Orbital Analysis of the Shenzhou-6 Manned Mission in Support of the Malindi Tracking Station

Technical Report

Prepared by

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ABSTRACT

This report presents an analysis of the orbital, re-entry and ground coverage aspects of the second Chinese manned mission, Shenzhou-6, carried out on October 2005. The flight was supported by the Malindi tracking station, in Kenya, managed by the Italian Space Agency (ASI). Before and during the mission, the Spaceflight Dynamics Laboratory of ISTI/CNR provided the ASI personnel in Malindi with trajectory and maneuver analysis, flight monitoring, tracking passes predictions and re-entry events sequence, reconstructed with in-house simulations. The outputs, when applicable, were compared with the data provided by the Chinese, for consistency checks.

The Malindi ground station played an important role in the Shenzhou-6 flight, as was in the case of the first manned mission, Shenzhou-5, on October 2003, when the Chinese inaugurated its use. Due to its critical geographical position, in fact, Malindi neatly integrated the existing network of ground stations and tracking ships, covering also a critical portion of the re-entry phase.

1. THE SHENZHOU-6 MISSION

1.1 Introduction

After a two-year gap since the first 21-hour manned flight, Shenzhou-5, on 15 October 2003, China was ready for a second much more ambitious mission, having implemented many important modifications and improvements on the space vehicle. The main goals of the second human tended flight were the launch of a two men crew, a five days mission and the first inhabitation of the orbital module in space, to conduct some unspecified experiments.

The components of the CZ-2F launcher arrived, by rail, from Beijing at the Jiuquan Satellite Launch Center (JSLC), in the Gansu province, in mid-September 2005 and were stacked vertically in the Vertical Assembly and Testing Building (VATB). Originally, the launch was planned for the end of September, but was later postponed to mid-October for unknown reasons. Apart specific technical motivations, the delay could have been decided to avoid superimposition with the Soyuz-TMA-7 mission to the International Space Station, to be launched on 30 September. In fact, one of the untold purposes of the Chinese flight was to obtain the maximum media coverage abroad, without sharing it with another significant space event. Another possible reason of the postponement, this one in order to maximize the attention of the Chinese public, could have been the opportunity to put the launch after the weeklong holiday following the National Day celebrations, on 1 October.

In any case, at the end of the review process, the launch of Shenzhou-6 was fixed at 3:00 UTC (11:00 Beijing time) on 13 October 2005 (see Table 1.1 for the time zones of interest in this report). The lift-off and landing would have occurred during daylight hours to enhance the safety of the crew.

Table 1.1

Time Zones of Interest during the Shenzhou-6 Mission

Location	Time Zone
Beijing	**UTC + 8 hours**
Jiuquan Satellite Launch Center	**UTC + 8 hours**
Primary Landing Site	**UTC + 8 hours**
Malindi Ground Station	**UTC + 3 hours**
Italy	**UTC + 2 hours**

1.2 Ground Tracking and Malindi Support

As in the case of the first manned mission, also for Shenzhou-6 the tracking network included four Yuanwang specially equipped ships, connected via satellite to the Chinese mainland, and seven ground stations, of which four in China and one each in Pakistan, Namibia and Kenya (see Table 1.2 and Figure 1.1).

Table 1.2

Tracking Stations used during the Shenzhou-6 Mission

Station Name	Latitude (°)	Longitude (°E)
Karachi	24.85	67.03
Kashi	39.48	76.03
Malindi	–3.00	40.20
Qingdao	36.07	120.37
Swakopmund	–22.67	14.57
Weinan	34.50	109.50
Xiamen	24.47	118.03
Yuanwang-1	29.00	130.00
Yuanwang-2	–30.00	190.00
Yuanwang-3	–25.00	9.00
Yuanwang-4	–35.00	105.00

As for the flight of Shenzhou-5, in October 2003, even in this case China asked for the availability and support of the Malindi S-band tracking station, in Kenya, managed by the Italian Space Agency (ASI). Having defined the appropriate instrumentation interfaces, a team of Chinese technicians was transferred in Malindi, to operate autonomously its own equipment, with voice and data links with the mission control center in China.

During the nominal Shenzhou-6 mission of 115.55 hours, corresponding to 76 complete revolutions, 16 passes over Malindi, with an elevation greater than 5 deg, were planned, including the last one during the critical re-entry phase. The expected total acquisition time above 5 deg was about 98 minutes, with minimum pass duration of 297 s, maximum duration of 440 s and average duration of 367 s. The first useful pass over Malindi was foreseen about 7 hours and 49 minutes after launch.

The importance of the Malindi station for the Shenzhou mission became clear when, due to the launch delay from the end of September to mid-October, a schedule conflict arose with an Ariane V launch, planned at Kourou on 13 October 2005, between 22:32 and 23:56 UTC. The Malindi S-band station is, in fact, part of the ESA's network operated in support of the Ariane launches, and this activity has the priority over any other commitment. In addition, an antenna involved in an Ariane launch must be prepared and kept idle some hours before and after its planned use, making the schedule conflict worse. In the specific case, the Ariane V launch on 13 October would have prevented Malindi to track Shenzhou-6 during a critical pass, approximately 21 hours after launch, corresponding to the first (contingency) re-entry opportunity on the primary landing and recovery site (42.019 °N, 112.64 °E), near the town of Siziwang Qi, about 80 km north of Hohhot, the capital of Inner Mongolia. This pass over Malindi was so crucial for the Chinese that they decided, on 10 October, to anticipate the launch by one day, to 12 October 2005. Moreover, in order to further attenuate the tracking schedule conflict with the Ariane V lift-off, the time of launch was anticipated by two hours, to 1:00 UTC, dropping the important requirement of a nominal landing in daylight.

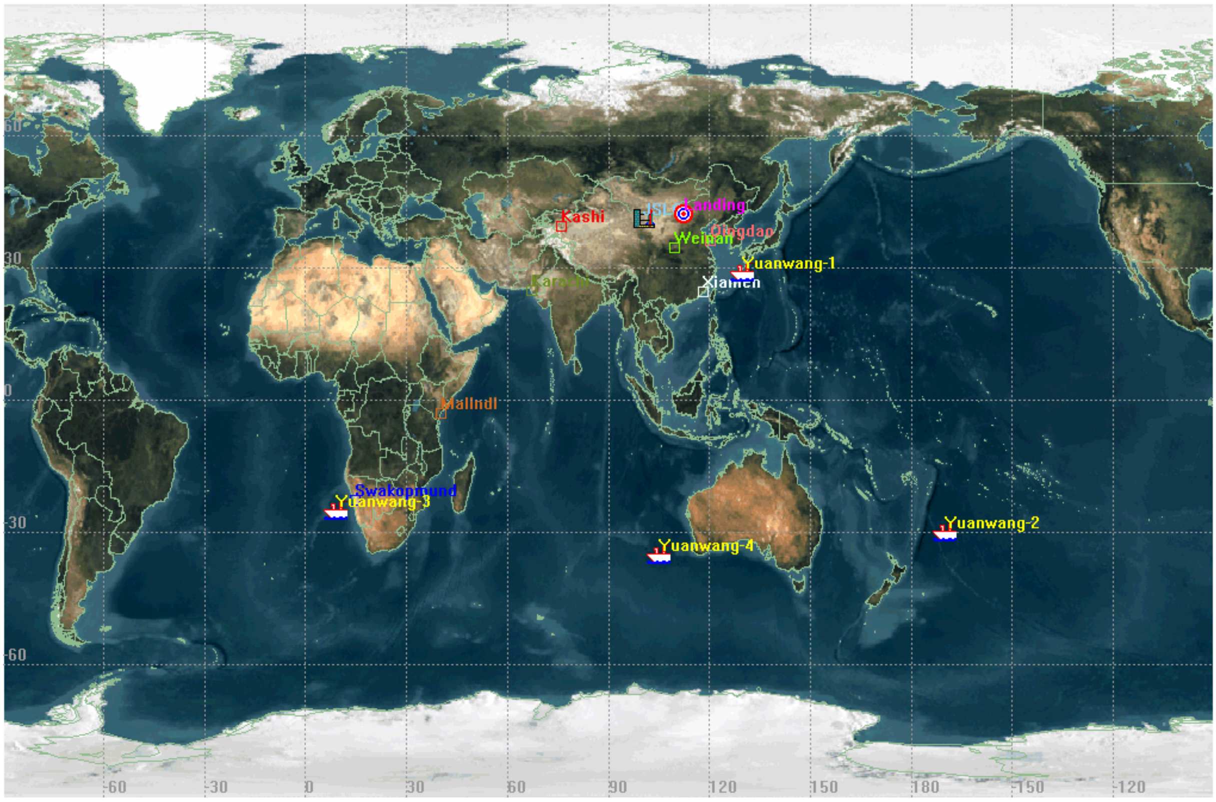

Fig. 1.1 – Geographical distribution of tracking ground stations and ships, launch complex (JSLC) and primary landing site

1.3 Launch

Shenzhou-6 finally lifted off, from the CZ-2F launch pad of JSLC (40.9419 °N, 100.2907 °E; altitude: 1073 m), at 1:00:03.583 UTC on 12 October 2005. The ascent was nominal, with the escape rocket separating 120 seconds after launch. Sixteen seconds later, the four boosters were discarded at an altitude of 52 km. The payload fairing and the first stage detached 200 seconds after launch. The second stage burned for a further 383 seconds and the spacecraft separated from the upper stage at 200 km. The vehicle then used its own propulsion system to be placed into a 211 × 345 km orbit, with an inclination of 42.40 deg, about 21 minutes after launch.

The spent CZ-2F upper stage was left into a 192.5 × 345.2 km orbit, inclined of 42.40 deg, while two operational debris, with a radar cross-section of less than one square meter, were left into elliptical orbits of 186.3 × 496.2 km (object C) and 167.2 × 511.3 km (object D), inclined, respectively, of 42.59 and 42.53 deg with respect to the equator.

