OPTIMISATION OF
CLUSTER CONSTELLATION MANOEUVRES

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ABSTRACT *– The Cluster mission is an investigation of the Earth's magnetosphere using four spacecraft in nearly identical polar orbits of equal period. The orbits are designed such that the spacecraft fly in a constellation forming regular tetrahedra at two selected points of particular scientific interest. The paper deals with the optimisation and implementation of manoeuvres to achieve the constellation chosen for the first period of northern cusp crossings. How particular functionality of the optimisation software influences manoeuvre planning is described. Operational experience gained during manoeuvre implementation is discussed together with the achieved constellation accuracy.*

KEYWORDS: Cluster, Constellation, Manoeuvre, Optimisation.

INTRODUCTION

The Cluster mission is an investigation of the Earth's magnetosphere using four spacecraft in nearly identical polar orbits of equal period. The orbits are designed such that the spacecraft fly in a constellation forming regular tetrahedra at two selected points of particular scientific interest. Regular tetrahedra are desirable as they provide the best three dimensional coverage of the scientific phenomena. Furthermore, by equalising the orbital periods, the same evolution of the constellation is repeated each revolution.

The orbits have a perigee radius of about four Earth radii and an apogee radius of 19.6 Earth radii. Each year, during a 1.5 month period centred around the end of February, an arc of the orbits passes near the northern cusp of the Earth's magnetosphere. During these periods, another arc of the orbits crosses the magnetopause and the bow shock in the southern hemisphere. The first constellation of the Cluster mission, the northern cusp constellation, is specified by locating the first tetrahedron near the northern cusp crossing and the second tetrahedron between the magnetopause and bow shock. This paper deals with the optimisation and implementation of the manoeuvres required to achieve this constellation. The evolution of the constellation over one revolution is shown in Fig. 1 and further details of tetrahedron location, size, orientation and required accuracy are given in the next section.

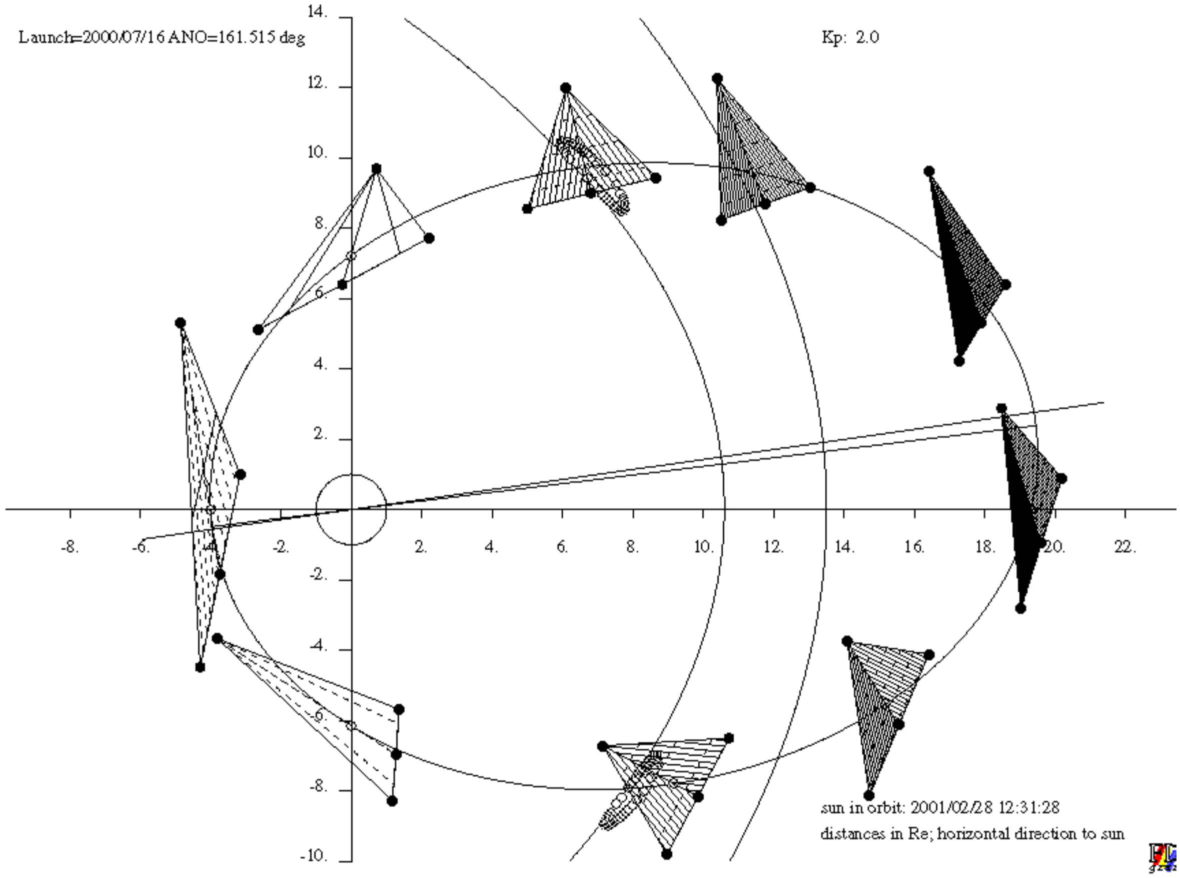

Fig. 1. Constellation Evolution

To ensure that full scientific data is recovered from the northern cusp constellation, it is intended that it is formed at least two months before the central crossing time and remains available with the appropriate accuracy for a four month period. This requirement is made difficult to satisfy by the fact that for scientific reasons, the four month period shall remain manoeuvre free. During the course of the mission other spacecraft constellations will be used, with the constellation being changed typically every six months.

