

CRYOSAT-2: FROM LEOP TO ACQUISITION OF THE REFERENCE ORBIT

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Abstract: *The Cryosat-2 satellite was successfully launched on a Dnepr rocket on the 8th of April 2010 from the Baikonur Cosmodrome, Kazakhstan. The ESA Earth Explorer mission Cryosat is dedicated to the precise monitoring of the changes in the thickness of marine ice floating on the polar oceans as well as variations in the thickness of the vast ice sheets that overlie Greenland and Antarctica.*

Two months after launch Cryosat-2 acquired its reference orbit after the execution of several sequences of manoeuvres. The scope of this paper encompasses two main topics: firstly it recapitulates the analysis started during the preparation for the launch of the first Cryosat satellite in order to design the orbit control strategy for this mission given the thrust limitations on board the satellite, and secondly it details the generation of the final reference orbit for Cryosat-2 and the operational aspects of the orbit determination and control activities from the launch to the final acquisition of the reference orbit.

Keywords: *Cryosat, Earth Observation, polar orbit, reference orbit, LEOP operations.*

1 Introduction

Four and a half years after the loss of the first Cryosat satellite due to a launch failure in October 2005 the new Cryosat-2 satellite, with a number of improvements, was launched on 8 April 2010 from the Baikonur Cosmodrome on a Dnepr launch vehicle.

The CryoSat mission provides data to determine the precise rate of change in the thickness of the polar ice sheets and floating sea ice. It is capable of detecting changes as little as 1 cm per year. The information from CryoSat mission will lead to a better understanding of how the volume of ice on Earth is changing and, in turn, a better appreciation of how ice and climate are linked.

This paper covers two major objectives: The first one is to recapitulate the analysis of the possible ways to generate a suitable reference orbit for the Cryosat mission, which was carried out in the frame of the preparation for the launch of the first Cryosat satellite. The second objective is to present how this analysis has been applied to the generation of the reference orbit for the Cryosat-2 satellite together with a description of the operational activities on the Flight Dynamics Orbit Determination and Control (FD OD&C) side that led to the acquisition of the reference orbit in June 2010.

The orbit control strategy for Earth Observation missions is typically based on a reference orbit that has to be followed within a predefined dead-band. This is the case for the ESA Earth Observation missions ERS-2 and Envisat, which follow sun-synchronous, polar orbits with a ground-track repetition cycle. The orbit control strategy for Cryosat is also based on the concept of a reference orbit and a dead-band but the reference orbit has some special and unique features. This is driven by the fact that Cryosat cannot perform significant out-of-plane manoeuvres and therefore does not allow to control the sub-satellite points in the traditional way. This topic was subject of an extensive analysis during the preparations for the launch of the first Cryosat satellite.

The generation of the final reference orbit for the first repetition cycle of the Cryosat-2 satellite was completed after the conduction of the LEOP operations. During the three days of the Cryosat-2 LEOP, the FD OD&C team focused on assessing the dispersion of the satellite orbit at injection and performing an orbit determination every twelve hours based on the tracking data coming from the Ground Segment Network and the DORIS instrument. As soon as the operational orbit of Cryosat-2 was stable and consistent with all the sets of tracking data available and before starting the generation of the reference orbit, an assessment of the required altitude evolution of the reference orbit pointed out that the requirement of flying a frozen orbit could be relaxed with a consequent positive impact on the load of operations and the fuel consumption.

The drivers for the design of the sequence of in-plane manoeuvres aiming to start the first control cycle around the reference orbit were:

- Minimization of the number of slew manoeuvres.
- Change of the eccentricity vector towards the target eccentricity evolution.
- Characterization of the propulsion system for a variety of manoeuvre sizes.

2. Orbit control for Earth Observation missions: the classical approach vs. the Cryosat case

The orbit control strategy for Earth Observation missions is typically based on a reference ground-track that has to be followed within a predefined dead-band. This operational requirement is driven by payload instruments (SAR for instance) which are designed to perform periodical observations of certain locations on the Earth surface. The generation of such a reference ground-track is achieved by producing a so called reference orbit; its projection on the Earth surface model gives the desired reference ground-track. The generation of a reference orbit provides, as an additional operational advantage for a mission, the possibility to perform long term mission planning.

The nominal orbit control strategy for the ESA Earth Observation missions ERS-2 and ENVISAT is based on sun-synchronous reference orbits with a repeat pattern, with a fixed mean local solar time of the ascending node (22:30 and 22:00 respectively) and frozen eccentricity. The deviation of the S/C orbit from the reference orbit is measured in terms of perpendicular distance in ground-track and in deviation of the Local Time of the Ascending Node (LTAN).

These reference orbits are obtained by propagating an initial state vector assuming the non-spherical Earth gravity as the only relevant perturbation and iterating on the initial state to achieve the required closure of the ground track and a frozen eccentricity. The drag force and the gravitational acceleration due to the Sun and the Moon are not included in the generation of the reference orbit.

The orbit control is achieved later on by executing two types of manoeuvres in order to keep the distance to the ground-track and the LTAN within a predefined dead-band:

- In-plane manoeuvres to change the semi-major axis (and eccentricity) which allows to control the ground track deviation from the reference orbit at the Earth Equator. The eccentricity is controlled around a frozen eccentricity vector.
- Out-of-plane manoeuvres to correct the inclination, allowing to control the deviation from the reference ground-track at high latitudes as well as the drift of the ascending node and its local time.

The Cryosat orbit control is different from the other ESA Earth Observation satellites described above because:

- The propulsion system does not allow the execution of significant out of plane manoeuvres.
- There is no requirement on the LTAN evolution. No Sun-synchronism is required.
- The intended repeat cycle is very long compared to those of ERS-2 and Envisat.

