Coverage simulation of satellites Mozi and Jinan 1 during the quantum key distribution

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Abstract. Satellites Mozi and Jinan 1 are both in orbit for the quantum-dedicated missions by Chinese scientists. Satellite Mozi was sent into space in 2016; it has accomplished its whole goals by the end of 2017. Satellite Jinan 1 was sent into space in 2022, and has finished its main in-orbit demonstration experiments. If joint campaigns of these two satellites are considered, the efficiency of quantum key distribution will be boosted. Based on the up-to-date precision orbit elements for both Mozi and Jinan 1, the coverage of Jinan 1 with respect to the worldwide ground reference points is simulated and analyzed; in order to make some comparisons, the coverage of the joint campaign of Jinan 1 and Mozi with respect to the worldwide ground reference points is also computed and analyzed; the results have shown that the effective time for quantum key distribution is almost doubled when Mozi and Jinan 1 are considered as a whole campaign.

1. Introduction

The satellite Mozi has been in space for more than 8 years; it has obtained more than 3 outstanding accomplishments, including the first Satellite-based entanglement distribution over 1200 kilometers, the first satellite-to-ground quantum key distribution, and the first ground-to-satellite quantum teleportation experiment [1-5]. Jinan 1 was launched in 2022, and has been proven successful in the practical operation of quantum key distribution, which has some advantages over Mozi, such as low weight of payload, transportable ground stations for tracking the quantum satellite, inexpensiveness of satellite system development, and so on [6]. Follow-on practical engineering projects for quantum telecommunication are being carried out or have been included in the blueprint. Although satellite Mozi has come to the end of its lifespan, it is a good idea to conduct a joint campaign that considers Mozi and Jinan 1 together, aiming to boost the efficiency of quantum key distribution from space to ground users. Herein, two cases are studied. One is the simulation of coverage of mere Jinan 1 with respect to ground reference virtual stations; the other case is the simulation of coverage of both Jinan 1 and Mozi with respect to ground reference virtual stations. A comparison of the two cases reveals that the access time for key distribution will almost double if both Jinan 1 and Mozi are considered together. The simulations have shown that satellite Mozi can be best-made use of if it is included in Jinan 1 routine operations.

2. Simulations of coverage of satellites with respect to ground stations

The orbit elements for Mozi and Jinan 1 are presented as follows in the form of two line elements [7]. Table 1 includes the detailed information of orbit elements for Mozi and Jinan 1.

Table 1. Orbit elements for Mozi and Jinan 1.

QSS (Mozi)	
1 41731U 16051A	24322.11439118 .00015792 00000+0 35137-3 0 9995
2 41731 97.3032	233.8254 0010405 44.3273 315.8807 15.43670523460235
LZWN (JINAN 1)	
1 53300U 22087B	24322.16807901 .00050017 00000+0 69717-3 0 9990
2 53300 97.3103	41.1544 0006660 163.1089 197.0389 15.56748173129232

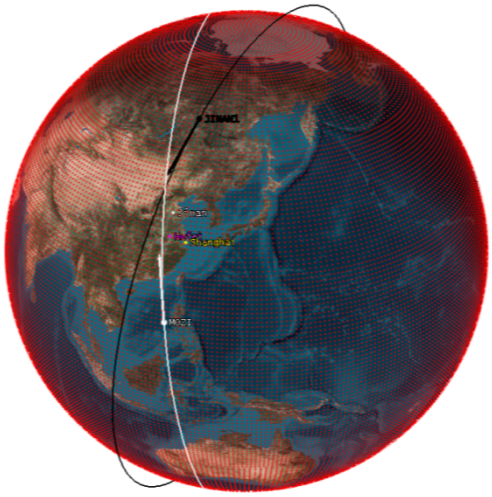

Figure 1. Grids on the Earth's surface and the footprints of Mozi and Jinan 1.

In order to make simulations, we make a grid net on the surface of the Earth. Every grid is 1°×1° separated. Every grid is denoted by a red point in Figure 1; as it is shown in Figure 1, the white curve is the footprint of Mozi, which is moving upward from the south to the North; the black curve is the footprint of Jinan 1, which is moving downward from the North to the south. Every grid is equivalent to a virtue ground station during the simulation. The simulation is carried out during a one-week-long orbit.

