European Space Agency
Agence Spatiale Européenne

directorate of technical and operational support
ground systems engineering department
mission analysis office

MAO Technical Note No. 30

INT-MOC-MA-RP-1002-TOS-GA

INTEGRAL Rescue Orbits

by

G Janin & R Mugellesi Dow

June 2002

European Space Operations Centre

Robert-Bosch-Str. 5
D - 64293 Darmstadt

PAGE INTENTIONALLY LEFT BLANK

Abstract

If, following a malfunction of the Proton launcher for INTEGRAL, the satellite is delivered on a non-nominal Transfer Orbit (TO), this paper indicates possible rescue orbits, which can be reached and would allow performing at least a part of the scientific mission. As non-nominal TO, only lower apogee heights are considered. Ground coverage, eclipse and evolution of orbital parameters are discussed but the operational feasibility of the rescue mission is not investigated in this paper.

In order to keep optimum ground coverage, it is proposed to try aiming for a synchronous orbit by all means. Possible synchronous orbits offering a sufficiently long arc above the radiation belt (altitude > 40000 km) are 72- (nominal), 48-, 24- and 16-h orbits. Using the available DV capability, range of possible rescue synchronous orbits are listed in terms of the TO apogee height.

If TO apogee height is higher than 35000 km, a stable synchronous orbit with at least 50 % of the time above 40000 km altitude is offered. However, the initial perigee height may have to be as low as 1000 km. The two baseline ground stations (Redu and Goldstone) are sufficient for operating the satellite and receiving scientific data. Maximal eclipse duration never exceeds specification (1.8 h) during the nominal mission.

In the particular case of a 24-h orbit (reachable when TO apogee height is between 45000 and 65000 km), only one station (Redu) is sufficient for operating the satellite and about 70 % of the time can be dedicated to scientific observation.

If the TO apogee height is below 35000 km, the situation becomes more dramatic:

- *It is no more possible to stay above the radiation belt for a substantial time*
- *More than two stations may be needed for coverage*
- *Eclipse times may exceed the specifications or may be a large proportion of the orbit period*

The particular case of a total failure of the Upper Stage (TO º Parking Orbit) is investigated. Eclipse duration can be as high as 40 % of the orbit period and direct continuous ground coverage is close to impossible. Using the fact that the orbit inclination is identical to the one of the International Space Station (ISS) orbit, it is proposed to transfer to this orbit. Making use of natural perturbations for node alignment, this would take about 140 days. Maintaining a small phase difference with the ISS, the ISS could then be used as a relay satellite for ground communication.

In a dedicated chapter, the initial ground station acquisition is analysed in more details, in particular the azimuth and elevation profile in terms of Upper Stage burn duration for Villafranca and Redu.

Finally, assuming a nominal TO, the consequence of a Perigee Raise Manoeuvre failure is investigated. Depending which manoeuvre fails, an extension of the drift period may be required.

PAGE INTENTIONALLY LEFT BLANK

Table of Content

PAGE INTENTIONALLY LEFT BLANK

Table of Figures

List of Tables

PAGE INTENTIONALLY LEFT BLANK

1. INTRODUCTION

In the history of spaceflight, non-nominal performance of the launcher Upper Stage (US) is not uncommon (the nominal Proton launch and first part of transfer orbit for INTEGRAL is recalled on a 3-D altitude map in Figure 1). In case such an unfortunate situation occurs to INTEGRAL, this paper lists what could be possible rescue orbits.

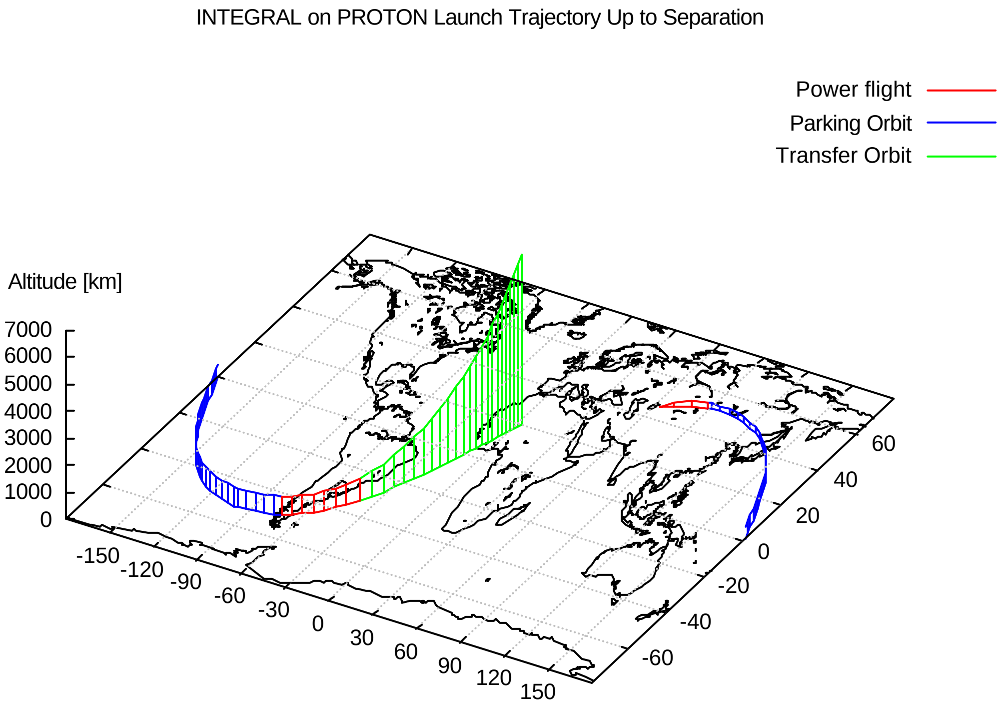

Figure 1 (original in colour). The nominal Proton launch and first part of TO.

Assumptions taken for this analysis are listed in the next Chapter while the advantages of aiming for a synchronous orbit are shown in the following Chapter. In addition to the nominal 72-h orbit, three other types of synchronous orbits will be proposed: 48-h, 24-h and 16-h. A case of a 24-h and 16-h orbit will be investigated in details in order to show how the selection of this type of orbit can rescue the scientific mission.

Then, the case of a small or no burn of the US will be considered and some indications will be given on how to gain some hope of not loosing the mission completely in such a dramatic situation.

In a dedicated chapter, the initial ground station acquisition is analysed in more details, in particular the azimuth and elevation profile in terms of Upper Stage burn duration for Villafranca and Redu.

Finally in a last Chapter, assuming a nominal TO, the consequence of a Perigee Raise Manoeuvre (PRM) failure is investigated.

2. ASSUMPTIONS

2.1 Launcher Main Stage Malfunction

A launcher malfunction can occur to any of the stages. If one of the main stages is malfunctioning, under the best circumstance a low Parking Orbit (PO) is reached. In such a case, the launcher authorities has confirmed that the Upper Stage (US) has the capability to correct for the wrong initial state at US start of burn and to reach as closely as possible the target orbit.

Such a circumstance was encountered during the launch of CLUSTER 2 on 2000 August 9, where the Fregat US compensated to a great deal for lower than nominal performance of the Soyuz launcher.

Thus, a malfunction of one of the main stage, if a viable PO is reached, is equivalent to a performance reduction of the US. An investigation of underperformance of the US does therefore cover all cases of launcher malfunction not leading to loss of the satellite.

2.2 US Malfunction

If there is no loss of satellite (due for instance by a stage explosion), the only consequence is the satellite to be injected in a wrong orbit. If the burn duration or thrust modulus is lower than nominal, a Transfer Orbit (TO) of lower apogee height is reached. Possible change in angular parameters due to non-nominal thrust direction will have less important consequences on the orbit and will not be considered in this analysis. Only cases with lower apogee height will be investigated.

TO perigee height will be assumed to be nominal (685 km). A lower TO perigee height will not cause any major change in the conclusion reached along the following Chapters.

Relation between apogee height reached and length of US burn is shown on Figure 2, assuming a nominal TO perigee height of 685 km. This diagram is approximate as it is based on a simple calculation assuming constant specific impulse (352 s), thrust (83.2 kN) and mass flow. Nominal US burn duration is 424 s.

2.3 Spacecraft's Orbit Change Capability

The INTEGRAL on-board propulsion unit will allow acquiring the desired operational orbit. It has the following performance:

- ✓ Specific impulse: 228 s
- ✓ Maximum *DV* capability: 228 m/s

In this simplified analysis, the specific impulse is assumed to be constant and no loss, such as gravity loss, will be considered for the manoeuvres.

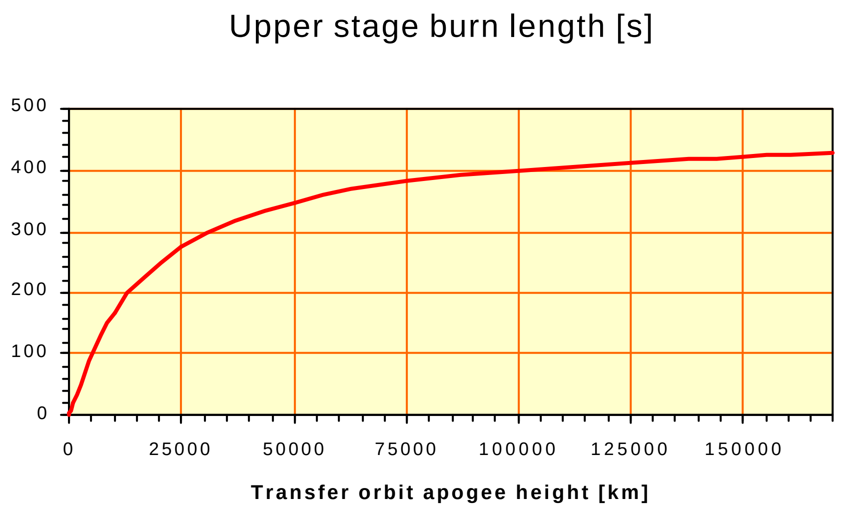

Figure 2. Approximate US burn length in terms of TO apogee height for a nominal perigee height of 685 km.

3. SYNCHRONOUS RESCUE ORBITS

3.1 Synchronous Orbits

INTEGRAL does not have any on-board data storage capability and one of the main criteria for orbit selection is to have sufficient ground coverage. A class of orbits maximising coverage are synchronous orbits. On such orbits, the phase of the satellite is chosen such as to have permanently the best coverage possible.

Therefore, once the non-nominal TO has been determined, the first task of the mission analyst is to investigate, which near-by synchronous orbits can be reached by using the on-board propulsion unit within its capability.

Possible synchronous orbits for INTEGRAL are the following:

- 72-h, nominal INTEGRAL orbit [Ref. 1]
- 48-h, such as nominal orbit of INTEGRAL launched on Ariane 5 [Ref. 2] or XMM
- 24-h, such as orbit of ISO, Hipparcos (nominal) or GEOS-2
- 16-h, coverage pattern periodicity: 48-h
- 12-h, such as orbit of GEOS-1 (rescue orbit following the Thor Delta 2914 lower than nominal TO apogee height injection on 1977 April 20 [Ref. 3])

The second main criterion for INTEGRAL orbit selection is to maximise scientific return. As INTEGRAL's detectors are not operated in the radiation belt, no observation can be performed below 40000 km altitude. This precludes the 12-h orbit, which apogee height cannot reach such an altitude.

For given TO apogee height, Figure 3 shows possible target perigee heights leading to a 16-, 24-, 48- or 72-h synchronous orbit. The corresponding apogee height is shown on Figure 4 and the % of time when science data are collected (spacecraft above 40000 km altitude) is shown on Figure 5.

