A REVIEW OF SWARM FLIGHT DYNAMICS OPERATIONS FROM LAUNCH TO ROUTINE PHASE

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Abstract: *The three Swarm spacecraft were launched at the end of 2013 into a common low Earth orbit. In the following months the spacecraft were manoeuvred into their final constellation by the execution of over 400 manoeuvres and over 400,000 seconds of thrusting using a low thrust cold gas system. The approach to this demanding orbit control problem was to ensure a robust and safe mission implementation which ensured that the impact of any spacecraft problems were minimized. The successful completion of this early part of the mission was achieved in mid April 2014 after some challenging operations which were expertly handled by the Swarm Flight Dynamics Team.*

Keywords: *Swarm, Orbit Determination, Flight Dynamics, Operations*

1. Introduction

Swarm is a three spacecraft ESA Earth Explorer mission intended to measure the Earth's magnetic field to unprecedented accuracy. The identical spacecraft were launched together on 22nd November 2013 aboard a Rockot launcher with a Breeze-KM upper stage into closely separated near polar orbits before embarking on a three month orbit insertion phase to manoeuvre them into their operational constellation.

This paper presents a review of the flight dynamics (FD) operations from launch up to the insertion of all three spacecraft into their operational constellation. After a brief description of the mission and spacecraft, it will mainly focus on orbit related aspects of the operations since it was in this area that the mission most differs from previous ESA controlled missions.

The pre-routine phase includes the launch and early operations phase (LEOP) and orbit insertion phase (OIP). As well as describe the operations undertaken, the paper will emphasize what was new or challenging to ESOC FD and how and why the pre-launch plan had to be adapted to meet post launch challenges.

The spacecraft were launched into orbits with inclination 87.55 degrees and semi major axis 6868 km. Their planned final operational constellation (illustrated in Fig. 1) involves two satellites flying side-by-side, separated in right ascension of the ascending node (RAAN) by 1.4 degrees with the same inclination of 87.35 degrees and semi major axis around 30 km lower than the injection orbit, while the third orbits with inclination 87.95 degrees and at about 530 km. The lower pair share a common eccentricity vector and must cross the equator within 10 seconds of each other.

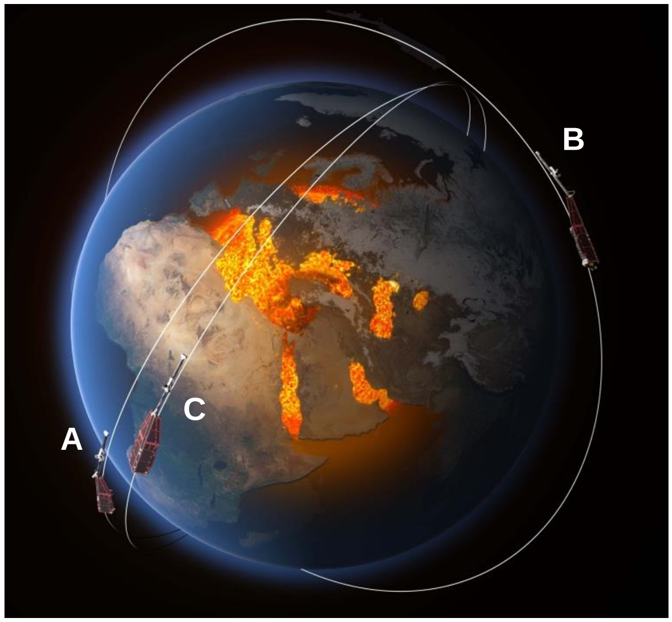

Figure 1 Swarm operational constellation 3 years into the routine mission

2. Mission Overview

2.1. Scientific Objectives

The primary aim of the Swarm mission is to provide the best ever survey of the geomagnetic field and the first global representation of its variation on time scales from an hour to several years. This requires separation of various contributions to obtain simultaneously a characterisation of both the internal geomagnetic field and the ionospheric-magnetospheric current systems. Of course this aim has imposed requirements on both the design of the individual spacecraft and the mission design in terms of the constellation.

2.2. Spacecraft Overview

The spacecraft illustrated in Fig. 2 are identical, three axis stabilized and each consist of a box with triangular cross section with length around 5 meters and a 4 meter long deployable boom assembly (DBA). The spacecraft dry mass is around 370 kg.

The propulsion system is cold gas using Freon 14 with a single high pressure system consisting of two identical tanks feeding two low pressure systems (A and B). Each low pressure system has its own dedicated feed module with a latch valve and a pair of pressure regulators in series intended to provide a stable low pressure environment.

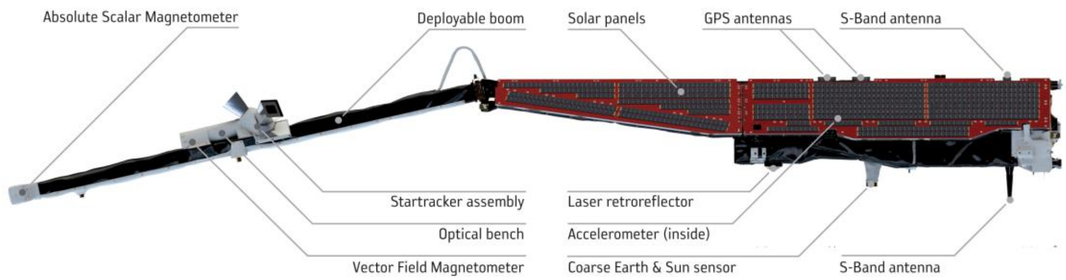

Figure 2 Swarm Spacecraft after DBA deployment

Each low pressure system consists of 2 pairs of orbit control thrusters (OCTs) with a nominal force of 0.05 N each, one pair (X-THR) against the nominal flight direction and one pair (Y-THR) on the side of the spacecraft providing thrust for inclination control. The A and B low pressure systems have their Y-THR on opposite sides of the spacecraft. The same low pressure systems also include 8 attitude control thrusters (ACTs) with a nominal force of 0.02 N. The ISP of the thrusters was estimated pre-launch to be 44 s.

The actual thrust force exerted by the thrusters at any time is related to the pressure in the low pressure system. The high pressure tank pressure varied with the amount of fuel remaining and with any temperature variation of the tanks but the set point of the pressure regulators was intended to ensure a constant low pressure of 1.5 bar, corresponding to a thrust force of close to 50 mN per thruster. The as built set point of the pressure regulator was actually closer to 1.3 bar, this corresponded to a thrust force of around 43 mN per thruster. The thrust force could be adapted by changing the thruster throat diameter but it was not possible to do this for Swarm.

Each spacecraft was loaded with between 102.8 kg and 105.5 kg of fuel prior to launch, depending on the exact dry mass of each spacecraft.

The spacecraft have star trackers (STRs) located on the DBA, they are a scientific instrument which are also used for attitude control by the AOCS system. The three STR heads are hot redundant and autonomously handle switch-overs for blindings.

As well as the STR the spacecraft also have AOCS magnetometers (MGMs) and coarse Earth Sun sensors (CESSs) mainly for lower AOCS mode operations. In addition to the ACTs the spacecraft have magnetotorquers (MTQs) as actuators for attitude control in fine pointing and orbit control modes.

2.3. Spacecraft Instruments

The spacecraft payload consists of a high precision vector field magnetometer (VFM) and absolute scalar magnetometer (ASM). The ASM, located at the tip of the DBA, is used to perform in flight calibrations of the VFM to ensure absolute accuracy of this main instrument. The VFM and camera heads of the star tracker instrument are mounted on a rigid structure called optical bench, midway the DBA. The STR precisely measures the VFM orientation and is also used for attitude control on board.

The electric field instrument makes in-situ measurements of the local ion distribution and its moments in order that the local electric field can be determined and accounted for in the magnetic field measurements.

The spacecraft also carries a GPS receiver, laser retro reflector and an accelerometer to support precise orbit determination. The operational orbit determination is performed using the GPS receiver on board navigation solution.

3. Launch and Early Operations Phase

3.1. Summary of LEOP Operations

The spacecraft were launched with the DBA stowed and the instruments including the STR and GPS switched off. The mission relied on S-band tracking for orbit determination and the AOCS used CESS and MGM for attitude control in rate damping mode (RDM) and coarse pointing mode (CPM). The spacecraft uses much more fuel in these lower AOCS modes and so there was a need to get to a situation where the spacecraft were in fine pointing mode (FPM) as soon as possible. As a result the main events of the launch and early operations phase (LEOP) were:

- first acquisition and initial orbit determination using S-band data,
- deployment of the boom,
- initialization of the on-board orbit propagator by telecommand (TC) for use in FPM before GPS switch on,
- checkout of the STR by comparison with CESS combined with MGM data,
- checkout and verification of on-board orbit propagator,
- transition to S-band high rate TM mode to allow better TM band width, this required reliance on reconstructed carrier Doppler data only as the TM modulation for this mode was incompatible with Ranging,
- checkout and verification of S-band HR Doppler data,
- transition to FPM,
- checkout and verification of GPS navigation solution by comparison with ground orbit determination
- transition to use of GPSR on board for AOCS and timing,

Finally the LEOP ended when the mission timeline was established for commanding the spacecraft.

The fact that there were three spacecraft meant there were conflicting demands in terms of station pass allocation between the spacecraft from FD for early orbit determination and flight control team (FCT) for commanding time. In addition, the LEOP timeline was rather compact and in the event of even minor contingencies or delays the allocation of stations needed to be rearranged in real time.

3.2. Early Orbit Determination

The spacecraft were launched on a single launch vehicle and injected into nearly the same orbit. In fact the upper stage separation mechanism imparts slightly different impulses on the three spacecraft at separation using springs with different forces so that the spacecraft semi major axes are nominally separated by around 100 m from each other. This meant that their orbital periods are around 0.1 seconds different and was intended to ensure a safe separation of the three spacecraft.

The launcher system required that the upper stage performed a yaw manoeuvre before separation so that the spacecraft injection was 45 degrees to the velocity direction. A failure of this system either in the spring forces, the location of the spacecraft on the upper stage or the orientation of the upper stage could result in a separation which was not only non-nominal but could also result in a collisions between the spacecraft after launch.

Although there are 3 separate spacecraft involved in the LEOP, the ground station support available was not 3 times that of a single spacecraft mission. Tracking passes from KSAT stations at Svalbard and Troll as well as ESTRACK support from Kiruna was available for early orbit determination using S-Band data only since the GPSR was not switched on until 12 hours into the mission. This situation led to concern that in the event of a non-nominal launch or separation from the upper stage there would be insufficient data to properly determine the orbits of all three spacecraft independently.

In order to mitigate this concern the Swarm orbit team implemented a novel combined orbit determination scheme which used a priori knowledge of the nominal separation impulses and the fact that the three spacecraft were separated from the same launch vehicle to formulate a priori observations of the spacecraft relative state at the separation epoch. When included, these pseudo observations created a coupled three spacecraft orbit determination so that tracking data from a single spacecraft could be used to determine the orbits of all three. This meant that flight dynamics demands on distribution of ground station passes to particular spacecraft for the purposes of ensuring a robust early orbit determination could be reduced. This was found to be very helpful to the FCT so they could better plan the early LEOP operations with other considerations in mind, especially in case of a non-nominal spacecraft scenario which could require a post launch re-plan of the LEOP timeline.

This system was found to be very useful in pre-launch system tests and simulations. If a non-nominal separation of the spacecraft from the upper stage was simulated there was no way for this to be detected other than through determination of the spacecraft orbits. Using the combined orbit determination with the nominal separation constraints the orbit determination team found that the combined solution started to show a very poor fit after only one full orbit (with second northern hemisphere station pass). This could be due to a non-nominal separation or possibly some inconsistent radiometric data in the fit. If the problem could be alleviated by reducing the weight of the velocity pseudo observation constraint this was a strong indication that the issue was not related to particular data problems. This indirect measure of the separation consistency with that which was expected was the only independent means of early warning of incorrect separation for ESA.

This system was used in the LEOP and showed early on that the separation was nominal in both the common injected orbit and the relative orbit injection by the separation mechanism.

Table 1 Swarm injection performance

	Swarm Alpha		Swarm Bravo		Swarm Charlie	
Elements	Pre-launch	First OD	Pre-launch	First OD	Pre-launch	First OD
S.M.A.	6868.286	6870.465	6868.194	6870.370	6868.415	6870.591
Inclination	0.001458	0.001878	0.001465	0.001890	0.001473	0.001900
Eccentricity	87.5478	87.55413	87.5478	87.5541	87.5478	87.5544
RAAN	279.2766	279.2843	279.2766	279.2843	279.2766	279.2846
Arg. Perigee	121.8183	116.7398	122.4241	117.3006	121.2102	116.3884
TAN	283.9763	289.0445	283.3704	288.4837	284.5843	289.3959

As a means for decoupling the orbit determination requirements from FCT requirements it was particularly effective and relied on throughout the planning and implementation of the LEOP.

3.3. Spacecraft performance

After the second OD was performed the S-band link was switched to high-rate (QPSK) TM modulation in order to allow more downlink bandwidth for TM. As a result the only data available to orbit determination was Doppler based on the on-ground reconstructed carrier. This was the first time such data was relied on for orbit determination in an ESA mission and it was the subject of analysis and verification before it was used to verify the GPSR navigation solution later in the LEOP. The results from an early Swarm Charlie OD in Fig. 3 show the data noise is comparable to the standard Doppler. Also it was found that the orbit determination solution was not adversely affect by the data.