The Cluster spacecraft are spin stabilised and have a typical thruster configuration which allows the execution of both axial and radial manoeuvres. The start of the constellation manoeuvre sequence follows the completion of the final main engine manoeuvre of the launch and early orbit phase (LEOP) of the mission. The manoeuvre sequence has a standard form; an axial manoeuvre at perigee, one or two radial manoeuvres, an axial manoeuvre at apogee and finally a further axial manoeuvre at perigee. The sequence of manoeuvres is repeated in full, or in part, as many times as necessary to achieve the required constellation accuracy. The paper describes this standard sequence and considers how it is influenced by advanced functionality of the optimisation software. Operational experience gained from manoeuvre implementation is discussed and includes comments on minimising the number of constellation manoeuvres by using biased spin change and slew manoeuvres for orbit control. Finally, results on the accuracy achieved for the northern cusp constellation are presented.

CONSTELLATION SPECIFICATION

Tetrahedron Geometry

The mathematical background of the two tetrahedra strategy is described in [1]. The first tetrahedron at the northern cusp corresponds to a true anomaly of approximately 131 degrees. The target inter spacecraft distance defining the size of the tetrahedron is selected to be 600 km. The second tetrahedron is placed between the magnetopause and bow shock at a true anomaly of approximately 227 degrees. The choice of 600 km for the first tetrahedron forces a second tetrahedron at the specified location to have size 598 km. To enhance the scientific return of the mission, the orientation of the southern hemisphere tetrahedron is selected to have one of its planes close to parallel to the surface of the magnetopause and the bow shock. This orientation can be freely chosen as although it influences the orientation of the northern cusp tetrahedron, there are no requirements on the orientation of the northern cusp tetrahedron.

Accuracy Requirements

The accuracy requirements for the Cluster constellations are expressed as short term and long term requirements on the inter spacecraft distances (ISD) of the first tetrahedron.

Short Term Accuracy

At a time close to the central crossing time,

$$| \mathrm{Mean\_ISD} - \mathrm{Target\_ISD} | < 0.1*\mathrm{Target\_ISD} \quad (1)$$

and

$$\mathrm{Max\_ISD} - \mathrm{Min\_ISD} < 0.02*\mathrm{Target\_ISD} \quad (2)$$

Long Term Accuracy

For each orbital revolution, over a period starting two months before the central crossing time and ending two months after the central crossing time, there shall be a time when the spacecraft are near the true anomaly specified for the first tetrahedron for which

$$\mathrm{Max\_ISD} - \mathrm{Min\_ISD} < 0.1*\mathrm{Target\_ISD} \quad (3)$$

This formulation of the accuracy requirements will also be applied to future constellations of the Cluster mission.

The first of these requirements that the mean inter spacecraft distance is within 60 km of the target inter spacecraft distance, is easy to satisfy. This reflects the fact that for the scientific success of the mission, the exact size of the tetrahedron is not so important. In other words, regular tetrahedra of sizes 540 km or 660 km would be considered as corresponding to perfect constellations. What is much more important is how close the achieved configuration is to a regular tetrahedron. This is governed by the second and third constraints which force the six inter spacecraft distances to take similar values. The allowed variation in inter spacecraft distance is 12 km for the short term constraint and 60 km for the long term constraint.

The second requirement is difficult to satisfy because the four month period around the central crossing time is to be kept manoeuvre free. The magnitude of the challenge set by this constraint can be appreciated by converting it into a requirement on the orbital periods of the four spacecraft which are close to 57 hours. When the end of the manoeuvre sequence is two months before the central crossing time, there are approximately 24 orbital revolutions before the crossing is reached. Therefore, a one second period error accumulates to a 24 second error at the crossing time. As the spacecraft move at approximately 2.3 km/sec at the northern cusp crossing time, a timing error of 24 seconds produces an along track error of 55.2 km. This is 4.6 times greater than the 12 km requirement. Therefore, the maximum period error allowed in this case is 0.2 seconds for a period in the order of 205200 seconds.

Of the three requirements, the long term accuracy requirement is the most important and the most difficult to satisfy. The second short term accuracy requirement is satisfied by conducting drift manoeuvres to bring the spacecraft together at the specified time. However, if the necessary drift manoeuvres are large, the spacecraft must be widely separated at the beginning of the manoeuvre free period and will not satisfy the long term accuracy requirement. Furthermore, a drift that acts over the first two months to bring the spacecraft together at the crossing time subsequently causes the spacecraft to move apart after the crossing time. Therefore, if a large drift is necessary to bring the spacecraft together, this same drift will cause the constellation to quickly degrade on the period after the crossing time.

MANOEUVRE PLANNING

This section discusses the basic manoeuvre sequence used to achieve the Cluster constellation and how functionality available within the optimisation software helps reduce the required number of manoeuvres.