2.1. Coverage of satellite Jinan 1 with respect to ground stations

When only Jinan 1 is considered, the coverage of Jinan 1 with respect to ground stations is simulated and plotted in Figure 2. The accumulated time is simulated and plotted in Figure 3.

From Figure 2, it is obviously seen that at higher latitudes, the coverage percentage is higher; at the polar area, the percentage of coverage could be as high as 10.5%; at the equatorial area, the percentage of coverage could be as low as 1.9%; at the mid-latitude area, the percentage of coverage could be about 2.9%. Simulation results have shown that from south latitude -87° to south latitude -90°, there is an uncovered zone if only Jinan 1 is considered; however, there is no uncovered zone at the north polar zone. If we deploy some satellites with an orbit inclination of 90°, such uncovered zones could be avoided.

Figure 3, in a solid week, apparently indicates that the accumulated access time is comparatively greater at higher latitudes; at the polar area, the accumulated access time could be as great as 17.8 hours; at the equatorial area, the accumulated access time could be as low as 3.2 hours; at the mid-latitude area, the accumulated access time could be about 4.9 hours.

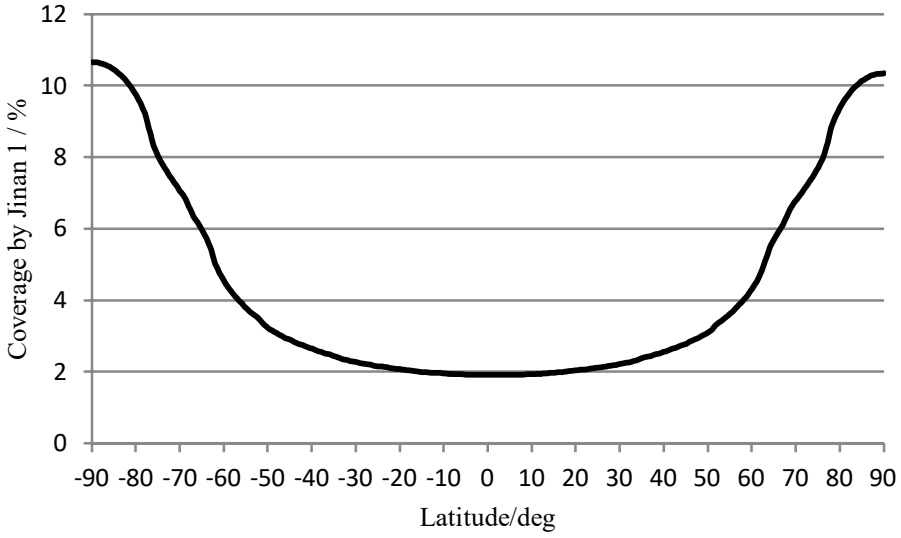

Figure 2. The percentage of coverage of Jinan 1 with respect to ground reference stations in a week.

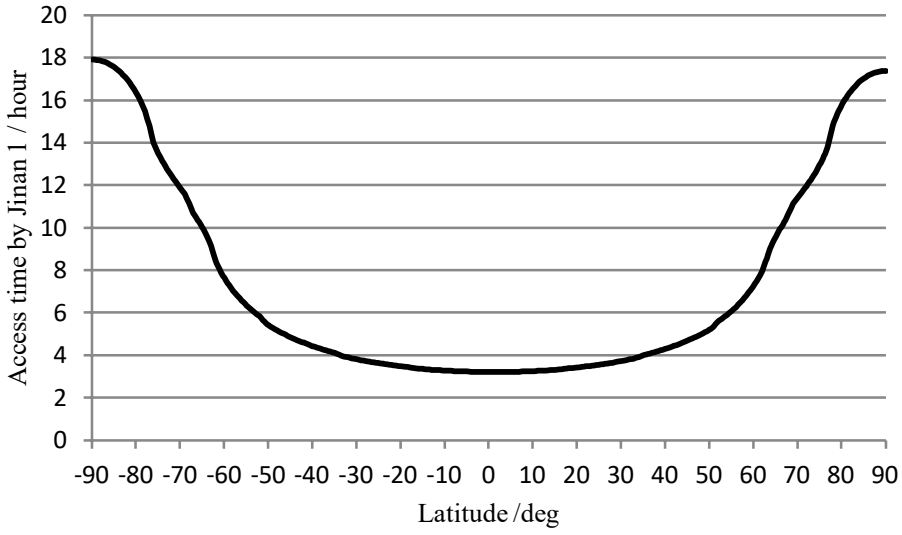

Figure 3. The access time of Jinan 1 with respect to ground reference stations in a week.

