

On the Design of Geodetic SVLBI Satellite Orbit and Its Tracking Network

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Abstract

SVLBI (Space Very Long Baseline Interferometry) has some important potential applications in geodesy and geodynamics, for which one of the most difficult tasks is to precisely determine the orbit of SVLBI satellite. This paper studies several technologies which possibly will be able to determine the orbit of space VLBI satellite. And then, according to the sorts and characteristics of satellite and the requirements for geodetic study and the geometry of GNSS (GPS, GALILEO) satellite to track the space VLBI satellite, the six Keplerian elements of SVLBI satellite (TEST-SVLBI) are determined. A program is designed to analyze the coverage area of the space of different heights by the stations of the network, with which the tracking network of TEST-SVLBI is designed. The efficiency of tracking TEST-SVLBI by the network is studied, and the results are presented.

Key words: SVLBI; precise orbit determination; orbit design; tracking network

1. Introduction

The unique radio astronomical technique of Space Very Long Baseline Interferometry (SVLBI) is an extension of the ground-based VLBI into the space. It has some important potential applications in geodesy and geodynamics, including the definition, practical realization, and the interconnection of different reference frames, determining the geocentric positions of VLBI stations, estimation of the gravity field of the Earth, and satellite orbit determination using the delay and delay rate observables. With the launching of the first SVLBI satellite of the VLBI Space Observatory Program (VSOP) of Japan, in February 1997, this technique has become a reality. An international team of scientists, working under the auspices of the FÖMI Satellite Geodesy Observatory, Hungary, has designed the GEDEX (Kulkarni et al, 1997), for the purpose of exploring the feasibility of the geodetic applications of SVLBI. However, several major problems also exist. It is not suitable for geodetic and geodynamic study, which requires precise tracking capabilities resulting in cm orbit accuracy. But the orbit determination of HALCA is accurate to 2-5 m (Frey, 2002), and it is quite difficult to be accurate to 10 cm.

At present, there is no dedicated research on the design of the orbit of geodetic and geodynamic SVLBI satellite, hence this investigation studies several technologies which possibly will be able to determine the orbit of space VLBI satellite. And then, according to the sorts and characteristics of satellite and the requirements of precise orbit determination for SVLBI satellite (TEST-SVLBI), the six Keplerian elements of which are

determined. And the tracking network of TEST-SVLBI is designed.

2. Orbit Determination Accuracy and Techniques of SVLBI Satellite

In the report prepared by the RADIOASTRON Navigation, Astrometry and Geodesy (NAG) Working Group about the precise navigation of the SVLBI satellite [NAG, 1989; ZHENG Yong, 1998] the following orbit determination accuracy requirements have been specified:

1) Standard Orbit: Required accuracy better than 1000 m, for satellite control, orbit prediction, tracking and data communication.

2) Precise Orbit: Required accuracy better than 50 m, for processing ground-to-space VLBI data, and most astrometric applications.

3) Highly Precise Orbit: Required accuracy better than 1 m, for Geodetic and some astrometric applications. Required accuracy better than 0.1m, for Geodynamic applications.

Several simulation studies have been reported for precise orbit determination for the different orbit configurations possible for the SVLBI satellites, from which the following tracking techniques and data types have evolved as some of the possible choices for precise orbit determination of the SVLBI satellites [NAG, 1989].

Data link between the satellite and the telemetry and/or observing ground stations: range and range rate; VLBI observations: time delay and delay rate; Microwave tracking

systems: Precise Range And Range-rate Equipment (PRARE); Difference Of Range (DOR) tracking: range difference and difference rate. Difference VLBI: angular distance between a radio source and the satellite, and its change rate; Laser ranging: two way ranges and one way ranges; On-board micro accelerometer: non-gravitational perturbing forces on the satellite; Global Positioning System (GPS) tracking.

For both SVLBI missions: VSOP and RADIOASTRON, a global network of tracking stations with international collaboration is being established [Altunin, 1991; SHEN Zhiqiang, 1998].

