

# **SPOT-1 EARTH OBSERVATION SATELLITE DEORBITATION**

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## **ABSTRACT**

The SPOT Earth observation system received French government approval in 1978. Designed by the French Space Agency CNES, and produced in cooperation with Belgium and Sweden, it comprises a series of low orbit satellites and associated ground facilities for spacecraft control and programming, image reception and production. The SPOT IMAGE company, a CNES subsidiary, is responsible for the distribution of SPOT products.

SPOT-1 was successfully launched on 22-nd February 1986 with a 3 year expected lifetime, and is still operational after 16 years in orbit !

The SPOT-2 satellite was launched on 22-nd January 1990, and SPOT-3 on 26-th September 1993. SPOT-4 was placed into orbit on 24-th March 1998, with the secondary mission VEGETATION and the passengers DORIS, POAM from the Naval Research Laboratory (US), and PASTEL from ESA. SPOT-5, the latest satellite in the family, was successfully launched on 4 May 2002.

SPOT satellites orbit is circular (altitude 822 km at the equator), near-polar(  $i = 98^\circ$ ), sun-synchronous (descending node at 10h30 a.m.), and phased (26 days cycle), with an orbital period of 101.4 minutes.

To respect CNES orbital debris mitigation advice, it has been decided to de-orbit SPOT-1 when SPOT-5 is declared operational. Without corrective action SPOT-1 would likely to remain in orbit for a great number of decades before falling back to Earth...

Unfortunately due to a lack of propellant, a straight atmospheric re-entry is not possible today, but a compromise solution was found to command SPOT-1 to use its residual propellant to maneuver into a lower altitude disposal orbit, from which re-entry could be completed within 15 years.

The paper reports on the technical choices performed during the deorbitation strategy development :

Final orbit features (circular or elliptical), attitude control in transient phase, type and number of maneuvers, and low cost aspect.

It presents the main steps of a joint study between ASTRUM and CNES teams, the consequent modifications on the onboard computer software (LV), and on the ground space mechanics software (OMGS), and finally, the operational scenario.

The main objective of this project is « to preserve space environment », in accordance with the IADC (Inter Agency Space Debris Coordination Committee) recommendations.

## 1. INTRODUCTION

The SPOT Earth observation system received French government approval in 1978. Designed by the French Space Agency CNES, and produced in cooperation with Belgium and Sweden, the system comprises a series of low orbit satellites and associated ground facilities for spacecraft control and programming, image reception and production. The SPOT IMAGE company, a CNES subsidiary, is responsible for the distribution of SPOT products.

SPOT 1-2-4 are still operational. SPOT-3 failed in 1996, having reached the end of its nominal mission lifetime. SPOT-5, the latest satellite of the family, was successfully launched on 4 May 2002.

SPOT system main features are high spatial resolution (down to 2.5 m with SPOT-5 SUPERMODE process), excellent geometric and radiometric quality, stereo-viewing capability, and revisit flexibility.

SPOT satellites orbit is circular (altitude 822 km at the equator), near-polar ( $i = 98^\circ$ ), sun-synchronous (descending node at 10h30 a.m.), and phased (26 day cycle), with an orbital period of 101.4 minutes.

Consequently to a solar panel partial damage (loss of 2/3 of a section/6), and to respect CNES orbital debris mitigation instructions, a joint study between ASTRIUM and CNES teams started last year, to be ready to de-orbit SPOT-1 when SPOT-5 is declared operational.

Unfortunately due to a lack of propellant, a straight atmospheric re-entry is not possible today, but a compromise solution was found to command SPOT-1 to use its residual hydrazine (65kg), to maneuver into a lower altitude disposal orbit (800/550 km elliptical orbit), from which re-entry by atmospheric braking (particularly in perigee), could be completed within 15 years.

This operation needs some modifications on the onboard software (AOCS and propulsion modules), and on the ground space mechanics software (OMGS), reported in this paper.

The main objective of this project is « to preserve space environment », in accordance with the IADC (Inter Agency Space Debris Coordination Committee) recommendations.

## 2. SATELLITE DESIGN

The satellite design is based on early eighties technology or what could be developed within a reasonable risk at that time. Considering the operational aspect of the mission, the satellite equipment is fully redundant, without any single point failures except for elements such as structure.