The first maneuver occurred at 7:54:45 UTC over the Southern Pacific Ocean, in visibility of the Yuanwang-2 tracking ship, when two of the main motors of the service module, with a combined thrust of 5000 N, were fired for about 62 seconds at the apogee, increasing the spacecraft velocity by approximately 40 m/s, at the expense of about 110 kg of propellant. The new orbit had a minimum geodetic altitude of 329.1 km, a maximum geodetic altitude of 346.7 km and an inclination of 42.41 deg. After about one hour and a half, the hatch between the re-entry and orbital modules was opened for the first time in flight, making available a second living and working compartment for the crew.

A second orbital maneuver occurred at 21:56 UTC on 13 October, over the Southern Atlantic Ocean, in visibility of the Yuanwang-3 tracking ship. It lasted only 6.5 seconds and raised the geodetic altitude of the perigee by about one kilometer, from 328.8 to 330.0 km. The apogee remained substantially unchanged at 345.6 km. The maneuver was apparently unplanned, but was decided to contrast an atmospheric drag higher than predicted, by applying a velocity increase of 4.8 m/s at the apogee. The small trajectory adjustment, again accomplished with two of the main rocket motors, consumed about 13 kg of hypergolic propellant.

No further orbital maneuvers were carried out during the remaining part of the mission, until the de-orbit burn, and the semi-major axis was left to decay by approximately 250 m.

1.4 Nominal Orbit

The sub-satellite ground track of the Shenzhou nominal orbit repeats itself after 31 revolutions, i.e. after about 1.9635 days. The corresponding repetitive ground track pattern, spanning approximately 47 hours, is shown in Figure 1.2. Taking into account the launch geometry, this implies that during the mission of Shenzhou-6, with a planned duration of 115.55 hours and 76 orbits, three re-entry opportunities in the primary landing and recovery site (42.019 °N, 112.64 °E; altitude: ~ 1000 m) existed.

The first one occurred after 14 orbits, about 21.5 hours after launch, and was the re-entry opportunity chosen for the first manned mission, Shenzhou-5, on October 2003, and for the first unmanned spacecraft test, Shenzhou-1, on November 1999. The second re-entry opportunity occurred after 45 revolutions, about 68.5 hours after launch, and has never been used so far. The third opportunity, 76 revolutions and about 115.5 hours after launch, was that chosen for the second manned flight, Shenzhou-6, while a fourth opportunity, 107 revolutions and about 162.5 hours after launch, was used for the unmanned re-entries of Shenzhou-2 (January 2001), Shenzhou-3 (April 2002) and Shenzhou-4 (January 2003).

Another important property of the orbit chosen for the Shenzhou missions, with a mean semi-major axis of 6714.5 km (see Figure 1.3), is clarified by Figure 1.4, where the spacecraft

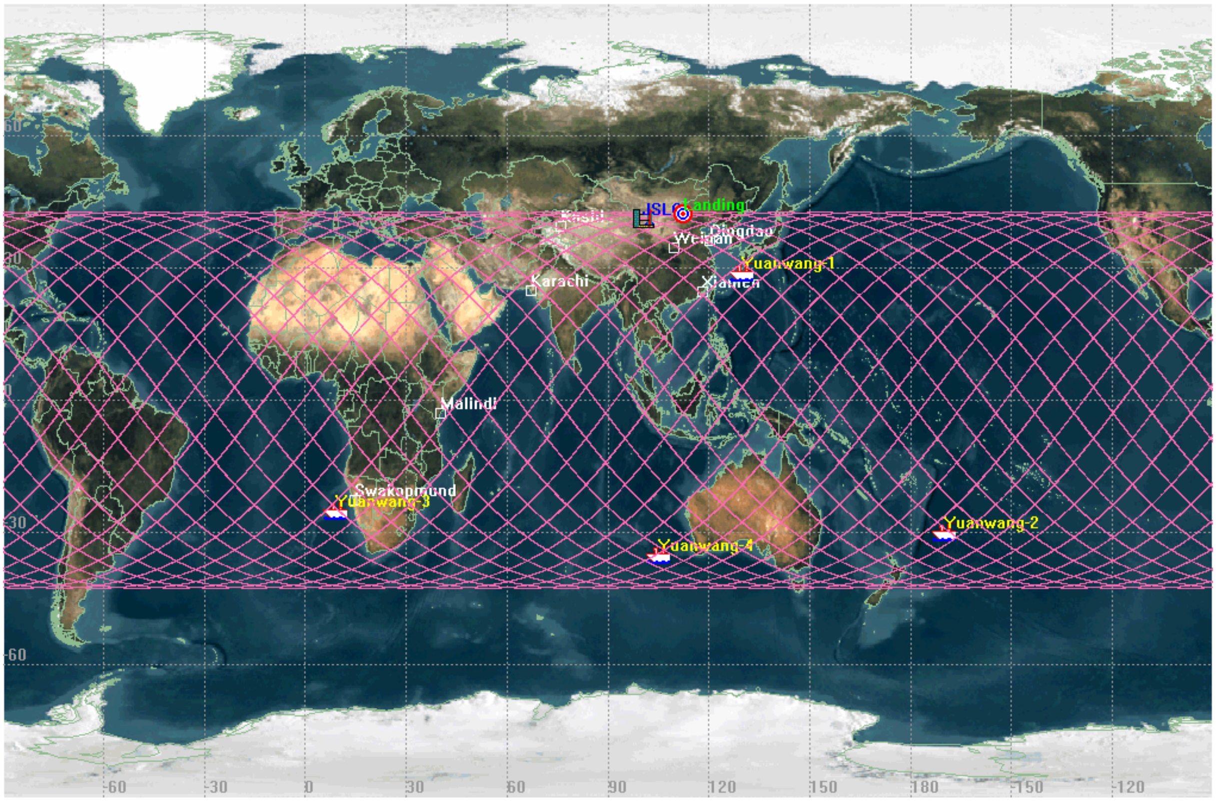

Fig. 1.2 – Shenzhou repetitive ground track pattern over 31 revolutions (about 47 hours)

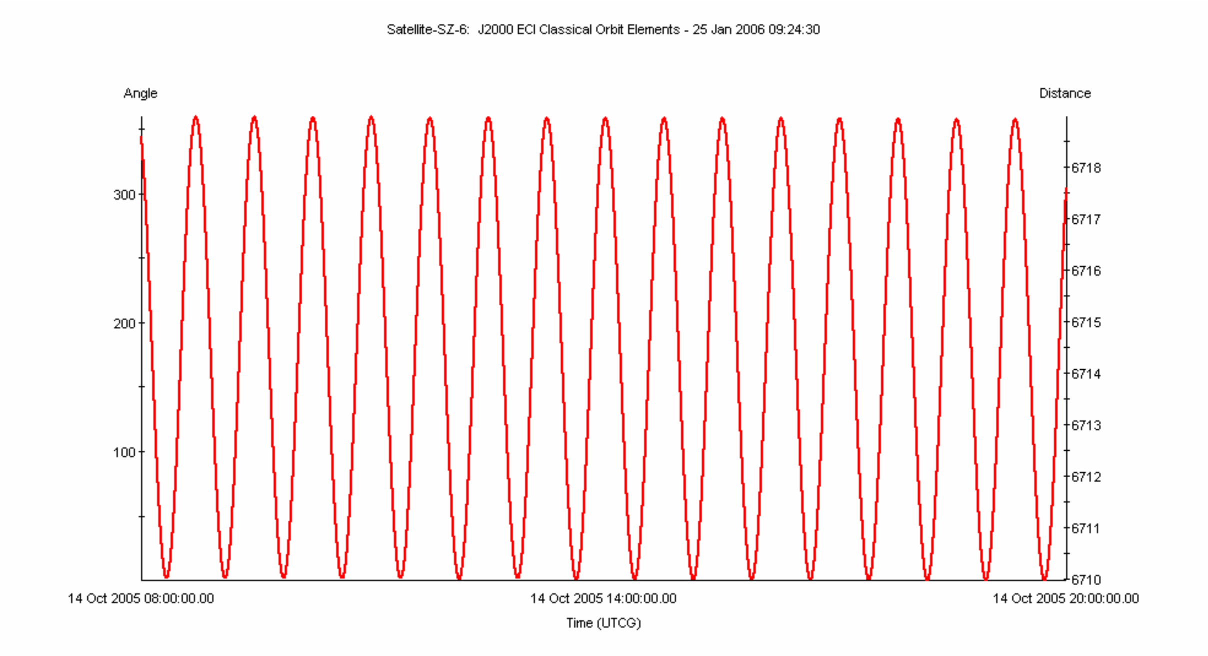

Fig. 1.3 – Shenzhou-6 osculating semi-major axis over 12 hours on 14 October 2005