Standard Manoeuvre Sequence

Each spacecraft has a target orbit which passes through a corner of a regular tetrahedron at two points on the orbit. A spacecraft can achieve its target orbit by implementing a basic sequence of manoeuvres comprising; an axial manoeuvre at perigee, one or more radial manoeuvres, an axial manoeuvre at apogee and a further axial manoeuvre at perigee. The first and second axial manoeuvres at perigee are often referred to as drift start and drift stop manoeuvres respectively.

The attitudes of the spacecraft are all similar and such that the axial manoeuvres have a considerable in-plane component at apogee and perigee. As such the axial manoeuvres are largely correcting in-plane errors. The out-of-plane errors, generated by required changes in the orbital inclination and node, are corrected by the radial manoeuvres. If the out-of-plane errors are small they can be corrected by a single radial manoeuvre close to apogee. For larger out-of-plane corrections, two radial manoeuvres may be needed located typically at true anomalies 120 degrees and 240 degrees. As the execution of the LEOP inclination manoeuvre for each spacecraft was extremely accurate, the out-of-plane error remaining to be corrected by the constellation manoeuvres was small and could be achieved with one radial manoeuvre.

If the basic sequence of manoeuvres is perfectly executed, and there are no other operations disturbing the orbit, the target orbit is perfectly achieved and there will be no need for any further manoeuvres. However, there is always some dispersion on manoeuvres and for Cluster one percent of the requested deltaV was a typical dispersion value. Some of the early constellation manoeuvres are large enough that a one percent error prevents the constellation being formed with the necessary accuracy. In this case, a trim manoeuvre is conducted to achieve the deltaV remaining from the original manoeuvre. There comes a point where the manoeuvre is suitably small that its dispersion will not cause the constellation accuracy requirements to be violated. The procedure for forming any of the Cluster constellations is therefore to repeat the basic manoeuvre sequence in full, or in part, as many times as necessary until the required accuracy is achieved. The number of times the basic sequence, or parts of it, is repeated is minimised when the manoeuvres can be made small as early as possible.

It was anticipated that only one repeat sequence would be required to form the northern cusp constellation, and furthermore, that the repeat sequence would only consist of drift start and drift stop trims for each spacecraft. It was not planned to correct the errors remaining after the radial manoeuvres. The radial manoeuvre error is an out-of-plane error, which does not grow with time, and was expected to make only a small contribution to the total error. Moreover, the axial manoeuvres at apogee control the along track position at the second tetrahedron. As the accuracy of this tetrahedron is less important than that of the first tetrahedron, trims of the apogee axial manoeuvres were also not planned.

The perigee manoeuvres control the along track position at the first tetrahedron and the orbital periods. With two perigee trim manoeuvres available for each spacecraft, the along track error at the first constellation can be maintained at zero and the spacecraft periods can be equalised. When there is only one perigee manoeuvre remaining for each spacecraft, only the along track error at the crossing time can be maintained at zero. This is done by adjusting the semi-major axes so the spacecraft drift to the target tetrahedron at the central crossing time.

The basic sequence of manoeuvres plus the part repeat sequence is referred to here as the standard manoeuvre sequence. Its original planning in terms of manoeuvre type, spacecraft number and orbital location is described in Fig. 2.

	Drift Start			Radial		Axial			Drift Stop				Trim 1				Trim 2
	1			1		1			1				1				1
	2			2		2			2				2				2
	3			3		3			3				3				3
	4			4		4			4				4				4
a0	p0	a1	p1	a2	p2	a3	p3	a4	p4	a5	p5	a6	p6	a7	p7	a8	p8

Fig. 2. The Standard Manoeuvre Sequence

It is seen from Fig. 2 that a series of 24 constellation manoeuvres were planned; six manoeuvres per spacecraft, four from the basic sequence plus two trims from the repeat sequence. The manoeuvre locations are selected such that whenever an axial manoeuvre is to be conducted, there is a manoeuvre free perigee passage prior to it to allow for accurate orbit determination. The next section describes how advanced functionality offered by the optimisation software reduces the required number of constellation manoeuvres.

Software Description

The Cluster constellation manoeuvre optimisation software minimises in an iterative fashion a non-linear cost functional subject to linear constraints. The linear constraints are sufficient to ensure that the spacecraft orbits are those associated with the two tetrahedra strategy. The user gives the software a sequence of manoeuvre opportunities at selected true anomalies or epochs. The initial guess can be the basic manoeuvre sequence with all manoeuvres assigned a zero deltaV. The software then adjusts the size and position of the manoeuvres until the optimal solution is found. Manoeuvre opportunities that are not needed continue to be allocated zero deltaV.

The cost functional used for the northern cusp constellation was the total fuel consumption. For manoeuvres to future constellations the cost function will be enhanced by the addition of a term to balance the remaining fuel between spacecraft. The software then favours solutions that manoeuvre the spacecraft with most fuel. The requirement is sensible as all four spacecraft are needed to acquire a three dimensional picture of scientific data and it avoids the case that one spacecraft runs out of fuel considerably before the others. The requirement was not used for the northern cusp constellation as the manoeuvre deltaVs were not large enough to make it worthwhile.