The parameters describing the Cryosat reference orbit are shown in Table 1.

Table 1. Cryosat reference orbit main parameters

Cryosat reference orbit	
Type	Near Polar Repeat Ground-track
Inclination	92 deg
LTAN	Not controlled.
Cycle length	5344 orbits
Cycle duration	369 nodal days ¹

Since only in-plane manoeuvres are possible, the perturbations causing changes to the orbital plane have to be included in the generation of the reference orbit i.e. third-body perturbations due to Sun and Moon have to be included. These perturbations do not have the same periodicity as the repeat pattern, which means that under these conditions it is impossible to create a reference orbit with a repeating ground-track in the traditional sense.

A reference orbit generated in the classical way for Cryosat would not show a homogeneous distribution of longitudes at the node crossings, since there would be a non-constant drift of the right ascension of the ascending node induced by the inclination drift. Such a reference orbit does not meet the science requirements of the Cryosat mission because a homogeneous distribution of longitudes at the node crossings is required in order to have the right density of ground-track crossovers.

This effect is compensated by designing a reference orbit with a non-constant orbital period. This strategy means, in other words, to advance or delay the Equator crossings times in such a way that a homogeneous distribution of nodes is achieved. The changes in orbital period are achieved by introducing artificial low-thrust accelerations as additional “perturbations” in the generation of the reference orbit as detailed in [1]. The generation of the first cycle of the Cryosat reference orbit will be described in section 3.3.

3. Cryosat-2 Orbit determination and Control Operations

Cryosat-2 was launched on the 8th of April 2010 at 13:57:00 UTC and separated from the upper stage at 14:13:28.2 UTC. The achieved orbit after the separation of Cryosat-2 had a semi-major axis approximately 0.16 km above the nominal reference value and an inclination offset of +0.023 degrees with respect to the launcher target. During the first six hours of LEOP the radiometric tracking data collected from the ground segment infrastructure with S-band stations at Malindi (Kenya), Troll (Antarctica), Svalbard (Norway) and Kiruna (Sweden) were processed and used to perform orbit determination. As a result of these orbit determination steps, stations were kept informed about the time delay to be expected at the acquisition of signal. The stations operated in this way for the first six hours after separation; afterwards the orbit solution was used to generate new station pointing elements for the subsequent passes.

3.1 Eccentricity analysis after injection

The evolution of the mean eccentricity vector after injection is shown in Figure 1. It librates around the frozen eccentricity vector with the argument of perigee evolving between 0 and 360 deg and a variation in module of almost three orders of magnitude. This determines the evolution of the satellite altitude above the model geoid, shown in Figure 2.

¹ A nodal day is defined as the time needed for a given point on the Earth surface to cross again the rotating orbit plane, namely 86221.25 seconds for the Cryosat reference orbit.

The mean frozen eccentricity vector for the Cryosat-2 reference orbit is $(-0.0000013, 0.0013060)$ with argument of perigee close to 90 deg. The total Delta-v needed to bring the eccentricity vector to its frozen value by performing in/against flight direction manoeuvres was 5.2 m/s. However, after evaluating the need of a frozen eccentricity together with the Cryosat-2 Project and Industry teams, the following resolution was adopted: a correction of the eccentricity vector that ensures an evolution of the S/C altitude above the geoid and altitude change rate within specific margins that guarantee the proper functioning of the key instrument on board: SIRAL.

A correction of the mean eccentricity vector accounting for a total delta-v of 1.3 m/s leads to a S/C altitude evolution profile within the requested range of altitudes as it can be seen in Figure 3, with special attention paid to the latitudes of greater interest for the Cryosat-2 ice mission. During operations this chosen eccentricity target was called the “quarter-frozen eccentricity”, since the needed delta-v for this orbit is a quarter of the one needed for the full frozen orbit (Figure 1). This term will be used in what follows to refer to the agreed eccentricity vector for the reference orbit of Cryosat-2. It was also decided to aim at further refinement of the eccentricity evolution when optimizing the routine orbit control maintenance manoeuvres.

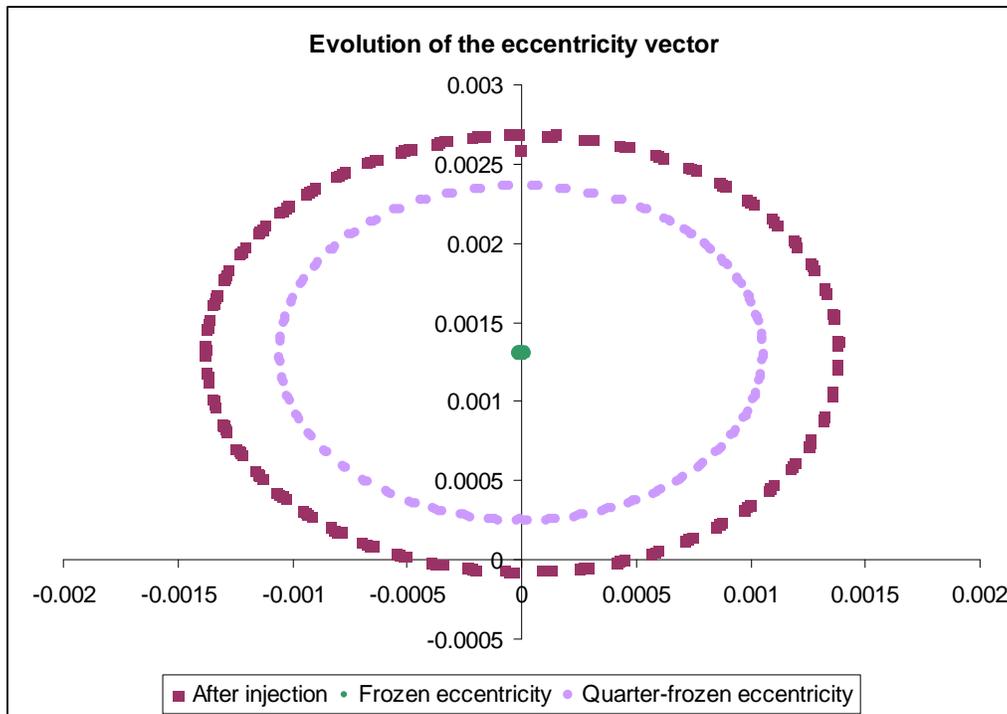


Figure 1. Evolution of the eccentricity vector for the reference orbit of Cryosat-2 under different working assumptions

