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Orbit decaying simulation of QUESS satellite and its reentry prediction

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Abstract: The Quantum Experiments at Space Scale satellite (short for QUESS) is one of the space missions proposed by the Chinese Academy of Sciences; its main scientific goals include carrying out three experiments in space. They are satellite-based quantum entanglement distribution experiments, satellite-to-ground quantum key distribution, and ground-to-satellite quantum teleportation. In 2017, three experiments were proved to be a great success, the results of which were published in Nature and Science, respectively. At present, orbit decaying for QUESS seems to be worsening partially due to the solar maximal activities during the recent years. Based on the precision orbit elements derived from the GNSS receiver onboard the QUESS, the orbit evolution is simulated, and the reentry predictions are carried out. The results provide consulting support for ground TTC staff to take effective measures to ensure QUESS' reentry without endangering the human activities on the Earth ground.

1. Introduction

The Quantum Experiments at Space Scale satellite (short for QUESS) includes a platform and a group of four payloads. The platform is composed of 6 basic subsystems; they are respectively responsible for power, attitude, structure, telemetry-tracking command (TT&C), data transmission, and housekeeping. There are four payloads aboard the QUESS platform, including a quantum experimental controlling unit, a quantum entanglement source, a quantum key communication equipment, and a quantum entanglement transmitter. QUESS has been proven to be one of the most fruitful spacecraft in China [1, 2, 3]. Based on the data set derived from QUESS in 2017, scientists of the QUESS task team published three publications in Nature and Science, respectively [4, 5, 6], including satellite-based quantum entanglement distribution experiment, satellite-to-ground quantum key distribution, and ground-to-satellite quantum teleportation, which were cited by ceremony introductions for 2022 Nobel prize in Physics [3]. The scientific goals of the QUESS mission were fulfilled, which cost only one year time. It has been 8 years since its launch into orbit. The orbit for QUESS seems to be worsening due to its long stay in space. In addition, maximal solar activities hasten the decay of its orbit. It is a privilege for the authors of this paper who have been operating and supporting the routine operation of QUESS to research the orbit decaying and its reentry into the Earth's atmosphere. They have access to the first-hand and comparatively latest precision orbit elements data set, which helps to simulate the orbit decaying and make predictions of its reentry at the next-to-real precision. During the simulations in this paper, the nearly latest available precision orbit elements of QUESS via GNSS telemetry were used. The precision dynamical force models are considered. Finally, the orbit evolution is simulated, and the reentry time is predicted in this paper. The results could help the ground operation staff of QUESS to make well-prepared countermeasures to prevent human beings from possibly getting hurt when the reentry event of QUESS happens in the future.

2. Orbit evolution simulation and reentry prediction

By Telemetry, Tracking, and Command (TT&C), Global-Navigation-Satellite-System-based receivers (GNSS receivers) could provide the precision orbit elements of QUESS as follows. The epoch for orbit elements is 8:0:0 UTC, Aug. 19, 2024 and the semi-major axis is 6, 830.1058 km; the eccentricity is 0.001411; the orbit inclination is 97.381287°; right ascension of the ascending node is 143.73024°; argument of perigee is 41.878601°; the mean anomaly is 299.679291°. According to the datasheet for the actual structure of QUESS, the maximal ratio for area-to-mass is estimated to be 0.01051 m^2/kg, and the minimal ratio for area-to-mass is estimated to be 0.002525 m^2/kg. The average for solar radiation flux is assumed to be 150 sfu; the coefficient for atmospheric drag is assumed to be 2.80475; the coefficient for solar pressure is assumed to be 1.0. Atmosphere density model NRLMSISE-00 is considered.