Target Optimisation

An exact position for a target tetrahedron can be defined in inertial space. However, as the area of the magnetosphere constituting the northern cusp is large, the position of the target can vary by several hundred kilometres without degrading the scientific return of the mission. This allows the flexibility to choose the position of the target to best fit the current position of the four spacecraft. For example, if the orbits of all four spacecraft are slightly lower than necessary, rather than increasing the semi-major axis for each spacecraft, a correspondingly lower target can be selected. The constellation manoeuvre optimisation software includes the option to re-optimise the target tetrahedra. This is an advanced feature of the software which has the benefit of reducing the number of manoeuvres necessary to achieve a constellation. This reduces the associated fuel consumption and the required operational resources.

It also introduces considerable flexibility into the process of forming the constellation. For example, it is possible to build the constellation without manoeuvring one of the spacecraft at all. The orbit of this spacecraft then defines the new target, and the other spacecraft are manoeuvred to form a constellation around it. This is controlled within the software by not allowing the selected spacecraft any manoeuvre opportunities.

The Selected Manoeuvre Sequence

If one of the spacecraft is not manoeuvred, four manoeuvres are saved from the basic sequence; two perigee axial manoeuvres, the radial manoeuvre and the apogee axial manoeuvre. Furthermore, the two perigee axial trims from the repeat sequence are also saved. Therefore, using the option of optimising the target, it is known that there exist solutions with only 18 constellation manoeuvres. However, a solution where one spacecraft is not manoeuvred at all may not be optimal. Therefore, the software is run with the option to optimise the target but allowing all manoeuvre opportunities for all spacecraft. The solution found has 17 manoeuvres and is shown in Fig. 3. It is referred to here as the selected manoeuvre sequence.

	Start			Rad		Ax			Stop					Trim1		Trim2
	1			0		1			1					1		1
	0			2		2			2					0		2
	3			3		0			3					0		0
	4			4		4			0					4		4
a0	p0	a1	p1	a2	p2	a3	p3	a4	p4	a5	p5	a6		p45		p53

Fig. 3. The Selected Manoeuvre Sequence

One manoeuvre from the basic sequence is saved for each spacecraft; the drift start manoeuvre is saved for S/C 2, the radial manoeuvre is saved for S/C 1, the apogee axial manoeuvre is saved for S/C 3 and the drift stop manoeuvre is saved for S/C 4.

It is known that optimising the target is likely produce an optimal solution with six trim manoeuvres rather than eight. It should be appreciated that which two of the trim manoeuvres will be saved cannot be known until all the manoeuvres of the basic sequence have been executed and all other factors perturbing the spacecraft orbits have been taken into account. The fact that the trim manoeuvres are delayed by spacecraft commissioning activities is noted by using their actual perigee number in Fig. 3. The software chooses a solution where there are no trim manoeuvres for S/C 3. In addition, as the drift start trim found for S/C 2 is considered too small to implement, the selected manoeuvre sequence has only five trim manoeuvres, two drift start trims and three drift stop trims.

IMPLEMENTED MANOEUVRES

The period of the first constellation manoeuvres was demanding from an operations point of view as, in particular, the deployment of the rigid booms was being conducted in parallel. To distribute operations, it was decided to manoeuvre at most two spacecraft together; S/C 1 and S/C 4 were treated as one pair, S/C 2 and S/C 3 as the other and the sequence of Fig. 4 was implemented.

Rad	Start	Rad	Start	Ax		Ax	Stop		Stop					Trim1		Trim2
	1	0				1			1					1		1
2			0	2			2							0		2
3			3	0			3							0		0
	4	4				4			0					4		4
a0	p0	a1	p1	a2	p2	a3	p3	a4	p4	a5	p5	a6		p45		p53

Fig. 4. Implementation of the Selected Manoeuvres

In order to complete all the operations by perigee 4, the radial manoeuvres of S/C 2 and S/C 3 where conducted at apogee 0 before their drift start manoeuvres. Whether the radial manoeuvres are conducted before or after the drift start manoeuvres is not important as they are correcting different orbital elements and are largely decoupled from each other. The requirement for an undisturbed perigee passage prior to an axial manoeuvre is also satisfied by this sequence.

The selected manoeuvres of Fig. 4 were not the only constellation manoeuvres conducted. Four additional trim manoeuvres were executed; two test manoeuvres and two manoeuvres to correct orbital perturbations caused by spin and slew manoeuvres. The full list of constellation manoeuvres is given in Table 1.

Basic Sequence: First Pass

The first twelve constellation manoeuvres were conducted in parallel with the deployment of the rigid booms. As rigid boom deployment involved slew and spin manoeuvres, the deployment had to be careful scheduled outside periods on which the spacecraft orbits were to remain undisturbed for purposes of orbit determination.