3. On the Precise Orbit Technologies of SVLBI Satellite

In the following, according to the requirement of less additional establishment to determine the orbit of SVLBI satellite with high precision, several technologies are studied.

3.1 GPS

Ever since the introduction of GPS technology, it has brought a revolutionary effect to the traditional survey and navigation, and it has also become an important means to precisely determine the orbit of low orbit satellite. But, at present, the satellite with onboard GPS receiver generally uses the relative positioning method, based on a OTF method, to deal with the double differential ambiguity. So, it needs to arrange a network with a certain density of GPS base stations, which will greatly increase the human, material and financial input, and the intense difficulty to lay the global terrestrial base stations. In addition, the SVLBI baseline length may be 1,000 km ~ 10,000 km, and the OTF may no longer work well, hence the precision of SVLBI satellite orbits determined by GPS positioning will sharply decline.

In 1997, Zumbeger introduced single point precise positioning technology (PPP). The paper [LIU Jingnan et al., 2004] has discussed the geometric PPP orbit determination of CHAMP satellite from onboard GPS data, the result has shown that the accuracy on radial is 30~40 cm, on tangent or normal is both 10~20 cm. And the paper has also analyzed the dynamic orbit smoothing based on the PPP, and has presented a semi-parameter orbit smoothing method, which uses a non-parameter item to absorb dynamic error. The result has shown that the accuracy on radial, on tangent and normal directions are respectively less than 18 cm, 8 cm and 12 cm. To use GPS system for precise orbit determination of SVLBI satellite, we have downloaded the broadcasting ephemeris documents of GPS satellite at 0:00 a.m. on July 21, 2005 1:58 (GPS time) from the NASA website, in RINEX format, from which the Keplerian orbital parameters of GPS satellites are extracted.

3.2 GALILEO

The lack of redundant satellites is one of the obstacles for

satellite orbit determination with on-board GPS system. The characteristics of higher orbit positions (24000km) and a large number of satellites (27) of GALILEO system will be very helpful for orbit determination of SVLBI satellites with on-board GALILEO receivers, on the one hand, in the same orbit altitude to receive more navigation satellite signals for improving the accuracy of orbits; on the other hand to receive adequate navigation satellite signals at a higher orbit. To use GALILEO system for precise orbit determination of SVLBI satellite, we have extracted the relevant satellite Keplerian orbital parameters (orbital moment : 2004-1-1 0:00:00UTCG) from (<http://www.gssf.info/>).

4. Coverage of the Tracking network and Software

4.1 Coverage of the Tracking network

The scope of a tracking network is a space coverage scope tracked by the network, which is an important indicator to measure the quality of the designed network.

The work region of the tracking network is the space tracking region that the stations of the network can provide space tracking, communications service to the satellites. The work region coverage of the network is the projection of the space tracking region on the surface of the earth. The earth is not a body in mathematical rules, to whose surface the direct projection cannot be processed. But the surface of the Earth is close to a spheroid or ellipsoid ball, to which the work region of the network can be projected and simply calculated [BIAN Shaofeng, 2005].

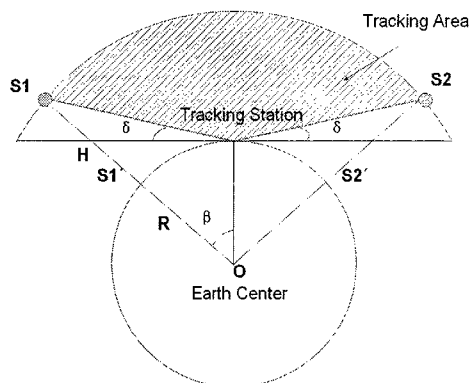


Figure1 The space tracking region by a station

The satellite is tracked at an elevation angle α , the smaller the α , the longer trails the atmospheric waves across, but the greater the waves decay, and therefore the useful signals received by the tracking stations are weakened. To ensure the communications and tracking efficiency of the tracking stations to the satellite, a lower limit δ is often given, generally is $\delta=5^{\circ}\sim 10^{\circ}$. When $\alpha\leq\delta$, the communication of the stations are considered invalid. Then the corresponding space tracking region by tracking stations is shown in figure 1. The projected

spherical coverage is the circle on the spheroid surface whose center is a tracking station with a spherical radius to S1 or S2 on the ball surface. At an altitude H of the satellite, the ground cover is shown in figure 2.