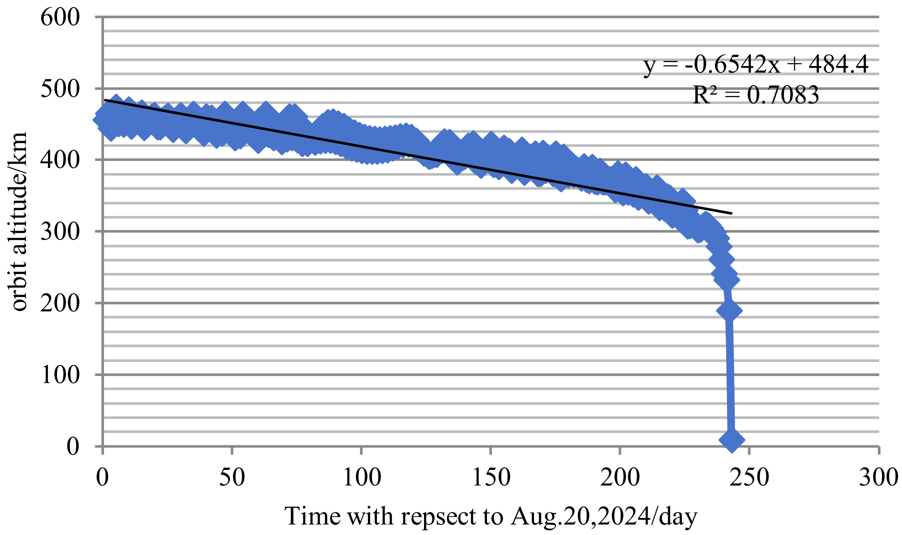

Figure 1. Orbit decaying in case of the maximal area-to-mass.

In Figure 1, the ratio for area-to-mass is 0.01051 m^2/kg, which corresponds to the maximal ratio of area-to-mass for QUESS. Most of the curve for orbit altitude versus time could be well fitted by the equation y=-0.6542x+484.4, where y represents altitude in km and x represents time in days; when x is 0, y is 484.4 km, and such occasion corresponds to Aug. 20, 2024. The fitted straight line indicates that there are about 654-meter daily orbits decaying in the case of the maximal ratio of area-to-mass. The simulations also show that at the time 16:53:18 UTC, Apr., 18, 2025, QUESS will be passing the dense atmosphere, and the body of QUESS will be burnt and vanish due to the furious friction of the atmosphere. The point of reentry is estimated to be at the point with geographic coordinates of (-61°W, -37°S). The point of reentry can be re-adjusted by changing the attitude of QUESS so that residuals of QUESSS might fall in sparsely populated areas or remote oceans. Such a study will be further discussed in another paper.

From Figure 2, simulations have shown that the variation of orbit inclination obeys the cosine function with an amplitude of +/-0.115 deg. Simulations have shown that during the case of maximal area-to-mass, QUESS might remain in orbit for about 240 days. It seems impending that QUESS will re-enter the Earth's atmosphere.

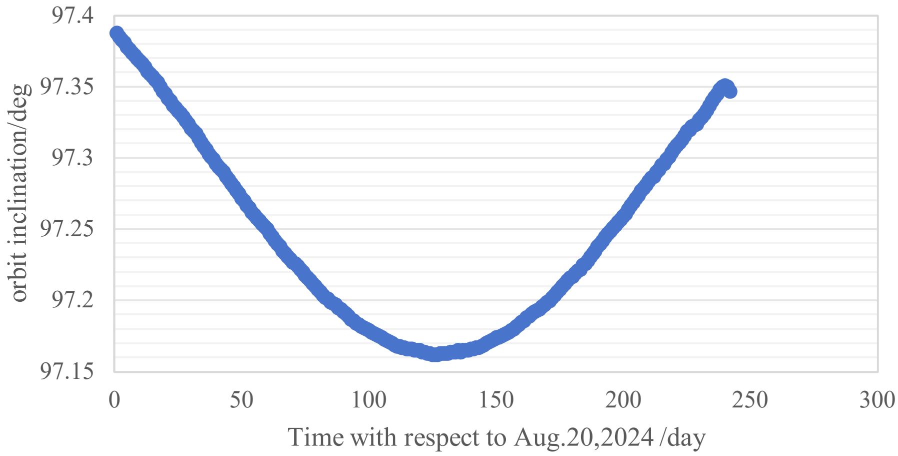

Figure 2. Orbit inclination variation in the case of the maximal area-to-mass.