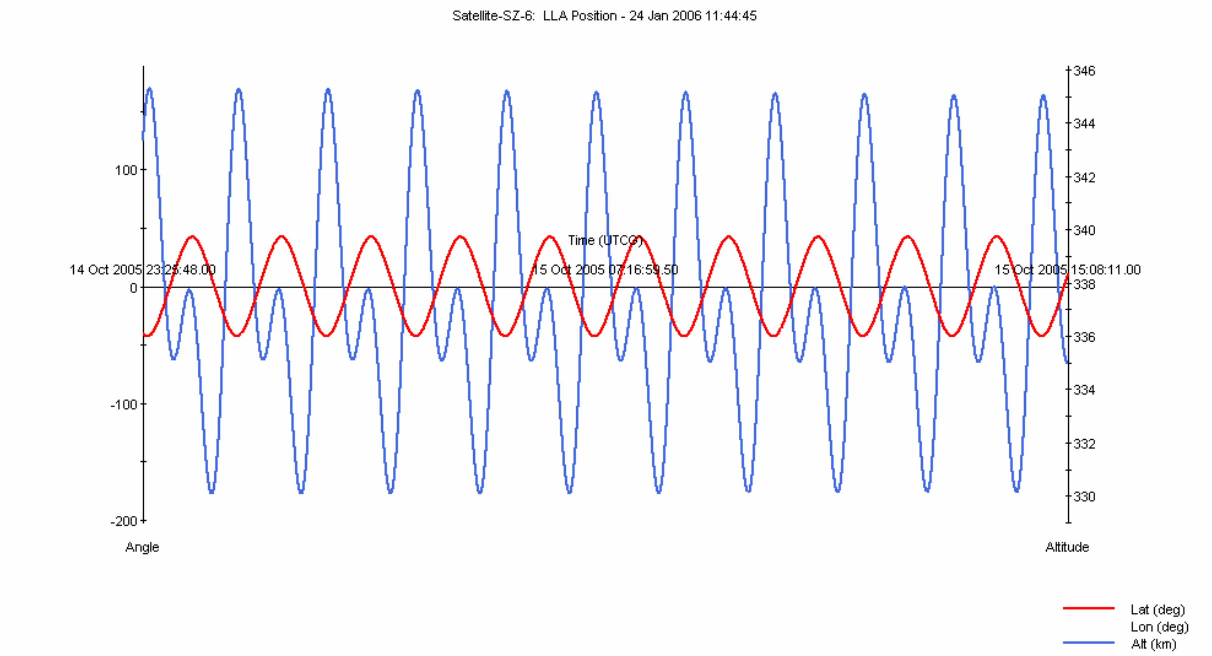

Fig. 1.4 – Shenzhou-6 osculating geodetic altitude (in blue) and latitude (in red) over 10 revolutions on 15 October 2005

osculating geodetic altitude (in blue) and latitude (in red), over a few orbits on 15 October 2005, are shown. Due to the small eccentricity ($\sim 5 \times 10^{-4}$), the Earth ellipsoidal shape and the osculating perigee orientation and behavior, each orbit is characterized by two altitude minima and maxima, one relative and one absolute. It is worth mentioning that the absolute apogee occurred close to the minimum latitude, while the relative apogee occurred when the spacecraft was approaching the maximum latitude.

1.5 Orbital Debris Evolution

The launch of Shenzhou-6 (2005-040A) originated three sizable orbital debris: the CZ-2F spent upper stage (2005-040B) and two significantly smaller and lighter objects, identified with the international designators 2005-040C and 2005-040D. The latter objects, with a radar cross-section of less than one square meter, were characterized by a considerable decay rate due to air drag: object C re-entered into the densest layers of the atmosphere on 14 October, while object D re-entered the following day (15 October). The CZ-2F second stage, with a diameter of 3.4 m, a length of 15.5 m and a dry mass of 5500 kg, decayed from orbit on 26 October 2005.

The manned mission terminated as planned on 16 October 2005 (see Section 3), resulting in the landing of the re-entry module and the atmospheric disintegration of the spacecraft service module. However, a functioning orbital module, designated as 2005-040E, was left in orbit to continue an unspecified set of tests and experiments, some probably of military and intelligence nature.

1.6 Orbital Module Flight

As in the previous Shenzhou missions, the orbital module (2005-040E) was separated and left in space before the retro-burn leading to the re-entry of the crew. The original orbit, inclined by 42.42 deg with respect to the equator, was similar to the operational Shenzhou-6 trajectory, having a minimum geodetic altitude of 332.7 km and a maximum geodetic altitude of 346.7 km (Figure 1.5). The corresponding osculating semi-major axis is shown in Figure 1.6.

In the following three days the semi-major axis gradually increased by 1.8 km, probably the result of a series of small maneuvers with the orbital module attitude control system. The first significant orbit rise was carried out on 19 October 2005, with a semi-major axis increase of 10.0 km. The resulting altitude and semi-major axis are shown in Figures 1.7 and 1.8, respectively.

Between 20 October and 12 December, the semi-major axis decayed by 11.2 km, due to air drag. On 12 December, the module was therefore maneuvered again, increasing the semi-major axis by 15.2 km (see Figures 1.9 and 1.10). Until 20 January 2006, the vehicle was then left decaying by 6.3 km, but such a decrease was largely compensated on 21 January, when a third significant orbit rise incremented the semi-major axis by 5.4 km (see Figures 1.11 and 1.12).

Current monitoring data show that all systems on the vessel, including power supply, experimental payloads and data management, are working well. However, it is not known if the orbital module has still a significant reserve of propellant on board and how long it will continue its mission. If not contrasted by further maneuvers, the air drag experienced by the 1500 kg satellite will lead to its re-entry in the atmosphere in the fall of 2006.

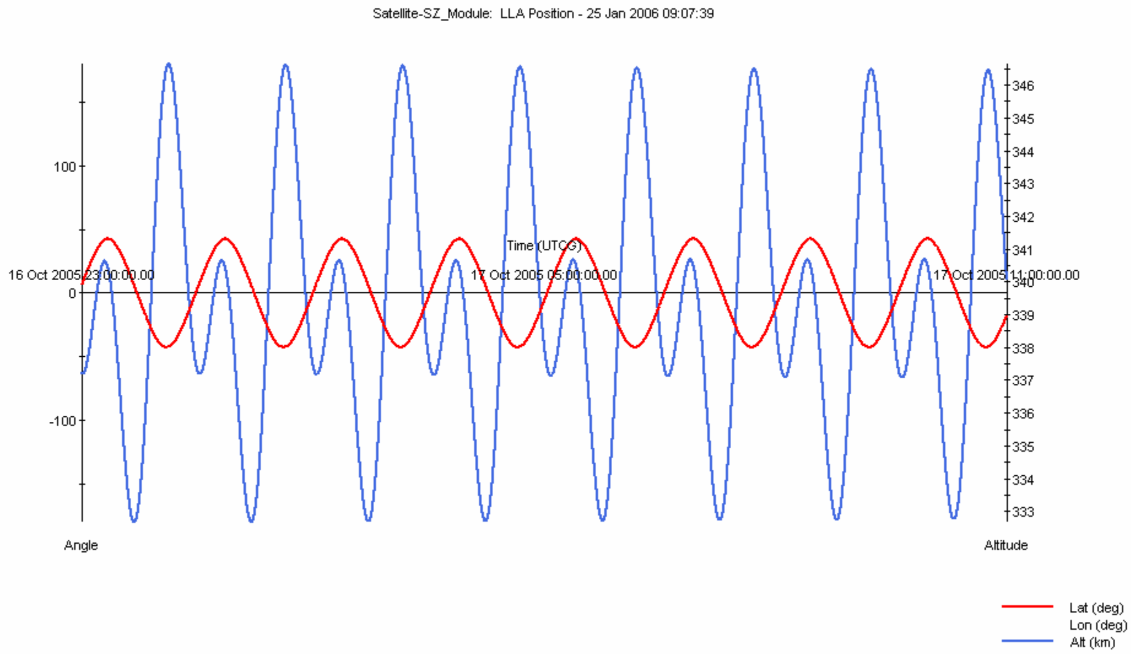

Fig. 1.5 – Orbital module osculating geodetic altitude (in blue) and latitude (in red) over 12 hours after separation (16-17 October 2005)

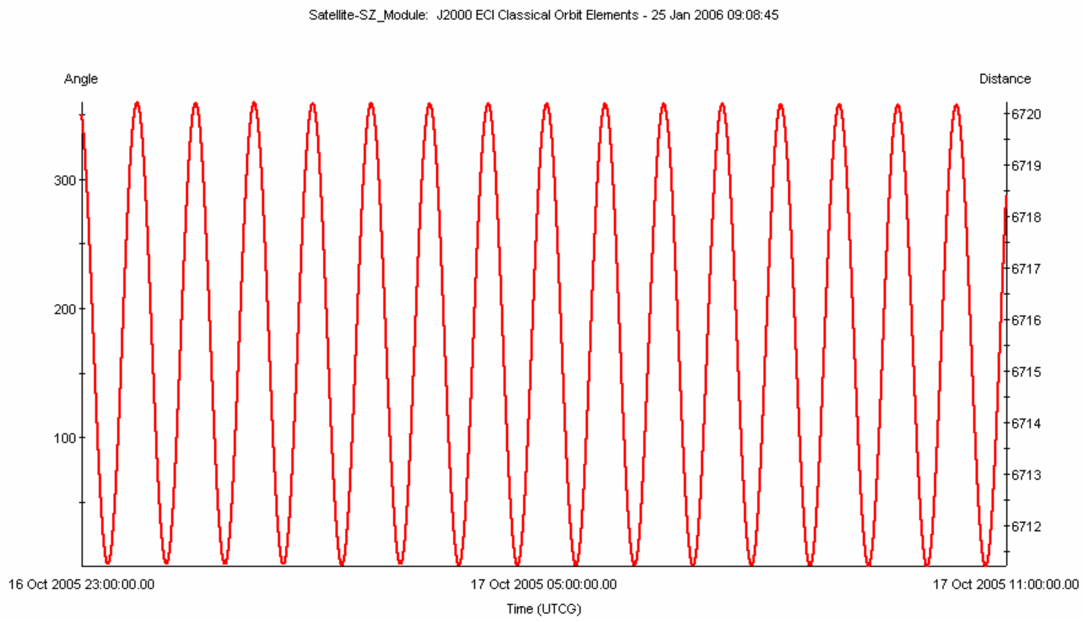

Fig. 1.6 – Orbital module osculating semi-major axis over 12 hours after separation (16-17 October 2005)