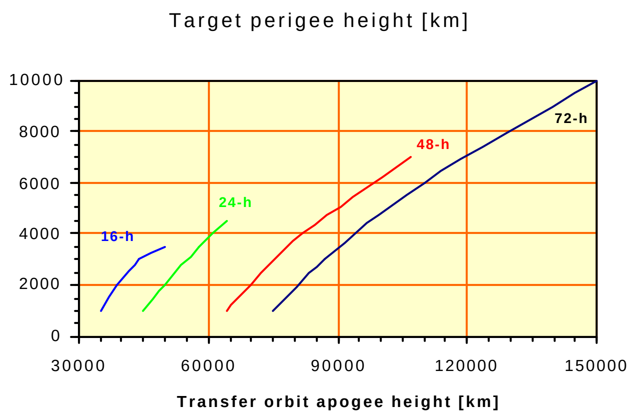

Figure 3. Target perigee heights in terms of TO apogee height and synchronous orbit type.

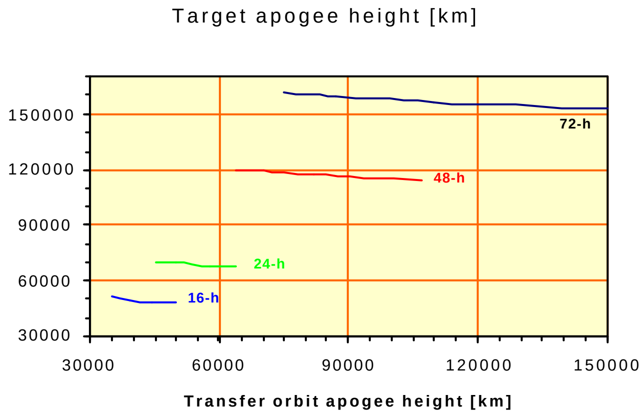

Figure 4. Target apogee heights in terms of TO apogee height and synchronous orbit type.

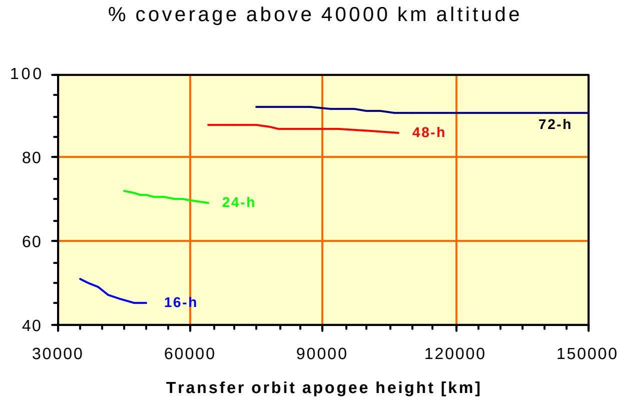

Figure 5. Time (in % of the orbital period) when the spacecraft is above 40000 km altitude in terms of TO apogee height and synchronous orbit type.

For each synchronous orbit type, sample cases are listed along the following Tables:

- Table 1: 72-h orbits, the last row of the Table corresponds to the baseline INTEGRAL orbit.
- Table 2: 48-h orbits, the last row of the Table corresponds to the baseline INTEGRAL launched on Ariane 5 48-h orbit.
- Table 3: 24-h orbits, the third row of the Table (1000 km target perigee height) corresponds to the ISO 24-h orbit.
- Table 4: 16-h orbits.

In the Tables, column 2 gives the minimum apogee height needed for reaching the perigee height listed in column 1 within the maximum *DV* capability of the on-board propulsion unit.

Concerning the target orbit acquisition manoeuvres:

- The apogee height raise manoeuvre has first to be performed when perigee height is low
- Perigee height raise has then to be performed when apogee height is high
- Perigee height raise costs more than apogee height raise

Target perigee height [km]	Apogee height [km]		Above 40000 km	
	Min. TO	Target	Hours	%
1000	75000	161600	66.2	92
3000	87000	159600	65.9	92
6000	110000	156600	65.6	91
10000	150000	152600	65.1	91

Table 1. Example of possible 72-h rescue orbits. The last row corresponds to the baseline orbit.

Target perigee height [km]	Apogee height [km]		Above 40000 km	
	Min. TO	Target	Hours	%
1000	64000	120100	42.0	88
2000	70000	119100	41.9	88
4000	82000	117100	41.6	87
7000	107000	114100	41.2	86

Table 2. Example of possible 48-h rescue orbits. The last row corresponds to the baseline 48-h INTEGRAL on Ariane 5 orbit.

Target perigee height [km]	Apogee height [km]		Above 40000 km	
	Min. TO	Target	Hours	%
1000	45000	70570	17.3	72
2000	50000	69570	17.1	71
3500	58000	68070	16.8	70
4500	64000	67070	16.5	69

Table 3. Example of possible 24-h rescue orbits. The third row (1000 km target perigee height) corresponds to the 24-h ISO orbit.

Target perigee height [km]	Apogee height [km]		Above 40000 km	
	Min. TO	Target	Hours	%
1000	35000	50600	8.1	51
2000	39000	49600	7.8	49
3000	44000	48600	7.4	46
3500	50000	48100	7.2	45

Table 4. Example of possible 16-h rescue orbits.

3.2 24-h Orbit Case

3.2.1 LEOP

Assumed in this example is the case of a TO apogee height of 63000 km (corresponding to a burn duration of 368 s according to Figure 2). Figure 3 shows that a 24-h synchronous orbit with a high perigee height or a 48-h orbit with a low perigee height can be reached. Let us decide for the 24-h orbit. To acquire it

- the apogee height is first raised from 63000 to 67600 km by a perigee manoeuvre of 29 m/s, most likely divided along several revolutions for reducing gravity loss
- the perigee height is then raised from 685 to 4000 km with an apogee manoeuvre of 182 m/s

Total *DV* (211 m/s) is within the capability of the on-board propulsion unit. The excess *DV* could be used for allowing an off-perigee manoeuvre better suited to ground coverage or to aim for a slightly higher perigee height.

Table 3 shows that the resulting 24-h orbit stays 70 % (16.65 h per revolution) above 40000 km altitude.

Assuming a nominal launch day/time, epoch at TO injection is 2002-10-17 @ 5:49:25 UTC. Injection occurs at true anomaly 12°.

TO coverage from the ESA LEOP ground stations plus Goldstone and Santiago during the first two days is shown on a Gantt chart in Figure 6.

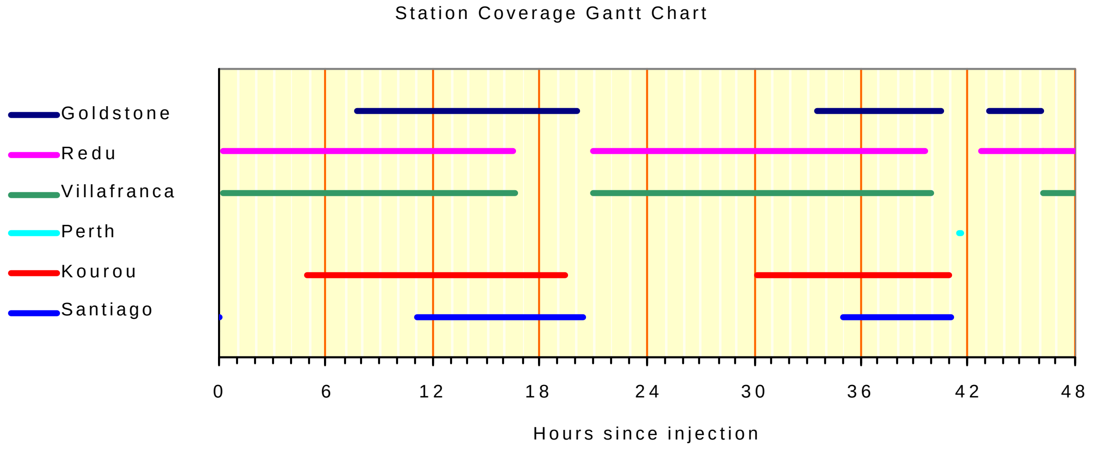

Figure 6 (original in colour). 685×63000 km TO coverage from LEOP ESA ground stations + Goldstone and Santiago during the first 2 days

3.2.2 Operational Orbit

A 24-h orbit is particularly attractive regarding ground coverage. Indeed, the 4000×67600 km 24-h orbit is continuously covered by Redu during 20.65 h. This is considerably more than 16.65 h, time when the spacecraft is above 40000 km altitude. This is illustrated on Figure 7.

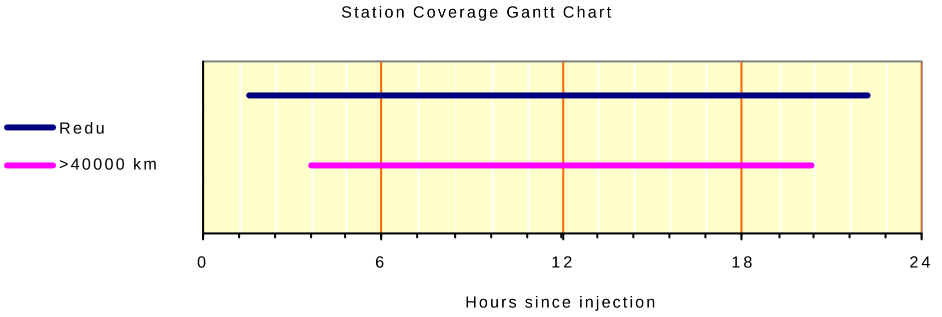

Figure 7. 4000×67600 km 24-h recovery orbit coverage from Redu, compared to time when spacecraft above 40000 km altitude.

Temporal evolution of the 24-h orbit is described along Figure 8 to Figure 11 showing respectively apo-, perigee height, inclination, RAAN and argument of perigee. Evolution of the orbit parameters is not basically different from the baseline orbit, with a raise of the perigee height and the inclination.

Eclipse duration (umbra and umbra + penumbra) is shown on Figure 12. Maximal duration is slightly longer (1.4 h) than on the baseline orbit (1.1 h), but still within specification (1.7 h).

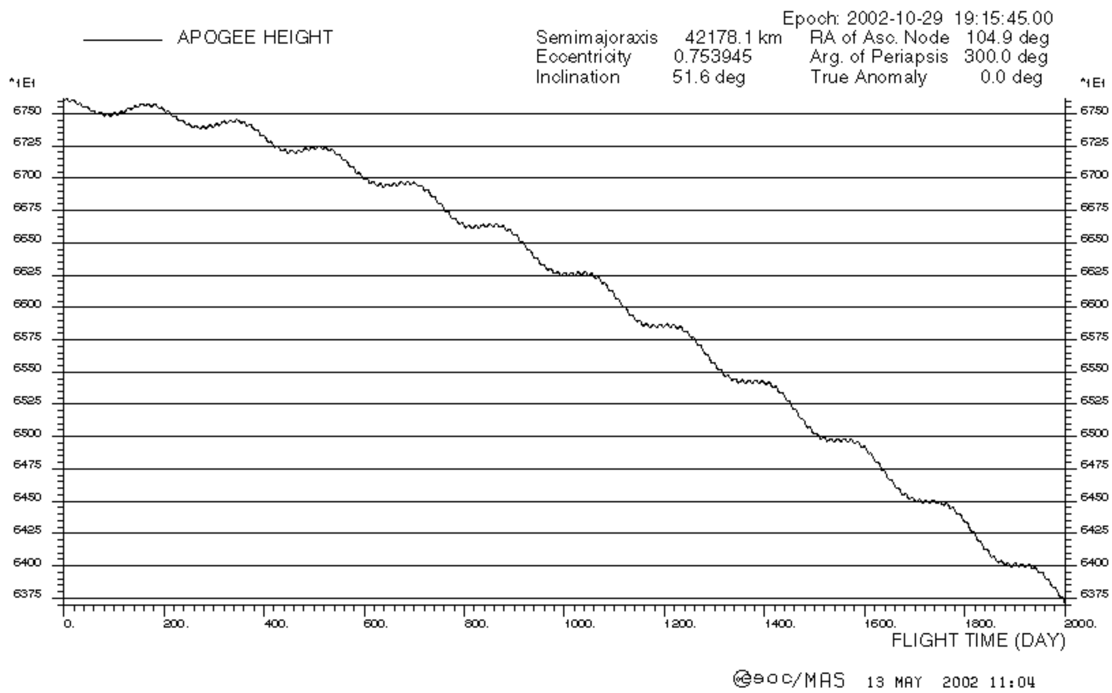

Figure 8. Apogee height history of the 24-h orbit.