Table 1. The Constellation Manoeuvres

ID	Manoeuvre	S/C	Epoch	Loc.	True Anomaly (degrees)	Thr.	Duration (seconds or pulses)	DV (m/s)
Basic Sequence: First Pass								
1	Radial	S/C 2	00/08/15 22:00	Ap 0	175.3	RAD	21.5 s	0.137
2	Radial	S/C 3	00/08/16 21:09	Ap 0	225.6	RAD	20.0 s	0.130
3	Drift Start	S/C 1	00/08/17 05:35	Pg 0	351.0	AX+	53.0 s	0.768
4	Drift Start	S/C 4	00/08/17 05:39	Pg 0	356.2	AX+	16.0 s	0.226
5	Radial	S/C 4	00/08/18 06:56	Ap 1	174.5	RAD	31.8 s	0.195
6	Drift Start	S/C 3	00/08/19 14:30	Pg 1	356.7	AX-	13.0 s	0.375
7	Apogee Axial	S/C 2	00/08/20 19:24	Ap 2	180.2	AX-	40.0 s	1.128
8	Apogee Axial	S/C 1	00/08/23 02:08	Ap 3	176.3	AX+	31.0 s	0.895
9	Apogee Axial	S/C 4	00/08/23 03:59	Ap 3	179.3	AX+	40.0 s	1.140
10	Drift Stop	S/C 3	00/08/24 09:17	Pg 3	15.7	AX+	11p 485w	0.598
11	Drift Stop	S/C 2	00/08/24 08:44	Pg 3	349.4	AX+	3p 367w	0.121
12	Drift Stop	S/C 1	00/08/26 17:39	Pg 4	343.3	AX-	4p 497w	0.224
Additional Test Trims								
13	Perigee Trim	S/C 3	00/08/26 18:04	Pg 4	0.0	AX+	1p 43w	0.005
14	Perigee Trim	S/C 4	00/08/26 18:06	Pg 4	0.0	AX-	1p 26w	0.003
Additional Trim following Boom Deployment								
15	Perigee Trim	S/C 1	00/10/18 02:39	Pg 26	0.0	AX-	1p 105w	0.012
Basic Sequence: Second Pass (Perigee Trim Subset)								
16	Perigee Trim	S/C 1	00/12/02 07:37	Pg 45	0.0	AX+	1p 35w	0.004
17	Perigee Trim	S/C 4	00/12/02 07:42	Pg 45	0.0	AX+	1p 39w	0.004
18	Perigee Trim	S/C 1	00/12/21 08:26	Pg 53	0.0	AX+	1p 16w	0.002
19	Perigee Trim	S/C 2	00/12/21 08:30	Pg 53	0.0	AX+	1p 11w	0.001
20	Perigee Trim	S/C 4	00/12/21 08:31	Pg 53	0.0	AX-	1p 17w	0.002
Additional Trim following Attitude Slew								
21	Perigee Trim	S/C 3	01/01/23	Pg 67	0.0	AX-	1p 7w	0.001

When the axial thrusters operate in continuous mode, the duration of a firing is an integer number of seconds which produces a worst case inaccuracy of 0.5 seconds in the burn duration. To achieve the desired accuracy of the Cluster constellations, the final trim manoeuvres have to be conducted with the axial thrusters operating in pulsed mode. With a spacecraft spinning at its nominal rate of 15 rpm, one revolution takes 4 seconds and is divided into 1024 clock counts. For each revolution, the thruster system can execute a pulse of any selected width between 1 and 511 clock counts. If necessary a single pulse can be implemented for which the worst case inaccuracy in firing duration is 4/(2*1024) = 0.002 seconds. This level of accuracy was not strictly necessary for the drift stop manoeuvres as it was expected that the subsequent deployment of the wire booms would further disturb the orbits. However, to gain the operational experience earlier rather than later, the drift stop manoeuvres were conducted using the axial thrusters in pulsed mode. Where the axial thrusters are used in pulsed mode, information in the form "3p 367w" shows that three thruster pulses were used, each with a pulse width of 367 clock counts.

Additional Test Trims

Of the three drift stop manoeuvres conducted in pulsed mode, the smallest was 121 mm/s. However, the final trim manoeuvres are much smaller than this with typical values of 4 mm/s or less. To implement a deltaV this small, the axial thrusters must execute a single pulse with a short pulse length. At this stage of the mission it was unknown to what level of accuracy the thruster system could reproduce these very small deltaVs.

Table 1 shows that there was only one drift stop manoeuvre from the basic sequence planned at perigee 4. As the available resources provided the capability of conducting more than one manoeuvre, it was decided to test the thruster system and execute two additional single pulse manoeuvres on S/C 3 and S/C 4. This was also the first time that more than two spacecraft had been manoeuvred at approximately the same time. This was a successful exercise as subsequent orbit determination showed the small manoeuvres had been executed with the same accuracy as the larger manoeuvres, namely with a dispersion of typically one percent.

Wire Boom Deployment: Spin Change Manoeuvres for Orbit Control

Wire boom deployment required three spin change manoeuvres per spacecraft. Even when the spin change manoeuvres are conducted in balanced mode, dispersion can produce a deltaV which influences the orbit. As the remaining constellation manoeuvres were predicted to be only a few millimetres per second there was no point in conducting them during wire boom deployment as the resulting orbit disturbance could render them redundant.

Wire boom deployment for S/C1 and S/C2 took place over the period 05 September 2000 to 06 October 2000. Wire boom deployment for S/C 3 and S/C 4 took place over the period 11 October 2000 to 16 November 2000. It was originally planned to use the manoeuvre optimisation software as a monitoring tool during boom deployment, with a run after each spin change manoeuvre, to check that future constellation manoeuvres were not becoming too large.