2.2. Coverage of satellites Jinan 1 and Mozi with respect to ground stations

From Figure 4, in the case of considering both Jinan 1 and Mozi, at higher latitudes, the coverage percentage is relatively higher; at the polar area, the percentage of coverage could be as high as 20.5%; at the equatorial area, the percentage of coverage could be as low as 3.87%; at the mid-latitude area, the percentage of coverage could be about 5.92%. Simulation results have shown that from south latitude -88° to south latitude -90°, there is an uncovered zone if both Jinan 1 and Mozi are considered; however, there is no uncovered zone at the north polar zone.

Figure 5, in a solid week, has indicated that the accumulated access time is relatively greater at higher latitudes; at the polar area, the accumulated access time could be as great as 34.4 hours; at the equatorial area, the accumulated access time could be as low as 6.5 hours; at the mid-latitude area, the accumulated access time could be about 10 hours.

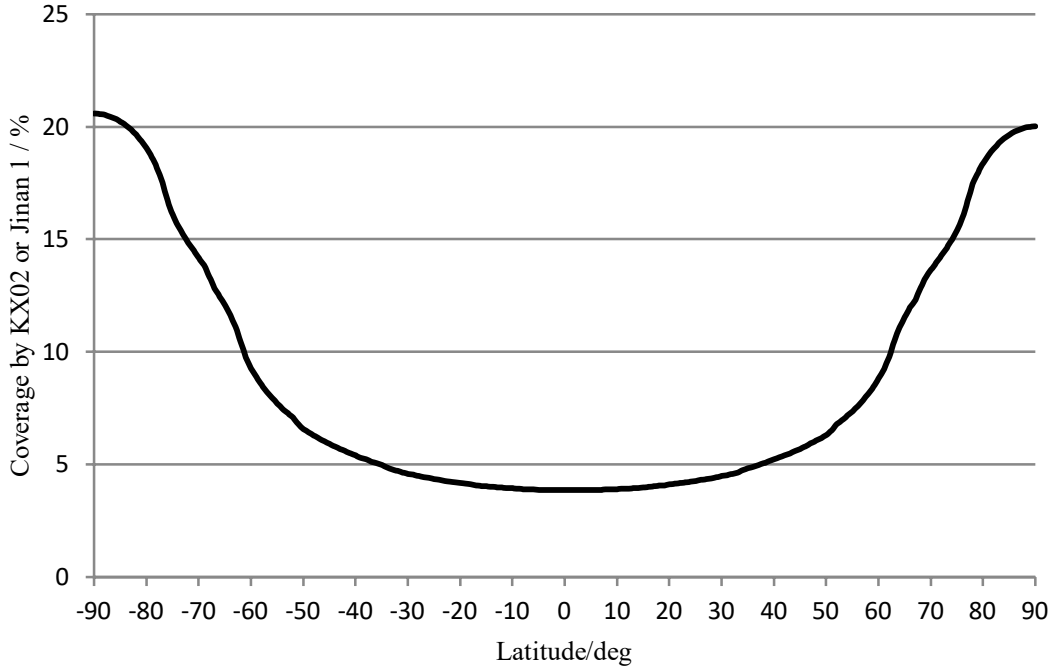

Figure 4. The percentage of coverage of Jinan 1 and Mozi with respect to ground reference stations in a week.