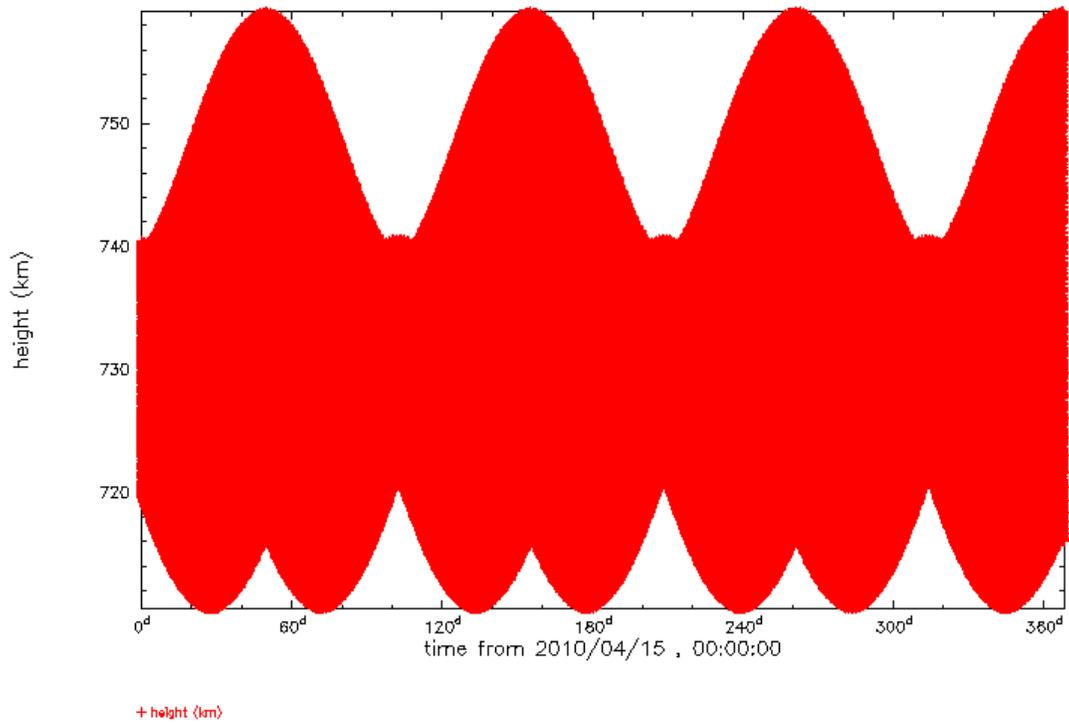


Figure 2. Evolution of the S/C altitude above the geoid for the Cryosat-2 reference orbit with no eccentricity correction after injection

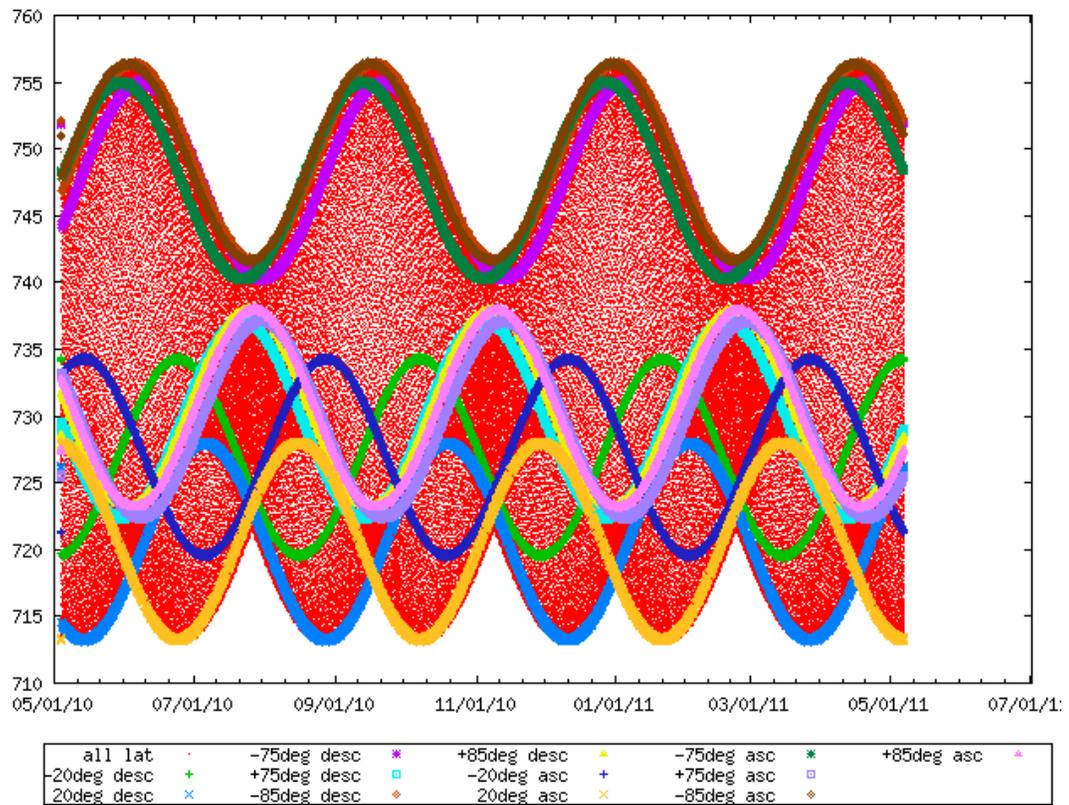


Figure 3. Evolution of the S/C altitude above the geoid for the Cryosat-2 reference orbit with quarter-frozen eccentricity

