MINISAT-01, CONCEPT AND EVOLUTION IN THE OPERATIONS OF A SUCCESSFUL SMALL MISSION

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ABSTRACT

In 1997 the Spanish Space Agency, INTA (Instituto Nacional de Técnicas Aeroespaciales) culminated several years of intense work with the launch of the MINISAT-01. It was conceived as a mini-satellite of 190 kg of mass, operating in low inclined orbit. Its payload consisted of several scientific instruments devoted to the astronomical investigation. This paper intends to summarize the MINISAT-01 decentralized operations concept, paying special attention to the flight dynamics activities from their conception to the launch as well as their evolution along the almost 5 years of outstanding performance of the spacecraft, which only ended with the atmosphere re-entry in February 2002.

1. INTRODUCTION

Launched in April 21 of 1997, the main characteristics of MINISAT-01 were:

Three axes stabilized
Four solar panels 50 w each
Service Module Mass 105 kg
Payload Module Mass 85 kg
Inclined retrograde orbit 158 degrees

1.1 Payload description:

LEGRI: (Low Energy Gamma Ray Instrument) Demonstration of the technological feasibility of construction of a new generation of gamma ray telescopes, optimized for low energy astronomy (20-100 kev), using HgI_2 detectors.
CPLM: (Comportamiento de Puentes Líquidos en Microgravedad) Testing a liquid bridge submitted to different conditions of acceleration in the microgravity field range in order to built a high sensitivity accelerometer.
EURD: (Espectrógrafo Ultravioleta Radiación Difusa) Conducting spectrography observation of diffuse extreme ultraviolet astrophysical radiation in the 300 to 1000 Å range.

2. MISSION ANALYSIS

It was mainly the payload, in particular the EURD, which imposed the main requirements to the mission analysis, although some other constrains derived from the launch vehicle, ground segment and the satellite itself were taken into account.

The EURD experiment had a series of limitations with respect to the kind of required orbit, in order to make its observations adequately:

1. Orbital height of more than 400 km above the Earth surface.

2. Orbital inclination as close to zero as possible (in any case below 41 degrees), in order to allow a correct observation of the ecliptic plane.

3. Eclipse duration time (during which observations take place) greater than 15 minutes.

4. Minimize the time passage above the south Atlantic anomaly, over which the observations were not allowed.

5. Availability of at least 2000 hours of observations along the mission duration..

Other requirements not related to the payload were:

1. A Minimum mission time of 2 years with a goal of three.

2. Only one Ground Station available, located at the Canary Islands.

3. MINISAT-01 had to be operative over the entire mission life without orbital control/propulsion subsystem.

4. The orbit had to be determined with the necessary precision to allow the proper operation of the payload and the correct pointing of the tracking antennas, using

ranging and doppler measurements made from the unique ground station.

The chosen launch vehicle was the Orbital Sciences Corporation Pegasus. It was carried aloft by the L-1011 aircraft to approximately 12,000 m. over Open Ocean in the Spanish territorial seas of the Canary Islands

To accomplish with the design goal of three years of mission life, the orbital height had to be maximized within the limits of a Low Earth Orbit (LEO). On the other hand, as the altitude over Earth surface increases, the other requirements are penalized since the eclipse duration time diminish and the number of passes with adequate visibility for the tracking station is reduced. However the orbital height must not fall bellow the initial lower limit imposed by the EURD of 400 km.

Thus the trade-off established a range between the 400 and the 800 km. Finally the optimum orbital height chosen was around 600 Km.

The minimization of the pass over the South Atlantic Anomaly and the objective of EURD of making observations as close as possible to the ecliptic plane, required the lowest possible inclination. Since the launch has to take place from the Spanish territory and there was not fuel allocated to correct the inclination, the range of achievable inclinations was 28 deg (the latitude of the Canary Islands) or greater

To avoid flying over inhabited lands in the launch phase, it was necessary to launch westward.

Attending to the above mentioned considerations and trade-offs the chosen inclination was 29 degrees retrograde, nominally 151 degrees.

