the line passing through both primaries, while the two triangular libration points L4 and L5 are at the vertices of an equilateral triangle. In the absence of perturbations, spacecraft motion in the vicinity of the colinear points is unstable, while the motion near the equilateral points is stable. In the real world, where the eccentricity of the lunar orbit ($e = 0.0549$) and the gravitational perturbation of the Sun and of the planets have to be taken into account, the motion of a spacecraft near any one of the libration points needs to be controlled.

Orbits in the vicinity of libration points can be of eminent importance for some applications. Pioneering work for the understanding of such orbits and their practical use has been carried out by Farquhar (1970).

Recently, small-size quasi-periodic orbits near L4 and L5 in the Earth-Moon system have been discovered (Simo et al. 1987). The orbits are mildly unstable (the maximum error growth is about a factor of four per year). Relatively simple orbit control schemes can be defined to keep the spacecraft near the libration point. The annual cost for orbit control amounts to about 4–5 m/s.

The transfer of the spacecraft from geostationary transfer orbit to the libration point orbit can be carried out in several ways. The two-impulse Hohmann transfer requires a characteristic velocity of about 1500 m/s and lasts for seven days. With a bi-elliptical transfer (three-impulse transfer, second impulse at about 10^6 km), the characteristic velocity is near 1350 m/s and the transfer time is 1–2 months.

With transfers using lunar swing-bys the cost for the transfer can be significantly reduced to 880–1060 m/s, depending on the date. Examples of the transfer are shown in Figs 2 and 3, where five impulses are considered. The first two impulses are used to raise the apogee of the geostationary transfer orbit, and the third one to modify the inclination. Transfer time is about two months. Eclipses may last for up to five hours. They can be avoided by orbit manoeuvres (phase changes). Small-size orbits near L4, and station visibility near L4 for two ground stations, are shown in Figs 4 and 5 respectively.

Telemetry transmission can be achieved with two low-gain antennae providing an omnidirectional link. A disadvantage of this option is a large power requirement of several hundred W. With a directional high-gain antenna of 0.5–1.0 m size, the power requirement is reduced to about 20 W. This solution is, however, only acceptable if no or only infrequent articulation of the high-gain antenna is required.

5. COLINEAR LIBRATION POINT L1 (EARTH-SUN)

The libration point L1 in the Earth-Sun system is located about 1.5×10^6 km from the Earth in the direction towards the sun. Since the point L1 is not suitable for any spacecraft (the sun's thermal noise would not permit reception of spacecraft data on ground) orbits are designed which carry out a motion around L1 without approaching too close the solar disc as seen from the Earth. Basically, two families of orbits are of practical use: Lissajous orbits and halo orbits.

Lissajous orbits change their shape and, ultimately, they cross the solar disc as seen from Earth. Therefore, manoeuvres are required to avoid the solar exclusion zone. Lissajous orbits of different sizes exist. Fig. 6 displays an example with a lateral excursion perpendicular to the Earth-Sun line of about 130 000 km. Figs 7 and 8 show different projections of the transfer trajectory from geostationary orbit to L1.

Figure 9. Halo orbits near L1 (Earth-Sun system). Synodical coordinates (origin at L1. z-axis perpendicular to ecliptic plane. x-axis along Earth-Sun direction, points towards the Earth. y-axis perpendicular to Earth-Sun direction)

Halo orbits (Fig. 9) are a limiting class of Lissajous orbits, where the amplitude has been chosen such, that the frequencies of the orbital motion perpendicular to the Earth-sun line become identical. The minimum amplitude A_y is about 670 000 km (the y-axis is in the ecliptic plane and perpendicular to the Earth-Sun line). This corresponds to a geocentric lateral excursion of the spacecraft from L1 of 25°. Two symmetrical classes of halo orbits exist: Class 1 with apogee above the ecliptic plane, and Class 2 with the apogee below the ecliptic plane. Each revolution has a duration of about six months.

The transfer from the geostationary transfer orbit to halo orbit lasts for about 120-140 days. A total velocity change of about 900 m/s is needed to reach from geostationary transfer orbit the transfer trajectory to L1. This amount includes the Ariane 5 launch window and gravity losses. The insertion manoeuvre into the halo orbit varies between 40–170 m/s. Mid-course corrections amount to about 30–40 m/s. Annual costs for station-keeping amount to about 3–4 m/s.

Orbits near L1 are eclipse-free. The thermal environment is thus very stable. For data transmission a high-gain antenna of about 1 m size is required. For this antenna size the 3 dB beamwidth in S-band is about 9°. It has to be examined if articulation of the high-gain antenna can be avoided through a suitable design of the scanning law and the data transmission system.

6. CONCLUSIONS

Several orbit options have been presented for a high-accuracy interferometric astrometry mission. In all cases a dual launch into the geostationary transfer orbit with Ariane 5 is assumed. The geostationary orbit offers relatively small data transmission distances. Near the equinoxes eclipses will occur during several weeks of up to 72 min. In the operational phase a single ground-station is needed.

The second class of orbits considered are quasi-periodic orbits near the Earth-Moon triangular libration points. Transfer costs from geostationary transfer orbit amount to 880–1060 m/s plus 50 m/s for mid-course corrections. Annual costs for station-keeping are about 3–5 m/s. Eclipses will occur only very occasionally. They can be avoided through orbit changes. Data transmission distance is about 350 000 to 400 000 km. Two ground-stations will provide about 80–90 per cent time coverage.

The third class of orbits considered are quasi-periodic orbits near the Earth-Sun colinear libration point L1. Two basic orbit options are offered: (a) Lissajous orbit and (b) halo orbit. Total transfer costs from geostationary transfer orbit are about 1100 m/s which includes mid-course corrections and insertion into the operational orbit. Annual costs for station-keeping are about 3–5 m/s. In case of Lissajous orbits an additional manoeuvre is required during its operational lifetime to avoid the solar exclusion zone. The orbits near L1 are free of eclipses. Two ground-stations will provide about 80–90 per cent time coverage. The propulsion requirements for the transfer to the libration points are lower than for the geostationary orbit.

In all options presented above, the data transmission is an important aspect. In geostationary orbit low-gain antennae are sufficient, while in the libration point orbits a high-gain antenna is needed. High-gain antennae are only acceptable if they do not need to be articulated at all or only very infrequently. The libration point orbits offer a more benign space environment (perturbing torques, radiation). A considerable drawback, is, however, the data transmission to Earth.

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