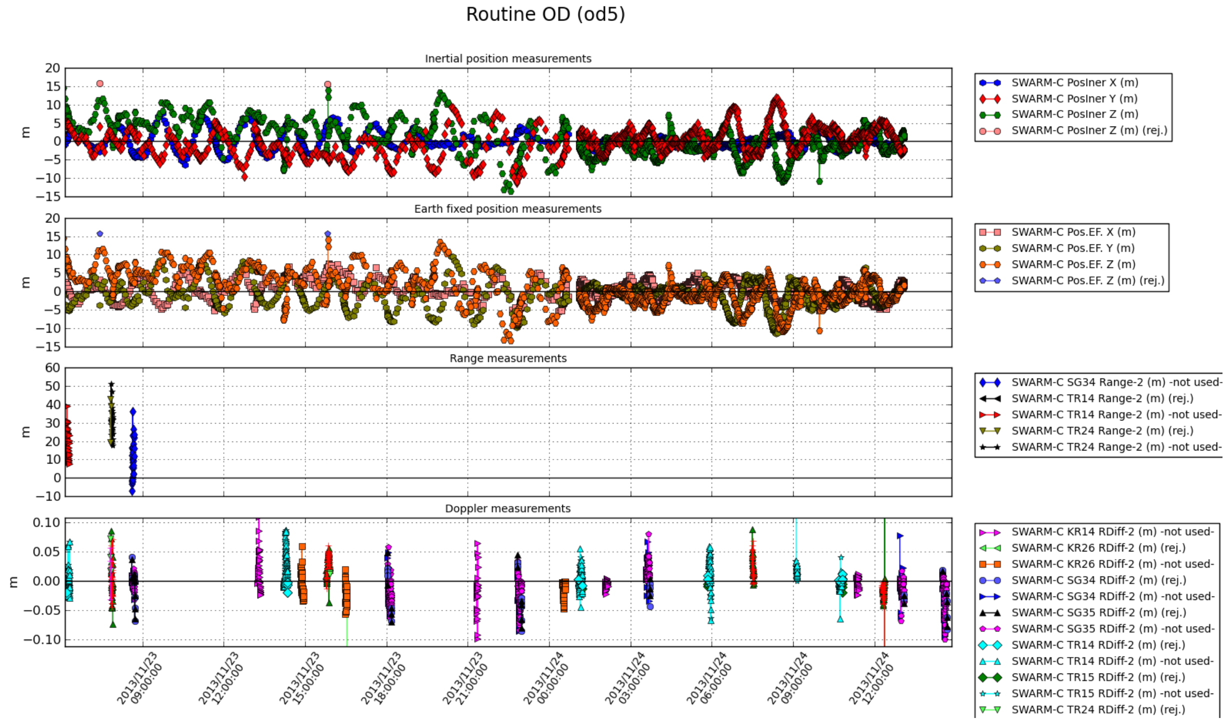

Figure 3 Orbit Determination residuals from Swarm LEOP using GPSR navigation solution and pass through of Range and Doppler radiometric data, including low and high rate Doppler.

Also from Fig. 3 can be seen the comparison of GPSR navigation solution with radiometric tracking data. After the analysis comparing orbit solutions showed no significant differences between the data sources it was concluded that the GPS data was reliable for on-board and on ground processing.

The LEOP was conducted without any major platform problems on the spacecraft and the spacecraft AOCS performance was considered nominal except for one issue related to the STRs. The issue caused problems in timely processing of STR data in the STR electronics during transitions to and from STR blinding. This necessitated a software patch for each spacecraft twice (for each STR electronics unit) and took some weeks to resolve, causing delays in other commissioning activities including execution of the manoeuvres.

The only significant payload issue was that the back-up ASM unit on Swarm Charlie failed irretrievably, this and other issues caused delays in the start of the spacecraft manoeuvres because of the need of a reconsideration and decision for the placement of each of the spacecraft in the constellation.

The LEOP was completed within the planned time and all planned activities took place.

According to the PVT method used by FD the following fuel consumption during LEOP was observed:

- Swarm Alpha was loaded with 105.5 kg fuel, of which 2.1 kg was used
- Swarm Bravo was loaded with 105.2 kg fuel, of which 1.9 kg was used

- Swarm Charlie was loaded with 102.8 kg fuel, of which 1.7 kg was used

A more accurate method based on pulse counting could not be used because of the lack of availability of TM during the low rate TM phase.

3.4 Decisions for Operational Constellation

The operational configuration chosen pre-launch involved Swarm Charlie raising its orbit by 40 km in semi major axis and 0.4 degrees in inclination whilst the other two spacecraft entered the lower side-by-side constellation lowering their orbits by 30 km and 0.2 degrees in semi major axis and inclination respectively.

After the LEOP and early commissioning activities there was a decision point intended to give the go-ahead for manoeuvres to start for the orbit insertion phase. However, this was delayed due to the STR issues and the ASM-related decision process mentioned above.
The final decision was taken to lower Swarm Charlie and to raise the orbit of Swarm Bravo.
In addition, there was around this time a request from the mission advisory group (MAG) of scientists to reconsider the placement of the upper spacecraft.
The pre-launch mission analysis was based on an assumption of high solar activity. This resulted in a mission design which aimed to separate the orbital planes of the upper spacecraft and the lower pair as quickly as possible because it was expected the mission could not last more than 4 years before the lower spacecraft reentered the Earth's atmosphere. This was the reason why the upper spacecraft would spend 70% of its fuel to perform this initial orbit adjustment so that after 4 years the plane separation would be 9 hours.
Based on FD analyses using the latest solar activity it became clear that the lower spacecraft would not re-enter after 4 years but would most likely last considerably longer. In Fig. 4 the altitude evolution using an atmosphere model using 50% and 95% MSFC predictions of solar activity is presented. Even in the 95% case, the spacecraft will be above 300 km until the year 2020. In the 50% case the orbit remains above 400 km until well beyond this date.
The MAG scientists came to the conclusion that a significant increase of the scientific return of the mission could be obtained by maximizing the time during which the two orbit planes are separated by about 90 degrees (+/- 30 degrees). In addition it was desirable to accelerate the travel time to arrive at approximately 90 degrees local time of the ascending nodes (LTAN) separation, as this would generally benefit the science return from the mission, irrespective of its duration.
After receiving this request, FD concluded that an adjustment of the orbit insertion phase was acceptable at this late stage if it affected the upper spacecraft only, so that the carefully developed manoeuvre scheme for the lower pair was not subject to a redesign.
After some iteration between FD, MAG and the project representatives the following was agreed:

- A LTAN separation of 90 degrees in 4 years will be achieved with 0.2 degrees inclination change in the upper spacecraft and a semi major axis change of 20 km. This will mean a difference between the lower pair and upper of 0.4 deg. inclination and 50 km semi major axis.

- This will cost around 31 kg for orbit change manoeuvres plus 5 kg for slews and attitude control for the upper spacecraft.
- The spacecraft will be in the desired LTAN separation range 90 degrees (+/- 30 degrees) from +2.66 years to +5.33 years.
- An orbit adjustment can be introduced after 2.66 years to reduce the drift rate by reversing the inclination change of the upper spacecraft. For example, reducing the inclination by 0.2 degrees (costing around 30 kg) reduces the drift between the planes from 22.5 to 13.5 degrees per year. This means that the desired LTAN range can be occupied for almost 4.5 years, up to a mission duration of 7.1 years.
- Depending on the spacecraft performance after 2.5 years of the routine phase, the decision for this orbit adjustment of the upper spacecraft will be made.

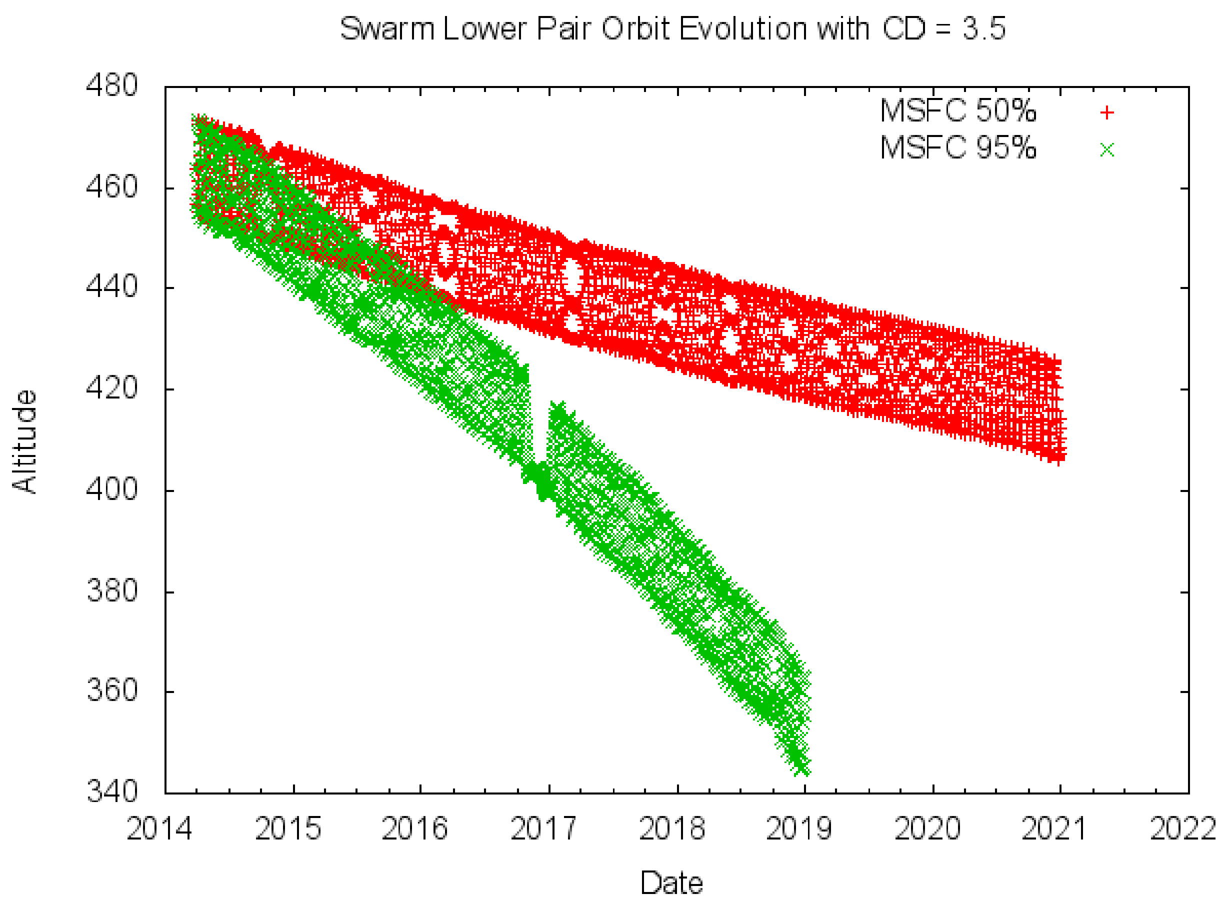

Figure 4 Long term altitude evolution of the lower pair

The orbit insertion phase was adjusted so that the orbit change for the upper spacecraft was reduced as stated above.

4.0. Orbit Insertion Phase

4.1. Design of the Orbit Insertion Phase

The Swarm orbit insertion phase in [1] starts with the spacecraft in the post LEOP orbits, separated by around 100 m in SMA and slowly drifting apart at a rate of 1.5 seconds a day in terms of node crossing times. A sequence of manoeuvres is implemented per spacecraft so that one of the spacecraft's orbits is reduced in SMA by around 30 km and in inclination by 0.2 degrees. Its orbit starts to drift in RAAN with respect to the remaining spacecraft and it orbits with a reduced period. After around 10 weeks the RAAN reaches its target of 1.4 degrees and a second spacecraft repeats the change performed by the first to stop the drift in RAAN and ALA. This is done when the first spacecraft has performed an integer number of relative orbit revolutions with respect to the second, so that the final separation in argument of latitude (ALA) between the two spacecraft is small. In between the manoeuvreing of these two spacecraft the third spacecraft is placed into an orbit higher in SMA by 20 km and inclination by 0.2 degrees.

The requirements for the lower constellation are as follows:

- RAAN separation of 1.4 ± 0.2 degrees
- Ascending node crossing between 4 and 10 seconds of each other
- Altitude difference always less than 5 km
- Eccentricity difference small enough to ensure that in the event of the spacecraft separation along track reducing to 0 seconds due to a safe mode of the trailing spacecraft there is no danger of collision at the poles. This has been shown to be eccentricity difference < 0.00007 .

In addition, to ensure that an integer number of relative orbit revolutions occurs when the RAAN separation is 1.4 degrees the change in SMA for the lower spacecraft from the starting point must be close to a multiple of 7.5 km.

These changes are performed using a low thrust cold gas system capable of 0.1 N (2x 0.05 N using OCTs), with 460 kg spacecraft many manoeuvres of long duration are needed. Also, in order to make the whole process feasible it is necessary to perform combined SMA and inclination change manoeuvres by executing the manoeuvres at non-zero yaw angles and performing slews in between manoeuvres.

