Chapter 38
Single-Station Orbit Determination with Astrometric Positioning and SLR Techniques

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Abstract The principle of single-station orbit determination using astrometric positioning and SLR techniques is to add a laser ranging unit onto the optoelectronic telescope system, so as to conduct laser ranging and astrometric positioning angle measurement at the same time. By melting and processing all the data together, the new technique will achieve single-station orbit determination of the objects. In this paper, the actual measurement data of satellite Ajisai is analyzed for its single-station single-lap and multi-lap orbit determination. However, due to the limited amount of actual measurement data, objects of three types of orbit altitude have to be simulated and the single-station orbit determination analysis is just based on them in order to make the conclusion more universal. After studying the actual and simulated data, it turns out that for single-station single-lap orbit determination, the ranging measurement data (measurement duration longer than 4 min) will improve the orbit determination accuracy from several kilometers to tens of meters and the 24-h prediction accuracy from thousands of kilometers to several kilometers.

Keywords Single-station orbit determination · Precision orbit determination · Laser ranging measurement · Astrometric positioning

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38.1 Introduction

With the rapid development of space exploration, the increasing number of space debris is causing greater damage to the space vehicles working and to be launched and will pose a potential threat to the manned space flight. To face the threat, we should make full use of different techniques to closely monitor the space debris and based upon which, to undertake collision warning, avoidance and clearance of the space debris. Small objects on the high or medium orbits are usually less bright. According to some calculation, the brightness of the space objects with a diameter of 10 cm on the geostationary orbit is only 20 magnitudes [1] and they are only visible through large caliber optical telescopes. Laser radar has a high accuracy of ranging measurement, but to achieve diffused reflection laser ranging measurement of the low orbit objects, the radar must have a high power laser in coordination with a large caliber reception telescope.

Shanghai Observatory developed a new system which has a high power laser ranging unit added onto a large caliber optoelectronic telescope. The optoelectronic telescope can get the angle measurement data [2] with astrometric positioning while the laser can get the ranging measurement data [3]. This paper focuses on the impacts of high accuracy laser ranging measurement data on the accuracy of single-station single-lap or multi-lap orbit determination and prediction.

38.2 Single-Station Orbit Determination with Actual Measurement Data

In this paper, we used the actual laser ranging measurement data and the astrometric positioning angle measurement data of satellite Ajisai. Its obit altitude is 1485 km with the inclination of 50° and cycle time of 116 min. The actual laser ranging measurement data come from Sheshan laser observation station of Shanghai Observatory while the actual astrometric positioning angle measurement data come from two devices: one is the ranging measurement telescope with an optical lens in Sheshan, which measures the angle and ranging alternatively, the other is the rotating CCD drift scan optoelectronic equipment in Tianhuangping, Anji, Zhejiang. After some analysis, we find that there are five groups of angle and ranging measurement data, each of which can be catalogued into the same lap. See Table 38.1.[1]

In the above data, the longest duration of ranging measurement is 5.6 min, while the shortest is 0.4 min; the longest duration of angle measurement is 10.2 min, while the shortest is 5.1 min. The data of lap 1 and 2 come from Anji,

[1] In the following tables, we will replace all the angle measurement with AM and ranging measurement with RM.

Table 38.1 Actual ranging and angle measurement data of satellite Ajisai

Lap	Beginning time of RM (UTC)	Duration /(min)	Beginning time of AM (UTC)	Duration /(min)
1	2011.03.07 11:46:50	1.2	11:40:57	6.8
2	2011.03.30 11:16:51	4.8	11:12:29	7.5
3	2011.11.15 19:03:23	4.3	19:08:59	5.1
4	2011.11.15 21:03:25	5.6	21:09:09	10.2
5	2011.11.21 11:36:16	0.4	11:29:29	5.5

Table 38.2 Accuracy of actual angle measurement of satellite Ajisai

Lap	Azimuth accuracy Arc s	Elevation accuracy Arc s
1	5.3	5.5
2	4.7	5.7
3	16.7	13.7
4	13.6	9.5
5	9.7	8.1

Zhejiang, while that of lap 3, 4, 5 come from Sheshan. As the distance between Anji and Sheshan is relatively short, we will consider the angle and ranging measurement data come from the same station in the following analysis.

38.2.1 Accuracy of the Actual Measurement Data

Before using the above data, we must analyze their accuracy so as to set the corresponding weight when determine the orbit. According to website ILRS, from March 1st, 2011 to February 29th, 2012, for satellite Ajisai, the largest ranging measurement error of Sheshan station is 43.92 mm while the average error is 27.36 ± 6.35 mm.