And then the earth center angle β is

$$\beta = \arccos\left(\frac{R \cos \delta}{R + H}\right) - \delta \quad (1)$$

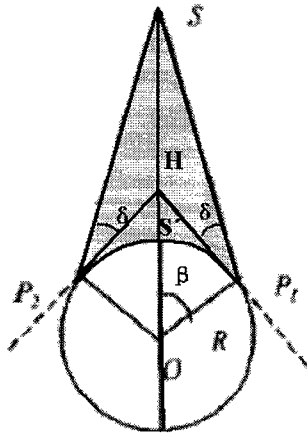


Figure 2. The ground cover by a satellite

With the surface area calculation formula in [math manual 1979], we can extrapolate surface area S (A) covering the ball:

$$S(A) = 2\pi R(R - R \cos \beta) \quad (2)$$

$$= 2\pi R^2(1 - \cos \beta)$$

And we use the Mercator's projection to convert spherical maps to plane.

4.2 Software

We have edited the NET-CovPlot software to calculate and map the ground coverage of the work area of tracking network, to facilitate the visualization design of tracking network for space vehicles in different heights. The software's diagram is in figure 3.

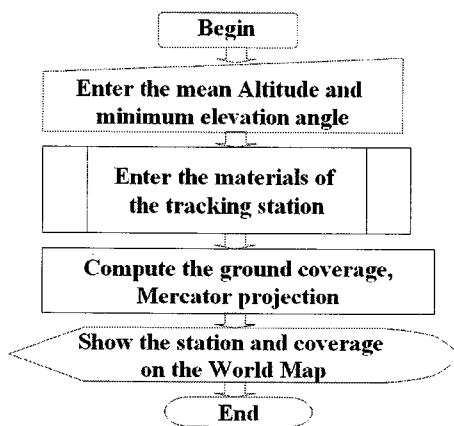


Figure 3. The software diagram

5. Parameters and Sorts of Satellite Orbit

5.1 Satellite Orbit Parameters

In the artificial satellite orbit theory, the six Keplerian parameters are often used to describe the shape, the size and the orientation in space of the elliptical orbit to determine the location of the satellite, which are listed in table 1.

Table 1 Orbit Parameters of man-made satellite

Orbit Parameters	function
Semi-maj.: a	describe the shape and size of the orbit
Eccentricity: e	
Inclination: i	describe the position of the orbit plane
RA of Node: Ω	
Arg. Of Perigee: ω	describe the orientation in space of the elliptical orbit in the orbit plane
Mean Anomaly: M	describe the position of the satellite in the orbit

5.2 The Sorts of Satellite Orbit

With the linking of the satellite and earth center, the intersection point of the linking line and ground surface is called a sub satellite point. When the sub satellite points are linked, they will form a track on the ground, which is called sub satellite point trajectory. By satellites orbital elements and the characteristics of sub satellite point trajectory, and within the earth gravitational condition, the satellite orbit can be divided into the categories [WANG Xiji., et al, 1997]:

- 1) Sorting by eccentricity of the orbit
- 2) Sorting by Inclination of the orbit
- 3) Sorting by height of the orbit
- 4) Sorting by the moving angular velocity of the orbit plane
- 5) Sorting by the repetition of the sub satellite point trajectory
- 6) Sorting by the relationship between earth rotation and satellite orbital cycle

6. Design of SVLBI Satellite Orbit

6.1 Shape and Size

SVLBI satellite is required to meet the needs of geodesy and astrometry, so it belongs to the exploration satellite of spatial science, which generally uses elliptical orbit with large eccentricity [WANG Xiji., et al, 1997].