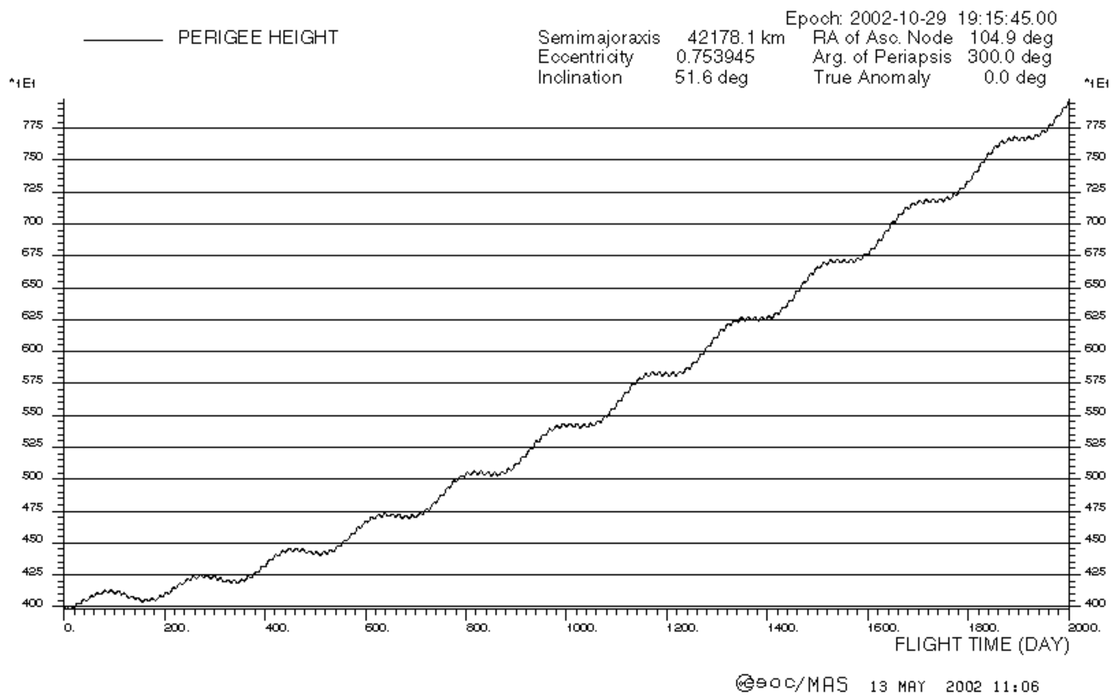

Figure 9. Perigee height history of the 24-h orbit.

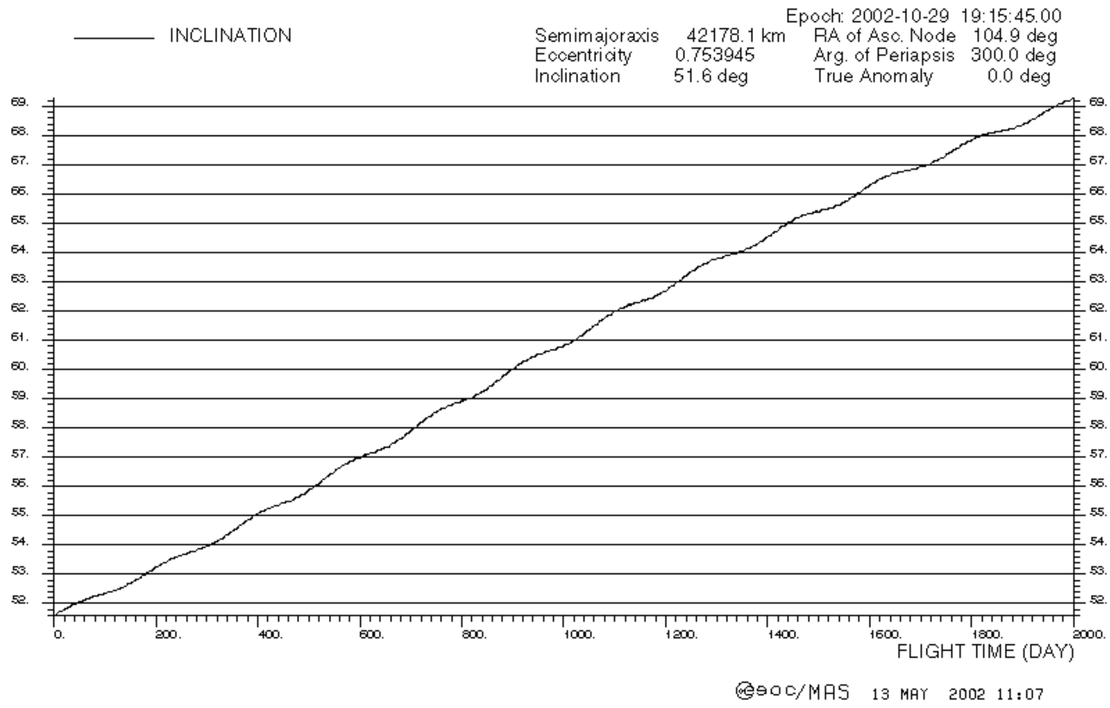

Figure 10. Inclination history of the 24-h orbit.

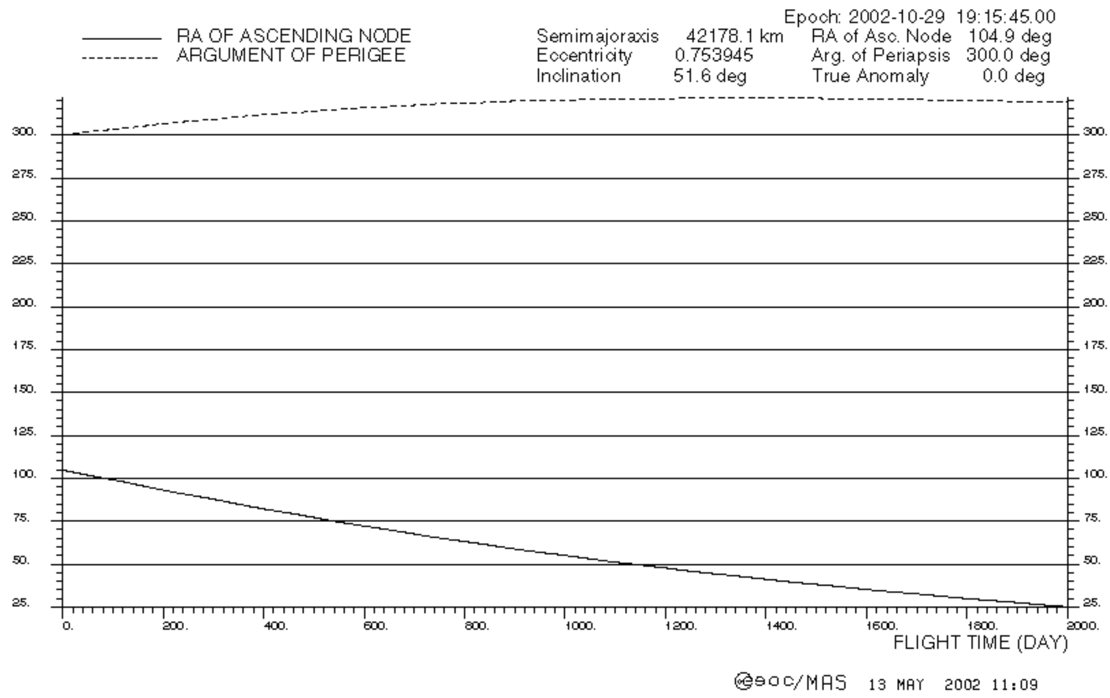

Figure 11. 24-h orbit history of the right ascension of the ascending node and argument of perigee.

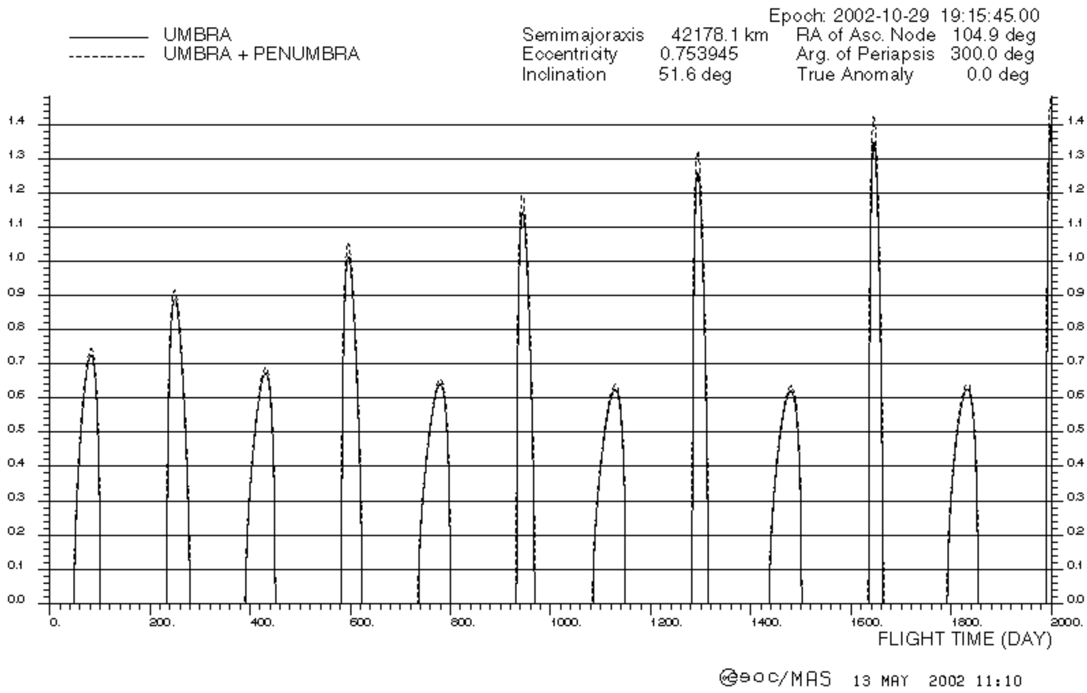

Figure 12. Umbra and umbra + penumbra duration history for the 24-h orbit.

3.2.3 Conclusion

Conclusion on the 24-h recovery orbit:

- One station (Redu) is sufficient for satellite operation and science data reception.
- Science data can be collected only 70 % of the time.
- Evolution of the orbital parameters is similar to the baseline orbit.
- Maximal eclipse duration (1.4 h) is higher than for the baseline orbit but within the specification of the satellite.

3.3 16-h Orbit Case

3.3.1 LEOP

Assumed in this example is the case of a TO apogee height of 37000 km (corresponding to a burn duration of 318 s according to Figure 2). Figure 3 shows that only a 16-h synchronous orbit can be reached. To this purpose

- the apogee height is first raised from 37000 to 50600 km by a perigee manoeuvre of 169 m/s, most likely divided along several revolutions for reducing gravity loss
- the perigee height is then raised from 685 to 1000 km with an apogee manoeuvre of 24 m/s

Total *DV* (193 m/s) is within the capability of the on-board propulsion unit. The excess *DV* could be used for allowing off-perigee manoeuvres better suited to ground coverage or to aim for a slightly higher perigee height.

Assuming a nominal launch day/time, epoch at TO injection is 2002-10-17 @ 5:48:35 UTC. Injection occurs at true anomaly 10°.

TO coverage from the ESA LEOP ground stations plus Goldstone and Santiago during the first two days is shown on a Gantt chart in Figure 13.