By comparing the actual angle measurement data with the precise ephemeris of satellite Ajisai, we got Table 38.2. Precise ephemeris is achieved by precise orbit determination using global SLR data, and the ephemeris accuracy [4] of satellite Ajisai is about 1 m. The angle measurement data accuracy of lap 1 and 2 is 4.7–5.7 arc s, more precise than that of lap 3, 4 and 5, whose accuracy is 8.1–16.7 arc s. The main reason for this is that the former two groups of data is collected by the rotating drift scan equipment, which has a large diameter of 30 cm, and which locates in a better place (at night the sky is darker than magnitude 19). Besides, in the rotating drift scan mode, the star images of the reference star and the target can both keep round, so all of the above help to get a more precise astrometric positioning result.

Table 38.3 Actual measurement data single-station single-lap orbit determination of satellite Ajisai

Lap	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
		Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1	AM	356.0	400.4	250.0	443.4	3646.4	2.15E + 5	13844.0	2.15E + 5
	AM + RM	147.0	64.8	112.0	195.9	405.8	12850.0	1035.5	12872.0
2	AM	1855.7	1168.6	418.9	1970.1	69081.0	1.05E + 6	66727.0	1.06E + 6
	AM + RM	16.5	15.6	33.6	35.4	58.3	3363.5	173.8	3364.5
3	AM	2543.7	2547.0	1002.9	3693.1	3.37E + 5	2.15E + 6	134060.0	2.17E + 6
	AM + RM	10.4	20.9	44.8	50.5	32.6	2067.2	93.2	2068.5
4	AM	75.7	140.2	48.2	166.1	1191.7	71999.0	4571.2	72052.0
	AM + RM	20.0	37.5	68.9	73.2	27.3	1321.1	175.9	1323.4
5	AM	1126.3	1090.9	517.7	1651.3	94832.0	1243500.0	79964.0	1248500.0
	AM + RM	136.9	108.9	85.7	194.8	2142.2	120050.0	7860.5	120290.0

38.2.2 Single-Station Single-Lap Orbit Determination with Actual Measurement Data

The single-station single-lap orbit determination of satellite Ajisai with actual measurement data uses the numerical method [5]: gravity field uses JGM-3 model, 20×20 order; Earth tide perturbation; Atmospheric drag perturbation, atmospheric drag coefficient Cd: 2.2, mass: 685 kg, area: 3.63 m^2, atmospheric density mode: Jacchia-77; Light pressure perturbation, coefficient Cr: 1.0; Lunisolar gravitational perturbation; Elevation mask: 10° without calculating the drag coefficient of atmosphere and light pressure [6]. By comparing the results with the precise ephemeris of satellite Ajisai, we got Table 38.3.

From Table 38.3 we find that when determine the orbit with only angle measurement data, the accuracy is from 166.1 to 3693.1 m. According to the duration in Table 38.1, lap 4 has the longest angle measurement duration of 10.2 min and the highest orbit determination accuracy of 166.1 m, while lap 3 has the shortest angle measurement duration of 5.1 min and the lowest accuracy of 3693.1 m. It's the same with 24-h prediction accuracy: lap 4 has the highest accuracy of 72 km while lap 3 has the lowest accuracy of 2175 km. So the duration of angle measurement is closely related to the accuracy.

When we combine the angle and ranging measurement data together, both orbit determination accuracy and 24-h prediction accuracy are greatly improved. The orbit determination accuracy of lap 2, 3, 4 is higher than 80 m, while the 24-h prediction accuracy higher than 3.5 km. However, in lap 1 and 5, the orbit determination accuracy is higher than 200 m, but the 24-h prediction error of lap 1 is nearly 13 km while that of lap 5 is as large as 120 km. By studying the data in Table 38.1, it turns out that the ranging measurement for lap 1 lasts only 1.2 min and even worse for lap 5, which only lasts 0.4 min. On the contrary, lap 2, 3 and 4 all last longer than 4.3 min. So we can conclude that the highly accurate ranging

Table 38.4 Actual measurement data of single-station multi-lap orbit determination of satellite Ajisai

Lap	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
		Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
3 + 4	AM	31.1	49.5	13.9	50.8	44.4	348.9	24.1	349.0
	AM + RM	2.8	2.9	2.9	5.0	4.8	18.1	4.0	18.1

measurement data improved the accuracy of orbit determination and the longer we measure the ranging, the better the result will be.

No matter using the angle measurement data only or the combined data, the 24-h prediction errors appear mainly in direction T, namely the along track direction.