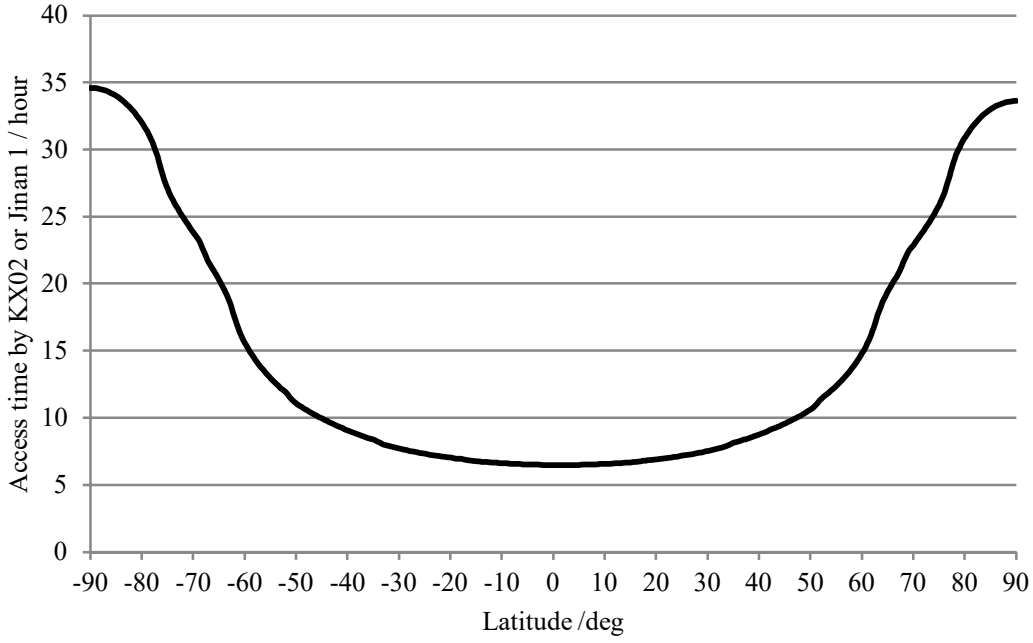

Figure 5. The accumulated access time of Jinan 1 and Mozi with respect to ground reference stations in a week.

Since both Jinan 1 and Mozi are nearly polar orbits, the variations of coverage of ground stations mainly come from the different latitudes, instead of different longitudes; therefore, we only present the variations of coverage of ground stations with the different latitudes. Simulations have shown that the coverage of efficiency has increased by 95% in the south polar region, increased by 104% in the

equatorial area, and increased by 104% in the mid-latitude area if both Jinan 1 and Mozi are considered together.

2.3. Prediction of passage time of satellites overground stations

At present, three main cities are deeply involved in the space-based quantum key distribution in China. They are Hefei, Shanghai, and Jinan. In Table 2, the passage time of satellites Mozi and Jinan 1 over the three cities in question is simulated, which could be used by campaign planning of Mozi and Jinan 1.

Table 2. Passage of satellites over specific ground stations.