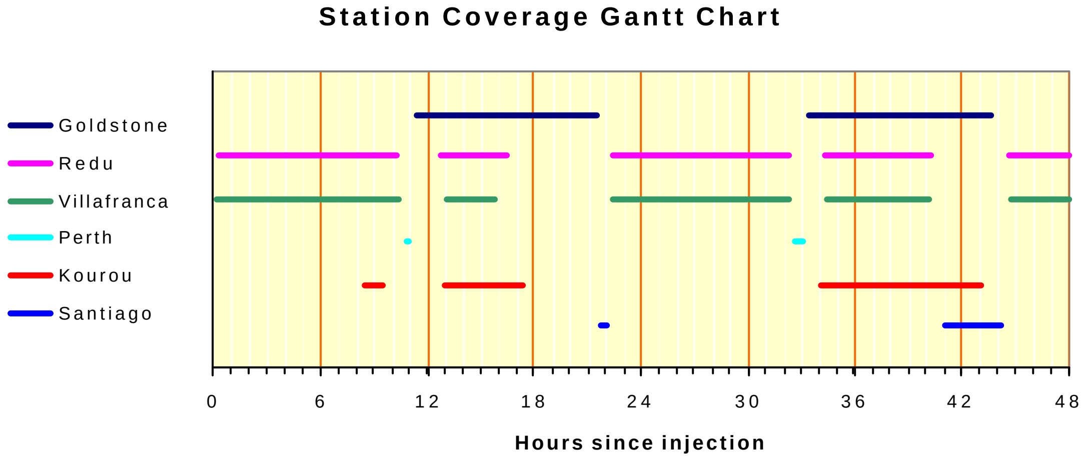

Figure 13 (original in colour). 685×37000 km TO coverage from LEOP ESA ground stations + Goldstone and Santiago during the first 2 days.

Figure 13 shows that Redu and Goldstone offers coverage with gaps of no more than 45 mn. Villafranca, Perth, Kourou and Santiago do not contribute much to coverage improvement.

3.3.2 Operational Orbit

Like for the nominal orbit, thanks to synchronicity with the Earth rotation it is possible, by carefully selecting the proper phase, to cover all the part of the orbit above 40000 km with the two baseline stations. This is illustrated in the Figure 14 Gantt chart. In addition, coverage gaps below 40000 km altitude are not longer than 1 h. 8.1 h per revolution (51 % of the time, see Table 4), the spacecraft is above 40000 km and can collect scientific data.

Evolution of the 50600×1000 km operational orbit parameters is described along Figure 15 to Figure 18. Parameters are no more evolving like the nominal orbit. Perigee height is fluctuating in a 700 km band above 1000 km and the inclination in a 5° band above 51.6°.

Eclipse duration (umbra and umbra + penumbra) is shown on Figure 19. Maximal duration is much higher than in the nominal orbit but stays within specification (1.8 h umbra + penumbra) during the operational lifetime (2.2 y). However, during the extended lifetime eclipse duration reaches 2.7 h at BOL + 2.4 y.

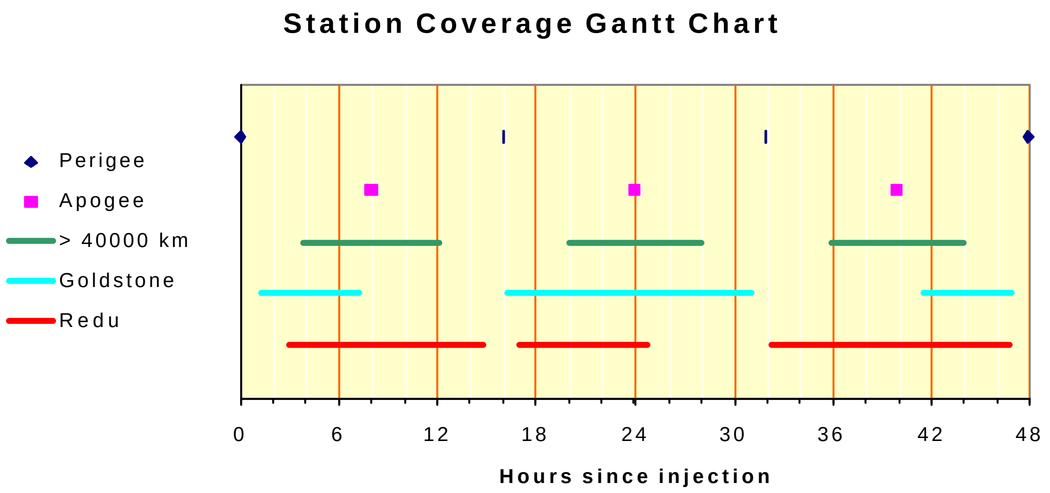

Figure 14 (original in colour). Ground coverage and time above 40000 km altitude of the 16-h orbit.

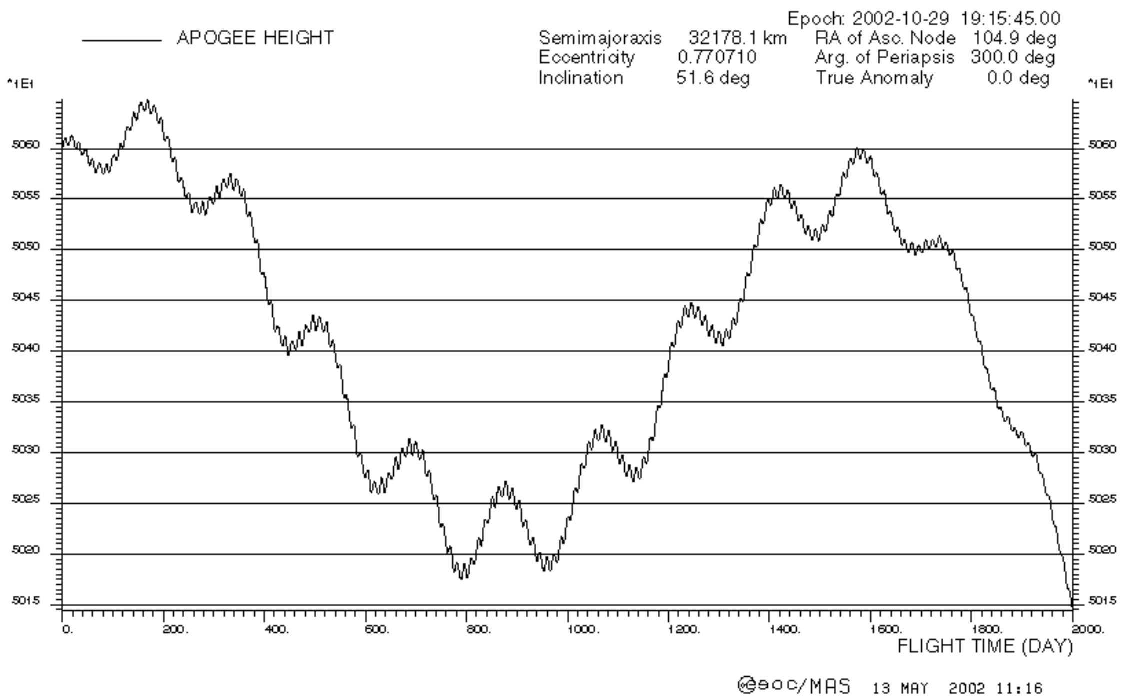

Figure 15. Apogee height history of the 16-h orbit.

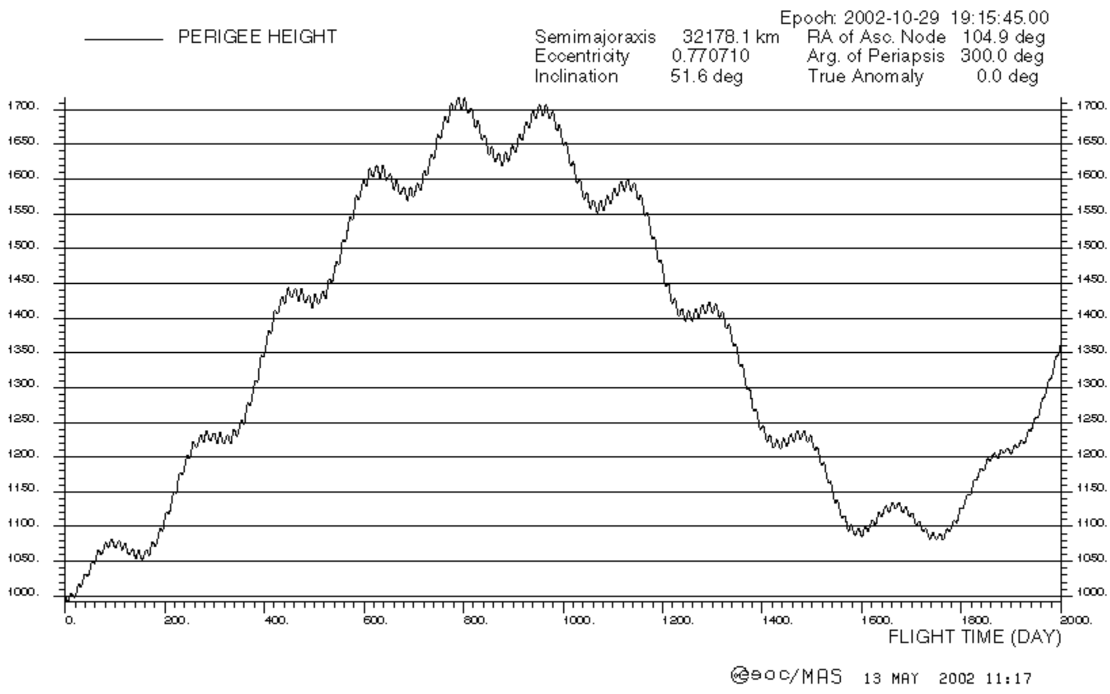

Figure 16. Perigee height history of the 16-h orbit.

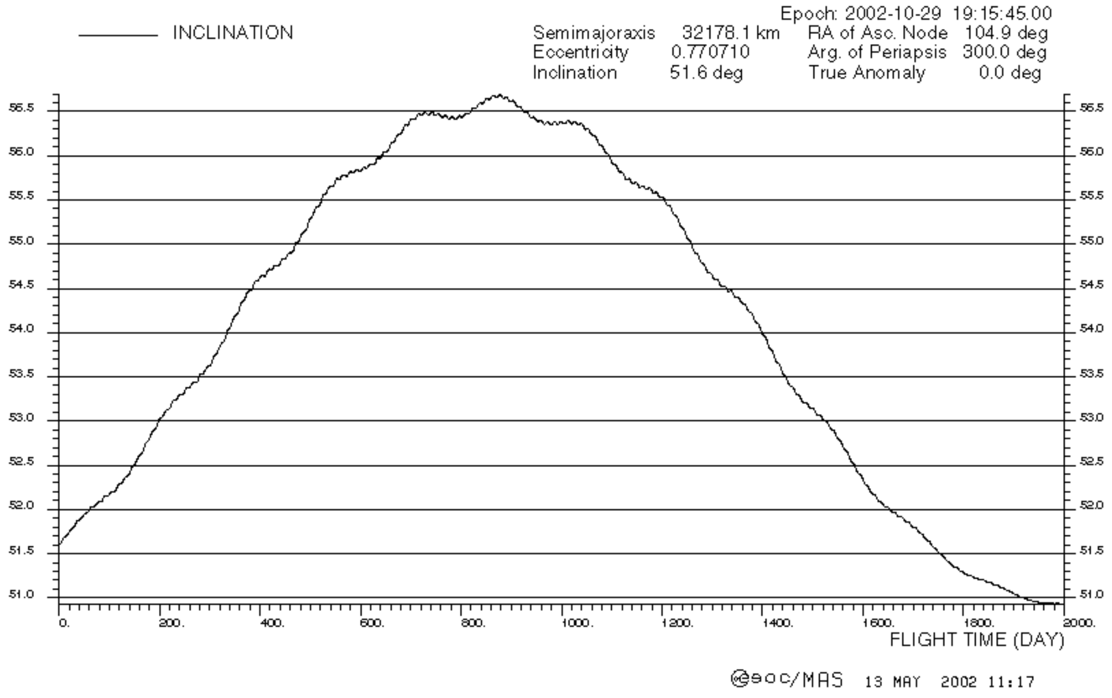

Figure 17. Inclination history of the 16-h orbit.