38.2.3 Single-Station Multi-Lap Orbit Determination with Actual Measurement Data

In Table 38.1, the data of lap 3 and 4 belongs to the same day and can be used to determine the orbits, while others are not suitable for multi-lap orbit determination as they belong to different days. The settings are the same as those in Sect. 38.2.2. Usually, in multi-lap orbit determination we should calculate atmospheric and light pressure, but in this case we skipped that because the time span between the two laps is short, only 2 h. Besides, according to our tests, if we calculate the atmospheric and light pressure here, it will lead to greater errors. Whatever, this is just a special case. Generally it's better to calculate the atmospheric and light pressure when we can measure the data for a relatively long time. By comparing the results with the precise ephemeris of satellite Ajisai, we got Table 38.4.

According to Table 38.4, if we determine the orbit using the angle measurement data from two laps, the orbit determination accuracy is about 50 m and the 24-h prediction accuracy is higher than 350 m. By some comparison, we find that the 24-h prediction accuracy in Table 38.4 is much higher than that in Table 38.3, namely, angle measurement data from two laps is more precise than the combined angle and ranging measurement data from a single lap. The reason for this is that data from two laps can better describe satellite orbits.

In Table 38.4, if we combine angle and ranging measurement data together, the orbit determination accuracy is higher than 5 m and the 24-h prediction accuracy is higher than 20 m. There are two reasons for this. On the one hand, the precise ranging measurement data improved the accuracy; on the other hand, the altitude of satellite Ajisai is 1485 km and is less influenced by the atmosphere, so the error is smaller.

No matter using the angle measurement data only or the combined data, the 24-h prediction errors appear mainly in direction T.

38.3 Single-Station Orbit Determination with Simulated Data

As we can only get limited amount of actual measurement data, we simulated objects of three different altitudes to make the analysis more universal: 1,500, 800 and 400 km, all the inclination is 80°.

38.3.1 Simulation Conditions

Station: Sheshan, Shanghai; Elevation noise: 2 arc s; Elevation system error: 1 arc s; Azimuth noise: 2 arc s; Azimuth system error: 1 arc s; Ranging measurement noise: 1.0 m; Ranging measurement system error: 0.4 m; Elevation mask: 10°; Observation conditions: do not observe earth shadow, do not observe in daytime.

Dynamic model: gravity field uses JGM-3 model, 20 × 20 order; Earth tide perturbation; Atmospheric drag perturbation, atmospheric drag coefficient Cd: 2.2, mass: 1000 kg, area: 20 m^2, atmospheric density mode: Jacchia-77; Light pressure perturbation, coefficient Cr: 1.0; Lunisolar gravitational perturbation.

There are two types of orbit determination using simulated data: single-station single-lap and single-station multi-lap. In each type, there are also two ways: angle measurement data determination and determination combining angle and ranging measurement data. Both ways use numerical method. Settings for single-station single-lap orbit determination are as follows. Gravity field uses JGM-3 model, 20 × 20 order; Earth tide perturbation; Atmospheric drag perturbation, atmospheric drag coefficient Cd: 2.2, mass: 1000 kg, area: 20 m^2, atmospheric density mode: Jacchia-77; Light pressure perturbation, coefficient Cr: 1.0; Lunisolar gravitational perturbation; Elevation mask: 10° without calculating the drag coefficient of atmosphere and light pressure. The settings for single-station multi-lap orbit determination are almost the same except that the drag coefficient of atmosphere and light pressure are counted.

Under the simulated conditions, the object whose altitude is 1500 km can be observed 16 laps in 4 days; the 800 km object can be observed 9 laps in 7 days and the 400 km object, without observing the earth shadow, can be observed 4 laps in 4 days. Considering the factors such as the duration of observation and the lifting and dropping section, for each simulated object, we analyzed its data from 4 laps.

38.3.2 Single-Station Single-Lap Orbit Determination with Simulated Data

The orbit cycle of 1500 km object is 116 min and the orbit determination result is shown in Table 38.5.

Table 38.5 Single-station single-lap orbit determination for the simulated 1500 km object

Lap	Duration (min)	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
			Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1	16.0	AM	49.1	37.4	11.2	59.1	579.0	30994.0	2438.4	31084.0
		AM + RM	5.5	3.2	5.8	8.5	14.3	383.8	27.1	384.6
2	13.3	AM	57.9	44.9	49.9	84.5	726.0	43585.0	3381.0	43711.0
		AM + RM	4.1	5.7	2.4	7.2	10.0	122.6	13.6	123.4
3	9.0	AM	252.7	148.7	149.7	326.4	2328.9	1.40E + 5	11366.0	1.41E + 5
		AM + RM	1.3	2.7	1.4	3.2	20.5	1099.1	85.6	1102.5
4	11.7	AM	45.5	23.4	59.7	76.7	474.0	27528.0	2092.2	27533.0
		AM + RM	9.0	6.5	3.0	11.5	26.6	445.9	34.9	447.0