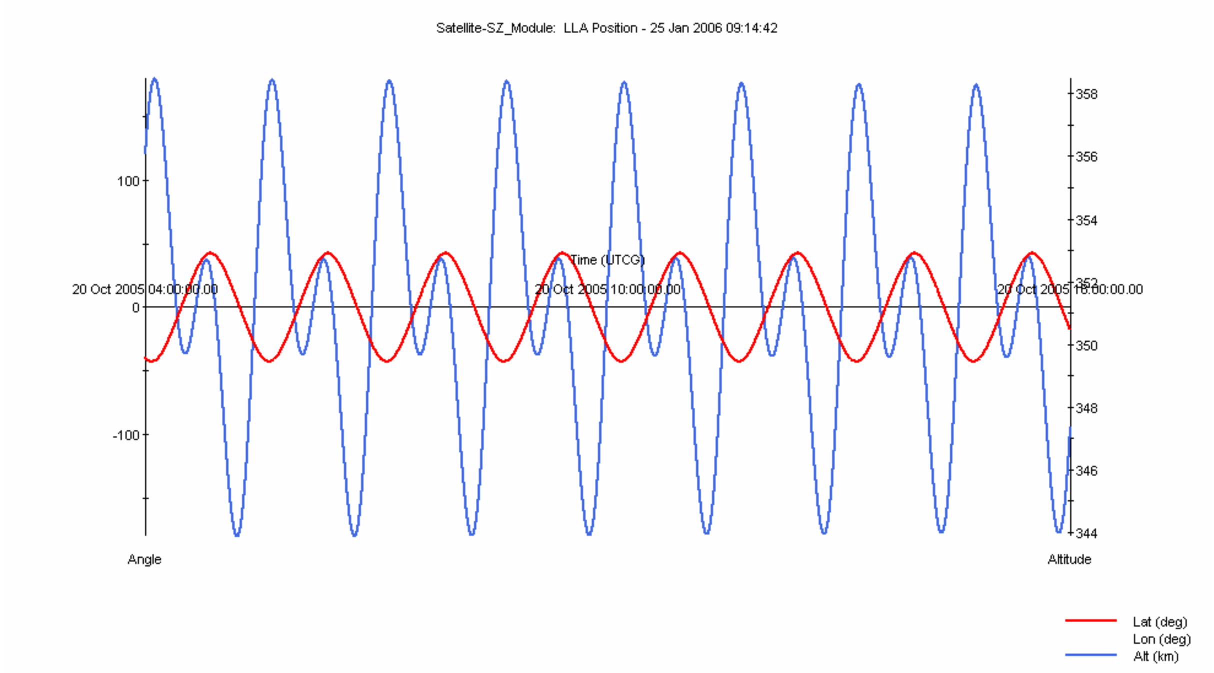

Fig. 1.7 – Orbital module osculating geodetic altitude (in blue) and latitude (in red) over 12 hours after first orbit rise (20 October 2005)

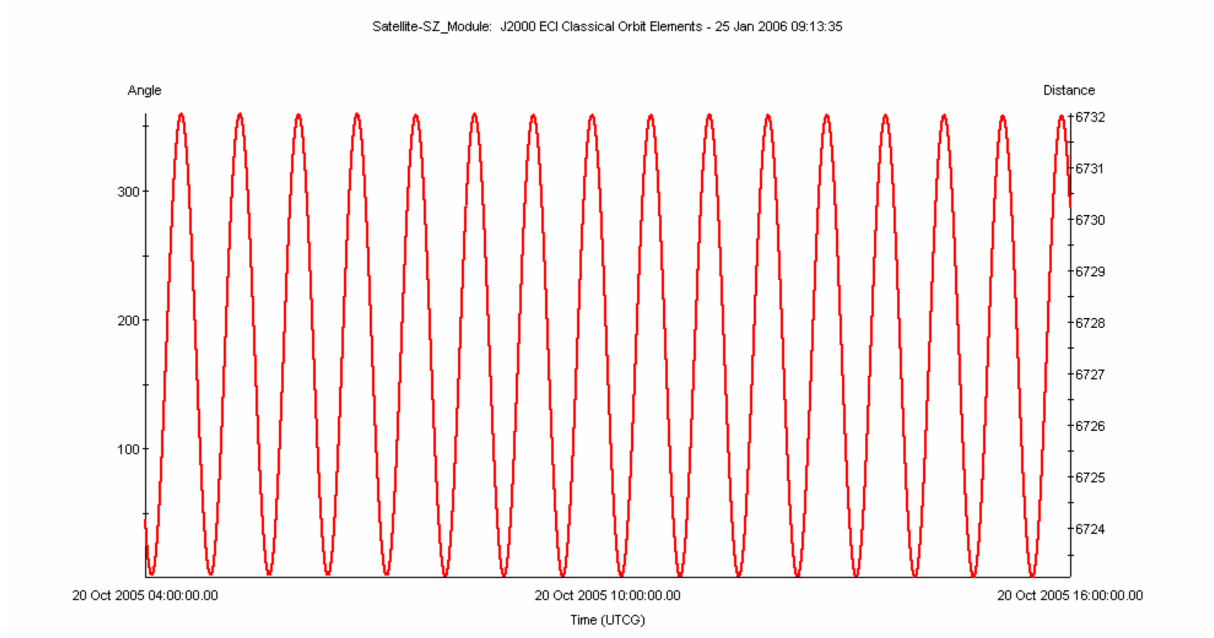

Fig. 1.8 – Orbital module osculating semi-major axis over 12 hours after first orbit rise (20 October 2005)

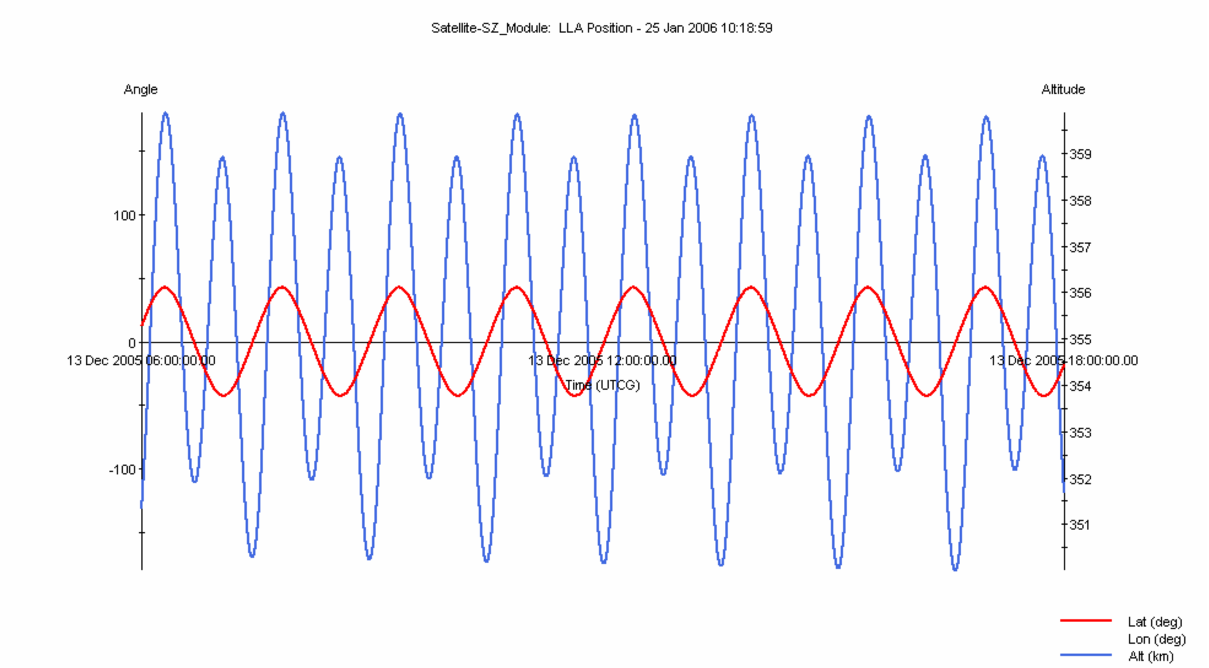

Fig. 1.9 – Orbital module osculating geodetic altitude (in blue) and latitude (in red) over 12 hours after second orbit rise (13 December 2005)

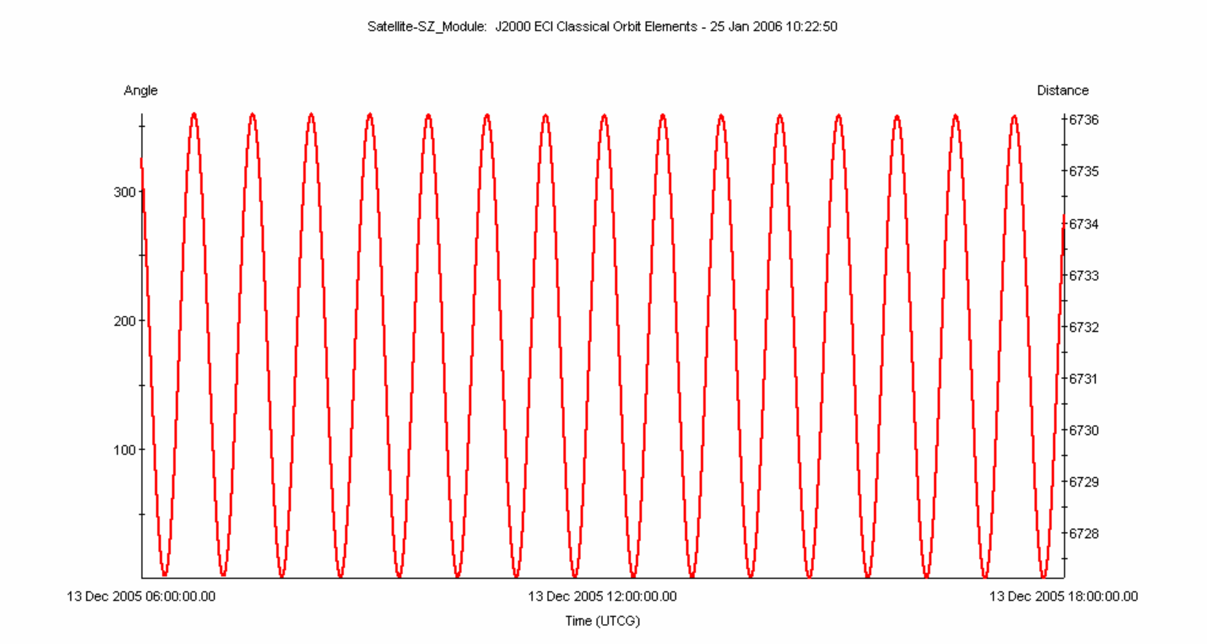

Fig. 1.10 – Orbital module osculating semi-major axis over 12 hours after second orbit rise (13 December 2005)