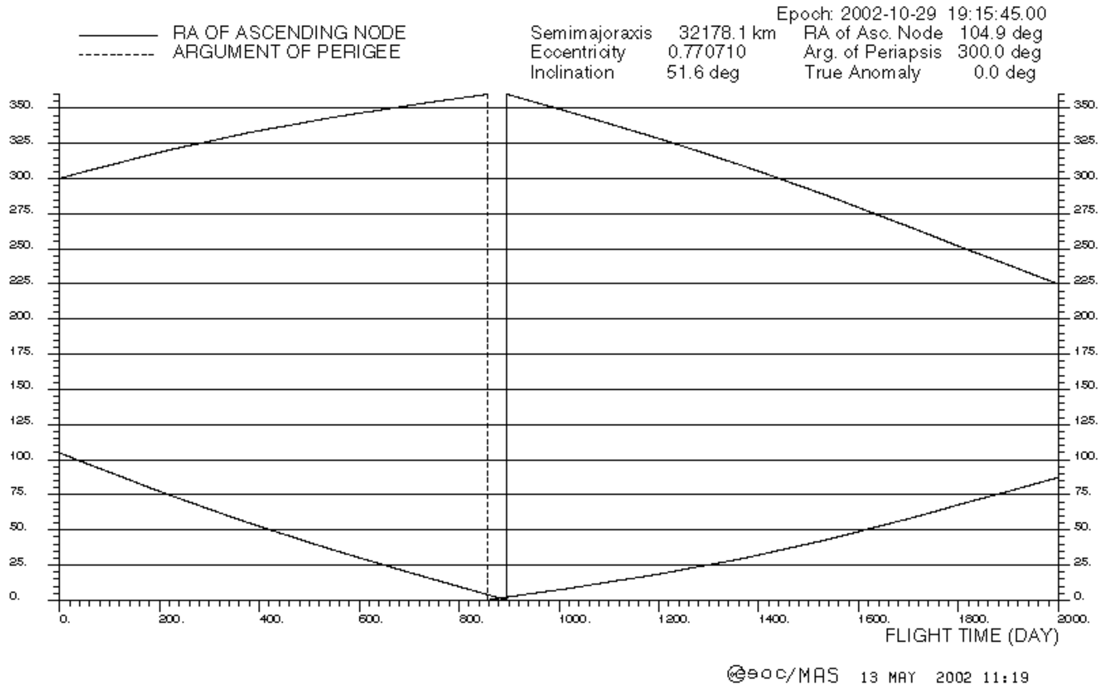

Figure 18. 16-h orbit history of the right ascension of ascending node and argument of perigee.

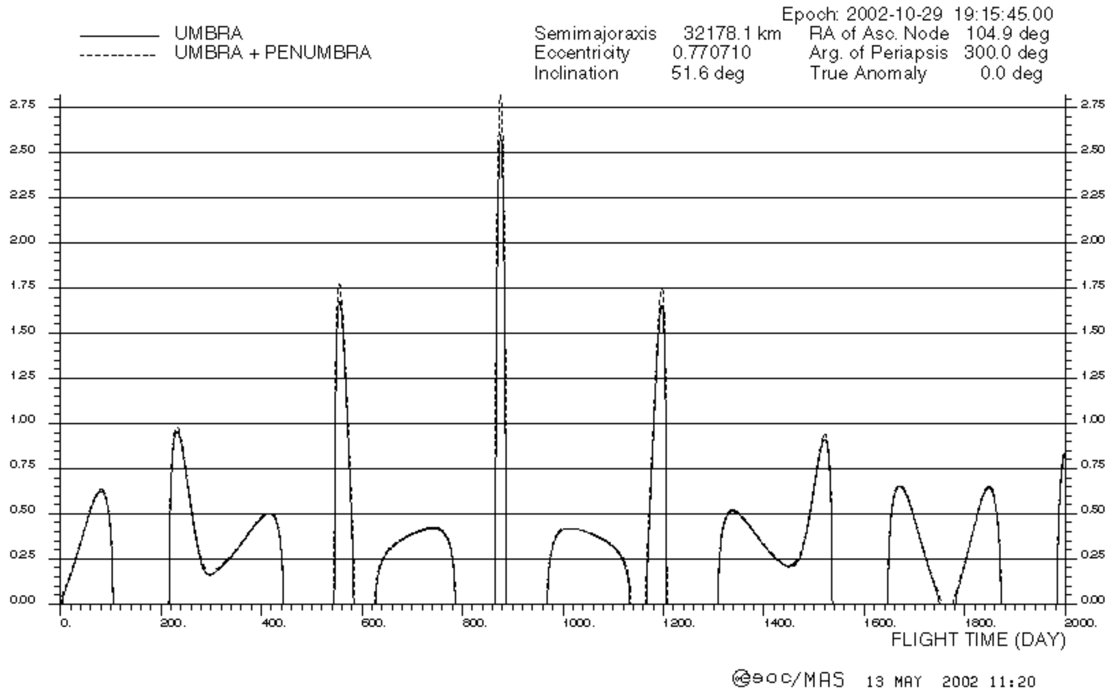

Figure 19. Umbra and umbra + penumbra duration history of the 16-h orbit.

3.3.3 Conclusion

Conclusion on the 16-h orbit:

- The 16-h orbit has a repeating cycle of 48-h during which there are three apogee passages.
- During LEOP, only two ground stations are needed for covering the orbit with gaps of no more than 45 mn.
- With the two baseline stations (Redu and Goldstone) it is possible to have complete coverage of the part of the operational orbit above 40000 km altitude.
- Gap free coverage of the scientific data can be accomplished during 8.1 h per revolution (51 % of the time).

PAGE INTENTIONALLY LEFT BLANK

4. LOW EARTH RESCUE ORBITS

4.1 TO Injection Fails

A Low Earth Orbit (LEO) will be reached when US burn is short or null. The worst case of a total absence of burn will be considered here. In this case the resulting orbit is the PO, which parameters are recalled here:

- Perigee×apogee height: 192×689 km
- Inclination: 51.6 °
- Right Ascension of Ascending Node (RAAN) if Proton launch is nominal: 104.9 °
- Argument of perigee: 82.33 °
- True anomaly at injection: 2.7 °
- True anomaly at start of "TO": 202.4 °
- Orbital period: 5604 s
- Epoch at injection into PO: 4:50:50 UTC, 590 s after lift-off (2002-10-17 @ 4:41:00 UTC)
- Epoch at start of "TO": 5:43:17 UTC, 3737 s after lift-off

The ascent phase and first two hours in LEO is represented in a 3-D altitude map on Figure 20.

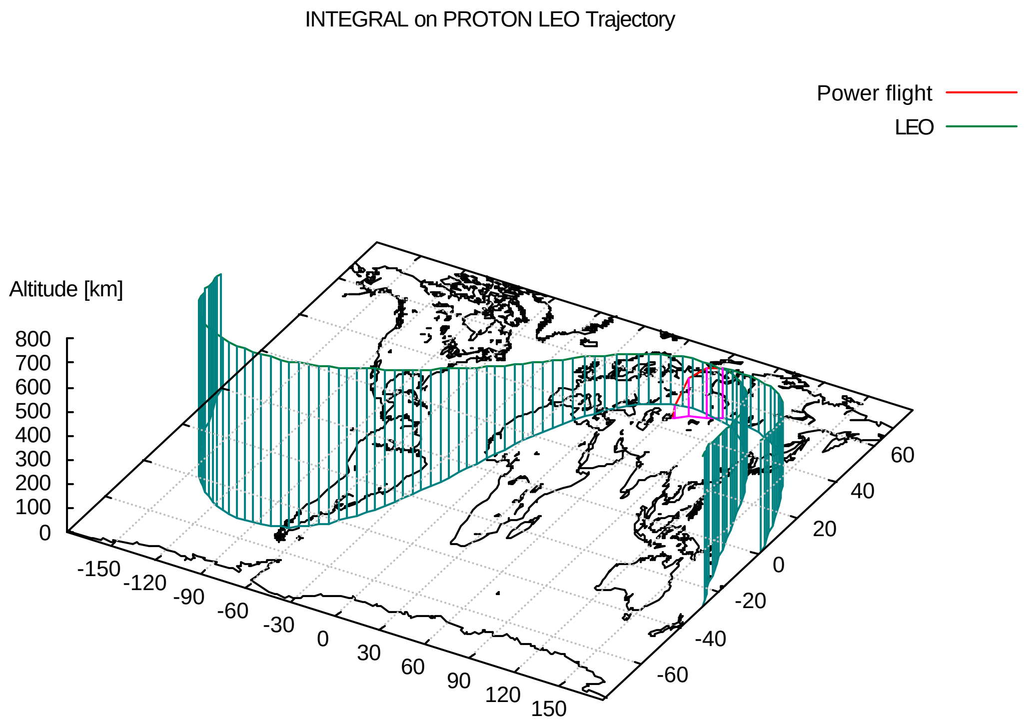

Figure 20 (original in colour). First two hours in LEO including launch ascent trajectory.

To keep consistent with the preceding sections, an epoch for the "TO" is defined as the start (coincident with the end) of the failed US burn, although the TO is identical to the PO. This epoch is used as initial time in the following diagrams.

It is well known that coverage of such a LEO is very poor. This is illustrated on the Gantt chart on Figure 21, where peri- and apogee passages and eclipses are also shown.

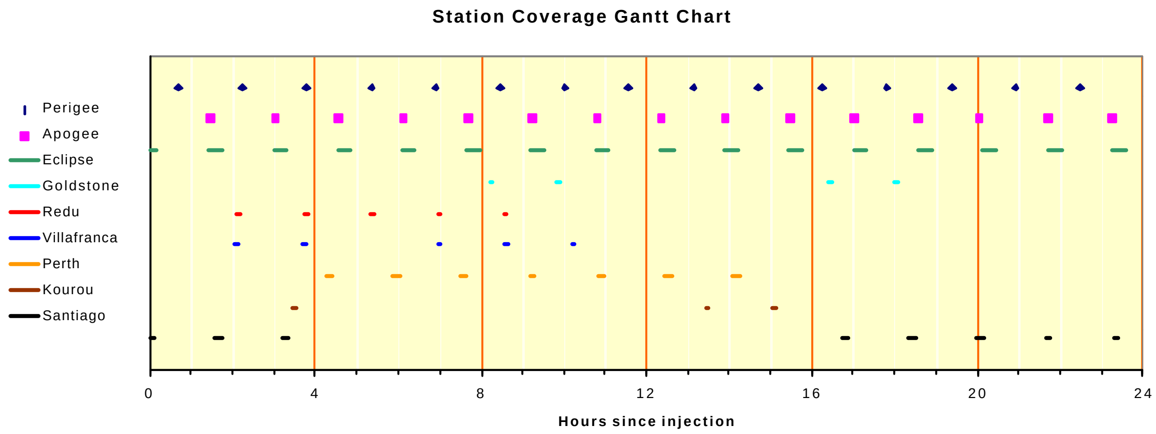

Figure 21 (original in colour). Parking Orbit Gantt chart during the first day showing peri- and apogee passages, eclipses and ground station coverage.

A corresponding ground track with coverage circles diagram is shown on Figure 22. Tick marks every 5 mn are shown along the orbit. Remarks on the coverage:

- Coverage circles are drawn assuming a mean circular orbits and do not show correct coverage estimates for elliptic orbits.
- The apogee being in the southern hemisphere (see Figure 20), Santiago (lat. –33.2°) and Perth (lat. –31.8°) give a much better coverage than Goldstone (lat. 35.3°).
- Equatorial stations like Kourou are not very efficient for coverage.
- On the other way, stations like Redu (lat. 50.0°) with latitude close to the orbit inclination give good orbit coverage.