Ground station	Satellite	Start time /UTC	End time /UTC	Access time /min
Hefei	Jinan 1	2024/11/18 3:44	2024/11/18 3:51	7.44
Hefei	Jinan 1	2024/11/18 14:03	2024/11/18 14:10	6.37
Hefei	Jinan 1	2024/11/18 15:35	2024/11/18 15:41	6.00
Hefei	Jinan 1	2024/11/19 2:53	2024/11/19 3:00	7.11
Hefei	Jinan 1	2024/11/19 4:26	2024/11/19 4:30	4.36
Hefei	Jinan 1	2024/11/19 14:43	2024/11/19 14:51	7.86
Hefei	Jinan 1	2024/11/20 3:33	2024/11/20 3:41	7.69
Hefei	Jinan 1	2024/11/20 13:53	2024/11/20 13:58	5.32
Hefei	Jinan 1	2024/11/20 15:24	2024/11/20 15:31	6.84
Hefei	Jinan 1	2024/11/21 2:42	2024/11/21 2:49	6.41
Hefei	Jinan 1	2024/11/21 4:14	2024/11/21 4:20	5.70
Hefei	Jinan 1	2024/11/21 14:32	2024/11/21 14:40	7.68
Hefei	Jinan 1	2024/11/22 3:22	2024/11/22 3:30	7.76
Hefei	Jinan 1	2024/11/22 13:43	2024/11/22 13:46	3.60
Hefei	Jinan 1	2024/11/22 15:12	2024/11/22 15:20	7.40
Hefei	Jinan 1	2024/11/23 2:31	2024/11/23 2:37	5.29
Hefei	Jinan 1	2024/11/23 4:02	2024/11/23 4:09	6.61
Hefei	Jinan 1	2024/11/23 14:21	2024/11/23 14:28	7.30
Hefei	Jinan 1	2024/11/23 15:54	2024/11/23 15:58	3.54
Hefei	Jinan 1	2024/11/24 3:10	2024/11/24 3:18	7.64
Hefei	Jinan 1	2024/11/24 15:00	2024/11/24 15:08	7.72
Hefei	Mozi	2024/11/18 3:42	2024/11/18 3:50	8.24
Hefei	Mozi	2024/11/18 15:08	2024/11/18 15:12	4.09
Hefei	Mozi	2024/11/18 16:38	2024/11/18 16:46	7.91
Hefei	Mozi	2024/11/19 3:03	2024/11/19 3:10	7.37
Hefei	Mozi	2024/11/19 4:36	2024/11/19 4:42	5.40
Hefei	Mozi	2024/11/19 15:59	2024/11/19 16:07	8.25
Hefei	Mozi	2024/11/20 3:55	2024/11/20 4:03	8.03
Hefei	Mozi	2024/11/20 15:20	2024/11/20 15:26	6.04
Hefei	Mozi	2024/11/20 16:52	2024/11/20 16:59	7.30
Hefei	Mozi	2024/11/21 3:16	2024/11/21 3:24	7.91
Hefei	Mozi	2024/11/21 16:12	2024/11/21 16:21	8.39
Hefei	Mozi	2024/11/22 2:38	2024/11/22 2:43	5.16
Hefei	Mozi	2024/11/22 4:09	2024/11/22 4:17	7.55
Hefei	Mozi	2024/11/22 15:33	2024/11/22 15:40	7.18
Hefei	Mozi	2024/11/22 17:06	2024/11/22 17:12	6.34
Hefei	Mozi	2024/11/23 3:29	2024/11/23 3:37	8.19