Assuming the combined inclination and semi major axis manoeuvres a total of around 32 m/s for the lower pair, and 30 m/s for the higher spacecraft. This means a total of 1.7 or 1.6 days thrusting respectively.

The pre-launch plan for the OIP was based on the assumption that each spacecraft would perform manoeuvres of duration up to 1200 seconds, centered near each of the ascending and descending nodes for inclination change efficiency and allowing time for the spacecraft to slew at the expected rate of 0.1 degrees per second to the next node. According to these considerations there is a total of 122 manoeuvres for Swarm Alpha and Charlie and 115 for Swarm Bravo.

The manoeuvres are organized into batches of maximum duration of 3 days, including up to around 100 manoeuvres. The whole batch of manoeuvres is commanded in advance and daily orbit determination is performed to calibrate the thruster and AOCS performance and update the ground station pointing predictions for the next days.

Small test batches were planned at the start of the OIP in order to detect any problems in the propulsion system. These were planned to be similar to the main batches but including only 4-8 manoeuvres.

The plan of the orbit insertion phase is presented in Fig. 5. The manoeuvre batches were chosen to be performed as much as possible in the middle of the working week so that commanding could be performed on Mondays, manoeuvres executed on Tuesday to Thursday and orbit determination performed at the end of the week to prepare for the next manoeuvre batch.

For the execution of the manoeuvres of the first of the lower pair and the upper spacecraft relatively little precision in terms of orbit target is required and the manoeuvres are grouped into two relatively large batches plus the test batches. For the final spacecraft (Swarm Charlie) the inclination, SMA and eccentricity targets are much more precise in order that the relative orbit requirements with the other lower spacecraft can be met. Also, the timing of the final batches are more critical because failure to correctly execute can result in overshoot of the targets which takes time of fuel to correct. This is why the Swarm Charlie manoeuvres were split into more and smaller batches than the other two spacecraft. Also, the final Swarm Charlie batch is split into a main batch and a touch up batch with 2 days allowed in between to perform orbit determination. At the very end of the OIP Swarm Charlie performs some small drift stop manoeuvres to insert the spacecraft into its operational constellation with Swarm Alpha.

The manoeuvres were to be executed twice per orbit at each node with the thrust vector orientated via a yaw attitude bias so that the desired semi major axis combination was performed. This typically required the thrust vector some 60 degrees from the velocity direction. The nominal configuration is to use the X thrusters for ascending node manoeuvres with a ~60 degree yaw bias, perform a slew to ~30 degree yaw and perform the descending node manoeuvres using the Y thrusters. This meant that the slew between manoeuvres was minimized.

4.2. Execution of the Orbit Insertion Phase

The decisions for the constellation establishment took place after launch and during the early commissioning. After some initial delay, the first manoeuvres were planned to take place finally in late January 2014 and would continue until early April of the same year.

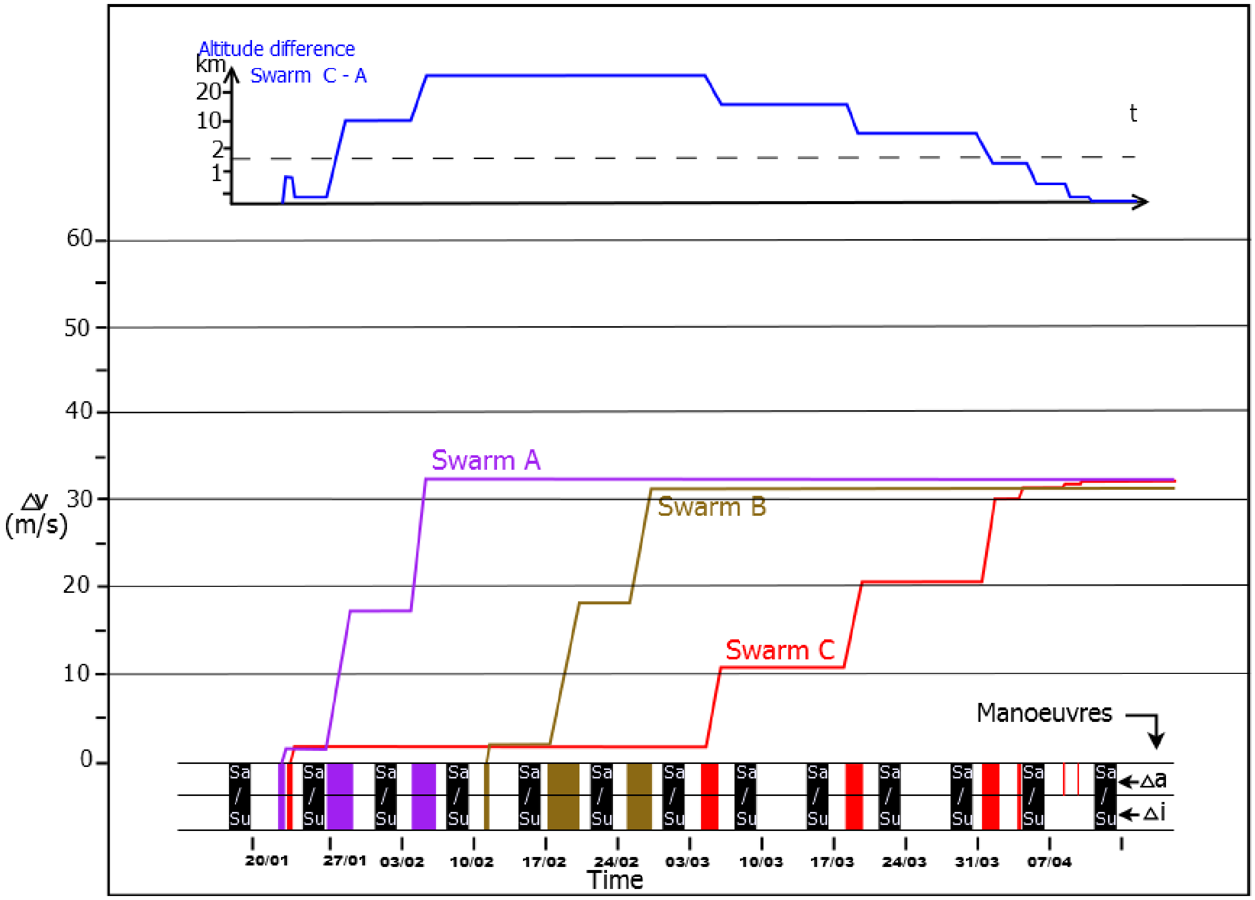

Figure 5 Orbit Insertion Phase plan at the start of manoeuvreing.

4.2.1 Manoeuvre Optimization Configuration

The manoeuvre optimization was performed separately for Swarm Bravo (upper spacecraft) and a combined optimization was performed for Alpha and Charlie. The Swarm Bravo optimization targeted a particular semi major axis, inclination and if inexpensive in terms of fuel, the frozen eccentricity as well.

The Alpha and Charlie optimization targeted the difference in RAAN to be 1.4 degrees and the difference in inclination, semi major axis, eccentricity vector and argument of latitude to be zero. If it was inexpensive the frozen eccentricity was targeted too. The final mass was the cost function for the optimization.

Each manoeuvre batch was treated as 2 manoeuvres in the optimization. The ascending and descending manoeuvres in the batches were combined into 2 sets each of which was free in a combined sense to move in direction, duration and location in their orbits in order to minimize the cost function.

The manoeuvre batches for Alpha and Bravo were designed to be executed in batches as large as possible since absolute orbit precision was not a requirement. For Charlie however, the precision of the orbit relative to Alpha was important, and it was important to design the strategy so as to minimize the possibility that manoeuvre failure caused a crossing of the spacecraft order, or an overshoot of the RAAN target. As a result the optimization was further constrained by fixing the relative delta v sizes of the manoeuvre batches so that the Swarm Alpha main batches were of equal size and the Charlie batches were of ratio 22:24:19:5 for batches 1, 2, 3A and 3B respectively. The Charlie batches 3A and 3B were to be performed in the same week, 3B being a touch-up batch for 3A to ensure very small inclination error and hence RAAN drift.

4.2.2 Operations Cycle

The cycle of operations was driven by an additional constrain that weekend work was desired to be minimized. This meant that manoeuvres were planned to start on Tuesday morning and last until Thursday evening at the latest. Orbit determination, manoeuvre optimization and command generation were to take place on the Monday and orbit determination including calibration of the batch was to take place on the Friday before the weekend.

During the batches the manoeuvres were monitored by observing the low pressure system pressure transducer readings (LPT), on-board determined attitude and error with respect to the commanded attitude, fuel consumption by observing the high pressure system pressure (HPT) and temperature.

The ground station passes were suspended between 22:00 and 05:00 UTC each day, but for the early morning passes during manoeuvre batches the personnel at the ground station were alerted to the possibility that a search could be necessary in case the batch was aborted overnight.

The orbit determination was performed using the on-board GPS navigation solution. This data was the output of the on-board Kalman filtered orbit solution and of course provided full 3-D geometry of the spacecraft position and velocity throughout the orbit from the mass memory TM dumps performed at each ground station pass. This meant that the orbit could be rapidly reconstructed during or after a manoeuvre batch. Orbit determination was performed on a daily basis, and orbit predictions performed using the performance of the manoeuvre batches to predict the future performance. Also estimated were drag scale factors for the spacecraft.

4.2.3 Alpha and Charlie Test Batches

The test batches for Alpha and Charlie were performed first, the Bravo test batch was put off until the Bravo manoeuvres were to be executed. The test batches consisted of 2 pairs of manoeuvres for each spacecraft performed in a manner similar to the main batches. The manoeuvre execution showed no performance issues to cause a delay in the subsequent batches for Swarm Alpha. The average LPP was used to establish an initial expected thrust level for the thrusters based on a linear model interpolating between the on-ground measured thrust at 1.3 and 1.5 bar.

4.2.4 Frozen Eccentricity Targeting

The optimization was performed with and without the frozen eccentricity constraint. After launch, when the manoeuvre operation was still planned to start in December it was realized that the frozen eccentricity cost 2 kg per spacecraft to achieve. On this basis it would not be included in the orbit control. When performed for a start in late January the cost of the frozen eccentricity control had dropped to close to zero. This was because the manoeuvres had to be executed at the nodes, and so the cost of shifting the eccentricity vector in the $e\ sin\omega$ direction was free, but in the $e\ cos\omega$ it was not. The delay in the start of the manoeuvre execution meant that the evolution of the eccentricity of the spacecraft orbits around the frozen eccentricity was such that the manoeuvre locations for both Alpha and Charlie were now favorable for the desired frozen eccentricity targeting. In fact, whether or not the frozen eccentricity was explicitly targeted, the same optimization solution was arrived at.

4.2.5 Swarm Alpha Manoeuvre Batches

The first Swarm Alpha batches were commanded to be executed between early morning 28th January until the evening of the 30th January and would contain 34 orbits or 68 manoeuvres in total. The duration of each manoeuvre was close to 20 minutes and the yaw angles were 62 degrees for the ascending node (X-THR used) and 33 degrees on the descending node (Y-THR used).The LPT TM data for this batch is shown in Fig. 6. The upper plot shown the whole batch and the lower plot shows a detail of the first four manoeuvres in this batch. The low pressure system pressure was expected to be a steady 1.3 bar for the duration of the OCM but it was soon realized that the low pressure varied between 1.3 and 1.4 bar during OCM execution. Fluctuations are due to execution of ACTs during the OCM firing. In fact for the X-THR firings (first and third manoeuvre in lower plot of Fig. 6) there are quite frequent ACT firings but for the Y-THR firings on the same plot the ACTs are firing almost continuously.