On such a LEO, eclipses are relatively important and occur at every revolution. At BOL, they last about 20 mn (21 % of the time). There is no way to prevent them.

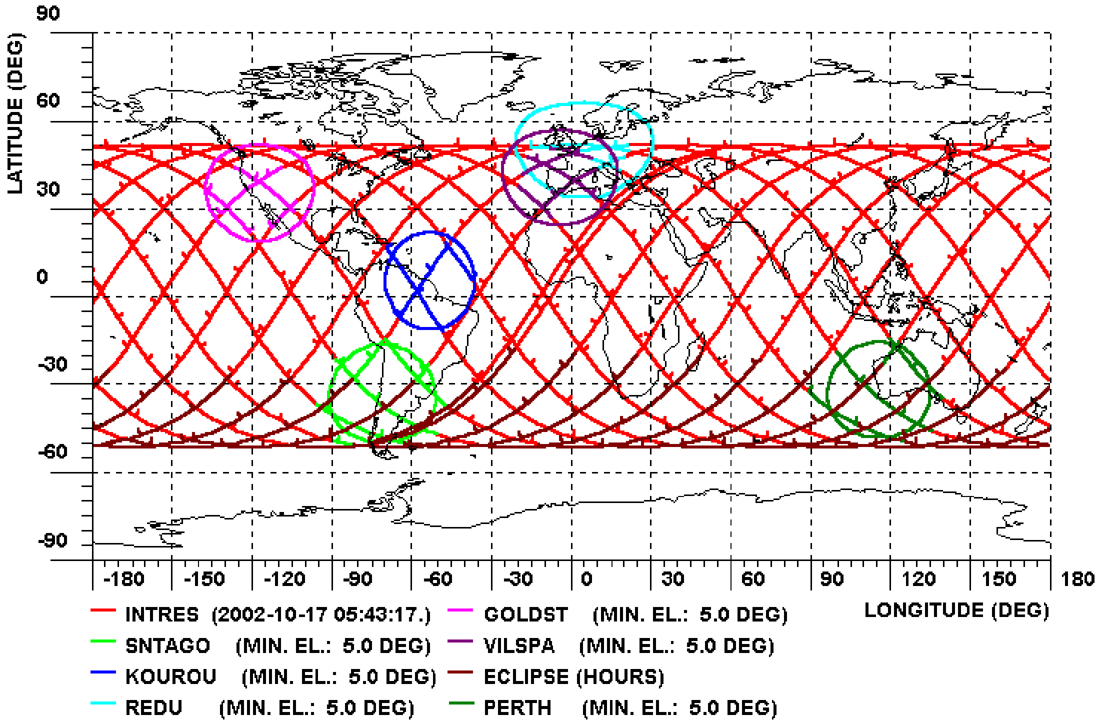

Figure 22 (original in colour). Parking Orbit ground track and coverage circle diagram during the first day. Tick marks every 5 mn along the orbit.

4.2 *How to Improve Ground Coverage?*

Two solutions are offered for improving ground coverage:

1. Increase considerably the number of ground stations.
2. To use existing satellites as data relay.

4.2.1 Communication with a Net of Ground Stations

The use of additional ground stations for the recovery of an astronomy satellite stranded on a non-nominal orbit has occurred several times in ESOC's history. In particular, following the failure of the ESRO UV astronomy mission TD-1A on a Sun-Synchronous Orbit in 1972, ESOC was faced with the task of spreading a dense net of portable ground stations all over the planet. As a result, data could be retrieved in real time from TD-1A and the mission was a full success. Such a possibility is to be contemplated for INTEGRAL.

As the number of necessary ground stations decreases with the altitude of the spacecraft, all effort should be performed to raise the orbit as high as possible. This has the additional advantage of reducing atmospheric drag and extending orbit lifetime.

With the available *DV* capability, a circular orbit at an altitude of 860 km can be reached. At this height, altitude maintenance is estimated to be about 0.04 m/s per year during low solar activity. Maximal eclipse duration is 35 mn (34 % of the orbital period).

4.2.2 Communication with the ISS

Instead of communicating with ground stations, it would be easier to use a data relay satellite. In this respect, an interesting possibility is the use of the International Space Station (ISS) as a relay satellite. As INTEGRAL's orbit has the same inclination as the ISS, only a node and altitude adjustment would be necessary. The node adjustment can be accomplished at no cost by using differential natural perturbations and the altitude change can be accomplished with the available spacecraft *DV* capability. Once INTEGRAL is in the ISS orbit, a small phase difference would be maintained, allowing a continuous communication link.

The use of the ISS as a relay satellite would have the following advantages:

1. Continuous data link with ISS
2. Use ISS as data relay/buffer satellite and even possibly for preliminary data processing
3. Download data from ISS to ground through ISS ground communication facilities

The ISS is on a near-circular orbit at an altitude between 375 and 400 km (Figure 23), average altitude is 387.5 km. To reach the vicinity of the ISS, the following would have to be done:

Raise INTEGRAL perigee height from 192 to 387.5 km, *DV* = 56 m/s

Wait on this intermediate orbit until differential node regression rotates node to ISS orbit node

Decrease INTEGRAL apogee height from 685 km to actual ISS altitude km, *DV* = 84 m/s if altitude = 387.5 km.

Total *DV* = 140 m/s. *DV* capability left would be used for orbit maintenance.

An estimate of the waiting time on intermediate orbit can be done the following way:

- Present ISS RAAN: 265.7° on 2002-05-05 @ 5:45:20 UTC
- Expected ISS RAAN regression rate: -5.0308°/day.
- Expected ISS RAAN on INTEGRAL launch day (2002-10-17): 265.7° - 830.1° = 155.6°
- INTEGRAL RAAN on day of launch: 104.9°
- RAAN interval to be covered by INTEGRAL: 155.6° - 104.9° = 50.7°
- Expected INTEGRAL regression rate on 387.5×689 km orbit: -4.6655°/day
- Corresponding differential regression rate: 0.3654°/day
- Waiting time for RAAN equalisation: 50.7°/0.3654 = 139 days.

By chance, these 139 days waiting time is quite reasonable (a 360° interval would have taken 3 years to be covered). This time will be anyway needed for preparation of the ISS for INTEGRAL data science reception.

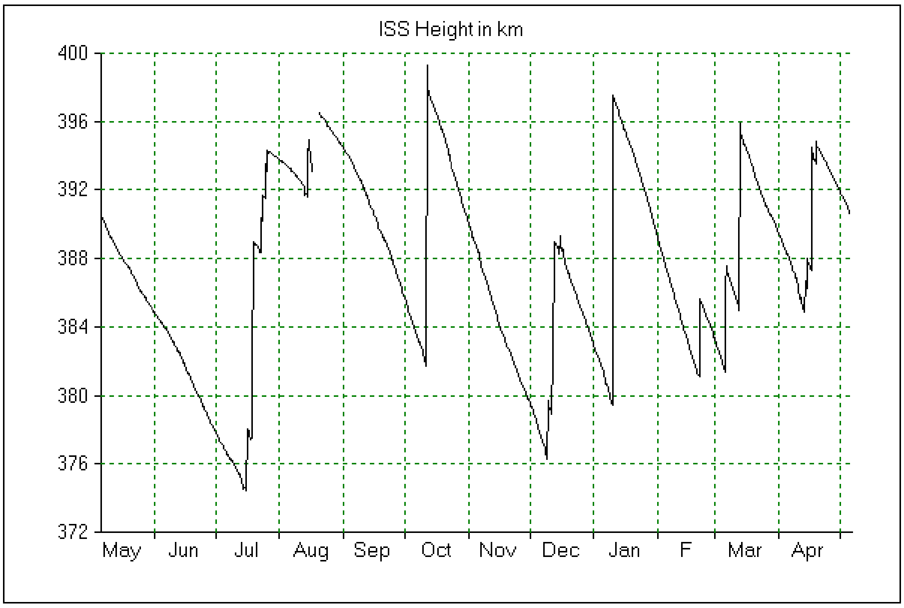

Figure 23. ISS altitude excursion during one year.

The phasing of INTEGRAL (slightly ahead or behind ISS) can be accomplished at zero cost by a small adjustment of the apogee or perigee height while in intermediate orbit.

Orbit maintenance for keeping the altitude of INTEGRAL at the mean ISS level is estimated to be about 20 m/s per year in period of low solar activity. However, the ISS having a less favourable surface to mass ratio than INTEGRAL, following the altitude excursion of the ISS orbit (Figure 23) may require sometime a lowering of the INTEGRAL altitude. This will increase the orbit maintenance *DV* but it should not exceed 40 m/s per year.

Maximum eclipse duration on the ISS orbit is 36 mn (39 % of orbital period).

PAGE INTENTIONALLY LEFT BLANK

5. INITIAL GROUND STATION ACQUISITION

This chapter focuses on the initial ground station acquisition after separation and on a procedure to be followed at the stations of Villafranca and Redu. This becomes especially important under non-nominal circumstances, i.e. non-nominal US burn. The procedure has been developed with the aim of correlating the US burn performance, being out of Russian ground station visibility, to the antenna pointing parameters observable at Villafranca. It has been found out that the azimuth evolution versus time could provide good indications of the burn performance.

Ad-hoc interfaces have been established with the purpose of getting relevant data of the US performance in a timely manner and with an accuracy increasing with the time:

1. A direct voice communication has been set up with the contact person in Baikonour. This will provide to ESOC Flight Dynamics throughout the critical events, from launch to separation, the relevant data extracted from the US telemetry, such as US burn end time and separation confirmation.
2. The research group operating the Millstone/Haystack observatory in North America, and providing support to the US Space Command radar network tracking, will send to Flight Dynamics the orbital state of INTEGRAL about 40 min after the end of the burn, based on their radar observations.
3. According to the INTEGRAL/PROTON Interface Control Document (Ref. 4), about 45-65 minutes after separation, the Russian Energia Centre will be provided to Flight Dynamics their computed INTEGRAL orbital state at separation.

5.1 Upper Stage Burn Contingency

An analysis of the contingencies of the US burn has been done and the effects on the ground station visibility at Villafranca and Redu have been assessed. The study was performed to quantify the effects on station predictions due to performance errors of the US burn, de-pointing of the US burn direction, timing errors of the US burn (start time and duration).

The results showed that the errors in the duration of the US burn have more significantly an impact on the initial acquisition at Villafranca.

If the burn does not start at all, then there is no coverage from any stations until the second revolution after separation, about 90 minutes later. This is shown in Figure 24, where visibility duration from ground stations Ascension (ASC), Redu (RED), Santiago (SAN), Perth (PER), Villafranca (VIL) and Kourou (KOU) is plotted against the time from separation. Typical pass duration is about 7 minutes.

Shorter the US burn is, later start the passes at Villafranca and Redu and their duration becomes shorter. This has almost a linear behaviour with a time difference in acquisition of about 2 minutes for the cases here analysed. Figure 25, Figure 26 and Figure 27 show the ground station visibility duration versus the time from separation for a case of 30 %, 50 % and 75 % burn duration.

For a nominal burn duration (424 s), Villafranca has a pass starting 11 minutes after the end of the burn and lasts for the successive 16 hours. This pass has a maximum elevation of 78 deg.

The station of Redu has a pass starting 13 minutes after the end of the burn and lasting about 17 hours.