Table 38.6 Single-station single-lap orbit determination for the simulated 800 km object

Lap	Duration (min)	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
			Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1	5.0	AM	126.9	83.3	191.0	244.0	4753.3	1.81E + 5	12626.0	1.82E + 5
		AM + RM	3.5	0.6	2.6	4.4	17.1	1032.0	74.8	1033.0
2	10.3	AM	42.4	47.7	16.8	64.4	730.4	49656.0	3440.0	49679.0
		AM + RM	2.9	0.7	7.8	8.3	12.7	515.9	49.1	515.9
3	9.3	AM	26.7	31.0	13.1	36.5	484.7	29914.0	2073.9	29942.0
		AM + RM	5.7	4.9	7.0	7.9	16.0	779.8	63.6	781.5
4	6.0	AM	29.0	21.9	43.7	56.8	590.7	39159.0	2813.4	39200.0
		AM + RM	4.0	2.7	0.9	4.9	15.0	273.0	19.4	273.6

In Table 38.5, the orbit determination accuracy of single-station single-lap angle measurement data ranges from 59.1 to 326.4 m. The duration for lap 1 is 16.0 min and orbit determination accuracy is 59.1 m while 24-h prediction accuracy is 31 km. The duration for lap 3 is 9.0 min and orbit determination accuracy is 326.4 m while 24-h prediction accuracy is 141 km. So we can conclude that the accuracy is related to the duration: the longer we observe the higher accuracy we will get.

When we combine the angle and ranging measurement data together, the orbit determination accuracy ranges from 3.2 to 11.5 m while 24-h prediction accuracy ranges from 123.4 to 1102.5 m. The main prediction errors appear in direction T. The ranging measurement data greatly improved the accuracy of orbit determination and prediction.

The orbit cycle of 800 km object is 101 min and the orbit determination result is shown in Table 38.6.

In Table 38.6, the orbit determination accuracy of single-station single-lap angle measurement data ranges from 36.5 to 244.0 m while the 24-h prediction accuracy ranges from 29.9 to 181.8 km. When ranging measurement data is combined, the orbit determination accuracy improved from 4.4 to 8.3 m and the 24-h prediction accuracy improved from 273.6 to 1033.0 m. The main prediction errors appear in direction T.

Table 38.7 Single-station single-lap orbit determination for the simulated 400 km object

Lap	Duration (min)	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
			Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1	5.0	AM	45.6	82.8	41.0	101.8	3742.3	1.54E + 5	9644.2	1.55E + 5
		AM + RM	5.1	1.6	7.3	9.1	54.1	3000.6	178.8	3006.0
2	5.0	AM	6.0	18.5	16.4	25.4	394.8	29214.0	1783.5	29270.0
		AM + RM	4.1	0.5	3.2	5.2	21.2	174.0	18.9	174.1
3	5.0	AM	25.9	33.7	20.9	47.4	918.4	68145.0	4256.6	68280.0
		AM + RM	5.0	1.2	5.9	7.8	35.8	1691.1	98.9	1694.0
4	5.3	AM	25.8	38.0	21.8	50.9	1012.2	59291.0	3623.4	59410.0
		AM + RM	0.9	0.4	3.2	3.4	6.3	435.6	25.7	436.4

Table 38.8 Single-station multi-lap orbit determination for the simulated 1500 km object

Lap	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
		Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1 + 2 + 3	AM	6.5	3.3	4.1	8.3	19.9	72.3	10.8	72.7
	AM + RM	2.8	3.0	1.1	4.0	5.3	21.2	2.6	21.2
2 + 3 + 4	AM	5.5	4.0	3.4	6.3	22.1	98.1	14.2	98.4
	AM + RM	4.3	4.7	0.7	6.3	2.5	16.7	1.7	16.7

The orbit cycle of 400 km object is 93 min and the orbit determination result is shown in Table 38.7.

In Table 38.7, the orbit determination accuracy of single-station single-lap angle measurement data ranges from 25.4 to 101.8 m while the 24-h prediction accuracy ranges from 29.2 to 155.0 km. When ranging measurement data is combined, the orbit determination accuracy improved from 3.4 to 9.1 m and the 24-h prediction accuracy improved from 174.1 to 3006.0 m. The main prediction errors appear in direction T. There is one thing to point out, when the object altitude is lower, the real atmospheric condition becomes more complicated. We cannot fully simulate the atmospheric environment. Besides, we use the same atmosphere model when we simulated the observation data and determine the orbits. So the real 24-h prediction accuracy will be worse than the simulated one.