Table 1. Different attitudes lead to different locations for reentry points.

The ratio of area to mass under different attitudes/ (m^2/kg)	Longitude of the point of reentry /deg	Latitude of the point of reentry/deg	Time of reentry/UTC
Sin(15°)*0.01051	142.65	-40.84	10 Apr. 2027 05:16:39.805
Sin(30°)*0.01051	-9.483	-73.823	29 Dec. 2025 15:27:29.836
Sin(45°)*0.01051	12.512	-11.731	9 Aug. 2025 23:51:30.135
Sin(60°)*0.01051	119.722	-58.553	25 May 2025 15:46:37.744
Sin(75°)*0.01051	16.558	-82.148	26 Apr. 2025 18:58:42.715

In Table 1, we simulated the reentry points' variation in different cases of attitudes. During the simulations, different attitudes correspond to different ratios of area to mass. From Table 1, two reentry points with geodetic coordinates of (-9.483°W, -73.823°S) and (16.558°E, -82.148°S）are good candidates for QUESS to re-enter the atmosphere since there is sparsely populated in the south pole areas. From Table 1, it is found that large ratios of area to mass will accelerate the orbit decaying trend.

Table 2. Influence of solar flux on reentry point distribution.

Solar fluxes /sfu	Longitude of the point of reentry /deg	Latitude of the point of reentry/deg	Time of reentry/UTC
250	82.271	29.020	16 Nov. 2024 06:19:19.048
200	-173.847	76.624	1 Jan. 2025 13:54:58.724
150	-61.00	-37.00	18 Apr. 2025 16:53:18
100	38.450	8.687	16 Mar. 2026 22:44:49.614

Simulations in Table 2 show the influence of solar flux on reentry point distribution under the maximal ratio of area to mass. The greater the solar fluxes are, the more quickly QUESS re-enters the atmosphere. Under different solar fluxes, the reentry points seem somewhat random. To some extent, the reentry points are difficult and need demanding efforts in the future.

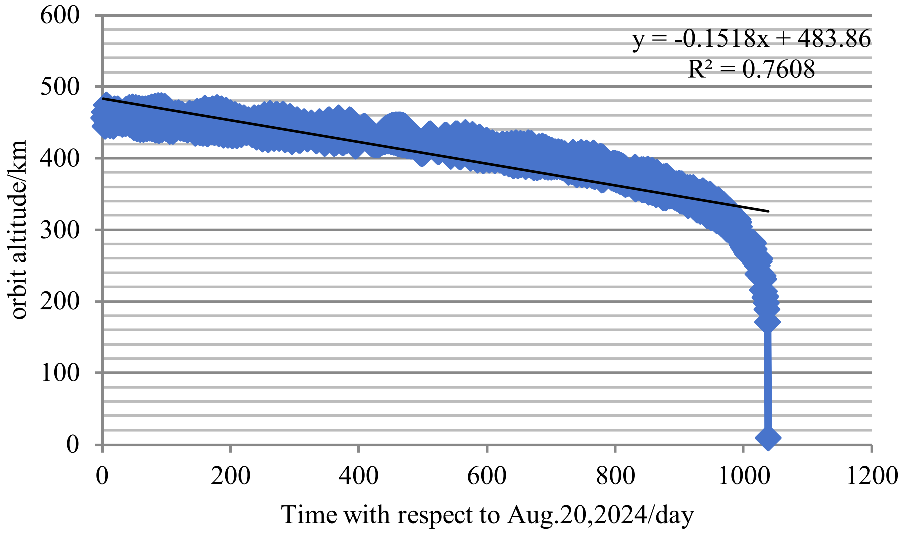

Figure 3. Orbit decaying in case of the minimal area-to-mass.