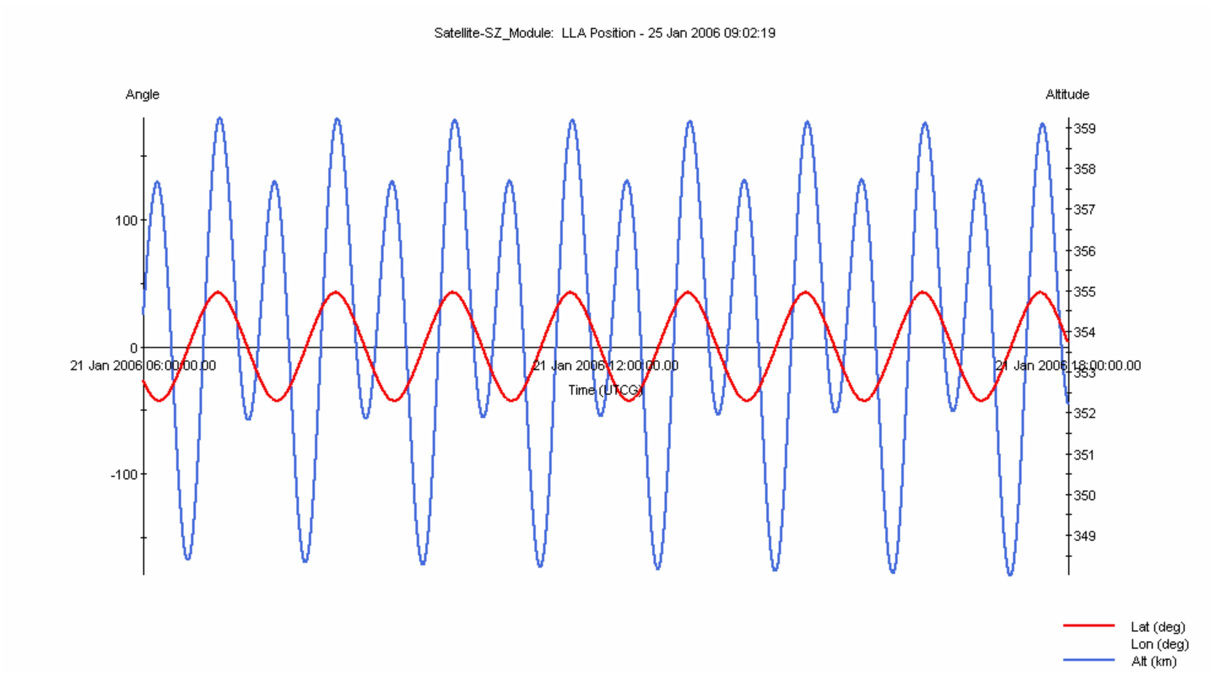

Fig. 1.11 – Orbital module osculating geodetic altitude (in blue) and latitude (in red) over 12 hours after third orbit rise (21 January 2006)

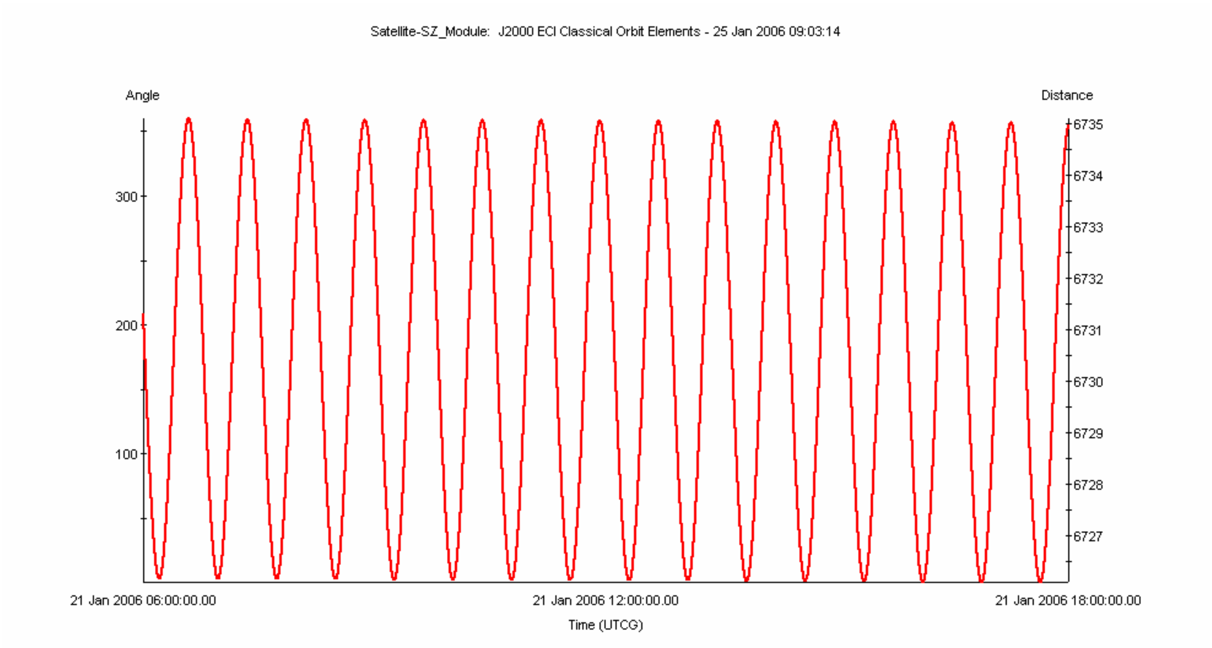

Fig. 1.12 – Orbital module osculating semi-major axis over 12 hours after third orbit rise (21 January 2006)

2. GROUND STATIONS COVERAGE

2.1 Ground Network Coverage

Telemetry acquisition, tracking and communications (TT&C) for the Shenzhou-6 manned flight were assured by the ground stations and ships listed in Table 1.2. During a 31-orbit repetition cycle, over approximately 47 hours, the ground coverage above the elevation of five degrees is shown in Figure 2.1. Table 2.1 shows the total duration of the spacecraft passes, over each station or ship, in the same time span. The network was able to guarantee a quite complete coverage over China, with the spacecraft in simultaneous visibility of 3 or 4 locations, in certain moments. Only 2 orbits, out of 31, did not present any useful pass. A number of visibility intervals in between one and four characterized the other orbits.

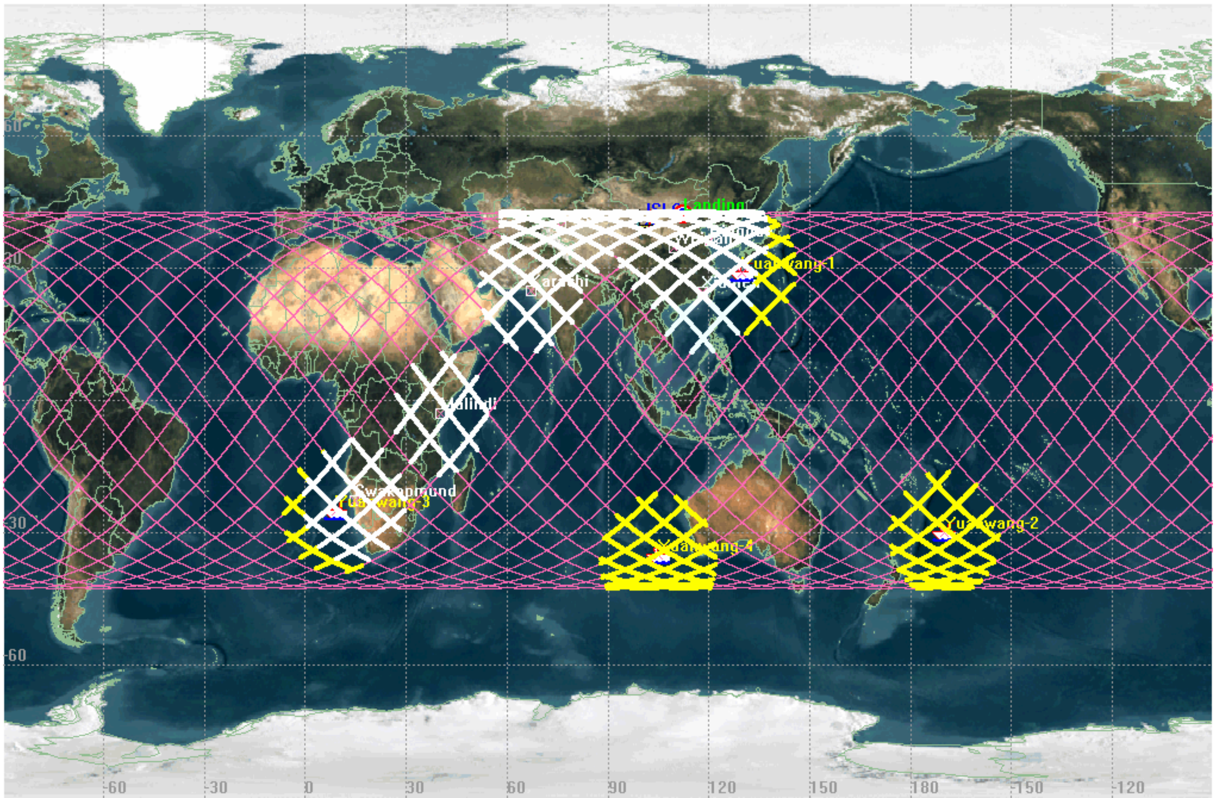

Fig. 2.1 – Ground coverage of the Shenzhou-6 flight over a 31-orbit repetition cycle (ground stations in white, additional ships contribution in yellow)