Hefei	Mozi	2024/11/23 16:25	2024/11/23 16:34	8.28
Hefei	Mozi	2024/11/24 2:50	2024/11/24 2:57	6.49
Hefei	Mozi	2024/11/24 4:23	2024/11/24 4:29	6.74
Hefei	Mozi	2024/11/24 15:46	2024/11/24 15:54	7.87
Hefei	Mozi	2024/11/24 17:20	2024/11/24 17:24	4.88
Jinan	Jinan 1	2024/11/18 3:43	2024/11/18 3:50	7.63
Jinan	Jinan 1	2024/11/18 14:04	2024/11/18 14:11	6.79
Jinan	Jinan 1	2024/11/18 15:36	2024/11/18 15:42	5.93
Jinan	Jinan 1	2024/11/19 2:52	2024/11/19 2:59	6.92
Jinan	Jinan 1	2024/11/19 4:24	2024/11/19 4:29	5.52
Jinan	Jinan 1	2024/11/19 14:44	2024/11/19 14:52	7.88
Jinan	Jinan 1	2024/11/20 3:32	2024/11/20 3:40	7.77
Jinan	Jinan 1	2024/11/20 13:54	2024/11/20 14:00	6.00
Jinan	Jinan 1	2024/11/20 15:25	2024/11/20 15:32	6.76
Jinan	Jinan 1	2024/11/21 2:41	2024/11/21 2:47	6.16
Jinan	Jinan 1	2024/11/21 4:13	2024/11/21 4:19	6.42
Jinan	Jinan 1	2024/11/21 14:33	2024/11/21 14:41	7.77
Jinan	Jinan 1	2024/11/22 3:21	2024/11/22 3:28	7.75
Jinan	Jinan 1	2024/11/22 13:43	2024/11/22 13:48	4.82
Jinan	Jinan 1	2024/11/22 15:13	2024/11/22 15:21	7.33
Jinan	Jinan 1	2024/11/23 2:30	2024/11/23 2:35	4.97
Jinan	Jinan 1	2024/11/23 4:01	2024/11/23 4:08	7.05
Jinan	Jinan 1	2024/11/23 14:22	2024/11/23 14:29	7.49
Jinan	Jinan 1	2024/11/23 15:56	2024/11/23 15:59	3.57
Jinan	Jinan 1	2024/11/24 3:09	2024/11/24 3:17	7.54
Jinan	Jinan 1	2024/11/24 4:42	2024/11/24 4:46	3.19
Jinan	Jinan 1	2024/11/24 15:02	2024/11/24 15:09	7.67
Jinan	Mozi	2024/11/18 3:43	2024/11/18 3:51	8.22
Jinan	Mozi	2024/11/18 15:07	2024/11/18 15:10	3.69
Jinan	Mozi	2024/11/18 16:37	2024/11/18 16:45	8.13
Jinan	Mozi	2024/11/19 3:04	2024/11/19 3:12	7.64
Jinan	Mozi	2024/11/19 4:38	2024/11/19 4:43	5.38
Jinan	Mozi	2024/11/19 15:58	2024/11/19 16:06	8.15
Jinan	Mozi	2024/11/19 17:32	2024/11/19 17:36	4.39
Jinan	Mozi	2024/11/20 2:26	2024/11/20 2:31	4.45
Jinan	Mozi	2024/11/20 3:57	2024/11/20 4:05	7.98
Jinan	Mozi	2024/11/20 15:19	2024/11/20 15:25	5.76
Jinan	Mozi	2024/11/20 16:51	2024/11/20 16:58	7.70
Jinan	Mozi	2024/11/21 3:17	2024/11/21 3:25	8.05
Jinan	Mozi	2024/11/21 4:52	2024/11/21 4:55	3.02
Jinan	Mozi	2024/11/21 16:11	2024/11/21 16:19	8.37
Jinan	Mozi	2024/11/22 2:39	2024/11/22 2:45	5.98
Jinan	Mozi	2024/11/22 4:10	2024/11/22 4:18	7.48
Jinan	Mozi	2024/11/22 15:32	2024/11/22 15:39	6.95
Jinan	Mozi	2024/11/22 17:04	2024/11/22 17:11	7.02
Jinan	Mozi	2024/11/23 3:30	2024/11/23 3:39	8.24
Jinan	Mozi	2024/11/23 16:24	2024/11/23 16:33	8.37
Jinan	Mozi	2024/11/24 2:51	2024/11/24 2:58	6.97