The Fig. 1 shows a 35 degrees perspective of a series of successive MINISAT-01 orbits as well as the visibility cone of Maspalomas

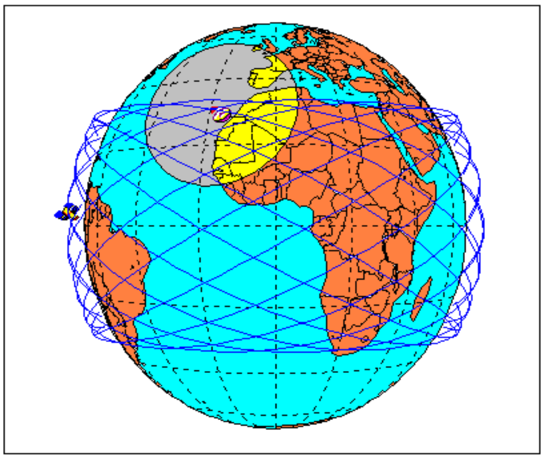

Fig 1: MINISAT-01 orbit and visibility cone

The selected null eccentricity provided orbital event sequences, like eclipses, tracking station passes etc. more homogeneous in duration and frequency which in turn facilitated the mission planning.

The orbital parameters finally achieved at launch are shown in table 1

Table 1: Orbital Elements at launch

Insertion time: 1997April 21 12:09:29.646 UTC	
Semimajor axis	6,951,796 meters
Eccentricity	0.0005
Inclination	150.985º
Arg. Of Perigee	347.373º
R A A N	123.243º
Mean Anomaly	141.2689º
Mean Altitude	575 Km
Orbital Period	1h 36 min

In order to assure contact periods grater than 8 minutes above 5 degrees elevation, only 20 degrees elevation passes were considered. This gives 5 to 6 available passes per day. Nominally only 5 were used. With an orbital period of about 90 minutes between the first and the fifth pass, the sequence lasted less than 8 hour. This allowed the Maspalomas Stations to cover the whole daily sequence with just one staff shift as requested by the Ground Segment requirements.

This tracking policy gave a total of 45 minutes of daily contact with MINISAT-01.

Finally, with respect to the launch window, there were two key requirements. The first two orbits should pass over Maspalomas to assure early contact. This was intrinsically accomplished by the fact of launching from the Canary Islands were the Station was located. In the second place a minimum of 10 minutes of solar illumination just after orbit insertion were necessary. A study showed that during the whole year, daily windows of at least 11 hours existed in the daylight portion of the day.

3. GROUND SEGMENT AND OPERATIONS CONCEPT

The ground segment concept consisted of the Mission Control Center (MCC) located in Torrejón (Madrid), the Scientific Operations Center (SOC) in Villafranca del Castillo (VILSPA) in Madrid and a unique Remote Tracking Station (RTS) in the Canary Islands, Maspalomas (see Fig. 2). Mission operations activities loop was closed by the Engineering Support Team (EST), located in Torrejón. The three sites were permanently connected via dedicated lines of 64 kbs. Mission Planning as well as FD (Flight Dynamics) calculations were performed off-line in the Torrejón MCC by gathering the required inputs from the

Engineering Team, the VILSPA SOC, and the RTS observations and transmitted in a daily basis to the RTS in Maspalomas. Mission planning and engineering support was available on-call out of the office working hours during the satellite passes sequence.

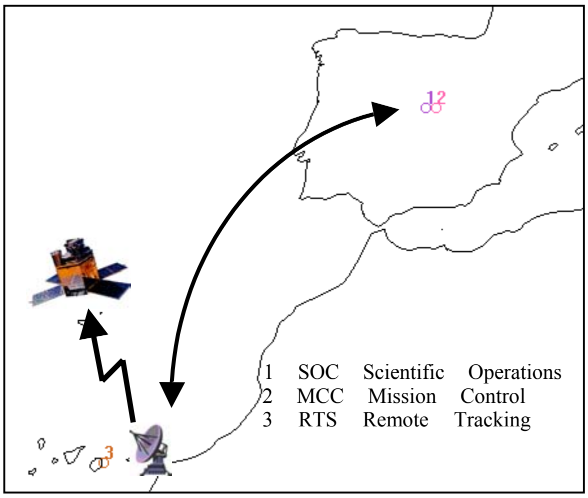

Fig 2: Geographical Ground Segment distribution

The MCC in Torrejón consisted of three workstation connected to a Local Area Network: the FD machine, the SHPA (Spacecraft Health and Performance Analysis) dedicated to the processing of the housekeeping telemetry, and the SSCM (Spacecraft Scheduller and Command Management) dedicated to the scheduling and generation of the command uploads.