Table 2.1

Total Duration of the Shenzhou-6 Passes during a Repetition Cycle of 31 Orbits (elevation ≥ 5 deg)

Station Name	Passes Total Duration (min)
Karachi	55.0
Kashi	64.2
Malindi	37.8
Qingdao	73.5
Swakopmund	49.6
Weinan	75.3
Xiamen	49.9
Yuanwang-1	68.5
Yuanwang-2	71.0
Yuanwang-3	52.2
Yuanwang-4	76.8

Table 2.2

Passes over the Italian Malindi TT&C Ground Station (Kenya) during the Shenzhou-6 Mission

Acquisition of Signal (elevation ≥ 5°) UTC	Loss of Signal (elevation ≥ 5°) UTC	Pass Duration (seconds)	Max Elevation (deg)	Min Range (km)
12/10/2005, 08:49:07	12/10/2005, 08:54:04	297	11.0	1191
12/10/2005, 10:23:50	12/10/2005, 10:30:19	389	21.5	792
12/10/2005, 20:09:52	12/10/2005, 20:15:10	318	11.9	1167
12/10/2005, 21:44:44	12/10/2005, 21:51:17	392	21.2	812
13/10/2005, 09:07:35	13/10/2005, 09:14:46	431	56.3	392
13/10/2005, 20:28:28	13/10/2005, 20:35:47	440	58.5	392
14/10/2005, 07:52:54	14/10/2005, 07:57:52	298	11.0	1194
14/10/2005, 09:27:37	14/10/2005, 09:34:08	390	21.6	780
14/10/2005, 19:13:47	14/10/2005, 19:19:03	317	11.9	1168
14/10/2005, 20:48:40	14/10/2005, 20:55:12	392	21.3	811
15/10/2005, 08:11:36	15/10/2005, 08:18:49	433	56.5	393
15/10/2005, 19:32:36	15/10/2005, 19:39:55	439	58.8	390
16/10/2005, 06:57:01	16/10/2005, 07:02:00	299	11.0	1191
16/10/2005, 08:31:45	16/10/2005, 08:38:15	390	21.5	793
16/10/2005, 18:17:52	16/10/2005, 18:23:09	316	11.9	1166
16/10/2005, 19:53:04	16/10/2005, 19:58:38	334	17.4	791

The last pass occurred during the re-entry phase

2.2 Coverage from the Malindi Ground Station

Table 2.2 summarizes the useful passes over the Italian Malindi ground station, in Kenya, during the manned Shenzhou-6 mission. It is evident that each repetitive cycle of 31 orbits included 6 specific passes, whose geometry was nearly exactly reproduced after 31 revolutions, or about 47 hours.

During the flight of Shenzhou-6, disregarding the schedule conflict with the Ariane V launch, at the end of 13 October 2005, there were 16 useful passes over Malindi, the first 7 hours and 49 minutes after launch, the last during the re-entry phase, after the retro-rockets burn and before the impact with the densest layers of the atmosphere.

3. DE-ORBITING AND RE-ENTRY

3.1 Retro-Rockets Burn and De-orbiting

On 16 October 2005, the re-entry phase began at 19:42 UTC, when the tracking ship Yuanwang-3, off the coast of Namibia, acquired the spacecraft. One minute later the re-entry operations were initialized, with the capsule assuming the proper retro-burn attitude, and at 19:44 the orbital module separated as planned to continue its extended mission.

At 19:45, two main hypergolic propellant engines of the service module, with a combined thrust of 5000 N, were fired for about 144 s, while the spacecraft was simultaneously in contact with the Yuanwang-3 ship and the Swakopmund tracking station, in Namibia. The burn consumed approximately 254 kg of propellant, reducing the speed of Shenzhou-6 by 119 m/s.[1] The parameters of the resulting de-orbiting trajectory, with apogee and perigee altitudes, with respect to the Earth equatorial radius, of 337.51 km and –61.28 km, respectively, were determined using the tracking data of the last pass over the Malindi station and are shown in Table 3.1.

Table 3.1

Shenzhou-6 De-orbiting Trajectory (True of Date)
Epoch: 16 October 2005, 19 h 56 m 00.06 s UTC

Trajectory Parameter	Value Determined
Semi-major Axis	6516.256 km
Eccentricity	0.0306
Inclination	42.4307 deg
Right Ascension of Ascending Node	358.2816 deg
Argument of Perigee	138.4358 deg
True Anomaly	223.6073 deg
Apogee Radius Vector	6715.653 km
Perigee Radius Vector	6316.859 km
Time of Flight from Apogee to the Height of 120 km	23.5 minutes
Flight Path Angle at the Height of 120 km	–1.746 deg

During the descent and final pass, Malindi acquired the Shenzhou-6 signal at 19:51:43 UTC, when the vehicle was still at an altitude of 315.5 km above the ground. The spacecraft

[1] The burn parameters, including the duration, were deduced from the published characteristics of the propulsion system and the de-orbiting trajectory determined with the tracking data gathered, a few minutes later, during the last pass over the Malindi station, in Kenya.

reached the maximum elevation in the Malindi sky (about 17.5 deg) at 19:56:00 and the loss of signal occurred at 19:59:46, when the vehicle was already descended at 238.4 km. Further details are displayed in Table 3.2, including the spacecraft range and altitude above the ground, based on the trajectory given in Table 3.1. Figure 3.1 shows the altitude evolution from retro-rockets burnout to atmospheric re-entry.

Table 3.2

Shenzhou-6 Re-entry Pass over the Malindi Tracking Station

UTC Time of 16 October 2005	Elevation (deg)	Azimuth (deg)	Range (km)	Altitude (km)
19:51:43.062	0.047	245.978	2026	315.5
19:53:04.062	5.019	254.297	1517	305.6
19:54:09.062	10.037	266.322	1149	296.7
19:56:00.062	17.464	311.818	790	279.6
19:57:42.062	10.088	358.262	1044	261.9
19:58:38.062	4.989	11.318	1334	251.6
19:59:46.062	0.058	20.579	1755	238.4

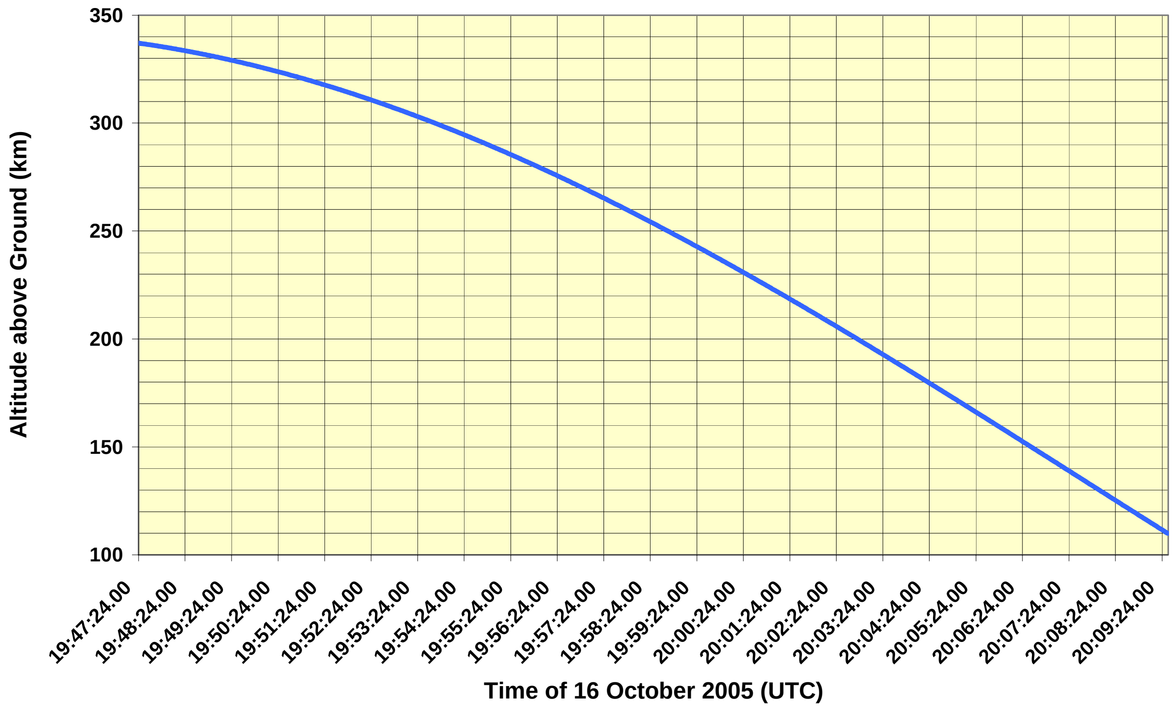

Fig. 3.1 – Evolution of the altitude of Shenzhou-6 from retro-rockets burnout to atmospheric re-entry

At 20:07 and at an altitude of about 144 km, over Central Pakistan and in visibility of the Karachi tracking station, the service module, destined to burn up in the atmosphere, was separated from the re-entry capsule. The crossing of the atmospheric re-entry interface, at an altitude of 120 km, occurred at 20:08:46 UTC over Indian Kashmir (latitude: 33.155 °N; longitude: 75.820 °E), in visibility of the Kashi tracking station, in Western China. Finally, the capsule crossed the Chinese air space around 20:09:30, at an altitude of 110 km.

At 20:20, with the velocity dropped below Mach 1, the main parachute deployed and three minutes later the heat shield at the bottom of the capsule was jettisoned, exposing the soft landing solid rockets and the gamma ray altimeter, designed to ignite them just before the impact with the ground. The soft-landing occurred at 20:32:50 UTC (4:32:50 local time), approximately 1 km from its planned target in Inner Mongolia and within sight of the recovery forces.

The re-entry ground track of Shenzhou-6 is shown in Figure 3.2, together with the visibility periods from the tracking stations, corresponding to elevations equal or greater than 5 degrees. From retro-rockets burnout to landing, the sub-satellite ground track spanned approximately 13,000 km.