The SPOT-1 platform performs the many housekeeping functions vital to the success of the mission. These functions are controlled by the onboard computer (OBC) flight software, and include automatic control of all onboard systems when the satellite is not within range of a TTC station, autonomous response capability in the event of a malfunction, and three-axis stabilization.

The three-axis stabilization system, is subject to a number of special requirements dictated by the image acquisition function.

## 3. AOCS DESCRIPTION

The most demanding constraint on the stabilization subsystem, or Attitude and Orbit Control Subsystem (AOCS), is the specified rotation rates which impact directly on image geometric quality. To ensure that the imaging instruments point continuously earthward (geocentric pointing), the spacecraft must rotate about an axis perpendicular to the orbital plane at a rate of precisely one

revolution per orbital revolution (i.e. :  $0.06^\circ/\text{s}$ ). At the same time, other rotational motions must not exceed  $0.001$  degrees/second (see figures 3.1 and 3.2).

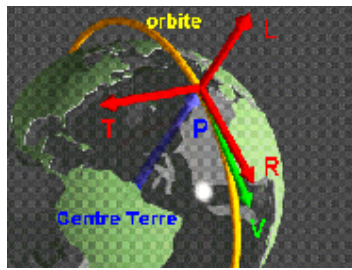


Figure 3.1 : local orbital reference system.

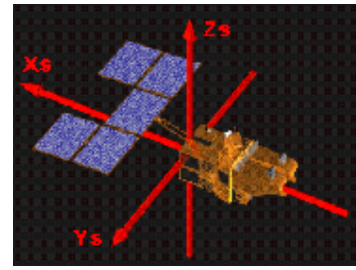


Figure 3.2 : satellite axes.

(with perfect geocentric pointing, we have :  $X_s = -T$  ,  $Y_s = -R$  , and  $Z_s = L$  )

The AOCS uses rate gyros (3), digital Earth and Sun sensors (STD and SSD) as input devices, and hydrazine thrusters, reaction wheels and magnetic torquers as control devices (see figures 3.3 and 3.4).



Figure 3.3 : earth-horizon sensors.



Figure 3.4 : hydrazine thrusters.

The AOCS has several modes of operation as detailed below :

The **fine-pointing mode** (MPF), which is the nominal mode, uses rate gyros, digital Earth sensors, and digital Sun sensors as input devices, the rate gyros measuring rotation rates. Because rate gyros tend to drift, attitude data has to be corrected by external "sightings" provided by earth-horizon and Sun sensors. Horizon-crossing sensors on the earthward panel can readily identify transitions between the cold of deep space and the significantly warmer earth. This information is used to determine the error between the required and actual directions of the earthward panel, allowing the sensors to update the attitude data for the roll and pitch axes. The Sun sensors, on the other hand, provide yaw drift. Twice per orbital revolution, the Sun crosses the plane of the satellite's earthward panel. As the Sun direction in this plane is known with precision, the drift can be readily measured. Once per revolution, a Sun sighting updates the rate-gyro yaw data.

Attitude data from the rate-gyros and the horizon-crossing and Sun sensors are fed to the onboard computer to estimate the satellite's actual attitude and rotation rates. The OBC then generates the appropriate commands for the AOCS actuators (reaction wheels and magnetic torquers) imparting to the spacecraft controlled rotational impulses, so ensuring that the imaging instruments always point directly towards the earth's centre.

The **fine earth-acquisition mode** (MAF2), is required during the attitude acquisition phase, and in the event of a temporary failure of the fine-pointing mode. The actuators are a set of small hydrazine thrusters (3.5 newton). Input data for the determination of the spacecraft's attitude and rotation rates come from the same sensors as for the fine-pointing mode.

The **maneuver modes** (MCC or MCO), are respectively used for small corrections to maintain the satellite in its Sun-synchronous orbit (semi-major axis corrections), and for larger corrections to maintain the orbit inclination. The hydrazine thrusters used for these maneuvers can generate 15 newtons of thrust.

A **safe mode** (MSU) is also available. This is activated only in the event of an onboard hardware or software failure, or a combination of the two. This mode ensures that no damage occurs to the satellite while awaiting the intervention of ground control.