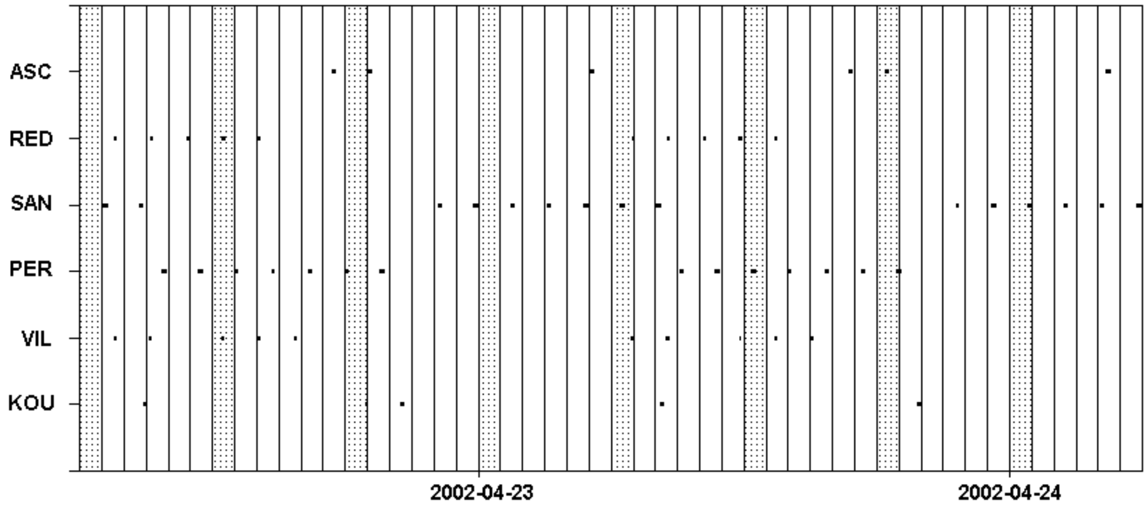

Figure 24. Ground stations Ascension (ASC), Redu (RED), Santiago (SAN), Perth (PER), Villafranca (VIL) and Kourou (KOU): sequence of passes in case of no US burn.

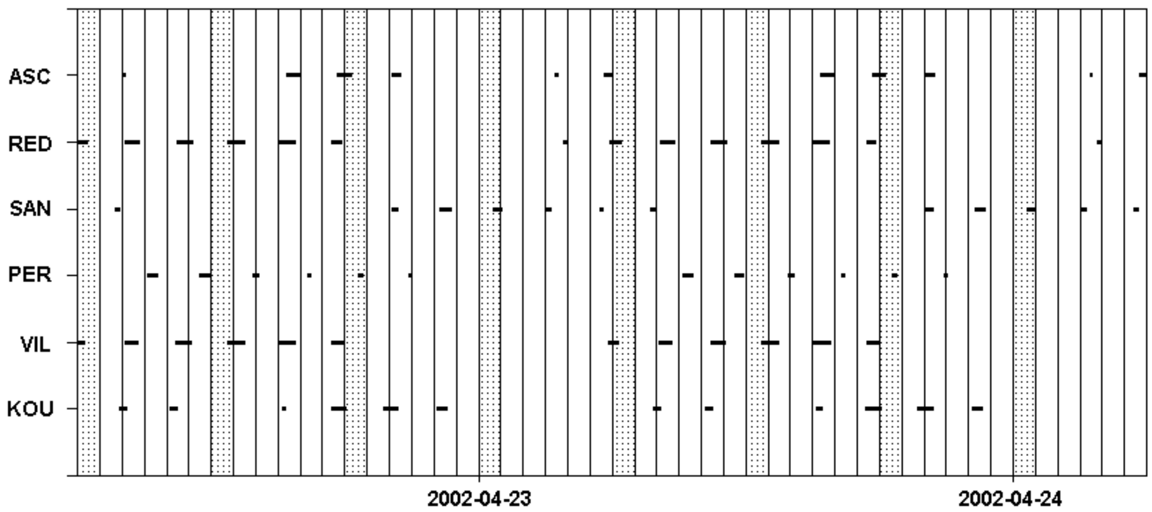

Figure 25. Ground stations Ascension (ASC), Redu (RED), Santiago (SAN), Perth (PER), Villafranca (VIL) and Kourou (KOU): sequence of passes in case of 30 % US burn.

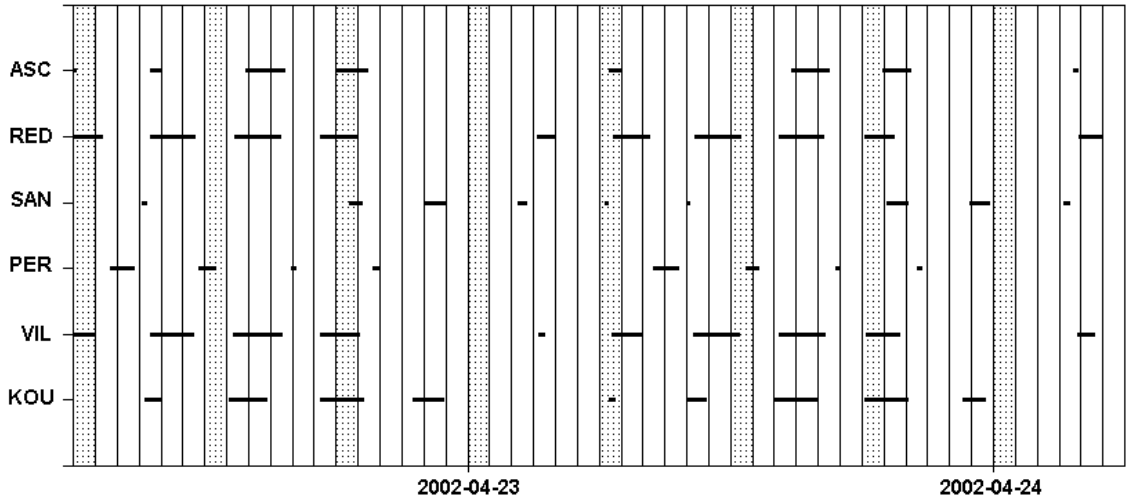

Figure 26. Ground stations Ascension (ASC), Redu (RED), Santiago (SAN), Perth (PER), Villafranca (VIL) and Kourou (KOU): sequence of passes in case of 50 % US burn.

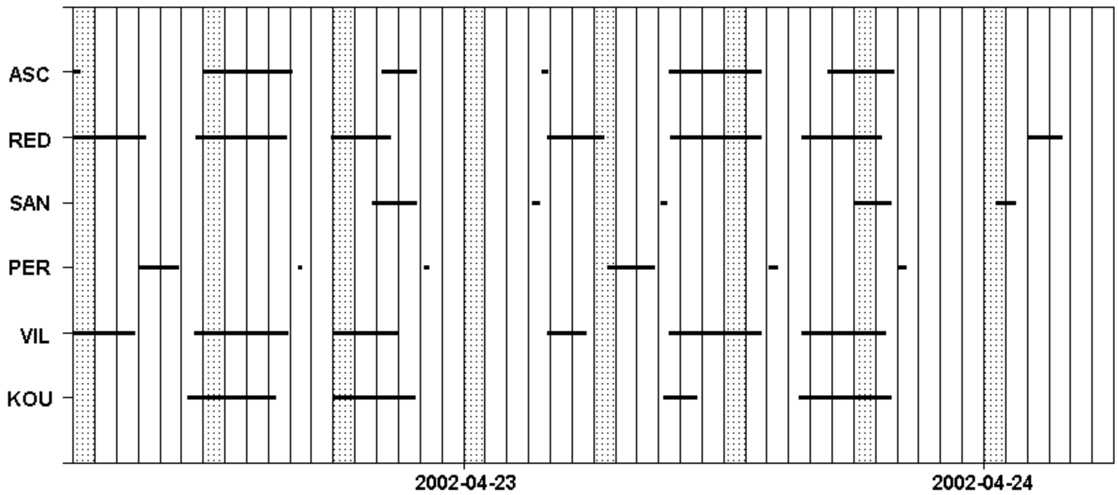

Figure 27. Ground stations Ascension (ASC), Redu (RED), Santiago (SAN), Perth (PER), Villafranca (VIL) and Kourou (KOU): sequence of passes in case of 75 % US burn.

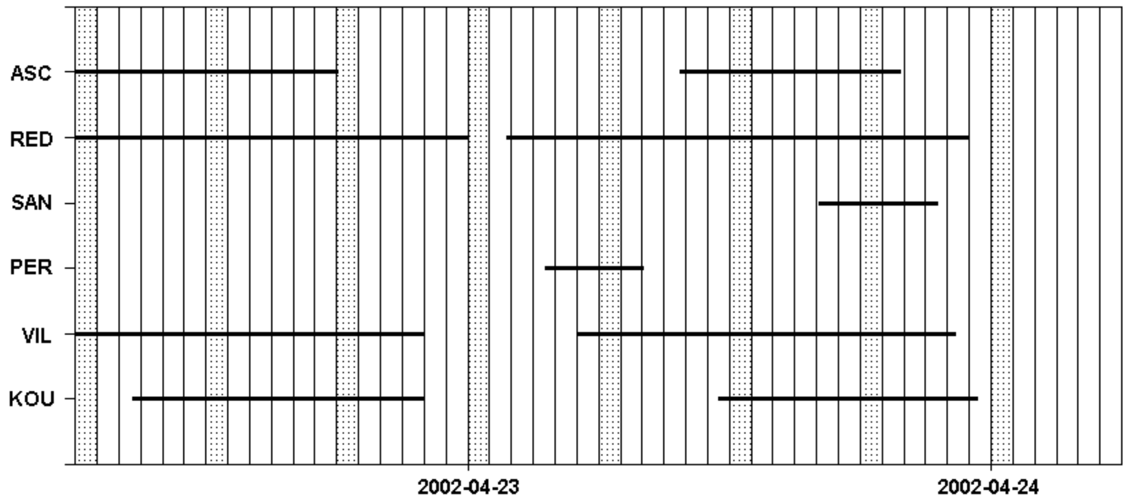

Figure 28. Ground stations Ascension (ASC), Redu (RED), Santiago (SAN), Perth (PER), Villafranca (VIL) and Kourou (KOU): sequence of passes for nominal US burn.

5.2 Ground Station Antenna Pointing

An analysis has been performed with the aim of identifying correlation between the burn performance and the parameter observable at the stations, that is the azimuth and elevation. It has been assumed that the parking orbit is nominal, that the burn starts at the nominal time and the only varying parameter is the burn duration.

Several cases have been simulated corresponding to a different percentages of the burn duration, ranging from nominal case, burn of 100 % duration, to the extreme case of a burn with 0 duration. The time evolution of the absolute value of the azimuth caused by different burn performance have been plotted in Figure 29 as function of the burn duration. The different curves correspond to evolution of the azimuth during the pass.

For the first 6-7 minutes, the azimuth values are close together, afterwards they start to separate. The AOS time gives therefore a good indication of the burn performance.

Table 5 contains the azimuth values at Villafranca corresponding to the different cases depicted in Figure 29. The third row lists the azimuth values for the nominal burn at the corresponding AOS times. The values differ from case to case for about 2 minutes.

Elevations are shown on Figure 30.

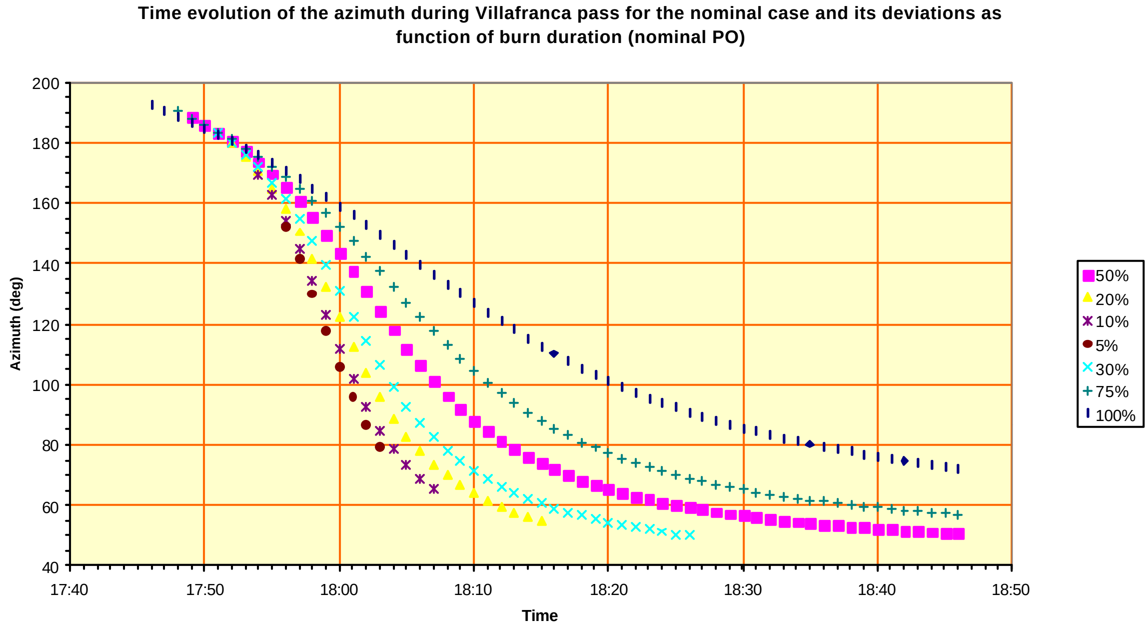

Figure 29. Time evolution of the azimuth at Villafranca for different US burn duration.