3.2 Eccentricity correction manoeuvres

Between the 2010/05/03 and the 2010/05/28 three sequences of in-plane manoeuvres in and against the flight direction were performed on Cryosat-2 in order to correct the eccentricity vector and get it nearer the quarter-frozen value.

The total delta-v required to achieve this target was 1.3 m/s in the along-track component. Since the semi-major axis at injection was 0.16 km above the reference, the delta-v had to be split in burns in and against the flight direction as follows:

Delta-v in the flight direction (positive sign in Table 2): 0.608 m/s

Delta-v against the flight direction (negative sign in Table 2): 0.692 m/s

The difference of 0.084 m/s corresponds to the delta-v needed to acquire the target reference semi-major axis.

3.2.1 Manoeuvre sequence design

The main drivers for the design of the sequence of manoeuvres were the following:

Minimization of the number of slews:

The Cryosat thruster configuration consists of two cold redundant branches of eight 10 mN Attitude Control and two 40 mN Orbit Control thrusters per branch. The 4 Orbit Control Thruster (OCT) are accommodated on the aft side of CryoSat such, that their thrust vectors are parallel to the x-axis (almost in the flight direction) of the satellite control coordinate frame. The OCTs are fired in pairs and produce a force into the flight direction and no net torque around any of the three principal axes.

For manoeuvres against the flight direction the satellite has to be turned by a 180 deg slew manoeuvre around its z-axis. This manoeuvre will last about 1800 seconds plus a setting time of 50 to 180 seconds.

The total number of slews to be performed during the whole manoeuvre sequence had to be minimized to the maximum extent possible. Therefore the switching between orbit manoeuvres in the flight direction and against the flight direction is kept to a minimum.

Efficiency loss due to spread of the burns:

As mentioned above, the thrust force achieved by the Cryosat-2 propulsion system is 80 mN. For a satellite mass of 725 kg the resulting acceleration is 0.00011 m/s^2 . Assuming the following efficiency for eccentricity correction:

$$\frac{2\text{Sin}\left(\frac{\alpha}{2}\right)}{\alpha}$$

where α is the spread angle in radians for the burn, a 5% efficiency loss corresponds to a manoeuvre spread angle of 63 deg approximately, which means a delta-v of 0.120 m/s. This efficiency loss was considered acceptable and therefore the size of the manoeuvres should not exceed 0.120 m/s.

Characterization of the propulsion system:

The operational manoeuvre implementation for Cryosat follows a procedure that involves the OD&C software devoted to the manoeuvre optimization and the Command Generation software, which produces a realistic acceleration profile prediction based on the ground measured characteristics of the propulsion system.

The Cryosat propulsion system is equipped with single stage pressure regulators for feeding the thrusters with constant pressure (more information about the Cryosat2 thrust model can be found in [2]). Due to the lack of in-flight experience about the workings of such pressure regulators, a series of burns of increasing size was agreed to be performed initially in order to understand their behaviour. Additionally, performing manoeuvres in this manner minimizes the effect of the manoeuvre uncertainty on the orbit.

The first manoeuvre performed after the LEOP was a 60 seconds test manoeuvre to assess the overall behaviour of the propulsion system, executed on the 2010/04/15. The burn took place within visibility of the ESA ground station in Kiruna so that parameters like gas pressure, temperature and thrusters on-times could be monitored in real time.

After the test manoeuvre the target for the main manoeuvre sequence was set to perform the 95% of the total delta-v needed to correct the eccentricity evolution. The required change in semi-major axis (0.084 m/s) to acquire the reference period could be absorbed by the eccentricity correction manoeuvres (1.3 m/s). The manoeuvres were arranged in three sub-sequences, each of them to be implemented and executed within a maximum of five days, allowing the retrieval of radiometric tracking data between two consecutive burns for calibration purposes.

Sub-sequence #1 was executed from 2010/05/03 to 2010/05/06 with a total of 5 burns against the flight direction with increasing durations of 120, 300, 600, 900 and 1500 seconds. The total predicted delta-v for sub-sequence #1 was 0.326 m/s against the flight direction. Two slews, one at the beginning and one at the end of the sub-sequence had to be performed.

Sub-sequence #2 was executed from 2010/05/18 to 2010/05/21 with a total of 7 burns in the flight direction with equal delta-v size of 0.084 m/s. The total predicted delta-v for sub-sequence #2 was 0.588 m/s in the flight direction.

Sub-sequence #3 was executed from 2010/05/27 to 2010/05/28 with a total of 4 burns against the flight direction, three of them with delta-v size of 0.084 m/s and the last one with a delta-v of 0.125 m/s. The total predicted delta-v for sub-sequence #3 was 0.377 m/s. Two slews at the beginning and at the end of the sub-sequence had to be performed.

The final burn to complete the remaining 5% of the total delta-v to acquire the quarter frozen eccentricity evolution and the reference period was split into two manoeuvres in the flight direction. The objective was to avoid having to perform an extra manoeuvre against the flight direction (with the consequent two extra slews) due to a possible over-performance of this final manoeuvre. The split had to take into account the information coming from the calibration of the manoeuvres executed up to that point in time in order to have a figure for the maximum expected over-performance.