#### 4. DEORBITATION STUDY

The deorbitation study started in June 2001, when the solar panel was partially damaged. « A phase » (mission analysis) and « B phase » (preliminary definition), were closed at the end of 2001, and the chosen strategy was presented in SPOT satellite's exploitation review (REVEX).

In 2002, we shall follow the deorbitation study with the detailed conception, development, and realization phases (C,D,E). Today, an operational rating (QO) is planned in December ending with a specific review (RQO), and the deorbitation operations are expected early in 2003.

The deorbitation study reveals that two different strategies were possible :

A first strategy using MCC maneuvers (a MCC maneuver comprises 2 small symmetrical thrusts on the same orbit). In this case, the final orbit will be a circular orbit (altitude 600 km), and a great number of maneuvers will be necessary...

A second strategy using MCO maneuvers (only 1 long thrust per orbit, near the apogee). Here, the final orbit will be an elliptical orbit (800/550 km), and only 10 or 12 maneuvers will be necessary for a two week duration operation. Each MCO maneuver will have a 1000s duration, and an hydrazine consumption estimated to 5 kg.

We have chosen the second strategy (MCO maneuvers), and this for several reasons. First, the better final orbit (inferior time to re-entry - see figure 4.1), the technical feasibility, and the short duration (low cost aspect).

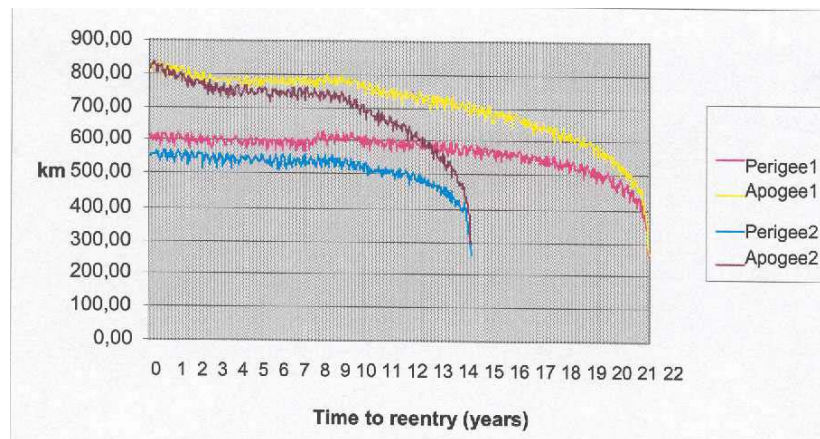
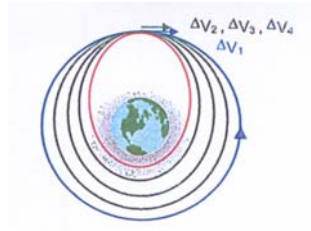


Figure 4.1 : Time to re-entry.

To summarize, the chosen strategy consists in lowering the orbit perigee with multiple apogee burns (MCO maneuvers), accompanied by ground-based check-out (see figure 4.2).



**Figure 4.2 : multiple apogee burns strategy.**

## 5. ONBOARD MODIFICATIONS

### SOFTWARE MODIFICATIONS (AOCS MODULE)

With the chosen strategy, thrusts (10 or 12 in MCO mode, using Z-/Y+ and Z+/Y+ thrusters) would have a fixed duration of a thousand seconds, and we should perform an orbit determination after two successive maneuvers.

The deorbitation study reveal that the MAF2 mode will be the waiting mode between two orbital maneuvers, and that the MPF mode will be used only for MAF2 to MCO transitions, without changing the existing software.

This, because the MAF2 mode has a better strength than the MPF mode, especially at final altitudes (< 600 km), where reaction wheels would be saturated. And it needs minor modifications (gains or coefficients adjust only), before the operation and probably after each orbit determination phase.

However, this AOCS modes sequence (MAF2 – MCO – MAF2), presents an inconvenience : hydrazine consumption in MAF2 mode, evaluated to 0.3 - 0.8 kg /day depending on altitude.

We plan only a minor modification on the OBC software, which consist in inhibiting the accelerative Z thrusters ( i.e. Z-/Y- and Z+/Y- thrusters) in MAF2 mode, to avoid residual accelerations.

### HARDWARE MODIFICATIONS (PROPULSION SUBSYSTEM)

The propulsion subsystem is composed of two separate propellant tanks, with two independent propulsive branches. We plan to interconnect the tanks before the deorbiting operations.