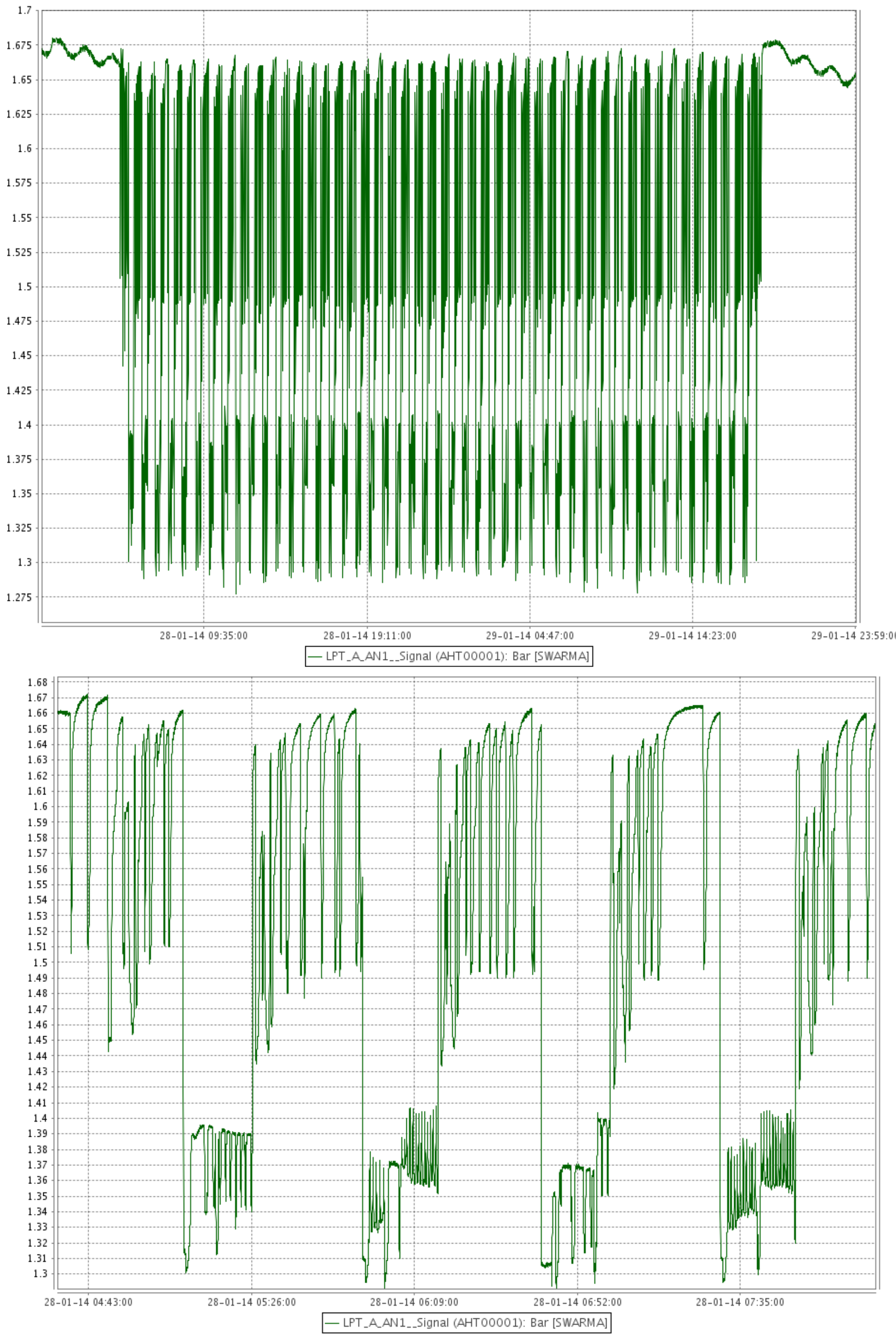

Figure 6 Swarm Alpha Batch 1 Low Pressure from Telemetry

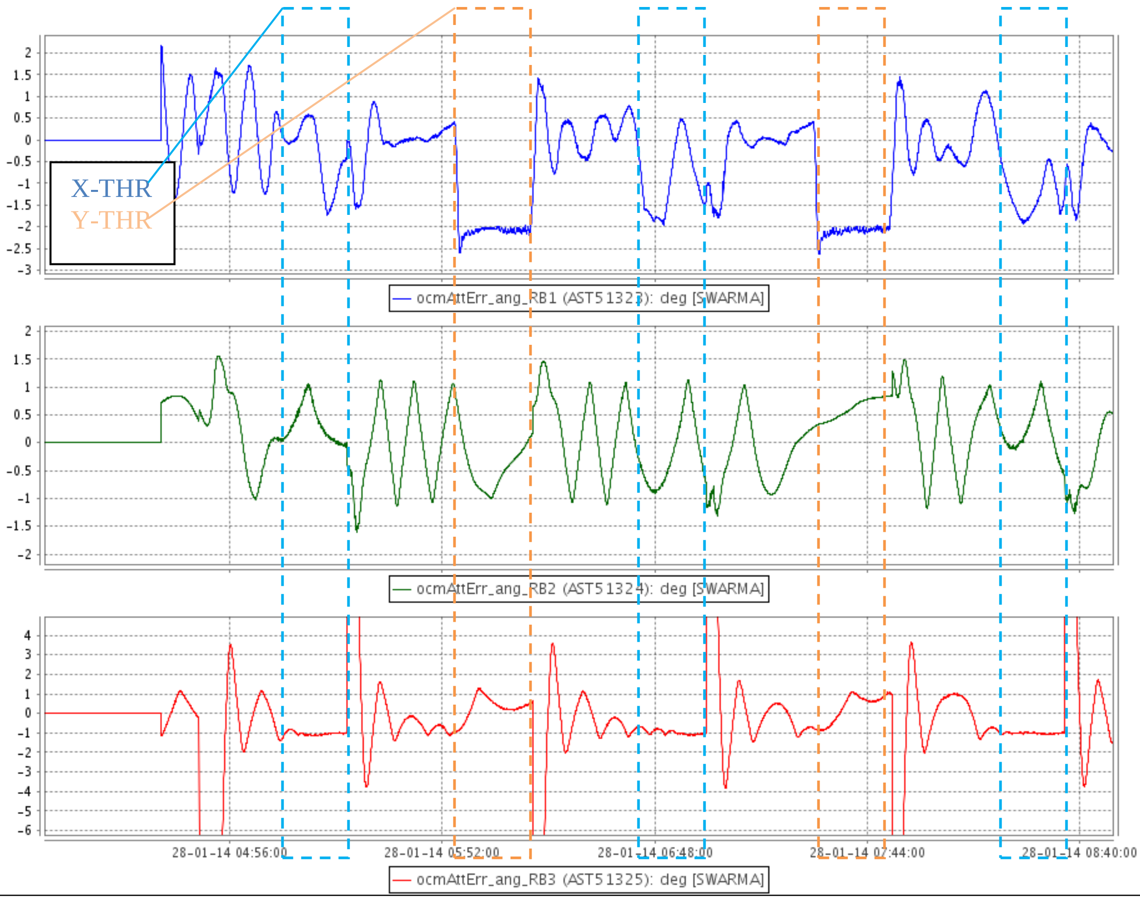

Figure 7 Swarm Alpha Batch 1 Attitude Errors in roll, pitch and yaw (top, middle bottom).

The reason for this is that the Y-THR exert a roll torque on the spacecraft and the ACTs are firing to counteract this torque. The result is seen in terms of the attitude error in Fig. 7.

It is clear that a 2 degree roll bias is apparent when the Y-THR are firing. There is also a consistent -1 degree bias in yaw when the X-THR are firing and a ca. +1 degree bias in yaw when the Y-THR are firing. These attitude errors are within specifications for the orbit control mode (OCM). As a result, the spacecraft would perform slightly more semi major axis change (due to the yaw errors the spacecraft is pointed more in the along-track direction at each node than planned) and slightly less inclination change. The roll errors using the Y-THR meant that an unplanned radial component to the delta v was introduced and as a result the eccentricity change was not exactly as planned.

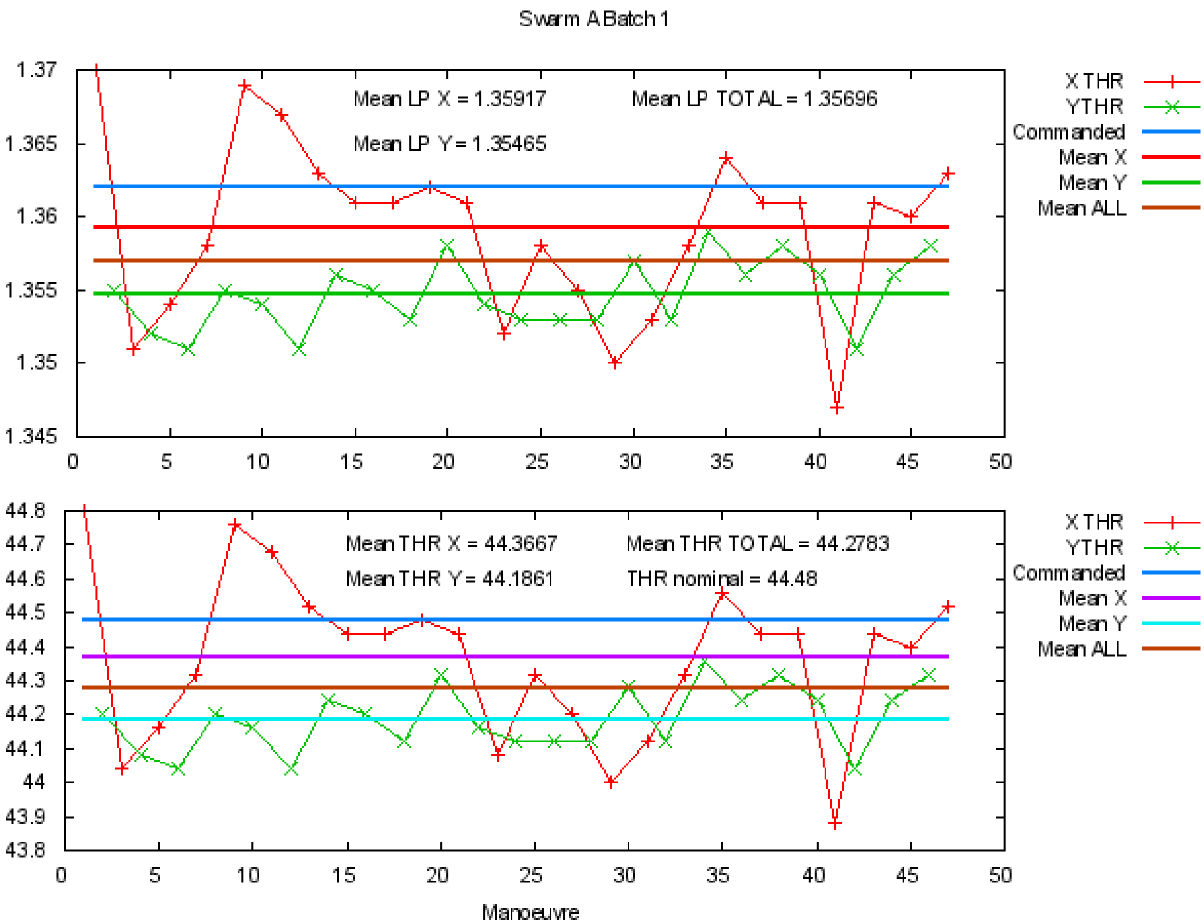

Figure 8 Swarm Alpha Batch 1 Manoeuvre Performance from TM in term of LPT (top) and derived thrust (bottom).

The LPT over each burn period was averaged and is plotted in Fig. 8. The thrust expected based on the linear thrust model is plotted in the lower figure. The test batch LPP of 1.362 bar, or 44.48 mN per thruster was commanded. The mean observed LPP was 1.357 bar or 44.278 mN in thrust. The Variability of the X-THR LPP and hence mean thrust level is due to the fact that the ACT actuations, which cause the LPP variation, are not continuously acting. The mean thrust will be higher if ACT actuation starts quickly after the OCT start driving up the pressure earlier. For the Y-THR firings the near continuous firing means that the mean pressure is not affected by ACT timing relative to OCT firing times.

The manoeuvre executed normally until the 47th manoeuvre on 29th April at around 17:50 UTC when a manoeuvre on the descending node aborted, causing the whole manoeuvre sequence to abort. The reason for this was eventually tracked down to an issue related to an on-board shared memory address between the Y-THR and another unrelated hardware command. It was found that at certain pre-determinable times the Y-THR would be commanded with an on-time of zero and this would trigger the abort sequence.

The fact that the manoeuvres were not executing was realized at the next pass, some hours later by which time there was no FD support on-site. However by the first pass next morning the spacecraft was only some 15 seconds late in AOS and was quickly acquired by the ground station.

The orbit determination for this batch showed some anomalous results. The estimation of the manoeuvre scale factors was performed on a per manoeuvre basis. The results for the X-THR showed a steady performance error of -9% and for the Y-THR a similar performance error of around 5.5% for all these manoeuvres. The overall average was found to be -1.8%. The reason for the large discrepancy in X and Y THR manoeuvres at ascending and descending nodes is not due to performance differences but rather due to the GPS navigation solution data. The data used was from the on-board GPS Kalman filtered solution. The data is therefore auto correlated in time and typically exhibits a sinusoidal once per revolution signature with amplitude of 5-10 m. Each burn has a DV of around 26 cm/s, 13 cm/s of which acts along track in this case resulting in around 240 m semi major axis change. The cross track component changes the position at the maximum latitude by around 170 m, as a result the 5-10 m amplitude noise could have an effect up to 12% depending on the phase of the signature compared to the manoeuvre location. Since it is not possible to get any other form of GPS navigation solution from the on-board system it was realized that the individual manoeuvre calibrations could not be relied upon. However, the overall calibration of the manoeuvre batches were found to be in reasonable agreement with the coarse linear model of the thrust force.

In any case, it is important to realize that the Swarm Alpha manoeuvre performance is not critical, since the manoeuvre targets are only relative to Swarm Charlie.