3.2.2 Implementation and performance of the eccentricity correction manoeuvres

The only manoeuvre parameter left for optimization before the operational implementation of the manoeuvre sequences was the argument of latitude (Position sur l'Orbite, PSO) of every manoeuvre. The OD&C software iterates to find the optimal change in the osculating eccentricity vector that leads to the evolution of the mean eccentricity vector over complete 2 days sub-cycles to be closer to the frozen eccentricity vector.

The performance of the first test manoeuvre and the subsequent three sequences of manoeuvres are shown in Table 2. At the end of the manoeuvre sequence#3 the total calibrated delta-v had been:

Calibrated delta-v in the flight direction:	0.584 m/s
Calibrated delta-v against the flight direction:	0.697 m/s

Table 2. Manoeuvre execution times and performance factors

Manoeuvre start time (UTC)	Duration (sec)	Optimized PSO (deg)	Delta-v in m/s			Performance	
			Radial	Along-track	Cross-track		
2010/04/15-17:46:30.000	60	195.21	0.0	0.0066	0.0		Test mano
			0.0	0.0055	0.0	0.840	
2010/05/03-17:54:31.000	120	195.21	0.0	-0.0115	0.0		Manoeuvre sequence #1
			0.0	-0.0114	0.0	0.992	
2010/05/04-00:29:43.000	300	194.424	0.0	-0.0286	0.0		
			0.0	-0.0281	0.0	0.982	
2010/05/04-18:37:59.000	600	191.811	0.0	-0.0568	0.0		
			0.0	-0.0564	0.0	0.992	
2010/05/05-17:43:41.523	900	188.406	0.0	-0.0859	0.0		
			0.0	-0.0843	0.0	0.981	
2010/05/06-18:26:05.157	1500	185.032	0.0	-0.1428	0.0		Manoeuvre sequence #2
			0.0	-0.1402	0.0	0.982	
2010/05/18-00:42:22.963	899	326.51	0.0	0.0840	0.0		
			0.0	0.0838	0.0	0.997	
2010/05/18-04:00:41.618	898	326.02	0.0	0.0840	0.0		
			0.0	0.0832	0.0	0.991	
2010/05/18-23:50:36.180	898	323.26	0.0	0.0840	0.0		
			0.0	0.0828	0.0	0.986	
2010/05/19-03:08:55.087	898	322.763	0.0	0.0840	0.0		Manoeuvre sequence #3
			0.0	0.0823	0.0	0.980	
2010/05/20-00:38:04.624	898	319.784	0.0	0.0840	0.0		
			0.0	0.0820	0.0	0.976	
2010/05/20-03:56:23.969	898	319.270	0.0	0.0840	0.0		
			0.0	0.0816	0.0	0.972	
2010/05/20-23:46:19.859	913	316.487	0.0	0.0840	0.0		
			0.0	0.0827	0.0	0.984	
2010/05/27-00:27:11.400	932	128.106	0.0	-0.0840	0.0		Manoeuvre sequence #3
			0.0	-0.0848	0.0	1.010	
2010/05/27-03:45:24.221	932	127.174	0.0	-0.0840	0.0		
			0.0	-0.0834	0.0	0.993	
2010/05/28-01:14:23.784	939	123.657	0.0	-0.0840	0.0		
			0.0	-0.0840	0.0	1.000	
2010/05/28-04:27:45.029	1397	118.976	0.0	-0.1250	0.0		
			0.0	-0.1247	0.0	0.998	
2010/06/15-03:01:57.751	762	230.506	0.0	0.0680	0.0		Acquisition
			0.0	0.0682	0.0	1.003	
2010/06/18-01:14:01.173	39	9.946	0.0	0.0035	0.0		
			0.0	0.0033	0.0	0.955	

The evolution of the 2 days averaged eccentricity vector from injection is shown in Figure 4. The effect of the eccentricity correction manoeuvres on the evolution can be observed starting 26 days after launch. The target is almost completely achieved at the end of manoeuvre sequence#3. The remaining delta-v to achieve the quarter-frozen eccentricity was 0.024 m/s to be executed in the flight direction. This delta-v was executed together with the burn to acquire the reference ground-track, after generation of the reference orbit.

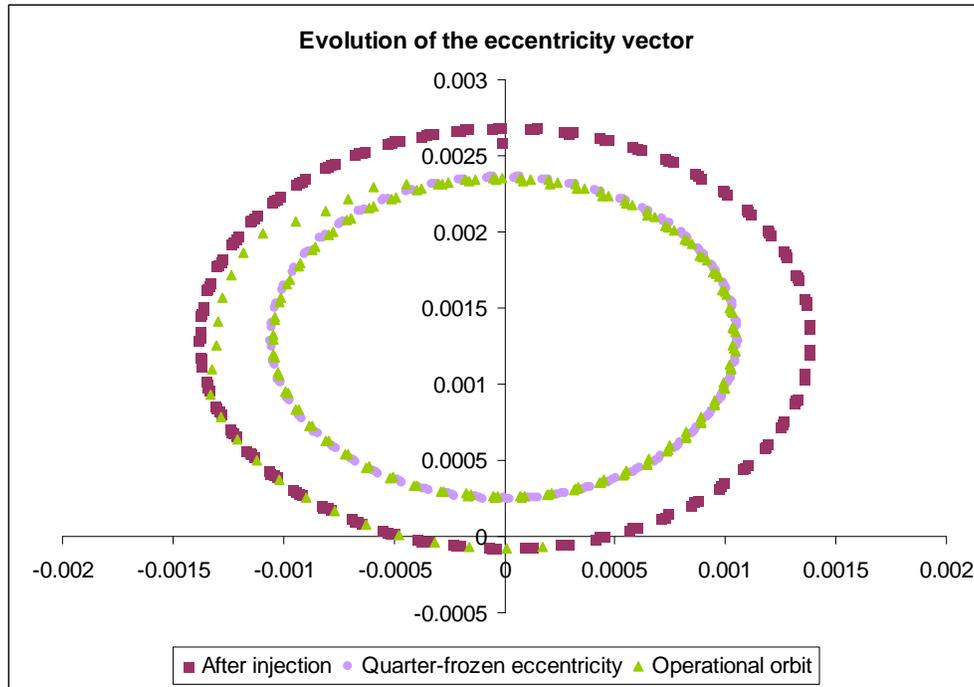


Figure 4. Evolution of the eccentricity vector of the Cryosat-2 orbit before and after the execution of the orbit control manoeuvres