To select the altitude of the perigee, on the one hand, a lower altitude is needed, so that the SVLBI antenna and ground VLBI antenna can formulate the baseline with the larger changes in length, which is conducive to the full coverage of the u-v plane of the radio source; On the other hand, if the

perigee altitude is too low, the orbit will be effected by the ionosphere that is to the most outer of the earth's atmosphere with altitude in 60~1000km. Above the latter ones, the electronic density is quite low [LIU Jiyu, 2003]. So, the altitude choice of the perigee can be 1000km.

The higher the apogee altitude, higher is the resolution of the radio source. But, for the satellite orbit determination by PPP of GNSS system, the GNSS tracking time efficiency should also be considered. With GPS and GALILEO satellites, we have summarized the positioning PDOP of the HALCA satellite in one orbit cycle, from UTC 07h 35m 46.104s to 13h 53m 12.352s of 2003 Jan 1, which is before the time that HALCA stopped sending data. The orbit parameters of HALCA can be found in [SHEN Zhiqiang,1998; Kulkarni,2003].The statistics of the positioning PDOP of the HALCA satellite by GPS and GALILEO in one orbit cycle is in figure 4, from which the conclusions are drawn and shown in table2~3. When the number of the tracking Galileo or GPS satellites is less than 4, then PDOP is 0.

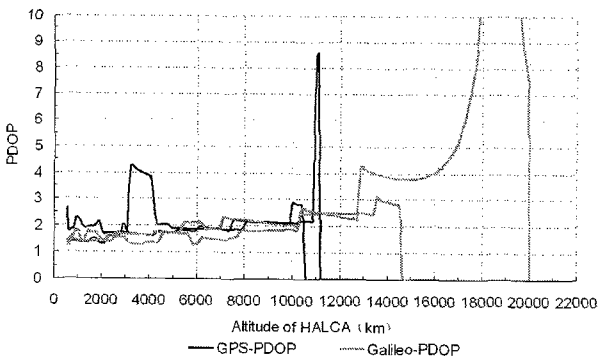


Figure 4 The positioning PDOP of HALCA by GPS and GALILEO

Table2. Statistics of positioning by GPS

Altitude (km)	<10500	10500 ~11000	>11000
by GPS	All the time	Partial time	Never

Table3. Statistics of positioning by GALILEO

Altitude (km)	<14650	14650 ~20000	>20000
by GALILEO	All the time	Partial time	Never

To accurately design the apogee height, it would involve several other orbital parameters. So, the satellite's apogee height will be determined after the determination of other parameters.

6.2 Choice of the Repetition of the Satellite Trajectory

One of the developing directions of ICRF is to expand the

number and spatial distribution of radio source, and the task of SVLBI requires observations and definition of the possible radio sources covering the space in all directions to increase the measuring quantity and to improve the geometric precision. In this way, it is better to choose the non-return of cyclical repetition orbit track.

6.3 Arg. Of Perigee (ω), RA of Node (Ω) and Mean Anomaly (M)

1) Argument Of Perigee: ω

The argument Of Perigee determines the orientation of the orbital plane and the perigee position, which is changing or be selected in the $0^\circ \sim 360^\circ$. An important task to design SVLBI satellite is to increase the observation coverage of radio source by the Southern Hemisphere ground VLBI.

From the north-south direction of the orbit, the apogee should be selected in the most southern part of the orbit, so the perigee is to the most northern end. In this way, in one orbit cycle of the satellite, most of the time is taken for the sky observation in the southern hemisphere. Therefore, the argument of perigee had better be 90 degrees.

2) RA of Node (Ω) and Mean Anomaly (M)

The right ascension of node (Ω) determines the orbit location in the orbital plane. And the mean anomaly (M) determines the location of satellites in the orbit at any moment. Both of them change in $0^\circ \sim 360^\circ$, so we can only choose the initial value for them.