It is however no additional work to include the spin change as a manoeuvre within the software and optimise it for constellation control. This was the procedure adopted and the spin change manoeuvres were often conducted in unbalanced mode. The aim was to produce an optimised deltaV to influence the orbit in a positive sense and thereby reduce the remaining deltaV required from future constellation manoeuvres. For all deltaVs above 10 mm/s, conducting the spin change in unbalanced mode produced a deltaV is the correct sense and reduced the remaining deltaV required from the constellation manoeuvres.

Trim Following Wire Boom Deployment

Wire boom deployment activities for S/C1 and S/C 2 were completed on 06 October 2000. As the orbits of these two spacecraft would not be disturbed by any parallel operations for several weeks, it was an appropriate time to conduct any necessary constellation manoeuvres. A drift start trim was conducted on S/C 1 to slowly bring it closer to the other three spacecraft. No corresponding manoeuvre was required for S/C 2.

The boom deployment activities for S/C 3 and S/C 4 were completed on 16 November 2000. An assessment was made as to whether any constellation manoeuvres were required at this time and it was seen that none were necessary. The fact that the 12 spin change manoeuvres, implemented over a period of two and a half months, resulted in the need for only one small additional constellation trim manoeuvre, confirms the success of using the spin change manoeuvres for orbit control.

Attitude Slews for Orbit Control

Prior to the repeat sequence perigee trims planned for December 2000, attitude slews had to be conducted to prevent the solar aspect angle (SAA) violating specified limits. The idea of using spin change manoeuvres for orbit control was extended to the attitude slews. They were included as manoeuvres within the software and optimised for orbit control. As a result, the slews for S/C 1 and S/C 4 were deliberately biased to achieve the deltaV specified by the optimisation software. For the other two spacecraft the slews were conducted in balanced mode as the required deltaV was close to zero. Biasing the slews was successful with 65% of the required deltaV being achieved.

Basic Sequence: Second Pass

The five perigee trims from the second pass through the basic manoeuvre sequence were successfully completed; two on 02 December 2000 and three on 21 December 2000. A good constellation was predicted over the period of interest from the beginning of January 2001 to the end of April 2001.

Additional Trim following Attitude Slews

The evolution of the SAA was such that the constraint would be violated towards the end of February 2001, forcing a slew manoeuvre for each spacecraft close to the central cusp crossing time. As this was undesirable from the point of view of scientific operations, it was decided to slew the spacecraft early in January 2001 thereby avoiding the need for further slews until the end of April 2001.

As a good constellation had already been achieved, rather than using unbalanced slews to generate a deltaV for orbit control, the opposite approach was now required. In addition to conducting the slews in balanced mode, their locations were to be selected to minimise the effects of any residual deltaV on the orbit. One option is to conduct the slew at apogee, as a given deltaV component in the velocity direction has a smaller effect at apogee than at any other point on the orbit. It is assumed that any residual deltaV from the slew manoeuvre has a direction close to the direction of the spacecraft spin axis at the mid-point of the slew. The drawback of using the apogee is that, at this point of the orbit, a deltaV with this direction has a significant component in the velocity direction.

There are two points on the orbit where the expected direction of any deltaV residual from the slew manoeuvre is perpendicular to the spacecraft velocity vector. When conducting the slews at these points, whatever the size of the residual deltaV, the spacecraft semi-major axis should remain unchanged. The relevant true anomalies are approximately 130 degrees and 230 degrees and it was decided to slew S/C 1 and S/C 2 on the ascending part of the orbit on 07 January 2001 and S/C 3 and S/C 4 on the descending part of the orbit on 09 January 2001.

Following the slews, the constellation was disturbed more than expected and a perigee trim for S/C 3 was executed to improve it. The reason for this was a small radial deltaV component produced by the slew. In a best case, the spin of the spacecraft could result in this radial deltaV being perpendicular to the velocity direction and having no effect on the semi-major axis. However, in a worst case it could be in the direction of the velocity vector and produce a significant effect as it is located well away from apogee. The overall result was similar to what would have been achieved if the slews had been conducted at apogee, producing a larger deltaV component in the spacecraft velocity direction but with reduced effect. In future, slews will be conducted around apogee as this is operationally simpler because the operation timing is less critical. Furthermore, whenever an attitude slew is conducted, a perigee trim manoeuvre is scheduled for the corresponding spacecraft in case a correction proves necessary.

CONSTELLATION ACCURACY

It is recalled that the constellation is formed using a two tetrahedra strategy where the first tetrahedron is at the northern cusp and the second tetrahedron is in the southern hemisphere between the magnetopause and the bow shock. However, the short and long term accuracy requirements are defined only in terms of the first tetrahedron at the northern cusp. The short term accuracy requirements are that near the central cusp crossing time, the mean inter spacecraft distance is within 10% of the target inter spacecraft distance (60 km) and the difference between the largest and smallest inter spacecraft distance is less than 2% of the target inter spacecraft distance (12 km).