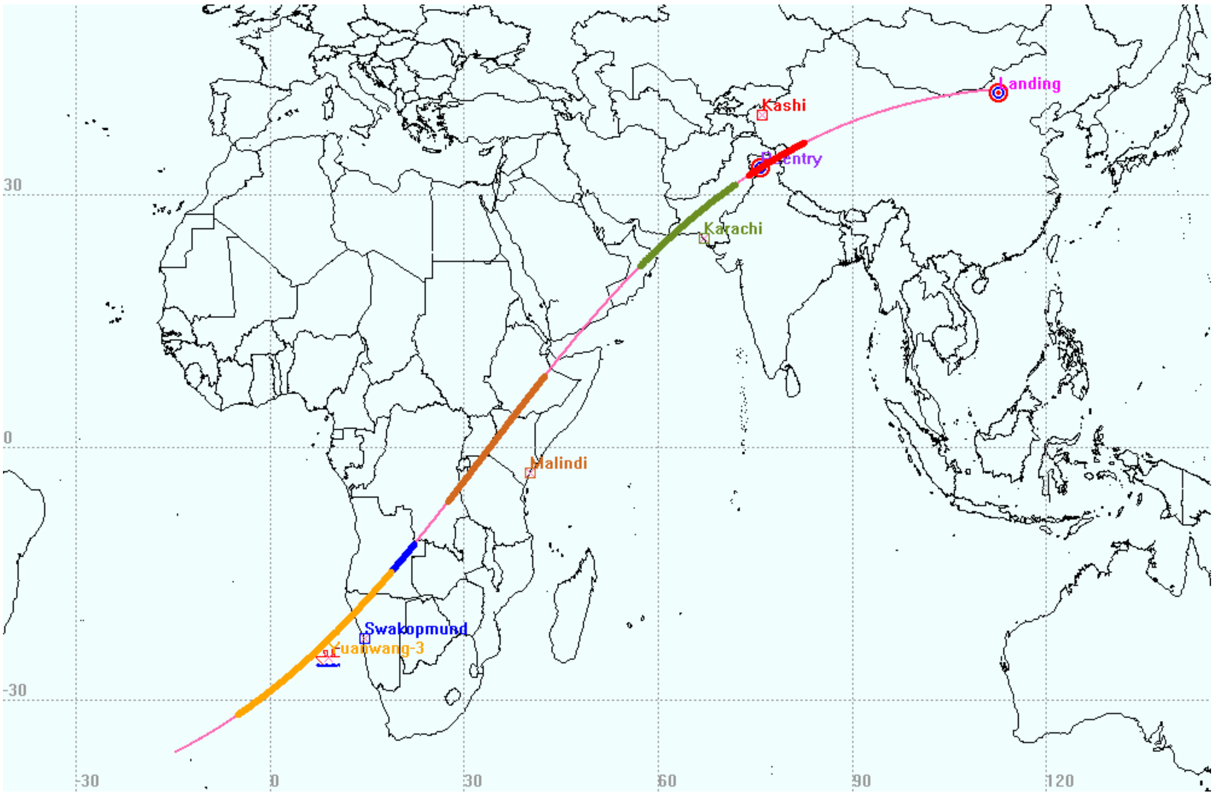

Fig. 3.2 – Re-entry ground track of Shenzhou-6 with the tracking stations visibility periods corresponding to elevations equal or greater than 5 deg

3.2 Re-entry Simulation

Assuming the de-orbiting trajectory determined during the last pass over Malindi, an average (and constant) lift-to-drag ratio of 0.2 for the Shenzhou descent module and the atmospheric interface at the height of 120 km, the re-entry trajectory was simulated using a simplified software model for the endo-atmospheric phase of the flight (Pardini and Anselmo, 1991).

This simulation was not intended to provide an accurate description of the descent module trajectory: too many variables and critical data were, in fact, unknown. However, the results obtained were useful to give an idea and overall picture of several important aspects involved in the ballistic phase of the re-entry, before pilot, drogue and main parachutes deployment (i.e. above the altitude of 10 km). The results are summarized in the following plots (Figures 3.3-3.9).