Jinan	Mozi	2024/11/24 4:24	2024/11/24 4:31	6.68
Jinan	Mozi	2024/11/24 15:45	2024/11/24 15:53	7.71
Jinan	Mozi	2024/11/24 17:18	2024/11/24 17:24	6.02
Shanghai	Jinan 1	2024/11/18 2:13	2024/11/18 2:19	5.22
Shanghai	Jinan 1	2024/11/18 3:44	2024/11/18 3:51	6.63
Shanghai	Jinan 1	2024/11/18 14:03	2024/11/18 14:10	7.26
Shanghai	Jinan 1	2024/11/18 15:36	2024/11/18 15:40	3.82
Shanghai	Jinan 1	2024/11/19 2:53	2024/11/19 3:00	7.66
Shanghai	Jinan 1	2024/11/19 14:43	2024/11/19 14:50	7.77
Shanghai	Jinan 1	2024/11/20 2:03	2024/11/20 2:07	3.33
Shanghai	Jinan 1	2024/11/20 3:33	2024/11/20 3:40	7.21
Shanghai	Jinan 1	2024/11/20 13:52	2024/11/20 13:59	6.63
Shanghai	Jinan 1	2024/11/20 15:24	2024/11/20 15:30	5.50
Shanghai	Jinan 1	2024/11/21 2:42	2024/11/21 2:49	7.33
Shanghai	Jinan 1	2024/11/21 4:15	2024/11/21 4:18	3.22
Shanghai	Jinan 1	2024/11/21 14:31	2024/11/21 14:39	7.85
Shanghai	Jinan 1	2024/11/22 3:22	2024/11/22 3:29	7.57
Shanghai	Jinan 1	2024/11/22 13:41	2024/11/22 13:47	5.66
Shanghai	Jinan 1	2024/11/22 15:12	2024/11/22 15:19	6.55
Shanghai	Jinan 1	2024/11/23 2:31	2024/11/23 2:37	6.73
Shanghai	Jinan 1	2024/11/23 4:03	2024/11/23 4:08	5.09
Shanghai	Jinan 1	2024/11/23 14:20	2024/11/23 14:28	7.74
Shanghai	Jinan 1	2024/11/24 3:10	2024/11/24 3:18	7.74
Shanghai	Jinan 1	2024/11/24 13:31	2024/11/24 13:35	4.10
Shanghai	Jinan 1	2024/11/24 15:00	2024/11/24 15:08	7.23
Shanghai	Mozi	2024/11/18 2:12	2024/11/18 2:15	3.13
Shanghai	Mozi	2024/11/18 3:42	2024/11/18 3:50	7.97
Shanghai	Mozi	2024/11/18 15:07	2024/11/18 15:13	6.36
Shanghai	Mozi	2024/11/18 16:39	2024/11/18 16:46	7.04
Shanghai	Mozi	2024/11/19 3:02	2024/11/19 3:10	7.98
Shanghai	Mozi	2024/11/19 15:59	2024/11/19 16:07	8.37
Shanghai	Mozi	2024/11/20 2:24	2024/11/20 2:30	5.38
Shanghai	Mozi	2024/11/20 3:55	2024/11/20 4:03	7.42
Shanghai	Mozi	2024/11/20 15:20	2024/11/20 15:27	7.38
Shanghai	Mozi	2024/11/20 16:53	2024/11/20 16:59	5.93
Shanghai	Mozi	2024/11/21 3:15	2024/11/21 3:24	8.22
Shanghai	Mozi	2024/11/21 16:12	2024/11/21 16:20	8.20
Shanghai	Mozi	2024/11/22 2:37	2024/11/22 2:43	6.65
Shanghai	Mozi	2024/11/22 4:09	2024/11/22 4:16	6.51
Shanghai	Mozi	2024/11/22 15:33	2024/11/22 15:41	8.00
Shanghai	Mozi	2024/11/22 17:07	2024/11/22 17:11	4.14
Shanghai	Mozi	2024/11/23 3:29	2024/11/23 3:37	8.21
Shanghai	Mozi	2024/11/23 14:55	2024/11/23 14:59	4.71
Shanghai	Mozi	2024/11/23 16:26	2024/11/23 16:33	7.78
Shanghai	Mozi	2024/11/24 2:50	2024/11/24 2:57	7.46
Shanghai	Mozi	2024/11/24 4:23	2024/11/24 4:28	5.03
Shanghai	Mozi	2024/11/24 15:46	2024/11/24 15:54	8.32

If both Mozi and Jinan 1 are considered together, for Hefei station, the average access time is 6.74 min, maximal time is 8.39 min, minimal time is 3.54 min, and there is 283 min available for quantum key distribution; for Jinan station, the average access time is 6.64 min, maximum time is 8.37 min, minimum time is 3.02 min, and there is 305 min available for quantum key distribution; for Shanghai station, average access time is 6.55 min, maximal time is 8.37 min, minimum is 3.13 min, and there is 288 min available for quantum key distribution.

3. Conclusions

Based on the simulations, it has shown that it is both advantageous and efficient if Jinan 1 and Mozi could be considered as a whole during the quantum key distribution application; the coverage could be doubled compared with the case of considering only Jinan 1; in one solid week, at the polar area, the accumulated access time could be as great as 34.4 hours; at the equatorial area, the accumulated access time could be as low as 6.5 hours; at the mid-latitude area, the accumulated access time could be about 10.0 hours; the access time is almost doubled compared with the only Jinan 1 case. In the future, more key-distribution-dedicated satellites from China will be deployed in space, which will further densify the satellite network, leading to quasi real time quantum key distribution operations.

Acknowledgments

The simulations for this research are partly based on online orbit sources, updated by Kelso [7].

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