3.3 Generation of the first repetition cycle of the reference orbit

The procedure to generate the first 369 nodal days repetition cycle of the reference could have been started after knowing the inclination after injection and the target for the eccentricity. However, it was decided to start only after the bulk of the eccentricity correction manoeuvres had taken place i.e. after manoeuvre sequence#3. This way, no additional manoeuvres to start and stop a drift of the ground-track deviation at the Equator towards an earlier-defined reference ground-track were needed.

The generation of the first cycle of the reference orbit and the reference ground track is described in the next subsections:

3.3.1 Generation of a pseudo reference orbit: closed ground-track.

An initial state vector was retrieved from the operational predictions at the foreseen epoch for the final acquisition manoeuvres. It was propagated assuming as main orbital perturbations the non-Spherical Earth gravity field to a (36,36) expansion and Sun and Moon gravity effect.

Iterating on the semi-major axis of this initial state, a closed ground-track covering 369 nodal days and 5433 orbit revolutions was achieved. Here closed ground-track only means that the first ascending node crossing was close within 0.2 km to the last one. The eccentricity vector evolution for the orbit generated through this iterative process is the quarter-frozen eccentricity.

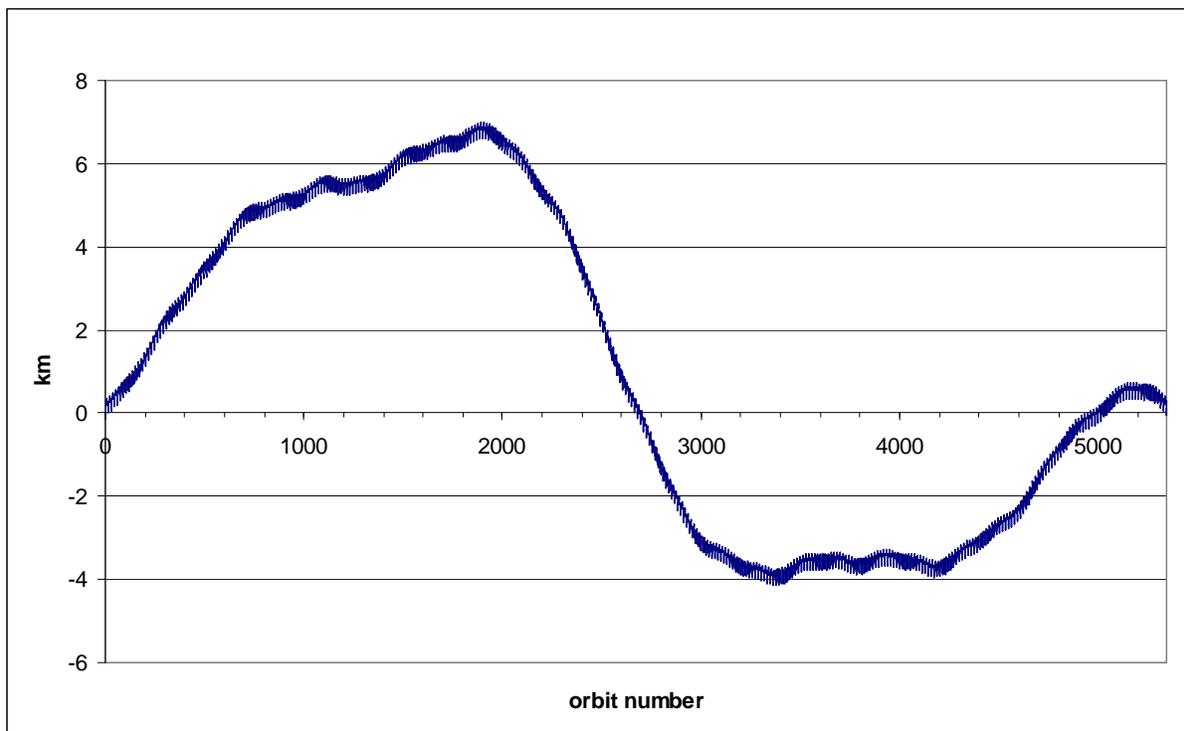


Figure 5. Deviation of the sub-satellite point at the ascending node crossing from the equidistant node crossing distribution (positive to the East)

3.3.2 Generation of a “fictitious” low-thrust acceleration profile.

The drift of the line of nodes in the orbit propagated in 3.3.1 is not linear due to the change in inclination induced by the third body perturbations. Consequently the ascending node crossings are not homogeneously distributed. In an equidistant node crossing distribution the distance between two adjacent node crossing longitudes should have been $1/5344$ of the Earth Equator circumference, i.e. 7.5 km. For every ascending node, the value of longitude assuming an equidistant distribution was subtracted from the longitude of the pseudo-reference orbit described in 3.3.1. The result is shown in Figure 5. As demonstrated in [1], if this longitude pattern is matched by a sequence of parabolic curves, the coefficients of those parabolas will give the acceleration profile needed to generate a reference orbit with homogeneous node crossings. The result of this match is shown in Figure 6 and Table 3.