In Figure 3, the ratio for area-to-mass is 0.002525 m^2/kg, which corresponds to the minimal ratio of area-to-mass for QUESS. Most of the curve for orbit altitude versus time could be well fitted by the equation y=-0.1518x+483.86, where y represents altitude in km and x represents time in days; when x is 0, y is 483.86 km, such occasion corresponds to Aug. 20, 2024. The fitted straight line indicates that there is about a 152-meter daily orbit decaying in the case of a minimal ratio of area-to-mass. The simulations also show that at the time 19:23:37 UTC, Jun., 22, 2027, QUESS will be passing the dense atmosphere, and the body of QUESS will be burnt and vanish due to the furious friction of the atmosphere. The point of reentry is estimated to be at (-68°W, -26°S). In the actual operation, such a point of reentry will be calculated again and again by means of adjusting the attitude of QUESS so that there will be no mishaps happening.

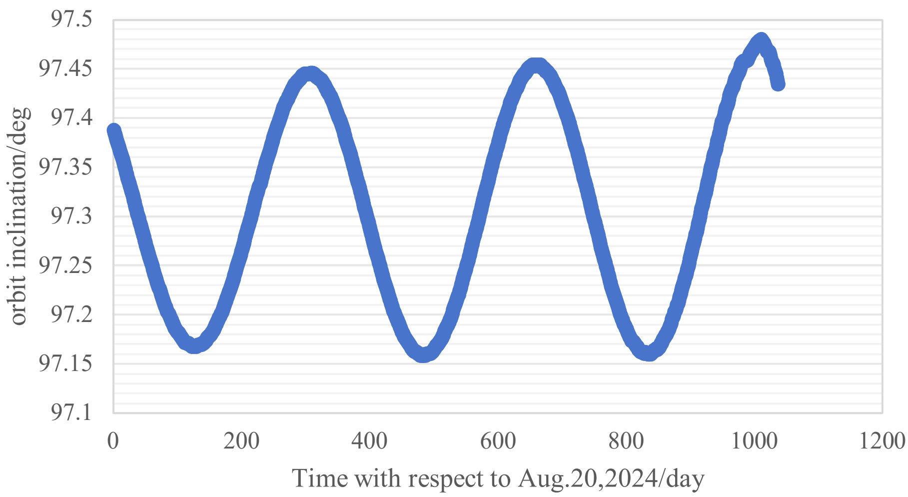

Figure 4. Orbit inclination variation in case of the minimal area-to-mass.

From Figure 4, simulations have shown that the variation of orbit inclination generally obeys the cosine function with an amplitude of +/-0.14 deg. Simulations have also shown that during the case of maximal area-to-mass, QUESS might remain in orbit for about 1, 020 days, which is a much longer time of stay in orbit than that for the case of minimal area-to-mass.

3. Conclusions

Based on the above-mentioned simulation, we can come to the following conclusions. Results derived from precision orbit and high precision force models have shown that QUESS might have a lifespan between 8 months and 34 months since Aug. 20, 2024. Monitoring data set from another space scientific satellite ASO-S, which is aiming at observing and monitoring solar activities, has proved that the year 2024 is one of the maximal-solar-activities years. That is one of the reasons that accelerate the orbit decaying of QUESS. On the other hand, results also have shown that if the ratio for area-to-mass is 0.01051 m^2/kg, the reentry point might be located at the geographical point (-61°W, -37°S); if the ratio for area-to-mass is 0.002525 m^2/kg, the reentry point might be located at the geographical point (-68°W, -26°S). QUESS is facing the impending event of reentry into the Earth's atmosphere. It is time that the ground operation staff be well prepared for countermeasures to prevent QUESS from endangering human beings while reentering the Earth's atmosphere. A careful scenario of readjusting of QUESS attitude should be well studied and prepared so that the reentry zone is ensured to be a sparsely populated area or remote ocean so no mishaps happen.

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