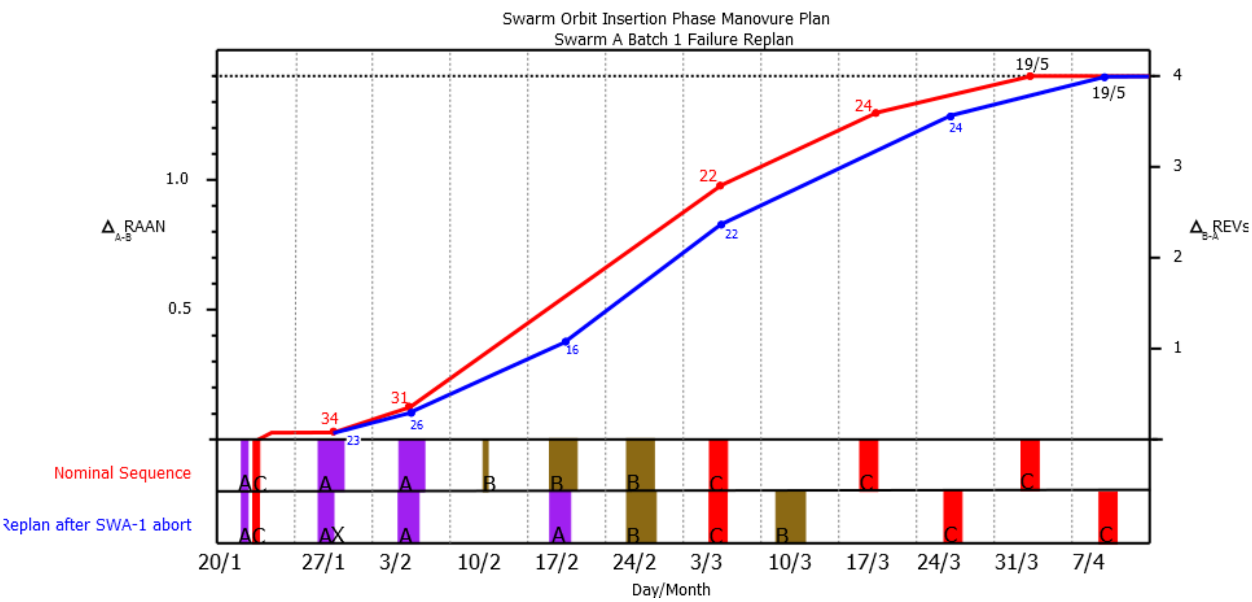

Figure 9 Re-planned Orbit Insertion Phase after Swarm Alpha batch 1 failure

More importantly at this stage was the fact that the first manoeuvre batch had aborted prematurely. A study performed before launch had been undertaken to show how failures in any batch could be compensated for by rearrangement of the remainder of the orbit insertion phase.

In Fig. 9 is shown the nominal manoeuvre sequence and the evolution in RAAN difference and the number of relative orbit revolutions between Alpha and Charlie over the orbit insertion. Once manoeuvred, Swarm Alpha performs 4 orbits more than Charlie in the time for it to reach 1.4 degrees in RAAN relative to Charlie.

The re-plan is performed with the aim of avoiding weekend manoeuvreing. This results in a sequence as shown in Fig. 9. Two further Alpha batches were required with a free week in between and the Bravo batches 1 and 2 were delayed by 1 and 2 weeks respectively. The overall sequence end was delayed by 1 week.

It was decided to perform the next batch of manoeuvre using only the X-THR, since it was not clear at this time what the reason for the manoeuvre abort was or whether a work around could be established. The yaw angles for ascending and descending nodes were 64 and – 58 degrees respectively. This meant that longer slews were required between the two nodes but since the spacecraft could slew at a rate of 0.1 degrees per second there was time to reach the other node safely at the correct attitude. Furthermore the fuel consumption was not affected since the shorter slew between yaw 64 and 33 degrees for batch 1 was already long enough for the cruise phase of the slew (maximum slew rate of 0.1 degrees/s) to be achieved so that no extra fuel would be spent performing the longer slew.

The geometry was acceptable in terms of power and thermal constraints and the performance of the remaining batches were comparable to that of batch 1, the major difference being that the absence of Y-THR meant that the eccentricity error was reduced and the fuel consumption was slightly reduced.

With the onset of eclipses in mid-March, and due to thermal and power concerns during later burns it was decided that the best configuration was to use the Y-THR after all. This was possible since the timing of the potential Y-THR failures was now known in advance and the manoeuvre optimization could use this information to omit the nodes when the OCT switch off would occur.

The final Swarm Alpha batch was performed back again in the nominal X/Y mode, and was successfully completed after checking that no manoeuvre would be affected by the Y-THR abort issue.

4.2.6 Swarm Bravo Manoeuvre Batches

Figure 9 shows that Swarm Bravo was to be manoeuvred next. Due to the power and thermal considerations it was considered wise to try to complete the Bravo manoeuvres before the onset of the eclipse season starting mid-March. It was this consideration, and the fact that for Bravo precise timing or performance of the batches was not a major issue that it was decided to omit the Swarm Bravo test batch altogether and instead start with the first main Batch immediately following the Swarm Alpha manoeuvres.

The Swarm Bravo optimization targeted an altitude increase to 510 km. An extra fuel cost was due to the altitude loss of 1.6 km from launch until the start of the manoeuvres of the orbit insertion. The inclination change was targeted to be +0.2 degrees.

The execution of the Swarm Bravo manoeuvres was in Y/X THR mode (Y at ascending node, X at descending node) and as a result for each batch a single Y-THR manoeuvre had to be omitted. The remaining manoeuvres were re-optimized to compensate. The frozen eccentricity was targeted even though this was not strictly necessary simply because the DV cost was acceptable.

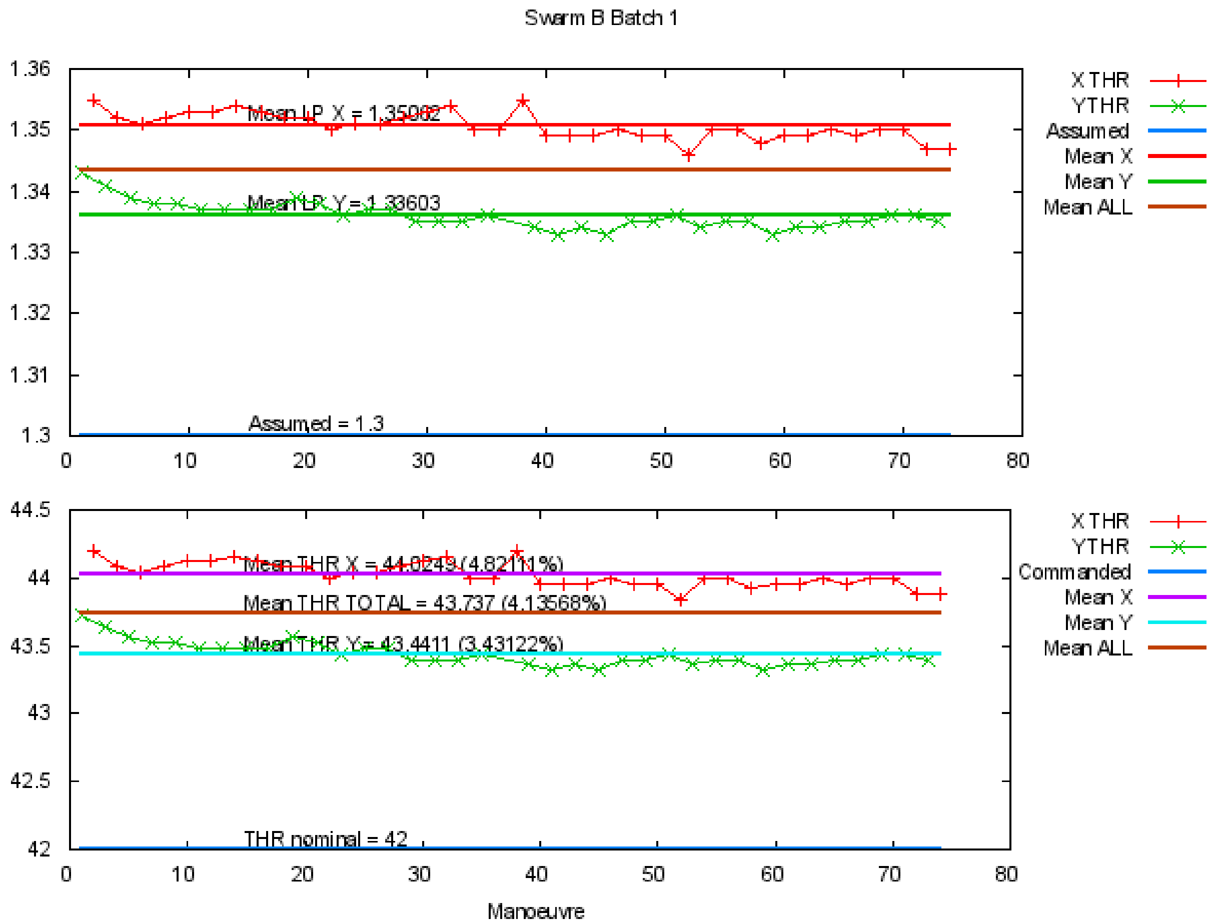

Figure 10 Swarm Bravo Batch 1 Manoeuvre Performance from TM in term of LPP (top) and derived thrust (bottom).

Swarm Bravo batch 1 containing 74 manoeuvres with yaw angles of +26 degrees and -112 degrees was executed and the resulting mean LPT and assumed thrust figures are presented in Fig. 10. A mean over performance in terms of thrust of 4.14% was observed and a very stable performance of both X and Y thrusters was seen. The orbit determination demonstrated an achieved orbit change consistent with an 4.5 % over-performance of the batch.

Swarm Bravo batch 2 containing 62 manoeuvres with yaw angles of +22 degrees and -117 degrees was executed and the resulting mean LPP and assumed thrust figures are presented in Fig. 11. A mean over performance in terms of thrust of around 0.1% was observed and a very stable performance of both X and Y thrusters was seen. The orbit determination demonstrated an achieved orbit change consistent with an 0.8 % over-performance of the batch.

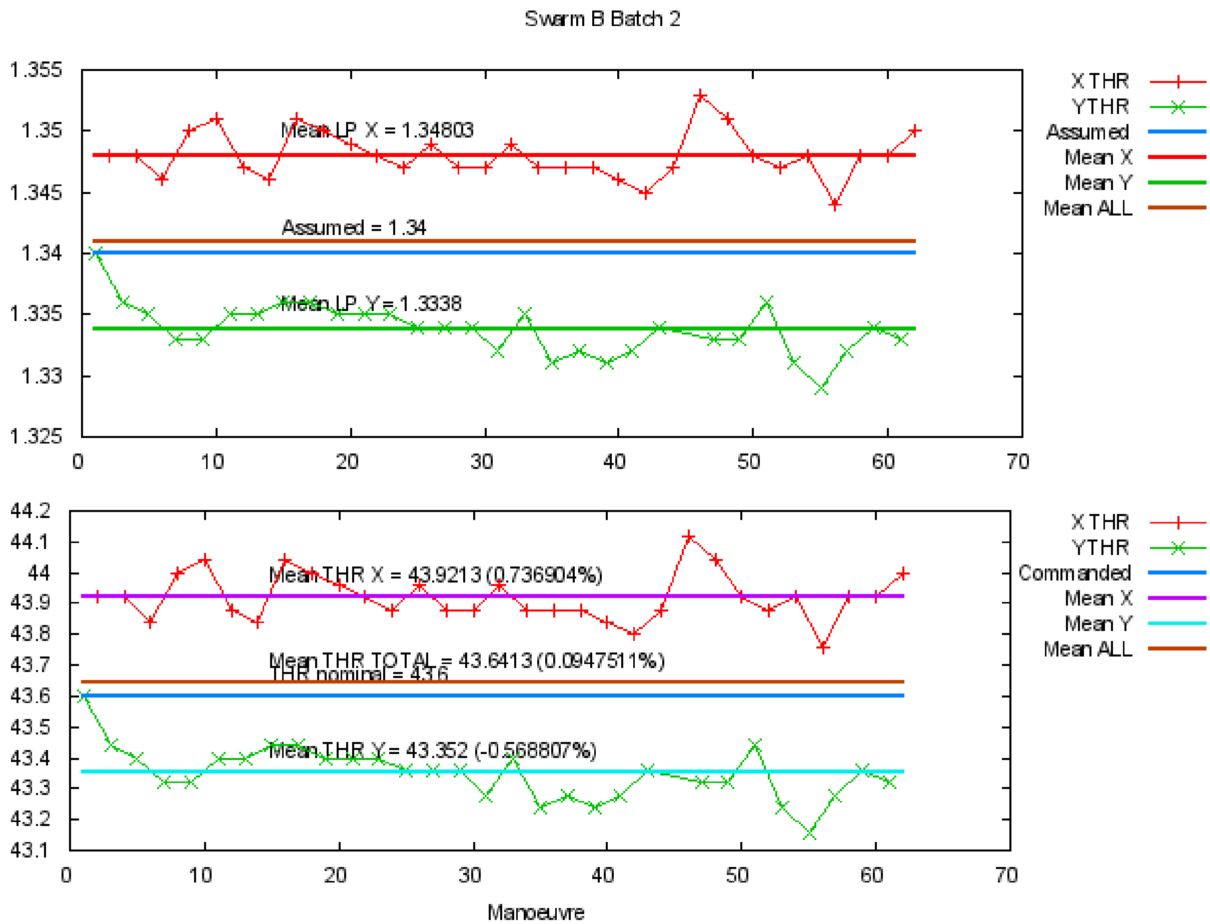

Figure 11 Swarm Bravo Batch 2 Manoeuvre Performance from TM in term of LPP (top) and derived thrust (bottom).