The long term accuracy requirement was intended to apply for a period of four months around the central crossing time of 17:00:21 on 28 February 2001. However, because of commissioning activities, full scientific operations only started on 01 February 2001. For this reason, the long term accuracy requirement is only considered over three months, one month before the crossing time and two months after. For each orbital revolution over this period, there should be a time when the spacecraft are close to true anomaly 131 degrees for which the difference between the largest and smallest inter spacecraft distance is less than 10% of the target inter spacecraft distance (60 km).

The short and long term accuracy criteria can be checked using the inter spacecraft distance information in Table 2 and Fig. 5.

Table 2. Variation of Inter Spacecraft Distance (km) with Date: Tetrahedron 1

Distance	-1 Month	Crossing	1/3 Months	1 Month	2 Months
S/C (1,2)	598.5	603.8	606.2	606.8	608.0
S/C (1,3)	601.1	603.0	604.3	605.0	610.3
S/C (1,4)	586.5	600.8	605.0	616.5	631.1
S/C (2,3)	596.3	602.2	605.0	598.0	590.9
S/C (2,4)	602.7	605.7	607.2	616.5	631.1
S/C (3,4)	602.7	605.7	607.2	608.2	610.9
Mean	598.0	603.5	605.8	608.5	613.7
Max - Min	**16.2**	**4.9**	**2.9**	**18.5**	**40.2**

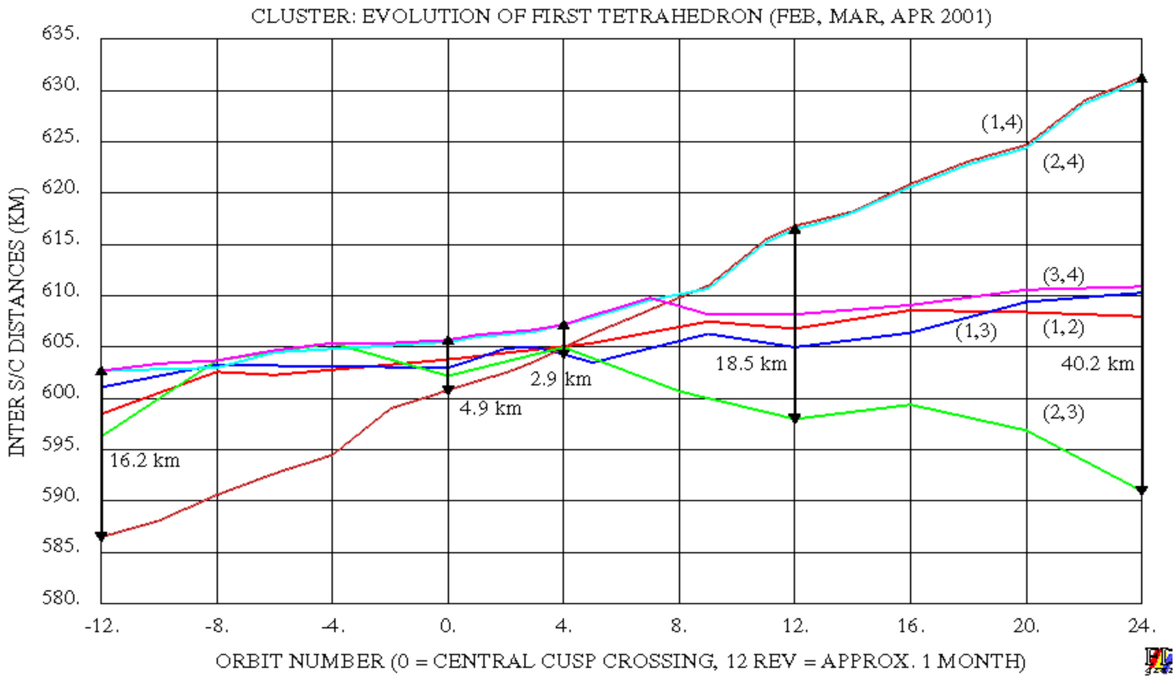

Fig. 5. Evolution of Tetrahedron 1

Short Term Accuracy

From Table 2 it is seen that near the central crossing time, the difference between the mean inter spacecraft distance and the target value of 600 km is 3.5 km. This is well within the required value of 60 km. Furthermore, all the inter spacecraft distances are within 5 km of each other. As this is considerably less than the specified 12 km, the short term requirements are comfortably satisfied.

Long Term Accuracy

Table 2 shows that for each orbital revolution over the relevant period, there is a time when the spacecraft are close to true anomaly 131 degrees for which the difference between the largest and smallest inter spacecraft distance is less than 41km. As this is considerably less than the specified 60 km, the long term requirement is comfortably satisfied.

The column corresponding to a time one third of the way through March is included as the best constellation is formed at this point. As the long term stability of the configuration is more important than the exact inter spacecraft distances at the central crossing time, it is not surprising that the best constellation is formed more towards the centre of the time interval of interest.

The success in forming the second tetrahedron located in the southern hemisphere is also of interest. Table 3 and Fig. 6 provide the relevant inter spacecraft distance information.