The artificial acceleration derived in this way for the reference orbit generation is less than the expected air drag level such that this reference orbit can be followed with a standard in-plane orbit control strategy. An important consequence is that following a reference orbit designed with this new approach does not imply additional fuel consumption, but only a re-distribution of the fuel consumption during a repeat cycle.

3.3.3 Propagation of the acceleration profile, generation of the final reference orbit.

The state vector from the orbit generated in 3.3.1 at the first ascending node was propagated over the first repetition cycle assuming the same perturbation as in 3.3.1 and the acceleration profile obtained in 3.3.2. As expected, the deviation of the longitude at the ascending node crossings of this orbit with respect to a homogeneous distribution shows sufficiently small differences, below 0.3 km as it can be observed in Figure 7. This is the first cycle of the reference orbit for Cryosat-2 and its

projection on the geoid is the corresponding reference ground-track. This process has to be carried out every year approximately for every repetition cycle.

Table 3. Artificial constant acceleration profile

Start time (UTC)	km/s ²
2010/06/14-01:16:31.019	0.00000000D-01
2010/07/19-04:41:49.494	-2.23000000E-12
2010/08/15-18:12:19.679	2.50000000E-13
2010/10/12-15:22:21.402	-3.31000000E-12
2010/12/04-20:04:59.276	2.73000000E-12
2011/02/07-11:19:09.197	-2.50000000E-12
2011/02/25-17:34:05.122	6.50000000E-12
2011/03/05-15:45:06.374	-4.50000000E-12
2011/03/20-19:34:53.745	7.20000000E-12
2011/03/26-07:53:00.404	1.90000000E-12
2011/05/08-01:13:15.023	-2.90000000E-12
2011/06/17-08:40:32.901	End of cycle 1