38.3.3 Single-Station Multi-Lap Orbit Determination with Simulated Data

Determine the orbit using the single-station multi-lap data of objects 1500, 800 and 400 km, with the atmospheric and light pressure calculated, we got the following results.

In Table 38.8, the orbit determination accuracy of single-station multi-lap angle measurement data ranges from 6.3 to 8.3 m while the 24-h prediction accuracy

Table 38.9 Single-station multi-lap orbit determination for the simulated 800 km object

Lap	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
		Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1 + 2 + 3	AM	6.1	2.3	4.7	8.0	5.2	23.7	7.1	23.9
	AM + RM	1.6	0.9	0.9	1.9	1.1	8.7	1.2	8.8
2 + 3 + 4	AM	11.3	6.4	5.4	11.8	20.9	59.5	7.5	59.5
	AM + RM	2.2	1.6	1.3	2.6	3.8	20.4	2.2	20.4

Table 38.10 Single-station multi-lap orbit determination for the simulated 400 km object

Lap	Orbit determination type	Orbit determination accuracy/m				24-h prediction accuracy/m			
		Direction R	Direction T	Direction N	3D position	Direction R	Direction T	Direction N	3D position
1 + 2 + 3	AM	5.2	2.6	11.9	13.0	12.0	41.9	32.1	44.2
	AM + RM	1.1	0.6	0.3	1.1	3.6	14.9	1.6	15.0
2 + 3 + 4	AM	5.3	3.2	1.3	6.0	16.7	70.4	4.5	70.6
	AM + RM	2.1	1.0	1.5	2.3	3.9	15.4	3.7	15.4

ranges from 72.7 to 98.4 m. When ranging measurement data is combined, the orbit determination accuracy improved to 4.0 to 6.3 m and the 24-h prediction accuracy improved to 16.7 to 21.2 m. The main prediction errors appear in direction T. Compared to the results in Table 38.5, the accuracy of multi-lap orbit determination and 24-h prediction is usually higher than the single-lap one.

In Table 38.9, the orbit determination accuracy of single-station multi-lap angle measurement data ranges from 8.0 to 11.8 m while the 24-h prediction accuracy ranges from 23.9 to 59.5 m. When ranging measurement data is combined, the orbit determination accuracy improved to 1.9 to 2.6 m and the 24-h prediction accuracy improved to 8.8 to 20.4 m. The main prediction errors appear in direction T. Compared with the results in Table 38.6, the accuracy of multi-lap orbit determination and 24-h prediction is higher than the single-lap one.

In Table 38.10, the orbit determination accuracy of single-station multi-lap angle measurement data ranges from 6.0 to 13.0 m while the 24-h prediction accuracy ranges from 44.2 to 70.6 m. When ranging measurement data is combined, the orbit determination accuracy improved to 1.1 to 2.3 m and the 24-h prediction accuracy improved to 15.0 to 15.4 m. The main prediction errors appear in direction T. Compared with the results in Table 38.7, the accuracy of multi-lap orbit determination and 24-h prediction is higher than the single-lap one. Due to the same reason in Sect. 38.3.2, the real prediction accuracy will be worse than the simulated one.

38.4 Conclusions

The single-station orbit determination of satellite Ajisai with actual measurement data shows: (i) For single-station single-lap orbit determination, the ranging measurement data (measurement duration longer than 4 min), will improve the orbit determination accuracy from several kilometers to tens of meters and the 24-h prediction accuracy from thousands of kilometers to several kilometers. (ii) The short-time ranging measurement data (measurement duration shorter than 1 min), will improve the orbit determination accuracy to within 200 m. (iii) For single-station two-lap orbit determination, the ranging measurement data will improve the orbit determination accuracy from 50 to 5 m and the 24-h prediction accuracy from 350 to 18 m. (iv) The accuracy of single-station multi-lap orbit determination and prediction is higher than that of single-station single-lap. (v) The main prediction errors appear in direction T.

The simulated data of objects 1500, 800 and 400 km shows: (i) For single-station single-lap orbit determination, the ranging measurement data will improve the orbit determination accuracy from hundreds of meters to within 12 m and the 24-h prediction accuracy from more than 100 km to within 3 km. (ii) For single-station multi-lap orbit determination, the ranging measurement data will improve the orbit determination accuracy from tens of meters to within 7 m and the 24-h prediction accuracy from nearly 100 m to within 22 m. (iii) The accuracy of single-station multi-lap orbit determination and prediction is higher than that of single-station single-lap. (iv) The main prediction errors appear in direction T.

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