Based on the above analysis, ω , Ω and M are changing, which can only be designed at a particular moment, for an example, the moment of orbit parameters is selected to be (1 Jan 2006, 00 h 00 m 00.00 s, UTC), when Ω is 193.24822 degrees, ω is 90 degrees, and M is 100 degrees.

6.4 Altitude Design of the Apogee

The orbital altitude of Galileo satellites is higher than that of GPS, and we focus on the use of the Galileo system to precisely determine SVLBI orbit and determination of the apogee altitude. So we will select the apogee height between 15000km and 20000km, based on orbit determination efficiency with Galileo system, and the other parameters remain unchanged. The conclusions are listed in table 4. So, the Apogee Altitude should be 15000 km.

Table 4. Orbit determination efficiency

Apogee Altitude	Orbit Determining technology and efficiency(one orbit cycle)	
	GALILEO	GPS
15000km	100%	71.78%
20000km	55.1%	31.9%

6.5 The Orbit Direction and Inclination

The choice of the direct orbit is helpful to reduce energy requirements of vehicles with earth rotation speed [BIAN

Shaofeng, 2005]. And this direct orbit can also extend the observation time of SVLBI and ground VLBI station antenna by using earth rotation, and so the quantity of observations is increased.

The orbital inclination of SVLBI satellite determines the location of the orbit plane. The choice conditions must meet the requirements that it is most likely to determine the SVLBI satellite orbit with on-board GNSS system. To determine the orbit inclination, we will select orbital plane inclination from 0 to 90 degrees at a step of 5 degrees, for each of which the positioning time coverage efficiency and the mean PDOP in a cycle positioned by Galileo and GPS satellites are calculated respectively. The conclusions are listed in figure 5-6. And the result shows that the orbital inclination should be 50 degrees. And the final determined parameters of satellite TEST-SVLBI are listed in table 5.

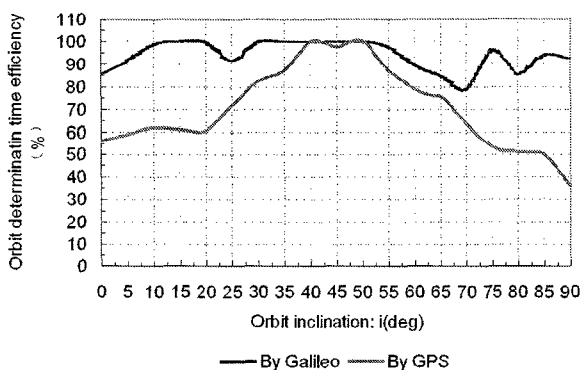


Figure 5 The positioning efficiency of TEST-SVLBI by GPS and GALILEO

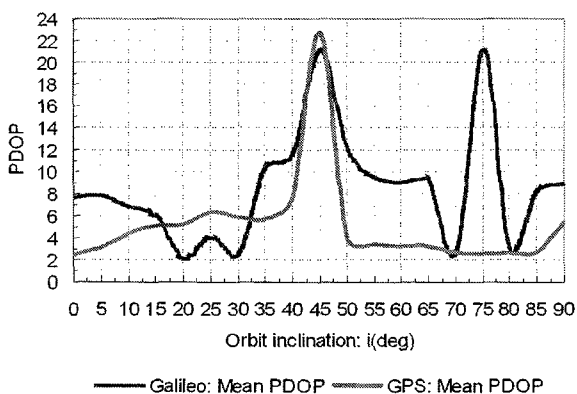


Figure 6 The mean positioning PDOP of TEST-SVLBI by GPS and GALILEO

Table 5. Orbital parameters of TEST-SVLBI

Orbital parameters	Value
Semi-maj.: a(km)	14378.137
Eccentricity: e	0.486850278
Inclination: i	50
RA of Node: Ω (°)	193.24822
Arg. Of Perigee: ω (°)	90
Mean Anomaly: M(°)	100
Orbit time: UTC	Jan.2006 00:00:00.00