The Maspalomas tracking station consisted of 4 PC. Two of them call STCS (spacecraft Test and Control Station) were dedicated to real time commanding (the prime and the backup). The other 2 were called DDSS (Digital Data Storage System) and were dedicated to the high speed TM (Telemetry) collecting and archiving (the prime and the backup). Fig. 3 shows a scheme of the overall system

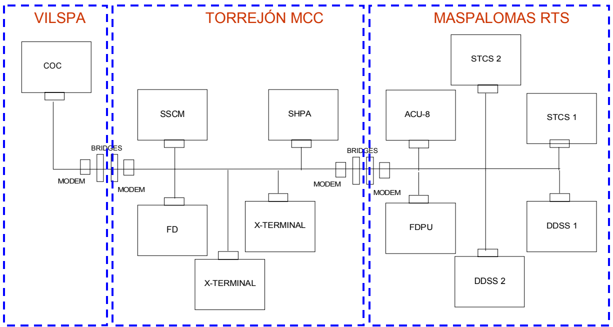

Fig 3: MINISAT-01 Ground Segment configuration

Two antenna systems were available: a 5 metres antenna used as the nominal one and the ESA's 15 m antenna with its Multi-Purpose Tracking System (MPTS) that provided ranging and/or integrated Doppler for the localization campaigns.

Four of the 5 scheduled passes per day were dedicated to upload the command stacks, download the scientific and housekeeping telemetry (1Mbs), check the spacecraft health in real time via the low speed telemetry (8kbs) and make ranging measurements. The last one was reserved for backup purposes.

The spacecraft operations planning were a 2-day-ahead conception (this gave the spacecraft 2 day autonomy out of ground contacts). This was the nominal configuration during most of the life of the satellite although in special cases 1day ahead was used, for example when onboard processor resets occurred and it was necessary rearrange the planning.

In the last months before reentry, a final task was requested to MINISAT-01 by SOC: extend the operational life as much as possible, to make unique observations inside the thin upper atmosphere layers. Special measures were taken to avoid loss of the priceless data, due to the high frequency of safe mode start occurrence, thus mission planning was forced to 0-day-ahead uploads. Even the 1.5h gap between ground station contacts was used several times to last minute re-planning. This ensured the maximum science operational time.

Along the mission life of MINISAT-01 9070 passes were scheduled for tracking, of which only 35 were missed (0.38 %), yielding to a remarkable Reliability of 99.61% of the tracking site at Maspalomas. The following table summarizes the causes of the failed passes [1].

Table 2: MINISAT-01 Failed Passed Cause

S/C FAILED PASSES	FAIL CAUSE	% OVER TOTAL
0	SATELLITE	00.00 %
30	EQUIPMENT	85.71%
2	OPERATOR	5.71 %
3	OTHERS	8.57 %

4. MINISAT-01 FLIGHT DINAMICS PRODUCTS

The Orbital Analysis of MINISAT-01 Flight Dynamics generated products used for four components of the mission:

The satellite ACS (Attitude Control System), needed to know in every moment its position in order to predict the expected geomagnetic field**.** For this purpose it integrates onboard the Newton equations with the geo-potential field including up to J2 term whose inputs were the Orbital ephemeris periodically uploaded from ground. Initially 2 daily sets of ephemeris were enough. As the orbit decayed and to maintain the precision, this number was progressively increased to a nominal four in the last year. In the late month of the mission, due to the reduced precision of the TLE (two line elements) orbital propagations (see point 5), which forced the ACS to frequently put the spacecraft into safe mode, up to 6 ephemeris sets were uploaded daily.

The Mission Planning and Engineering Team required the orbital events including Eclipses, Ground Contacts, and equator crossings.

The Scientific Team required ephemeris archives in several formats (i.e. Cartesian, keplerian), orbital events and orbit passes over the South Atlantic Anomaly.

The Remote Tracking Station required the Ground Contacts schedule and the pointing vectors for the antennas

All these products were generated for different time periods ranging from one week (maximum precision) to one month. In the later case, they were used just for long term planning and staff resources management.

5. ORBIT DETERMINATION

The software package used for the generation of the orbital predictions was Van Martin's MicroCosm. It is a high precision orbit propagator based in the GEODYN II Version 8609 [2].