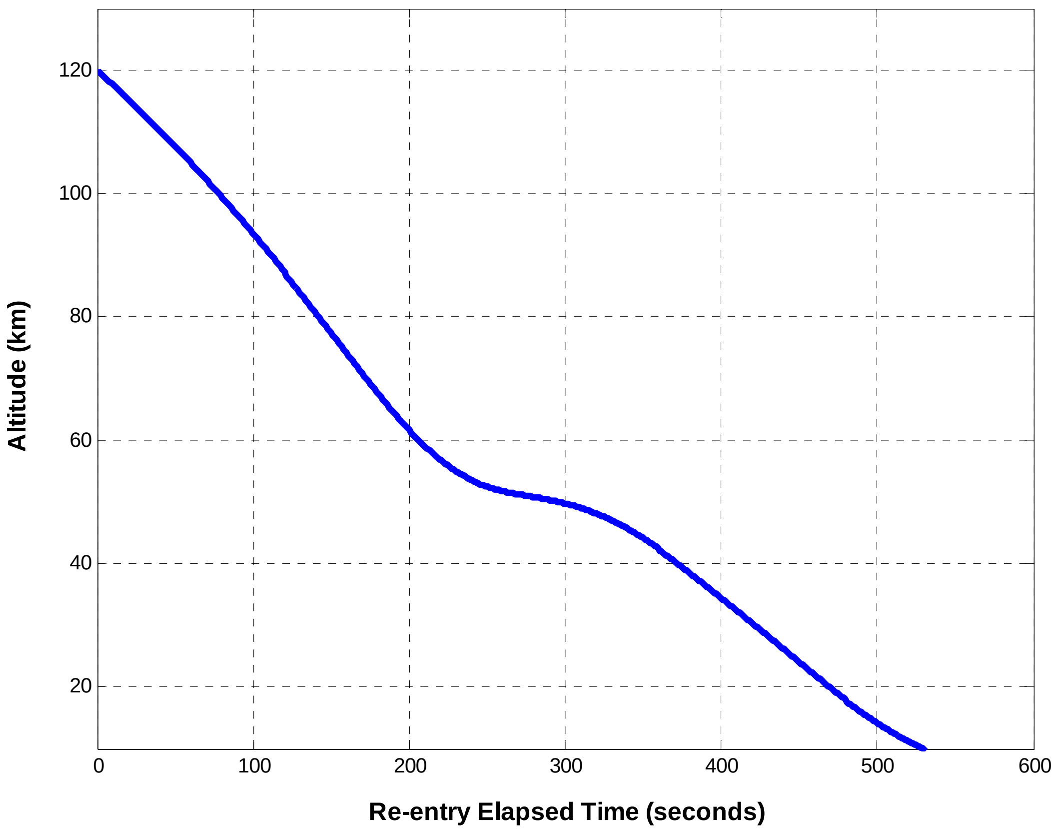

Fig. 3.3 – Re-entry simulation: descent module altitude vs. elapsed time

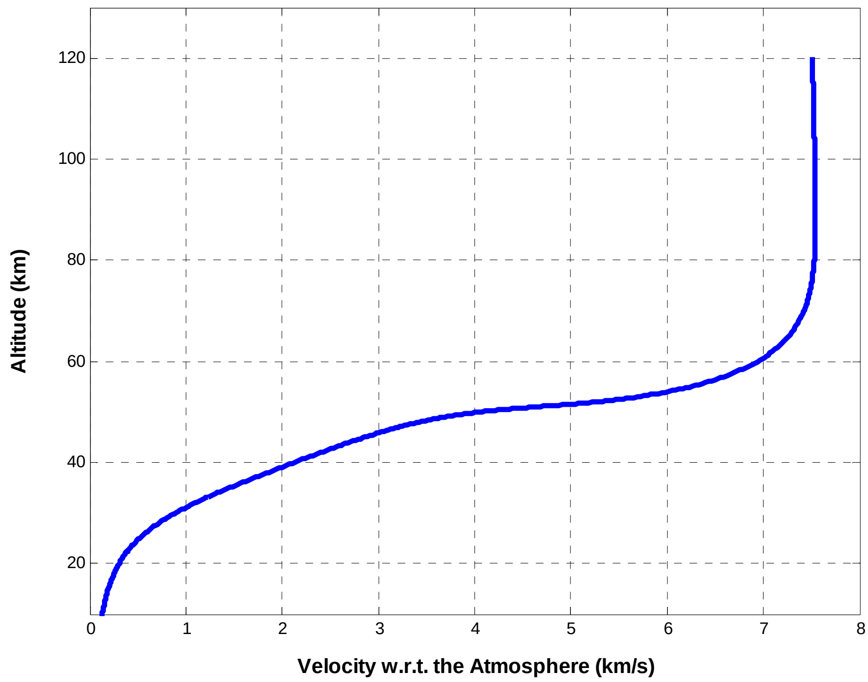

Fig. 3.4 – Re-entry simulation: descent module altitude vs. velocity

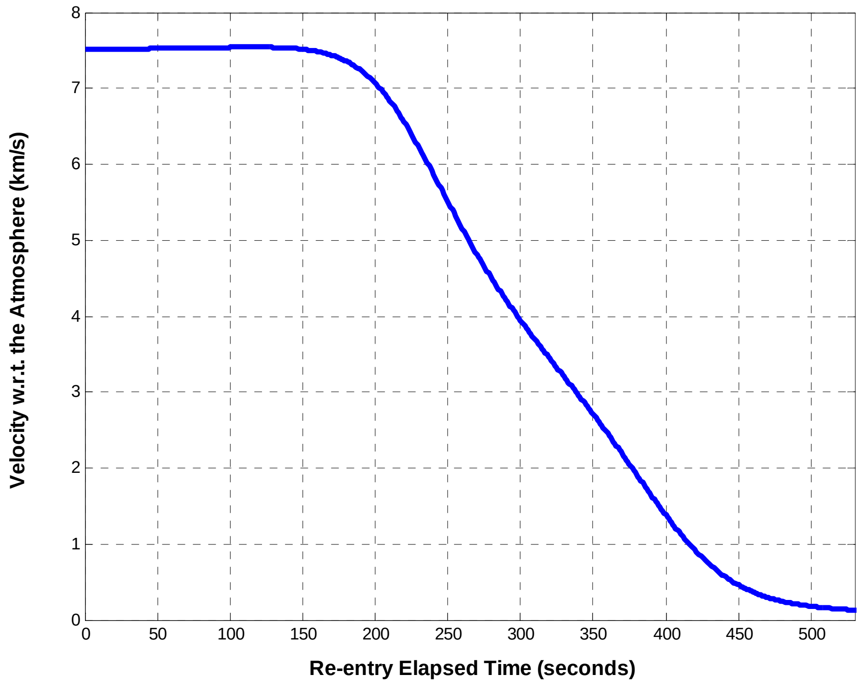

Fig. 3.5 – Re-entry simulation: descent module velocity vs. elapsed time

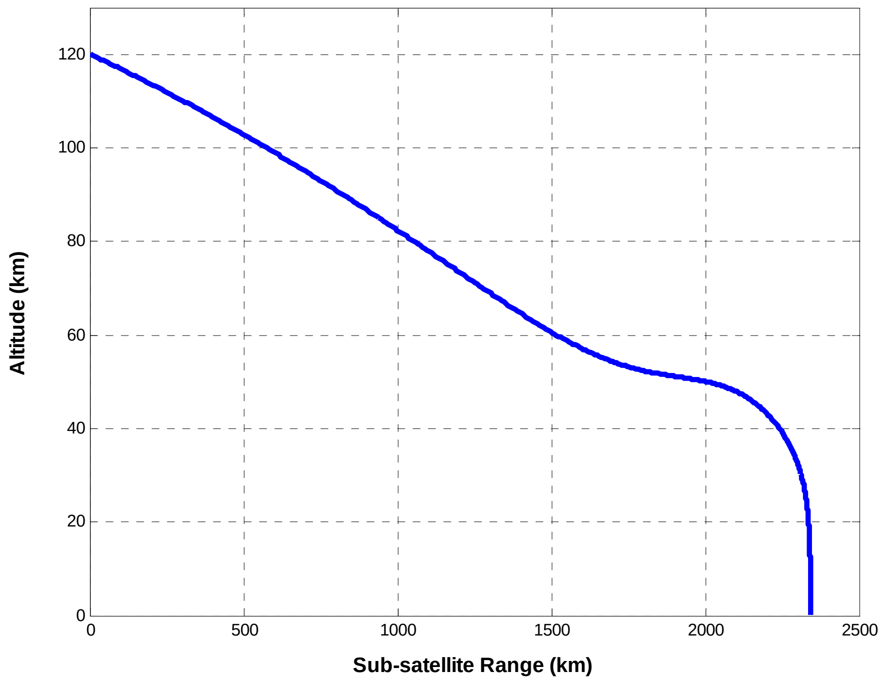

Fig. 3.6 – Re-entry simulation: descent module altitude vs. sub-satellite range

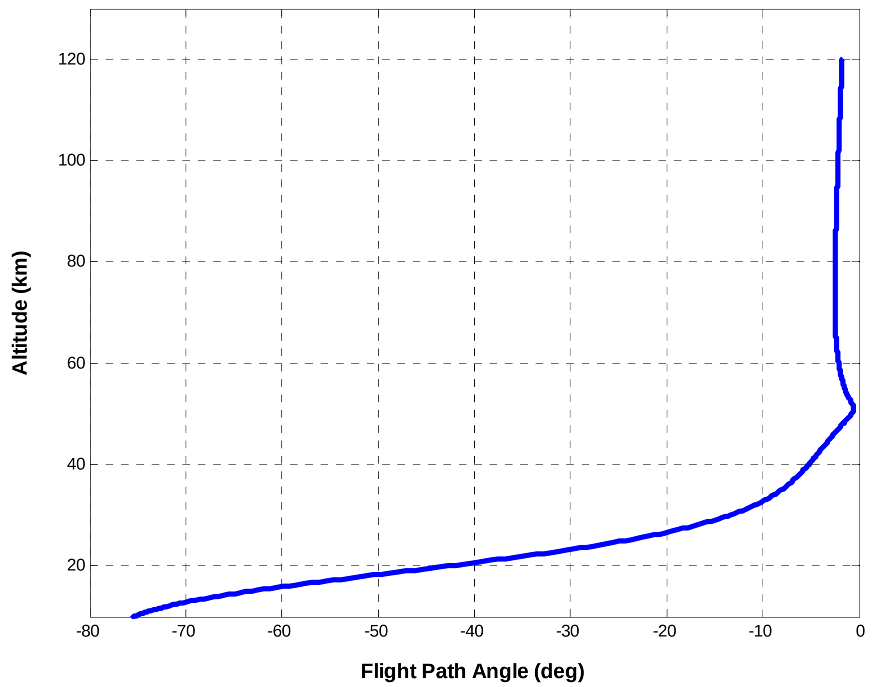

Fig. 3.7 – Re-entry simulation: descent module altitude vs. flight path angle

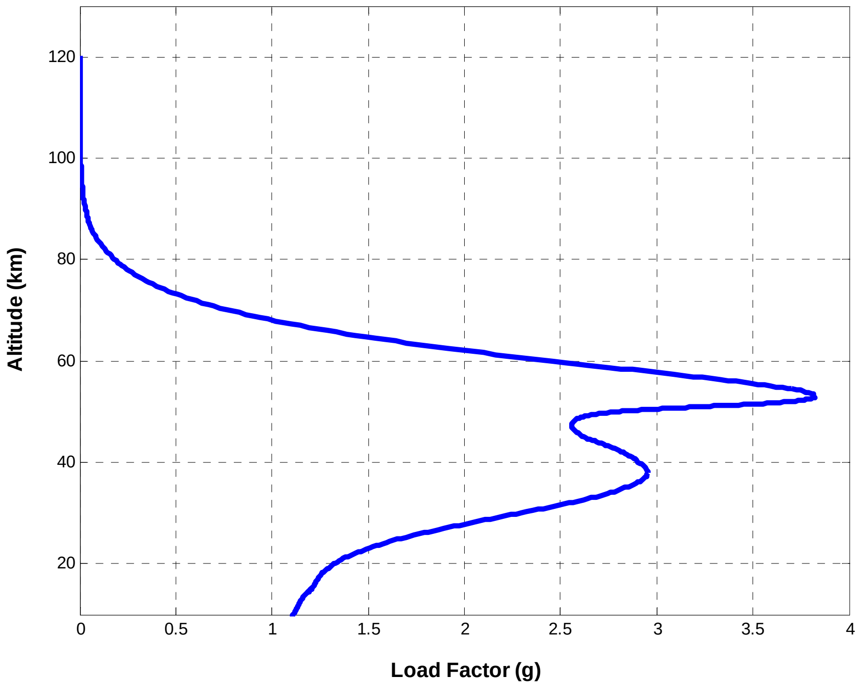

Fig. 3.8 – Re-entry simulation: descent module altitude vs. load factor

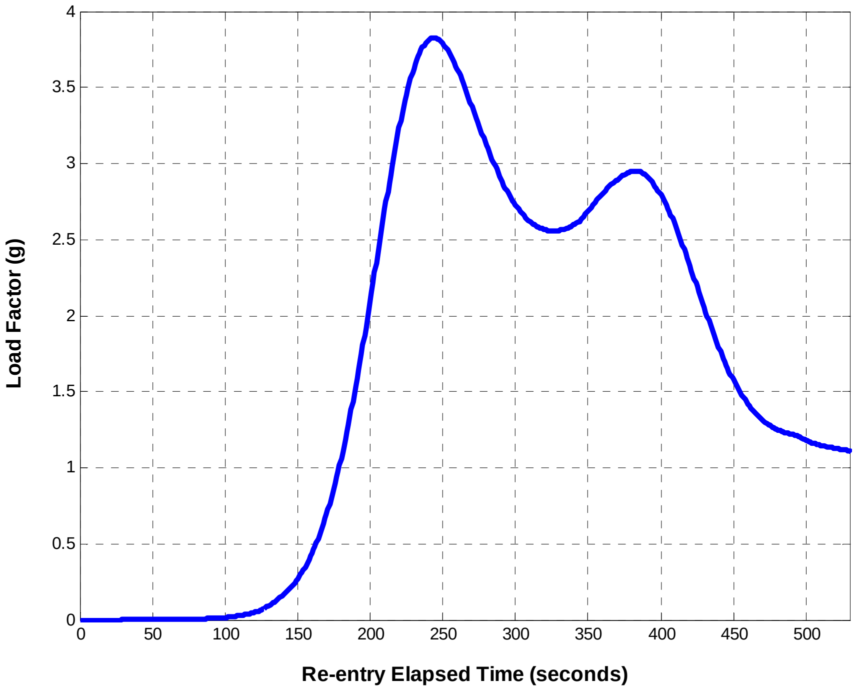

Fig. 3.9 – Re-entry simulation: descent module load factor vs. elapsed time

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Some of the analyses presented in this report were carried out using the Satellite Tool Kit (STK), version 4.3.0, by Analytical Graphics Incorporated (AGI). Several maps and plots were also obtained with STK. Software packages developed by the author (orbital analysis) and Carmen Pardini (modeling of re-entry dynamics) were used as well.

Updated information and details on the Shenzhou-6 mission preparation and progress were acquired from *Spaceflight Now* (http://www.spaceflightnow.com/), *Spacedaily* (http://www.spacedaily.com/), *Space.com* (http://www.space.com/) and *Sino Daily* (http://www.sinodaily.com/). Supporting orbital information on all objects associated with the Shenzhou-6 launch was obtained from Space Track (http://www.space-track.org).

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