7. Design of the Tracking Network

7.1 Coverage Efficiency of VSOP Network

In the VSOP of Japan, the observation data on HALCA satellite is received and recorded by the 5 tracking stations on the earth (Figure 7), which are Usuda in Japan, Green Bank in USA and the three DSN stations of USA (Goldstone of USA, Tidbinbilla in Australia, and Madrid of Spain). The orbit period of HALCA and TEST-SVLBI is 6.3 hours and 4.8 hours respectively, and the simulation time period should be a common multiple of a satellite period and a earth rotation period[YANG Ying,2005]. So for HALCA and TEST-SVLBI, the simulation time period should be 21days and 1day. With Net-covPlot, the time coverage efficiency for them are only 75.23% and 70.04% respectively.

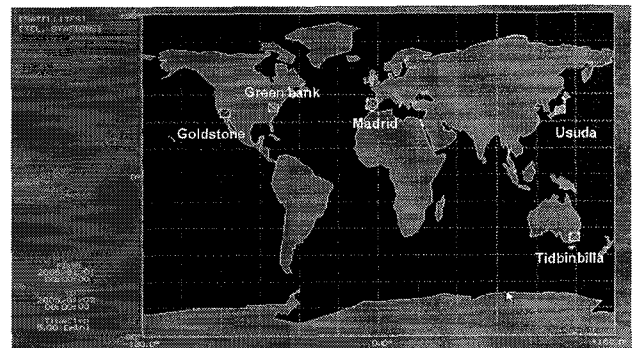


Figure 7 The 5 tracking Stations of VSOP

7.2 Design of the tracking Network

With the formulas (1) and (2), we have calculated the least number of tracking stations for TEST-SVLBI to be 3.7.

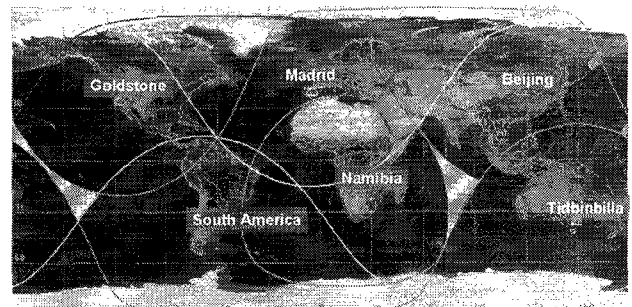


Figure 8 The tracking ground by the designed network

But, with the ground realities of land distribution, limitation of ground coverage and the complex shape of the Earth, so we must choose the overlapping coverage areas to meet global coverage. In this case, the initial choice is six tracking stations. Secondly, when we choose the tracking station close to the international ones, we adopt them. So the six designed stations

are Beijing, Namibia, South America, Goldstone, Madrid and Tidbinbilla, the latter three stations of which are from the international stations. And the coverage results are shown in figure 8, the shadow areas in which are for tracking blind area that covers only 5% of the global area.

With the designed tracking network above, the time coverage efficiency for HALCA and TEST-SVLBI are 92.61% and 93.51% respectively.

8. Conclusion

When SVLBI technology is used for geodetic and geodynamic study, one of the most difficult tasks is the precise determination of the satellite orbit. Based on the classification of satellite orbits and observation geometry condition of GNSS (GPS and GALILEO satellites) to determine the orbit of SVLBI, the six Keplerian parameters of SVLBI satellite are designed. With the developed software to design the satellite orbit tracking network; the remote tracking network for SVLBI satellite is simulated, whose tracking efficiency is studied and given out. This investigation presents the orbit design method of geodetic and geodynamic space VLBI satellite, which is quite important to select the suitable geodetic and geodynamic space VLBI satellite and to study the spatial geodesy method.

Before the launch of SVLBI satellite, the Keplerian parameters of SVLBI satellite should be determined with the changing of GNSS satellite, and if possible, with the coverage of SLR stations and the global ground VLBI network constantly. Secondly, it is needed to do further research on the attitude control, laser reflector lens, solar panels and the installation of an antenna structure and other physical properties of SVLBI satellite.

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