The precise orbit estimation can be divided in two problems: The first one is the orbit determination. For this purpose MicroCosm use the Cowell method, this is, the numerical direct integration of the movement equations in rectangular coordinates. The second problem is the estimation of the parameters, this is, the resolution of the relation between the observations (i. e. ranging, doppler etc.) and the computed values in the orbit integration. Microcosm uses a partitioned Bayesian least squares method for the statistical estimation.

Among the multiple formats supported by Microcosm to process the observations the chosen one was the so call Geos-C.

At launch date, FD required only ranging measurements (using the on-board coherent transponder) to achieve the necessary precision in orbital predictions. This made the computation process simpler. In the early months the typical orbit propagation used the ranging measurements of two or three passes chosen from consecutive sequences. Gradually it came into evidence that the ranging measurements have to be scheduled in passes belonging to the same sequence in order to achieve the 2% convergence criteria in the residuals. The convergence was reached in most of the cases in less than 6 iterations. The Fig. 4 shows the last iteration of a ranging propagation.

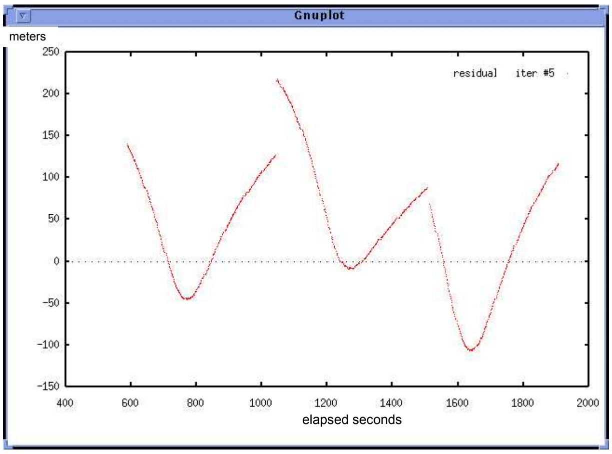

Fig 4: Only Ranging Propagation Residuals

Table 3: Typical Only Ranging Propagation

Number of Observations processed	1043
RMS Residual Value	32,76 m

Occasionally propagations using only doppler measurements were implemented in a similar way.

As the orbit decays its characterization becomes more complex due to the preponderant role played by the atmospheric drag which is the more difficult perturbation to modelize. In this sense, to reach the best precision of MicroCosm, the tables containing solar flux data (essential for the atmospheric density) and the Earth polar axe movement were updated monthly from external agencies like IERS (International Earth Rotation Service) and NOAA (National Oceanic and Atmospheric Administration).

Starting April 1999 and in order to increase the precision of the orbital predictions, ranging and doppler measurements were combined in the propagations. The Fig. 5 shows the residuals of the last iteration of a ranging/doppler propagation using measurements of four passes distributed in three consecutive sequences. It is a good example of reduced residuals.

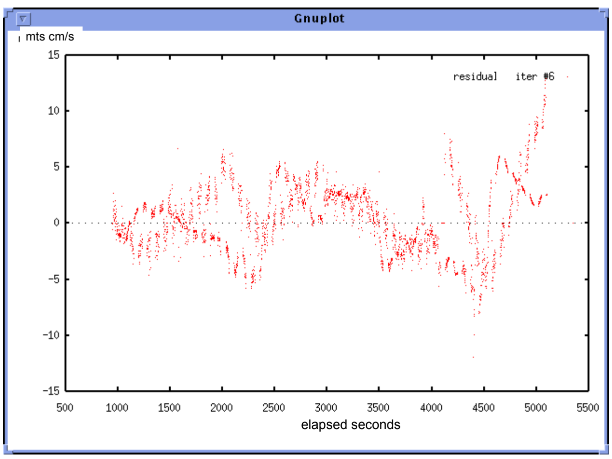

Fig 5: Ranging plus Doppler Residuals

Table 4: Typical Ranging / Doppler Propagation

N. of Ranging Observations processed	1536
RMS Residual Value	4.98 cm/s
N. of Doppler Observations processed	1532
RMS Residual Value	5,07 m

MINISAT-01 operations were extended in mid 1999 beyond its 2 years nominal life. In order to ensure tracking capability during some periods of unavailability of the ground ranging equipment, two methods were envisaged and successfully implemented: use of the 15 m antenna angular measurements and NORAD´s TLE propagations

The TLE archives contain mean keplerian elements. In order to use them as input elements for propagation using MicroCosm, it was necessary to use the SGP4 algorithm [3] to transform them into inertial elements.