The calibration of the first batch of Swarm Bravo was performed and the FD system updated so that the commands took this performance into account for the second batch. This was successful and resulted in an accurate commanding of Swarm Bravo for this batch in terms of delta v magnitude but for the direction no calibration was possible. Of course the errors in batch 1 were corrected for in the commanded directions of batch 2 but the FD system does not allow a priori biases in DV direction to be input in the commanded directions as it was not foreseen that predictable errors in the spacecraft attitude would be seen.

Figure 12 shows again roll biases of -2 degrees when using the Y-THR. Roll biases are also seen using the X-THR but these do not affect the orbit. Yaw biases of +1 degree and -1 degree at the descending node and ascending node manoeuvres using Y-THR and X-THR respectively are seen. This results in more inclination change and less semi major axis changed being performed than planned at each node.

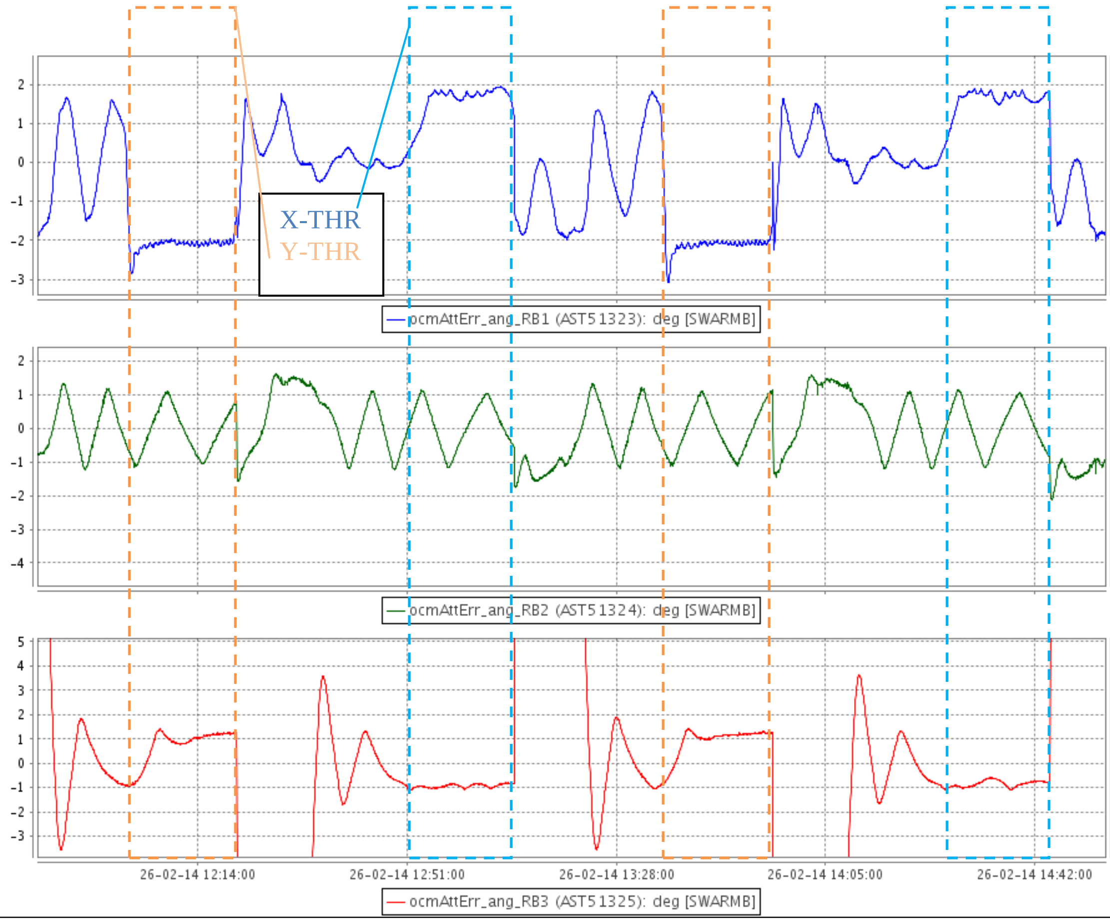

Figure 12 Swarm Bravo Batch 1 Attitude Errors in roll, pitch and yaw (top, middle bottom).

Finally, the orbit change performed for Swarm Bravo in semi major axis and inclination was 21.6 km, 0.198 degrees respectively, in batches of 11.8 km and 0.109 degrees and 9.7 km and and 0.089 degrees respectively.

4.2.8 Swarm Charlie Manoeuvre Batches

The Swarm Charlie manoeuvre execution had to be more precise than that of Alpha and Bravo because Charlie manoeuvres inserted the spacecraft into a constellation in RAAN, ALA and eccentricity. For this reason the drift had to be slowed gradually in such a way as to reduce to a minimum the impact of manoeuvre failures on the successful constellation realization and in order that manoeuvre execution errors could be compensated for by subsequent smaller batches.

The Swarm Charlie batches consisted of four batches making combined changes to the semi major axis and inclination:
C1: 46 OCMs between 05:06 UTC 4th March and 16:50 UTC 5th March
C2: 44 OCMs between 04:19 UTC 25th March and 14:25 UTC 26th March
C3A: 36 OCMs between 20:00 UTC 8th April and 23:48 UTC 9th April
C3B: 12 OCMs between 02:23 UTC 11th April and 11:45 UTC 11th April

Finally two pairs of drift stop manoeuvre (batch CDS1 and CDS2), purely in the along-track direction reduced the drift and eccentricity difference to zero and inserted the spacecraft into their operational constellation separated in ascending node crossing by 9 seconds.

From Fig. 9 it is clear that the batches are separated by 3 weeks between C1 and C2 and 2 weeks between C2 and C3A/B. C3A and C3B are in the same week. Clearly the simplest implementation of the Swarm Charlie manoeuvres would be to execute them all in one large batch but such a solution offers no solution to the problem of re-planning in case of batch execution failures. In fact, the reason for the placement of the manoeuvres as they were executed was in response to a re-plan because of the failure of batch A1. The previous plan allowed two weeks between batches so that there was always one week in which a failed manoeuvre batch could be re-planned and executed in case of problems.

The execution of the Charlie manoeuvre batches was similar to that of the other spacecraft. The performance of the batches in terms of the spacecraft attitude performance was qualitatively identical to that of Alpha and Bravo. In particular the same roll bias during Y-THR manoeuvres (which result in eccentricity vector errors) and yaw bias during both X and Y THR manoeuvres (which result in a skew towards greater semi major axis change than expected) are seen. However, the size of the manoeuvre batches gradually diminishing means that the errors can be compensated for in later batches so that only errors in inclination targeting of the final C3B batch give rise to any RAAN drift after the final manoeuvre execution. Also, errors in the eccentricity targeting of the Swarm Charlie batches were compensated by the final drift stop batches.

4.2.9 Fuel Consumption During the Orbit Insertion Phase

The expected fuel consumption during the OIP was:

Higher	29.65 OCT + 4.1 ACT = 33.75 kg Total
Lower pair	34.5 OCT + 4.5 ACT = 39.0 kg Total

Based on a launch at 490 km altitude, the lower pair to reduce by 30 km altitude and 0.2 degrees inclination, the higher spacecraft to increase by 20 km altitude and 0.2 degrees inclination.

What we have actually spent on the OIP is

Higher	31.0 OCT + 5.5 ACT = 36.5 Kg Total
Lower	32.4 OCT + 5.1 ACT = 37.5 Kg Total

The ACT consumption during the OIP was higher than expected by around 1 kg per spacecraft. This is because of the higher than expected actuations especially when using the Y-THR. The OCT spending was less than expected for the lower pair, and more for the higher spacecraft: Swarm Alpha semi major axis change was actually 26 km rather than 30, because of the need to target a semi major axis which gave an integer number of relative orbits between the lower pair. The inclination change was 0.20 degrees as planned. Swarm Bravo SMA change was actually 1.6 km higher than planned because Bravo lost 1.6 km altitude before the manoeuvre execution started. The inclination change was 0.2 degrees as planned.

4.2.10 Atmosphere and Coefficient of Drag

As part of the daily orbit determination daily scale factors for the drag coefficient were determined over each 24 hour period. The Atmospheric density model used was NRLMSISE-00 using USAF/NOAA Solar Geophysical Activity Report for the Solar flux and geomagnetic Ap values.

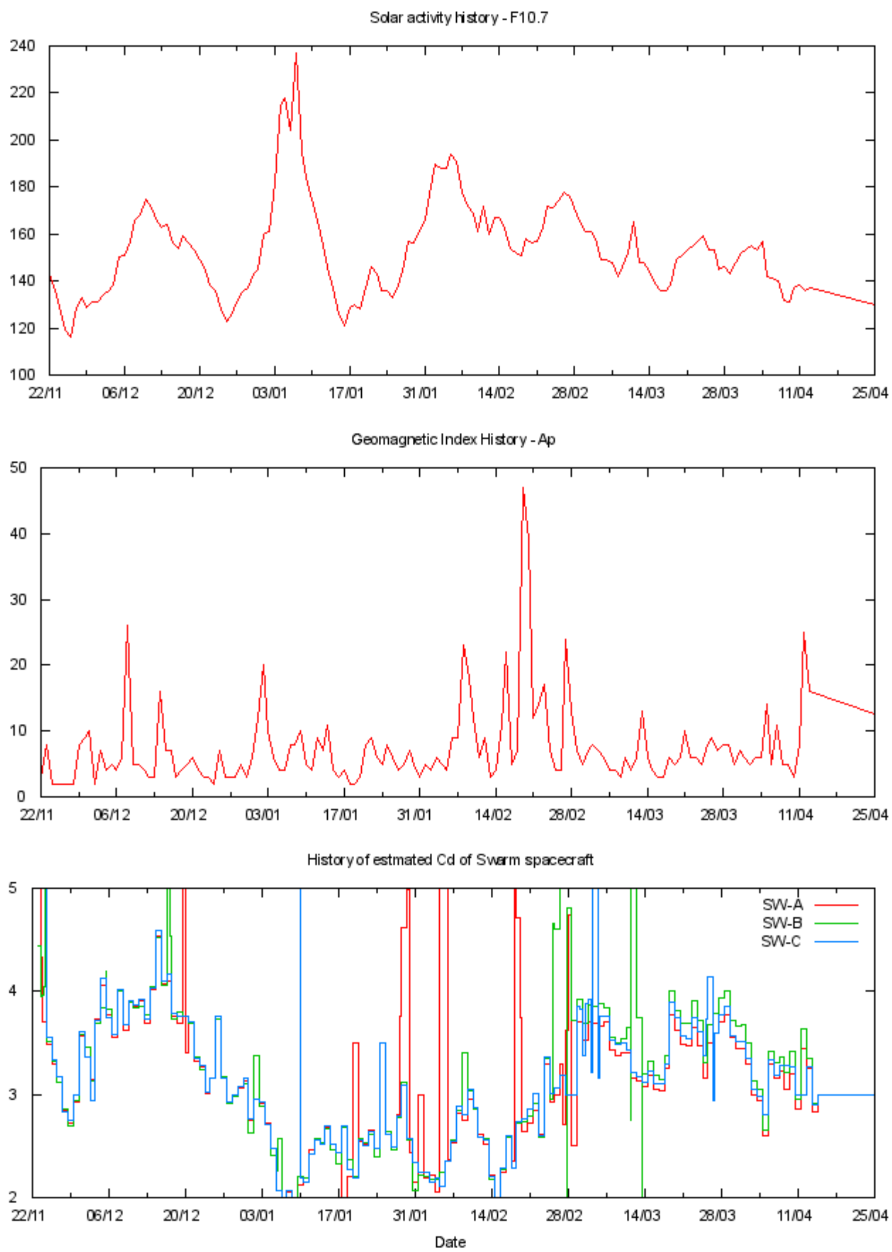

Figure 13 Atmospheric and Geomagnetic Indices and Cd history

The C_d are plotted for all spacecraft along with the F10.7 and Ap history for the OIP from launch up to the start of the routine phase in Fig. 13. The C_d history for all three spacecraft show a very similar evolution except for times when manoeuvre batches or calibration slews show a different C_d for one of the spacecraft. It seems that the period nature of the C_d is correlated with the LTAN, which is around 12:00 at the end of December and 06:00 on the 1st of March.

As the orbital planes of the upper spacecraft and the lower pair separates further investigation into the evolution of the drag parameters will follow. Particular attention will be paid to the evolution of the drag parameters during the routine phase for the lower pair as a function of LTAN.

4.2.11 Orbit Evolution During the Orbit Insertion Phase

Figure 14 shows the evolution of the semi major axis (at each ascending node) for all three spacecraft during the orbit insertion phase and in particular during the final weeks at the end of the phase when the SMA of Swarm Charlie and Alpha are brought together. Also in Fig. 17 is plotted the difference in SMA between Swarm Charlie and Swarm Alpha during this phase.

Figure 15 shows the evolution of the inclination (at each ascending node) for all three spacecraft during this phase and during the final weeks when the inclination of Charlie and Alpha are matched. Figure 18 shows the difference in inclination between the lower pair and Fig. 19 shows the evolution of the RAAN finally converging at 1.4 degrees at the end of this phase.