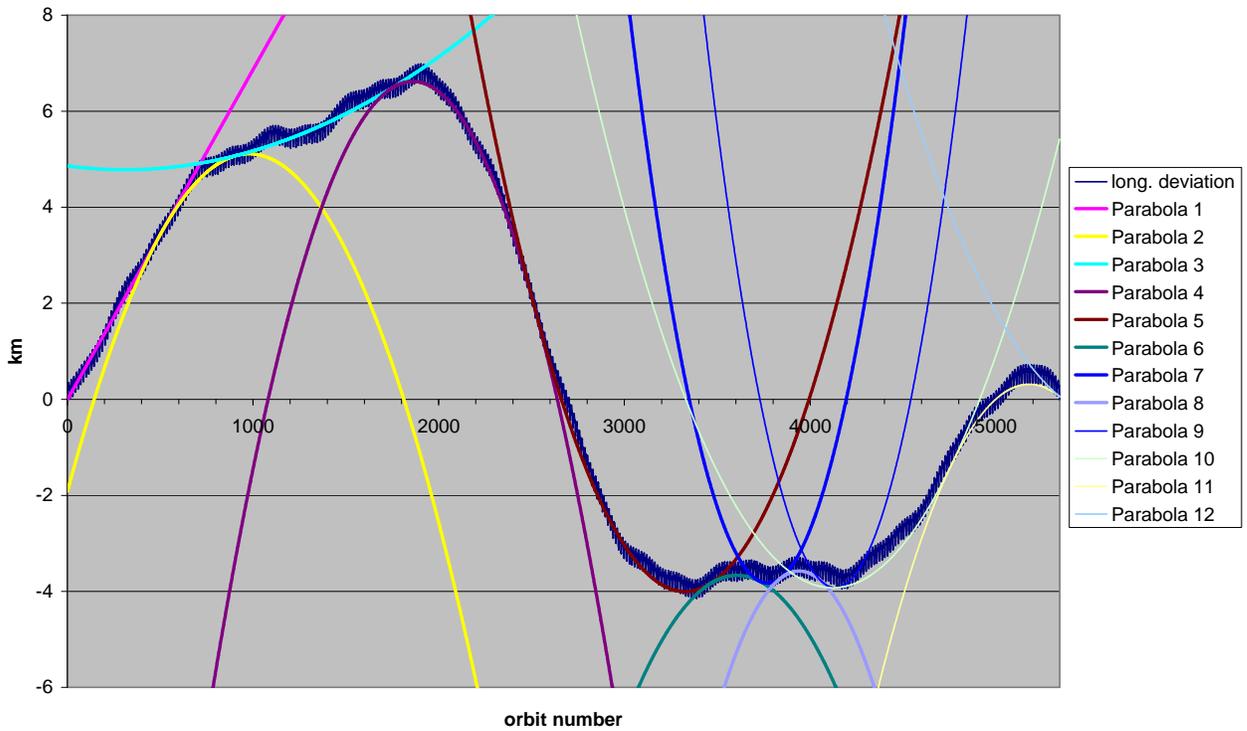


Figure 6. Fit of parabolic curves to the nodes longitude distribution pattern

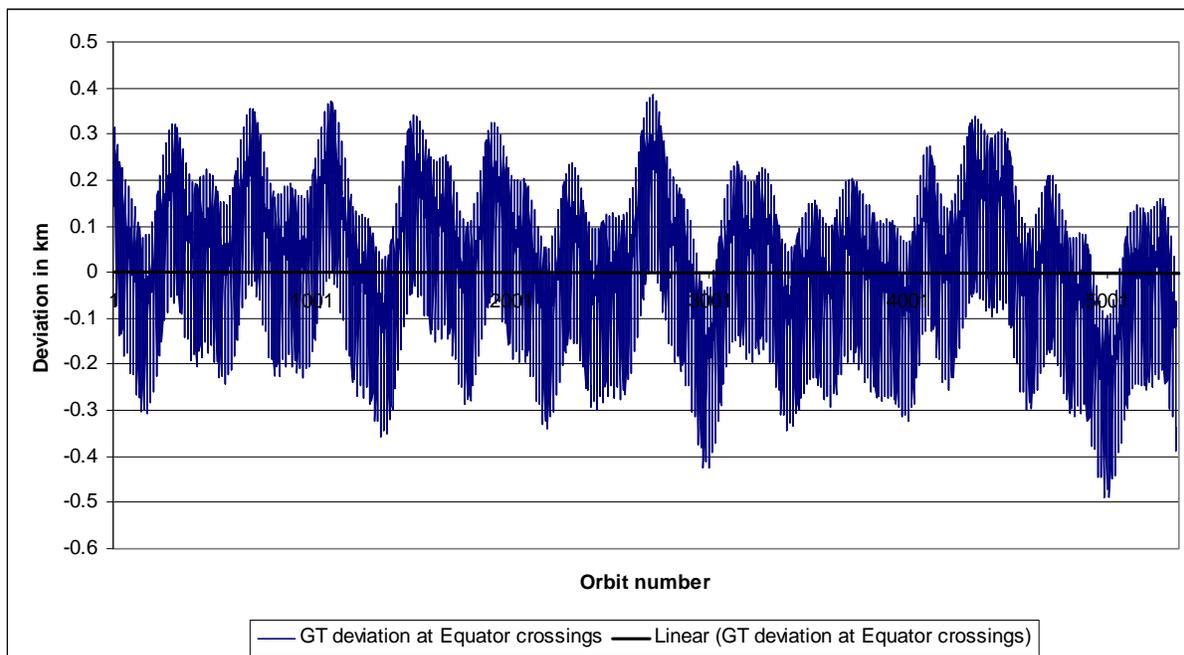


Figure 7. Deviation of the sub-satellite point at the ascending node crossing wrt an equidistant node distribution (positive to the East) for the final cryostat reference orbit (first cycle)

3.4 Acquisition of the reference orbit

After the generation of the reference orbit, the Cryosat-2 orbit was drifting approximately 1.1 km per day eastwards with respect to the reference ground-track, due to the semi-major axis being lower than the reference value. On the 2010/06/15 the ground-track deviation was reaching the east side of a 1 km dead-band around the reference ground-track, as shown in Figure 8. This was the right epoch to execute a drift-stop manoeuvre, since the orbit control strategy for Cryosat-2 is based in a 1 km dead-band around the reference.

The manoeuvre for the final acquisition, as it has been mentioned in section 3.2.1, was split into two burns in order to minimize the risk of having to perform more manoeuvres against the flight direction. The total optimized delta-v for the two burns was 0.068 and 0.0035 m/s respectively (see Table 2). The execution of the touch up burn was planned to take place after a good calibration of the first burn was available. The total fuel consumption from separation up to the execution of the touch up manoeuvre was 1.52 kg, out of a total initial fuel mass of 36.71 kg.

On the 2010/06/20 Cryosat-2 started its first orbit control cycle, when the ground-track deviation at the Equator crossings entered the 1 km dead-band. Since then the orbit control strategy based on an improved reference orbit with artificial accelerations has proved to be robust and no drawbacks have been identified in the routine execution of orbit control maintenance manoeuvres.

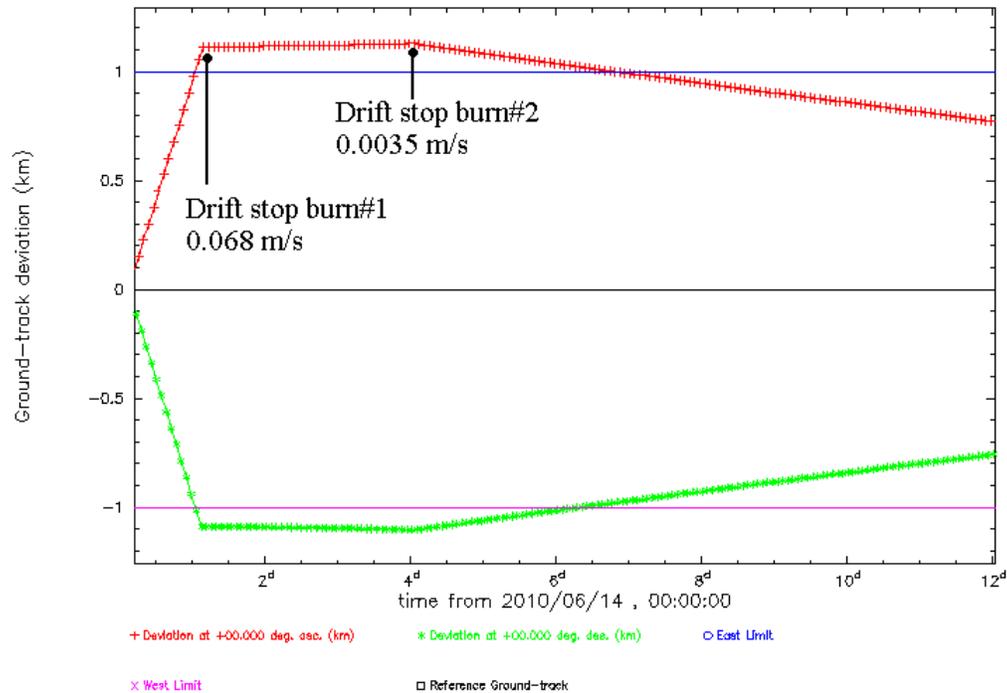


Figure 8. Cryosat-2 ground-track deviation evolution at the node crossings at the time of the final acquisition burns

4. References

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