The a posteriori assessment of the quality of the propagation made use of the pointing error files provided from Maspalomas with the difference between the program track and the auto track.

Traditionally angular measurements were discarded because they had less precision than the other available observations. However in the last two months, close to the MINISAT-01 re-entry and for not well known reasons, the ranging/doppler measurements started to give unreliable results. Azimuth and Elevation measurements provided by the 15 m antenna working in the auto-track mode with a precision of the positioning sensors of milidegrees were used as observations to make the orbit propagation. The obtained results were good, with very small residuals in azimuth an elevation as can be seen in the Fig. 6. It shows the last iteration of a typical propagation made with measurements of three passes distributed in two consecutive sequences.

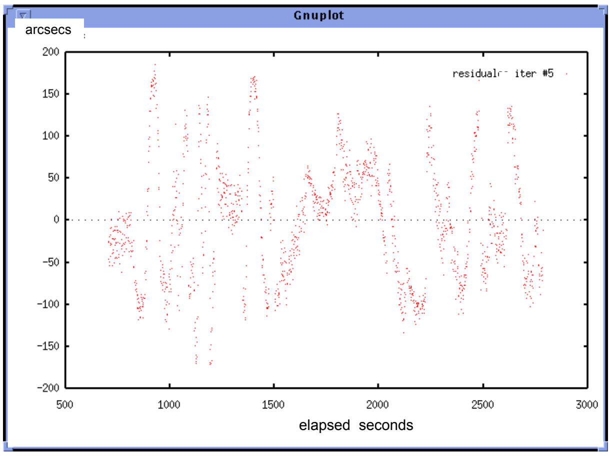

Fig 6: Angular Measurements Propagation Residuals

The Residuals in the Fig. 6 are so small that the system noise can be clearly appreciated.

Table 5: Typical Angular Measurements Propagation

N. of Azimuth Observations processed	805
RMS Residual Value	2.385 arcsec
N. of Elevation Observations processed	805
RMS Residual Value	4.289 arcsec

6. ORBIT EVOLUTION AND RE-ENTRY

As mentioned in the introduction, the initial design of the mission assured the goal of a maximum life of three years. However since all systems seemed to perform perfectly by April 2000 and some of the experiments were still providing valuable data, the mission was extended in a yearly basis. In this sense and since MINISAT-01 had no orbital propulsion, predictions were made in mid 2000 with the Satellite Tool Kit Long term propagator in order know the remaining orbital life. These predictions led to a reentry in late 2012 as can be seen in Fig. 7. Although the accuracy in the long term of this kind of calculations has always to be questioned, 2012 seemed to indicate that the “deadline” for MINISAT-01 was in any case in a very far time horizon.

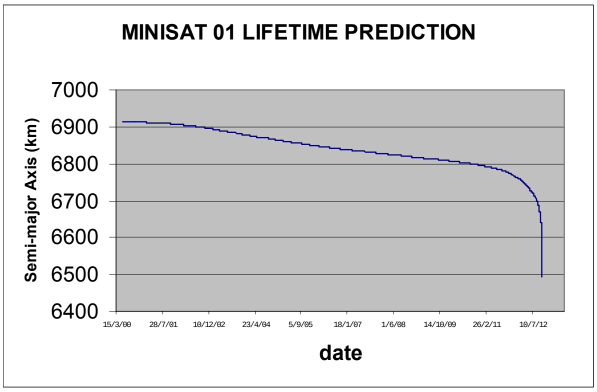

Fig 7: MINISAT-01 Lifetime Prediction in year 2000

However things changed quite a lot. This was due, no doubt, to the particular behavior of the solar cycle # 23. Following the nominal solar activity maximum in mid 2000, like in the previous cycle, a new Sun-spots peak occurred in late 2001 [4] (as can be seen in the Fig. 8), boosting the decay rate of MINISAT-01.