US burn duration	100 %	75 %	50 %	25 %	10 %	5 %
AOS time	17:46	17:48	17:50	17:52	17:54	17:56
Azimuth	192.0°	189.4°	187.0°	179.9°	171.8°	156.7°
Nominal azimuth at same time	192.0°	188.8°	184.7°	180.3°	175.6°	170.5°

Table 5. Azimuths at Villafranca in terms of percentage of US burn duration.

5.3 *Procedure for First Acquisition*

5.3.1 Villafranca

Prior to the launch, Flight Dynamics produces several files (maximal 10) determining the antenna pointing (this file is called STDM, Spacecraft Trajectory Data Message), one for the nominal case, one for the non-nominal case and a set of files as further backup of the non-nominal case.

The non-nominal file is artificially created by merging the AOS time and azimuth, corresponding to different duration of the US burn ranging from 100 % to 5 %, with a fixed AOS elevation. This file will be created for the station Villafranca. The files are based on the assumption of a nominal Proton parking orbit and will be delivered to the stations before launch. In case of a notification of a non-nominal parking orbit, about 20 minutes after launch, the set of STDM files will be re-generated based on the new parking orbit. The new set of STDM files will then be re-delivered to the stations.

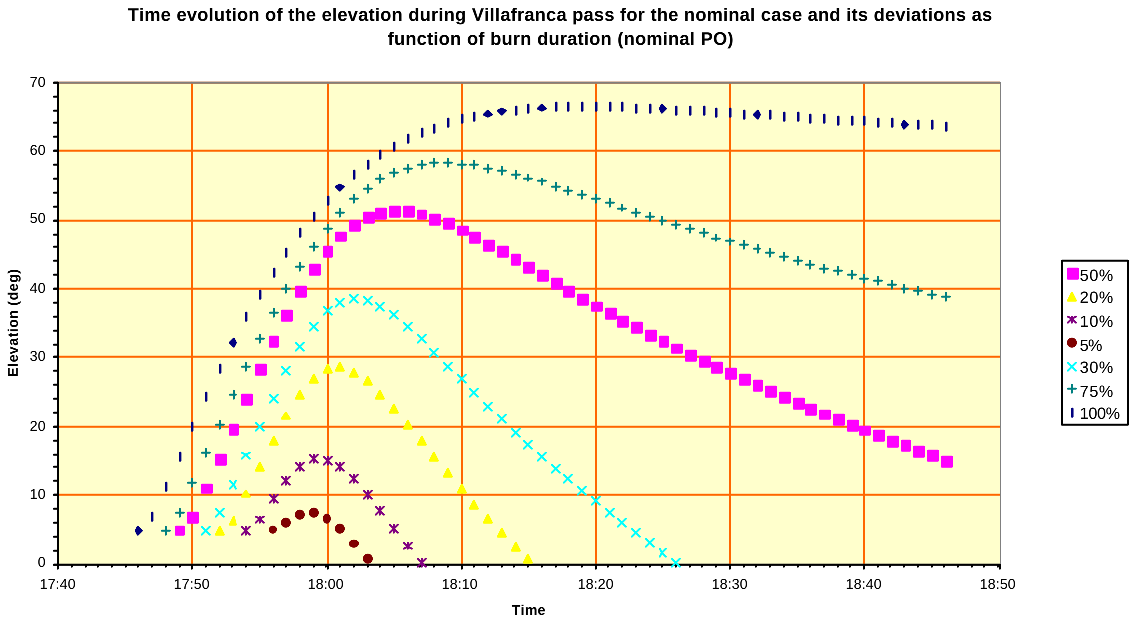

Figure 30. Time evolution of the elevation at Villafranca.

Villafranca is equipped with two antennae, VIL1 and VIL2.

One antenna in Villafranca, VIL1, will be provided with the nominal STDM and will follow the given antenna pointing. In case of missing the AOS for several minutes after the nominal AOS time, then a spiral search will be done and it will be repeated, if necessary. In the meantime, the operations team will perform several attempts according to contingency procedure using VIL1 antenna.

The second antenna in Villafranca, VIL2, will follow the non-nominal STDM file created by merging the different time and azimuth values for a fixed AOS elevation. By following this file, it should be possible to acquire AOS within about 12 minutes.

In case of unsuccessful result, a spiral search could be started in VIL2 around what could be considered the most likely case, for example from 95 % to about 65 % burn duration using one STDM after the other from the backup STDM set of the non-nominal case.

5.3.2 Redu

Redu will be provided with the nominal STDM. The antenna in Redu will follow the nominal STDM applying spiral search if required.

In case of a successful Villafranca acquisition with the artificial STDM the burn duration will be derived from the reported AOS time and a new STDM for Redu will be prepared as fast as possible. In case of AOS at Villafranca by using one of the backups STDM of the non-nominal case, Redu will be provided by this STDM.

PAGE INTENTIONALLY LEFT BLANK

6. Failure of a Perigee Raise Manoeuvre

The nominal sequence of PRMs is recalled in Table 6 (copied from Ref. 1).

Man. no.	Apsis no.	Apogee long.	October 2002, UT	Days since perigee 0	New perigee height (km)	*Dv* (m/s)	Duration thrust (s)
1	A3	158°	24, 04:21:26	6.9400	2387	50	2542
2	A4	–133°	26, 19:28:51	9.5704	4714	60	3981
3	A4	–133°	26, 21:35:12	9.6583	6955	51	4148
4	A5	–105°	29, 19:00:03	12.5504	9714	56	5328
5	A5	–105°	29, 21:28:51	12.6538	10000	5	516
6	P5	–105°	31, 08:12:51	14.1013	10000	<6	<600

Table 6. Manoeuvre sequence for station acquisition in the nominal case.

For this analysis, the following assumptions are made:

- TO is nominal
- Target perigee longitude: 255.1° E
- At a given apogee, only a total failure of the manoeuvres is foreseen (no case of partial failure)
- Manoeuvres are performed successfully at the next opportunity

Generally one can say that

- ➢ It is all the time possible to finally reach the desired longitude.
- ➢ Total *DV* is not affected by changing the timing and splitting of manoeuvres.

The main result of the analysis is summarised in Table 7.

Case	Man. no. fail	Actual drift rate [°/rev.]	Actual longitude	Dlongitude to be performed	Drift time [d] to next man.
1	1	84.9	157.6°	97.5°	3
2	2 + 3	69.5	227.1°	388.0°	15
3	4 + 5	28.0	255.1°	360.0°	36

Table 7. PRM failure cases.

In case 1 of Table 7, manoeuvre no. 1 fails at apogee 3. It is still possible at the rate of 84.9°/rev. to complete part of the longitude interval of 97.5° and to execute a large manoeuvre of 195 m/s at apogee 4. This large manoeuvre has to be divided in 4 parts and double coverage of all the manoeuvres is not possible. At apogee 5 a last manoeuvre of 27 m/s stops the drift: the target perigee longitude is reached at the nominal time.

In case 2, manoeuvre at apogee 3 is successful but manoeuvres 2 and 3 at apogee 4 fail. Due to the still high drift rate (69.5°/rev.) and the small longitude interval to complete (28°), one has to perform a complete 360° drift. This takes 15 days. At apogee 9, a drift reduction manoeuvre can be performed and, at apogee 10, the target longitude is reached. Total drift time is about 1 month.

In case 3, manoeuvres at apogee 3 and 4 are successful but drift stopping manoeuvre at apogee 5 fails. As one is already at the target longitude, there is no other way than to wait until a 360° round is completed. As the drift rate is only of 28°/rev., this takes 36 days. At apogee 17, a first drift reduction manoeuvre is performed and, at apogee 18, the drift is stopped. Total drift time is about 54 days, still within the commissioning period.

In case of non-nominal TO or only partial failure of a PRM (manoeuvre interrupted), any situation can occur. But whatever is the situation, it is all the time possible to design a PRM strategy aiming at the target longitude at no extra cost in *DV*.

7. CONCLUSION

Following a malfunction of the US, which practical consequence is a lower than nominal TO apogee height, using the available on-board *DV* capability (228 m/s) possible rescue orbits have been investigated from a ground coverage, eclipse and orbit evolution point of view. No consideration on operational feasibility has been included.

The conclusion is the following:

- Orbits are all the time stable: the perigee height does not substantially descent below its initial value.
- If the TO apogee height is above 35000 km, a synchronous orbit of 16-, 24-, 48- or 72-h can be reached:
  - A viable scientific mission with at least 50 % of the time above the radiation belt at 40000 km altitude is guarantied.
  - Initial perigee height may have to be tolerated to be as low as 1000 km.
  - Ground coverage is possible without gaps above the radiation belt with the two nominal stations (Redu and Goldstone).
  - Maximal eclipse duration never exceed specification (1.8 h) during the nominal mission.
- In the particular case of the 24-h orbit, which can be reached if the TO apogee height is between 45000 and 65000 km, only one station (Redu) is sufficient for operating the satellite and receiving scientific data.
- If the TO apogee height is below 35000 km:
  - An orbit with more than 50 % of the time above the radiation belt can no more be reached.
  - Number of ground stations for continuous coverage of the orbit will exceed two.
  - Maximal eclipse duration will exceed specification or relative time in eclipse can be a large proportion of the orbital period.
- If the US burn is short or vanishing small, the final orbit is a LEO:
  - Direct continuous ground coverage is close to impossible.
  - Time in eclipse may be as high as 40 % of the orbital period.
- Using the fact that the LEO inclination is identical to the one of the ISS orbit, it is proposed to transfer to that orbit:
  - Making use of natural perturbations for node alignment, this would take about 140 days.
  - Total *DV* for altitude transfer: 140 m/s.
  - Maintaining a small phase difference with the ISS, the ISS could then be used as a relay satellite for ground communication.
  - Orbit altitude maintenance would be no more than 40 m/s per year.
  - Maximal eclipse duration is 36 mn (39 % of the orbit period).

In case of a failure of a Perigee Raise Manoeuvre:

- It is possible to perform the manoeuvre at a later time and to reach the target perigee longitude with the nominal *DV* budget
- Drift duration may be extended up to two months, therefore still within the commissioning period.

8. REFERENCES

1. G Janin, INTEGRAL on PROTON Consolidated Report on Mission Analysis (CReMA) for the 72-h Orbit: Fall 2002 Launch, Issue 6, Rev. 1, *INT-RP-22772, MAS WP-404*, ESA-ESOC, September 2001.

2. G Janin, INTEGRAL on ARIANE 5 Consolidated Report on Mission Analysis (CReMA), Issue 1, INT-RP-14237, *MAS WP-406*, ESA-ESOC, October 1999.

3. E A Roth, GEOS Rescue – Mission Planning and Implementation in Near-real Time, *ESA STR-204*, October 1979.

4. PROTON/INTEGRAL Interface Control Document, Issue 0, Rev. 8, Khrunichev, 25 January 2002.