This presents several advantages :

- residual propellant (65 kg of hydrazine) better management, minimizing the unusable part.
- avoid pressures rebalancing between two maneuvers.
- pressure measurement better accuracy (pressure switch redundancy).
- procedure validation for the others satellites.

We have only to open two latching valves, with a  $\Delta P < 2.5$  bar (differential pressure condition).

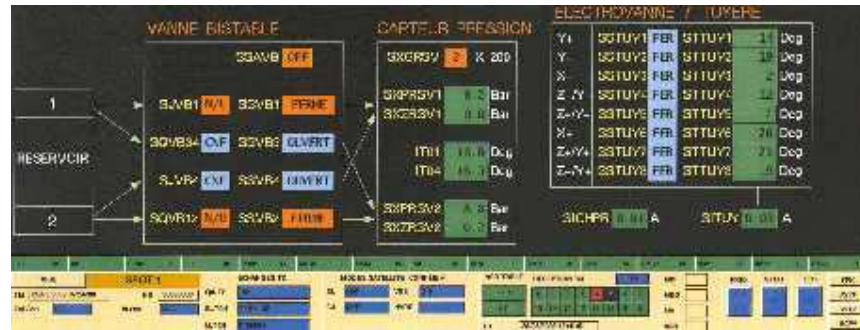


Figure 5.1 : Propulsion subsystem synoptic.

## 6. GROUND SPACE MECHANICS SOFTWARE MODIFICATIONS

The ground space mechanics software (OMGS) main functions are :

- orbit determination, using “tracking” of TTC stations.
- orbit control, programming orbital maneuvers (MCC and MCO).
- AOCS management, producing space mechanics commands (TCH MECSPA).

“Tracking” involves distance measurement (MDI), doppler measurement (MDO), and angular measurement (MA).

In nominal exploitation, we perform two orbit determinations per day (morning and afternoon), and we program a MCC maneuver (altitude correction) approximately every month, function of solar activity. A MCO maneuver (inclination correction) is planned every year. These operations are executed with a high degree of automation and security.

The ground space mechanics software has been designed for orbits closed to the SPOT reference one, and consequently, it's not consistent with the deorbitation operations.

The solution is to use the Orbit determination Operational Centre (COO), another operational entity of Toulouse Space Centre with which software is more adapted, during this critical phase. The COO will perform orbit determinations, and TTC stations designation, producing passages forecast.

## 7. OPERATIONAL SCENARIO

At the end of the deorbitation study, the operational procedures and the onboard modifications will be validated on the satellite simulator. A specific review (RQO), will close this operational rating.

After final decision of CNES directors to deorbit SPOT-1, the deorbitation operations will start :

A first MCO maneuver (calibration maneuver), a first orbit determination phase, and then a chaining of MCO maneuvers and orbit determination phases to the hydrazine exhaustion.

Finally, the satellite passivation.



## 8. LOW COST ASPECT

The deorbitation project keywords were better and cheaper.

We have respected this low-cost constraint for the study and development phases (using the existing software with minor modifications only), but also for the operational phase (short duration operation).

## 9. CONCLUSION

Faced with the orbital debris problem, CNES has defined rules for its future projects (see “Security requirements – Space debris” document). These requirements can’t be directly applied to SPOT-1 satellite which was developed previously.

However, CNES, as far as possible, will try to apply its recommendations and its defended positions at international level. Particularly, it will respect the rule which limits to 25 years the orbital lifetime after the end of operational mission.

SPOT-5 was successfully launched on 4-th May 2002 and is now operational. So, we plan the deorbitation operations reported here, early in 2003...



Figure 9.1 : SPOT constellation, awaiting SPOT-1 deorbitation (artist view).

## ACKNOWLEDGEMENT

Considering the number of people that over the years contributed to the success of SPOT system, the list of acknowledgements would cover many more pages than available there.

Lately the SPOT operations and space mechanics teams, in CNES Toulouse. Special thanks are due to Fernand ALBY (CNES space debris activity responsible), to the SPOT team in ASTRIUM Toulouse, and to Caroline.

## REFERENCES

CNES Security requirements – Space debris document ( ref. MPM-51-00-12 ).

IADC Space debris mitigation guidelines.