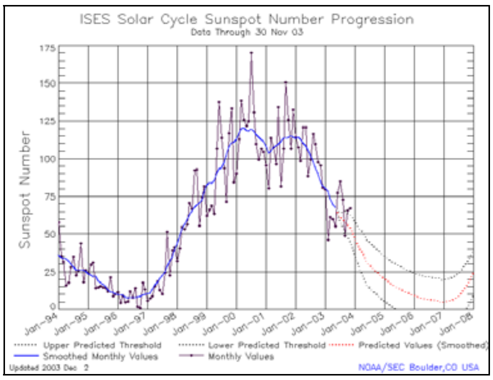

Fig 8: Solar Cycle 23 sunspots number peaks [5]

The chart in the Fig.9 shows the orbital height evolution. It can be seen clearly how there is an inflexion point in the curve that coincides with the second peak of the solar cycle #23.

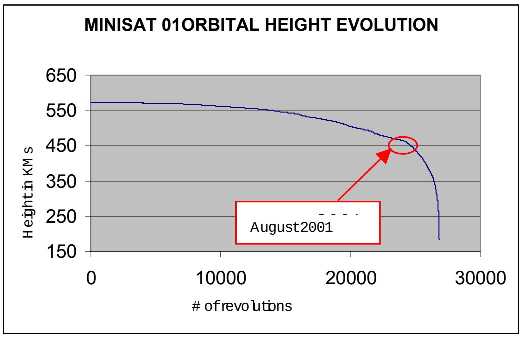

Fig 9: Orbital height evolution

In late December of 2001 lifetime predictions indicated February 2002 as the worst case date for the atmospheric re-entry. In this context the last pass was acquired by Maspalomas RTS on February 14th when the orbital height value was about 311 km. Nonetheless fruitless efforts to track MINISAT-01 were made until 2002 February 20th, when operations officially ended. Uncontrolled re-entry in the atmosphere occurred between the 26th and the 27th of that very month as reported by NORAD (see Fig. 10), having completed 26856 Earth revolutions

Decay: 2002/02/26 23:20:00 28.5 99.9 1.4474
24779 1997-018A SPN MINISAT 01 2002/02/27 04:14:00

PREPARATION DATE TIME: 270414ZFEB02
1. 24779/1997-018A /MINISAT 01 /PAYLOAD / SPN
2. 21 APR 1997
3. REV 26862/ASCENDING /26 FEB 2320Z
4. 28.5 DEG N 99.9 DEG E
5. DECAY WINDOW IS PLUS OR MINUS 05 HOURS.
6. INCLINATION 150.9 DEGREES.
TRAJECTORY PRIOR TO DECAY (DEG):

D/TIME	**057/2205Z**	**057/2220Z**	**057/2235Z**	**057/2250Z**	**057/2305Z**
LAT.	**14.4**	**-14.7**	**-29.2**	**-11.7**	**17.4**
E LONG	**041.0**	**341.9**	**272.4**	**204.3**	**144.8**

7. FINAL REPORT .

MINISAT 01 Decayed: 2002/02/26
1 24779U 97018A 02057.59078704 .09452770 -40714-4 13899-2 0 2594
2 24779 150.9276 318.8937 0000493 218.3461 141.7843 16.33285336268566

Fig. 10 NORAD's MINISAT-01 Re-entry Report

The report gives as re-entry coordinates: latitude 28.5 deg north and longitude 99.9 East deg, but with a great uncertainty window of plus/minus 5 hours covering a great strip of the Earth surface.

7. CONCLUSIONS

A simple small satellite mission operations concept has been shown. The distributed ground segment with three sites connected has proved to be robust and flexible enough as the conditions in the orbit determination forced to change the mission planning concept along the mission life.

A unique tracking station could cope with the entire mission, whit no need of external support, achieving a remarkable record of tracking reliability with only 35 spacecraft passes missed out of the 9070 scheduled. Combination of ranging, doppler and angular measurements from only one geographical location, succeeded in generating good orbital determination data. In the frame of a LEO mission, this data accomplished with the tracking needs and with the precise onboard position for the ACS pointing error requirement of ±3° in Pitch and Roll.

NORAD TLE files have proved to be a good backup method for tracking purposes in the absence of real observations.

The mission has coincided with the solar cycle # 23 maximum, which has had a strong influence in the orbit life time, making hard to predict it in the mean and long tern. This induced a reduction in the last mission extension. Anyway the initial goal of three year was more than exceeded, achieving 4 years and 10 months of total life

References

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