Figure 16 shows the evolution of the eccentricity vector (osculating eccentricity vector at the ascending node) for all three spacecraft. Notice that the final targeting of the eccentricity to the frozen value was not precisely achieved due to the spacecraft attitude during the Y-THR manoeuvres in particular. In Fig. 20 is shown the evolution of the difference in eccentricity vectors between Charlie and Alpha during the orbit insertion phase. Note from Fig. 21 that this difference at the end of the final drift stop manoeuvre was achieved to an accuracy of less than 5.10^{-6}.

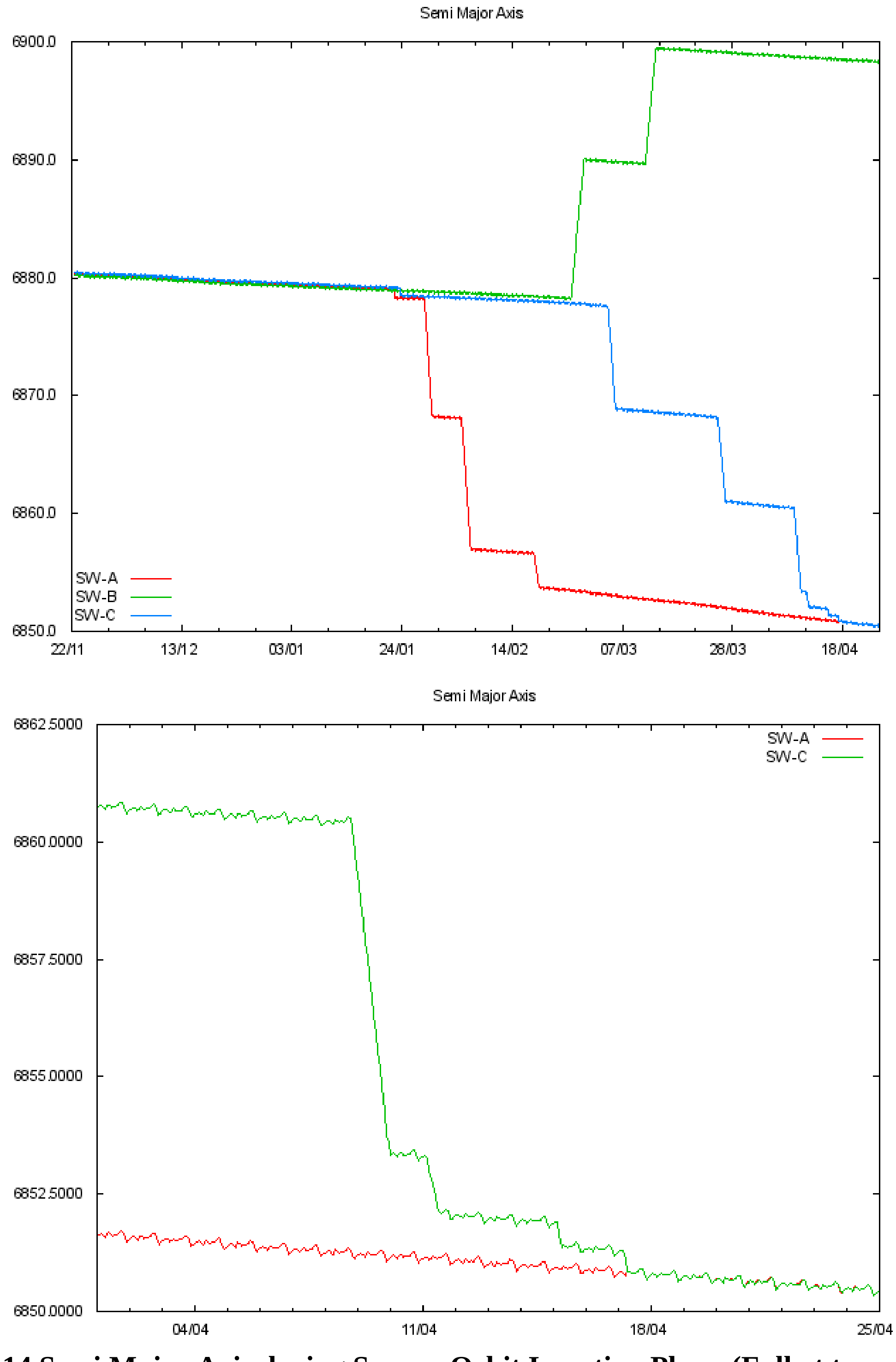

Figure 14 Semi Major Axis during Swarm Orbit Insertion Phase (Full at top and final weeks at bottom)

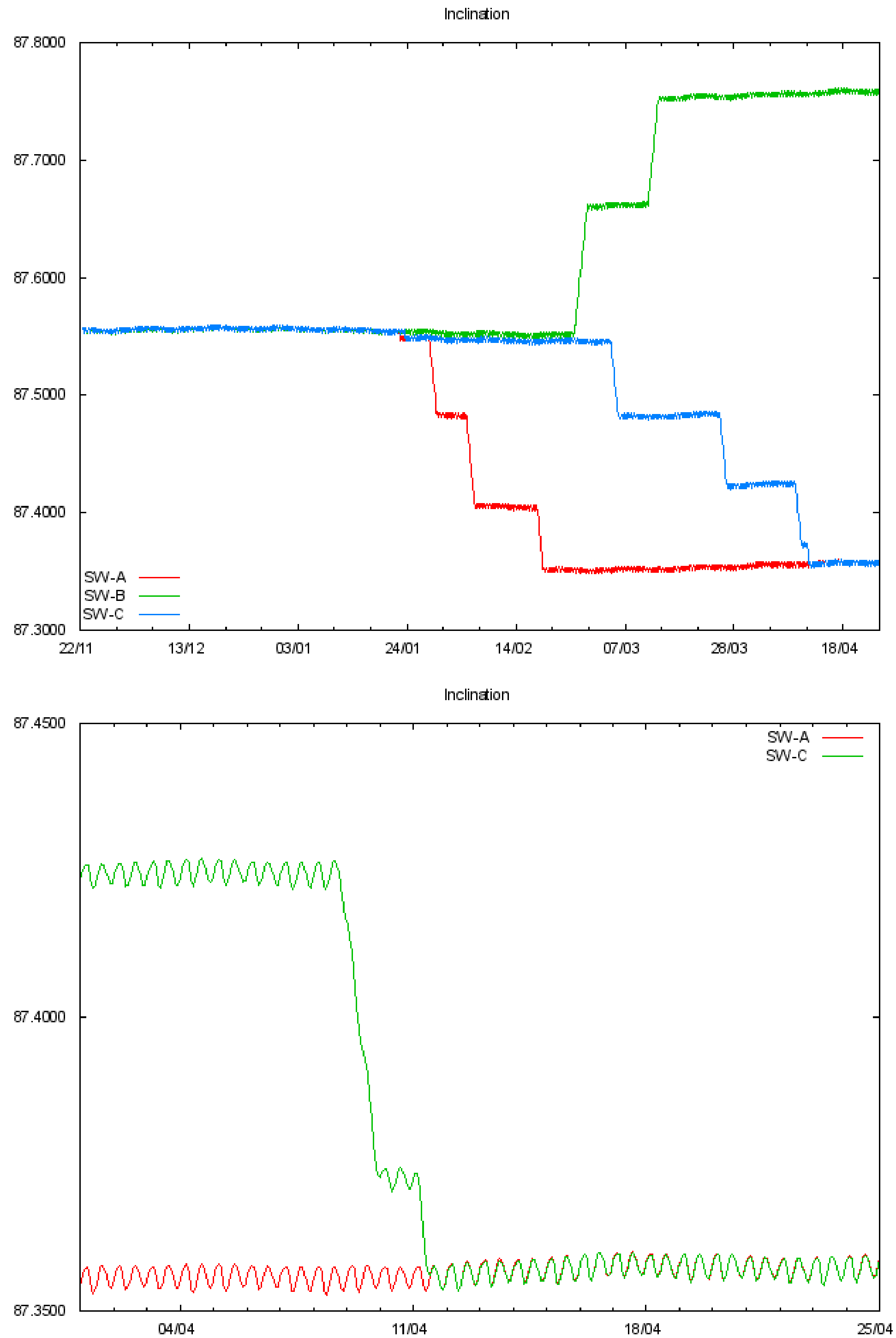

Figure 15 Inclination during Swarm Orbit Insertion Phase (Full at top and final weeks at bottom)