Table 3. Variation of Inter Spacecraft Distance (km) with Date: Tetrahedron 2

Distance	-1 Month	Crossing	1/3 Months	1 Month	2 Months
S/C (1,2)	584.5	598.6	602.4	602.6	601.6
S/C (1,3)	583.7	595.0	597.3	610.3	625.9
S/C (1,4)	588.7	598.5	601.6	609.7	622.0
S/C (2,3)	583.7	596.9	602.4	610.3	625.9
S/C (2,4)	595.0	597.0	599.7	596.7	596.8
S/C (3,4)	605.9	595.0	593.3	584.3	572.3
Mean	590.2	596.8	599.4	602.3	607.4
Max - Min	**22.2**	**3.6**	**9.1**	**26.0**	**53.6**

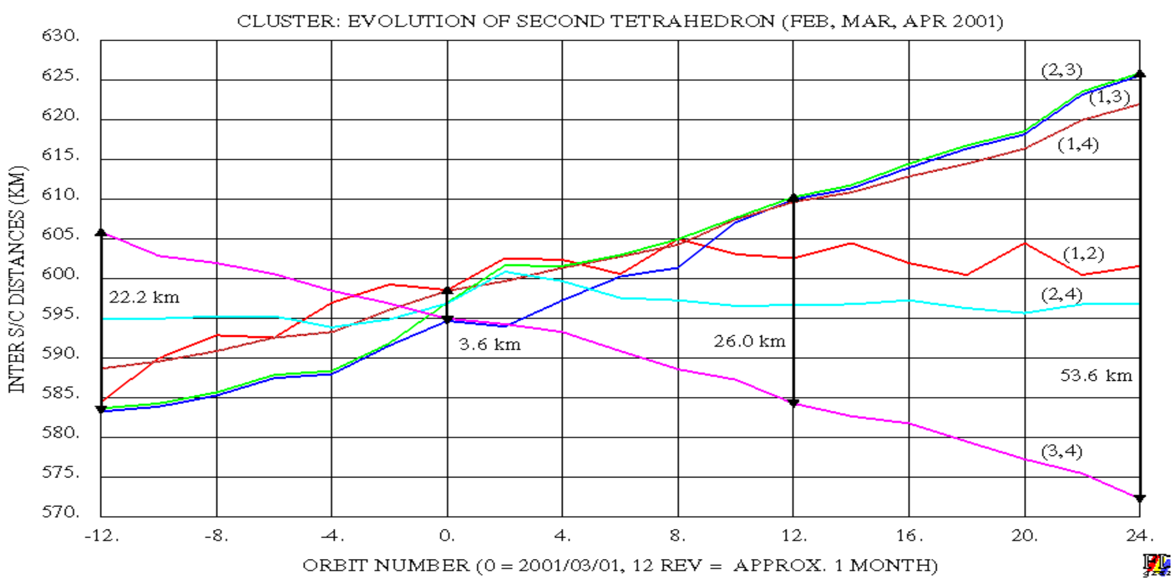

Fig. 6. Evolution of Tetrahedron 2

It is seen from Table 3 and Fig. 6 that if the short and long term accuracy requirements had been imposed on the second tetrahedron, both would have been satisfied.

CONCLUSIONS

The constellation manoeuvres follow a basic sequence comprising a perigee axial drift start manoeuvre, a radial manoeuvre, an apogee axial manoeuvre and a perigee axial drift stop manoeuvre. This sequence is repeated in full, or in part, as many times as necessary to achieve the required constellation accuracy. Meeting the short and long term accuracy requirements is made more difficult by the fact that a specified period around the central crossing time shall remain manoeuvre free. Two passes through the basic manoeuvre sequence were planned, with the second pass comprising only the perigee axial trims. This corresponds to a standard sequence of 24 manoeuvres, from which 17 manoeuvres were selected when the target location was optimised.

The constellation was achieved with the appropriate accuracy on 21 December 2000. In addition to the 17 selected manoeuvres, three extra trim manoeuvres were conducted before this date. Two were test manoeuvres to investigate the ability of the axial thrusters to deliver a deltaV corresponding to a single pulse of short pulse width. The third manoeuvre was a genuine constellation manoeuvre, a perigee trim to counter orbital disturbances caused by wire boom deployment. Therefore, a total of 18 manoeuvres were used to form the constellation and two test manoeuvres were conducted in addition. The use of spin and slew manoeuvres for orbit control contributed to the success in keeping the number of constellation manoeuvres to a minimum. There was also a perigee trim in January 2001 for constellation maintenance following attitude slews.

At the central cusp crossing time, the mean inter spacecraft distance was 603.5 km which is close to the 600 km target value. The individual inter spacecraft distances were all within 5 km of each other which easily meets the demanding 12 km requirement. Furthermore, at a similar location four orbits later the constellation was even better with the inter spacecraft distances within 3 km of each other. The most important criteria, that the constellation is maintained for the specified period around the central crossing time was also satisfied.

To summarise, the demanding constellation accuracy requirements were comfortably met using a minimum number of manoeuvres. This was achieved despite the difficulties of parallel commissioning operations disturbing the orbit. The operational experience gained in manoeuvring the spacecraft to the northern cusp constellation will be valuable for implementing future constellation change manoeuvre sequences.

REFERENCES

[1] Schoenmaekers, J., "Cluster Fuel Optimum Spacecraft Formation Control", ESA SP-326, Proceedings of the *3rd International Symposium of Spacecraft Flight Dynamics*, pp. 419-425, September 1991.