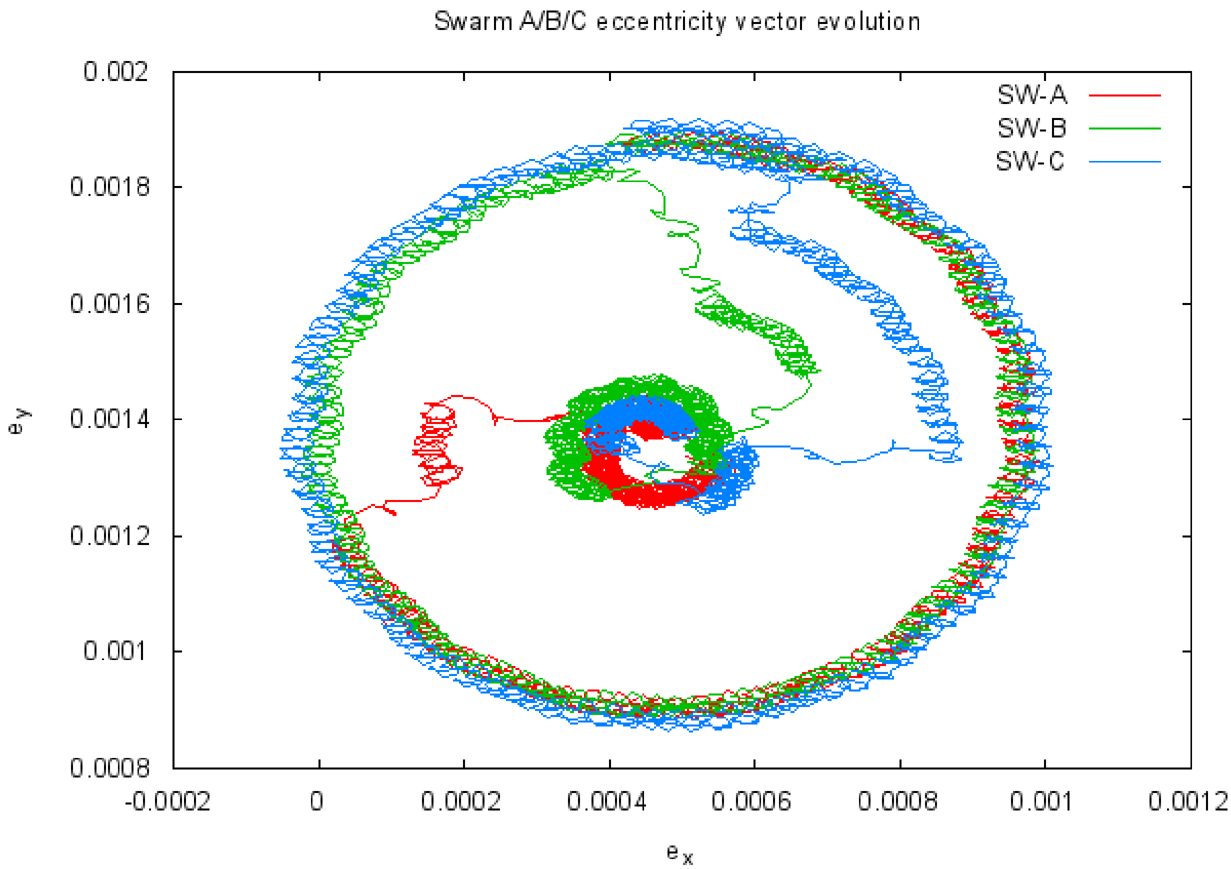

Figure 16 Eccentricity Vector Evolution during Orbit Insertion Phase

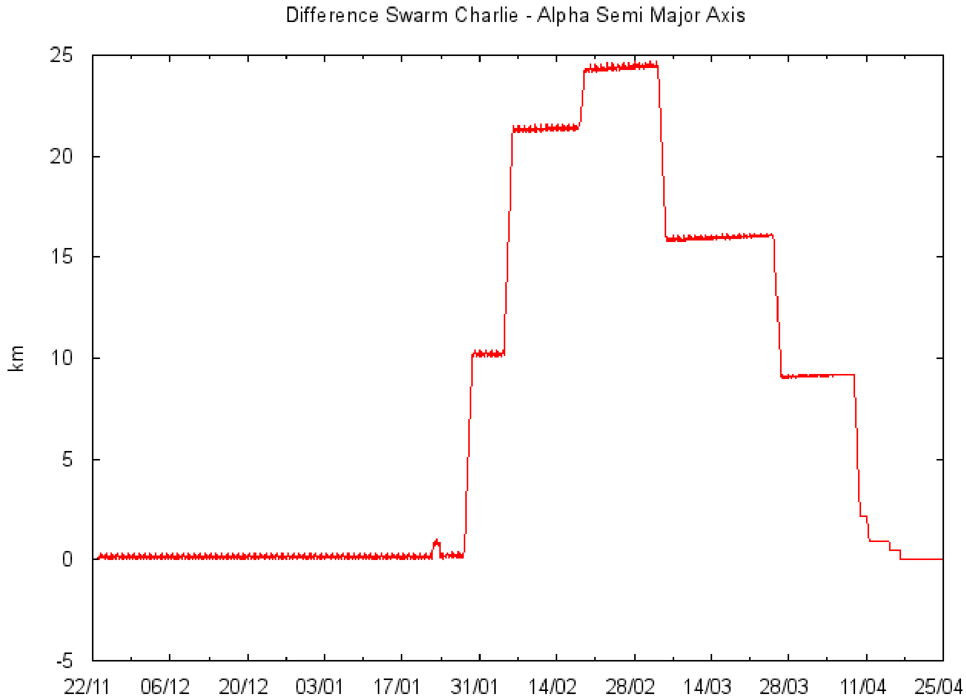

Figure 17 Semi Major axis difference Swarm Charlie - Alpha

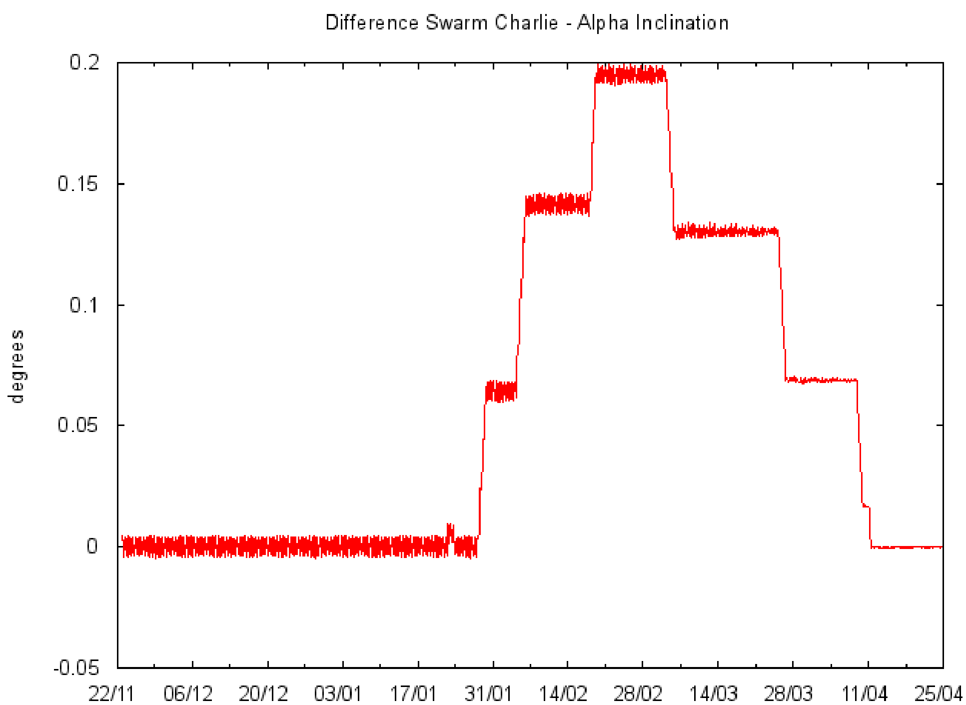

Figure 18 inclination difference Swarm Charlie - Alpha

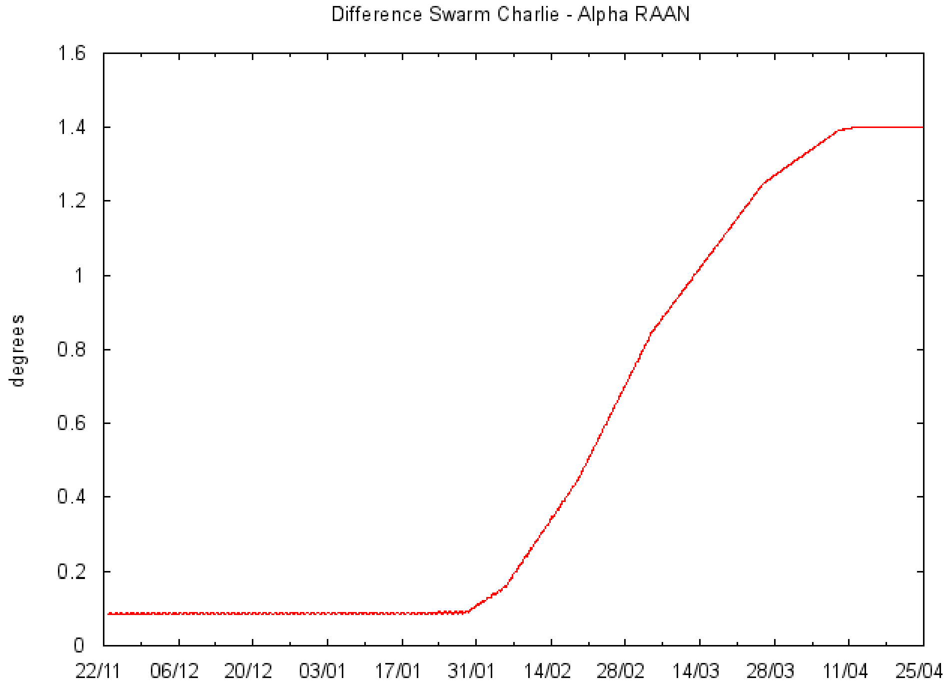

Figure 19 RAAN difference Swarm Charlie – Swarm Alpha

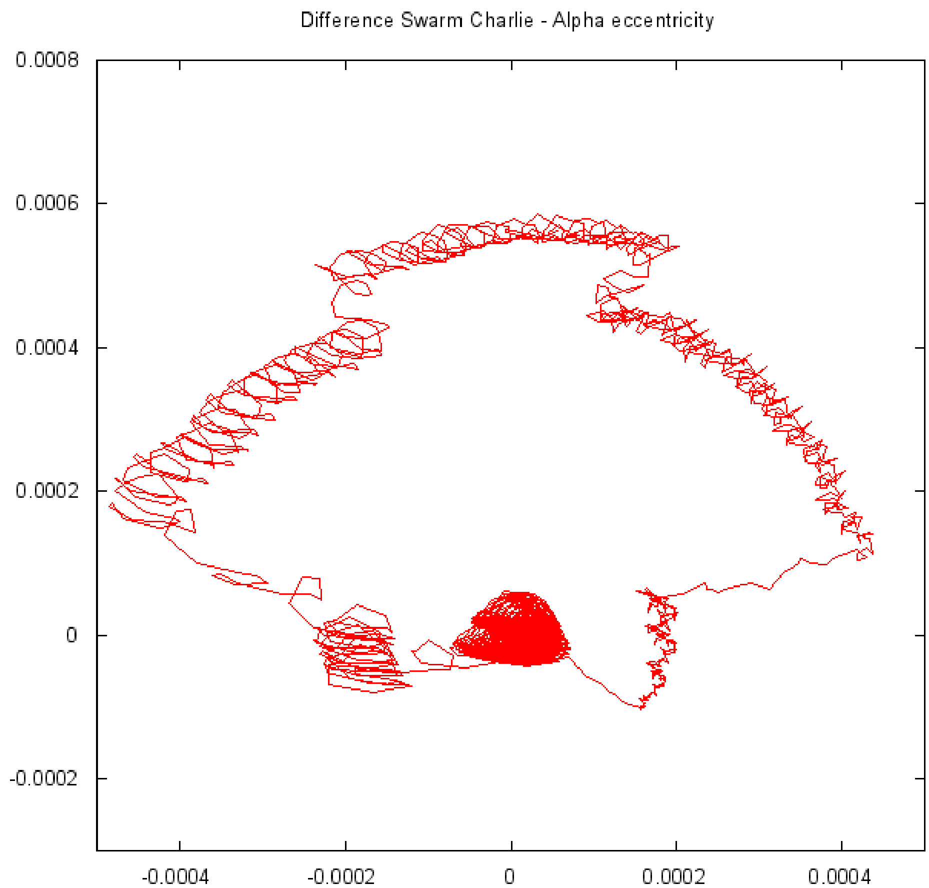

Figure 20 Eccentricity vector difference Swarm Charlie – Swarm Alpha

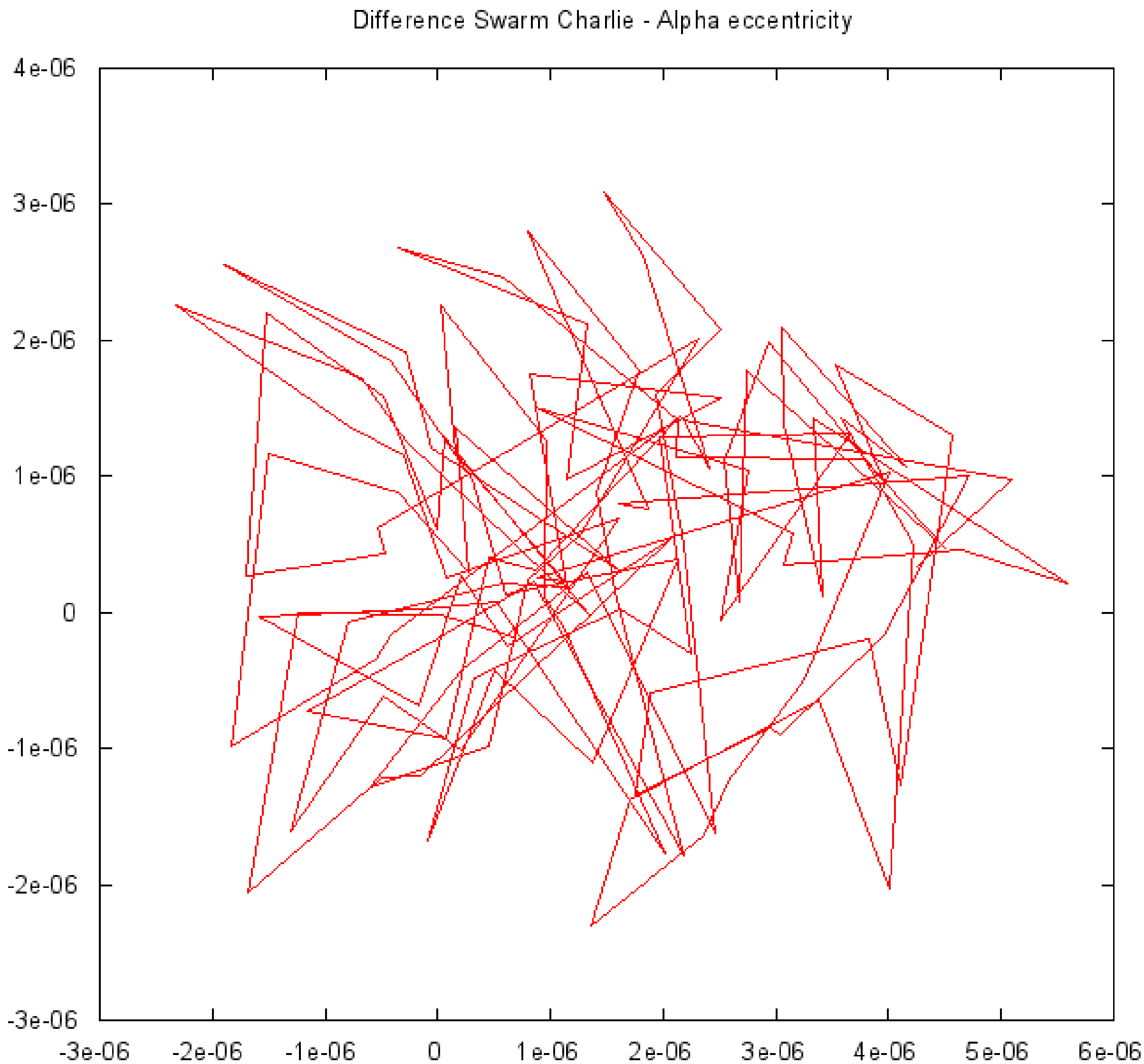

Figure 21 Final eccentricity difference between the lower pair

5. Conclusions

The Swarm orbit insertion phase was a challenging and rewarding part of a very interesting mission from a Flight Dynamics perspective.

The pre-launch mission design was adapted as a result of a delay in the manoeuvre phase, as a result of requests from mission scientists and as a result of the abort of the first main batch of manoeuvres. All of these significant changes could be easily absorbed because of the meticulous approach to planning of the team members and because of the use of flexible manoeuvre optimization software (MANTRA) to perform calculations. The execution of the manoeuvres was performed using X/Y THR, X/X THR and Y/X THR at the ascending/descending nodes respectively. Problems in manoeuvre execution were worked around by the team resulting in a successful orbit insertion.

The spacecraft performed with excellent reliability after some initial problems, which were resolved quickly by the industrial team. This reliability meant that many of the carefully established security measures in the design of the orbit insertion phase were unused.

The final orbit constellation was established on 17th April when the Charlie DS2 batch was executed. The final constellation was Swarm Charlie and Alpha separated by 1.3999 degrees in RAAN, 9 seconds in ascending node crossing time and with a drift in node crossing time less than 1 second per week. The eccentricity difference between the lower pair was less than 5.10^{-6}.

We now look forward to an interesting routine phase with enough fuel on board to ensure operations for several years to come.

7. References

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