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Commissioning of a small satellite constellation - methods and lessons learned

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I. Abstract

The Disaster Monitoring Constellation consists of a series of four spacecraft built by Surrey Satellite Technology Ltd. The aim of the constellation is to be able to perform daily revisits over any point on the Earth such that 32m resolution images can be taken. These images can be used for daily monitoring of natural and man-made disasters.

The constellation is made up of four spacecraft. Alsat-1, is an 88 kg microsatellite, which was launched on 28th Nov 2002, for the Algerian national space agency CNTS. It was joined in orbit by three additional microsatellites on 27th September 2003, Nisat-1 (Nigerian national space agency), Bilsat-1 (Tubitak Bilten, Turkey) and UK-DMC (British National Space Centre).

In order to exploit small satellites in constellations, a number of key technologies must be utilised. These include precise navigation, propulsion, and coordinated maneuvers planning. This paper describes the spacecraft, the key technologies and how they were used to form the four spacecraft into a working constellation.

II. Introduction to Disaster Monitoring Constellation

A. What is the DMC?

The Disaster Monitoring Constellation (DMC) has been worked on at the Surrey Space Centre since the mid '90s. It consists of four small earth observation spacecraft arranged in a "string of pearls" formation, that are orbiting at the same altitude, in the same plane, but phased by exactly 90°. Three of these spacecraft have an onboard imager with a swath width of 600 km, and one of the spacecraft, Bilsat-1, has a smaller swath, higher resolution imager with off-pointing capability. This provides the ability to image any point on the earth's surface on any given day, by one of the four spacecraft. This daily revisit feature allows repeated monitoring of any disaster situation, for example floods or fire, such that relief agencies can plan their strategies.

B. Spacecraft Design

The DMC spacecraft (Figure 1) is based on a conventional SSTL microsatellite core module stack, fitted with larger honeycomb panels top and bottom to allow for additional equipments and to increase the external area available for solar cell population. Figure 2 shows a view of the spacecraft with the external solar panels removed.

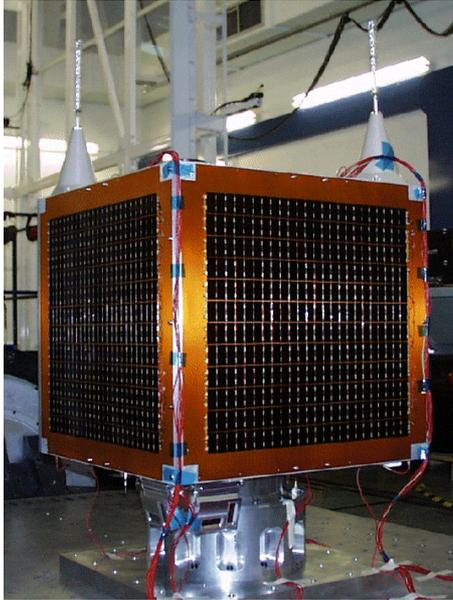


Figure 1- AISAT-1 spacecraft

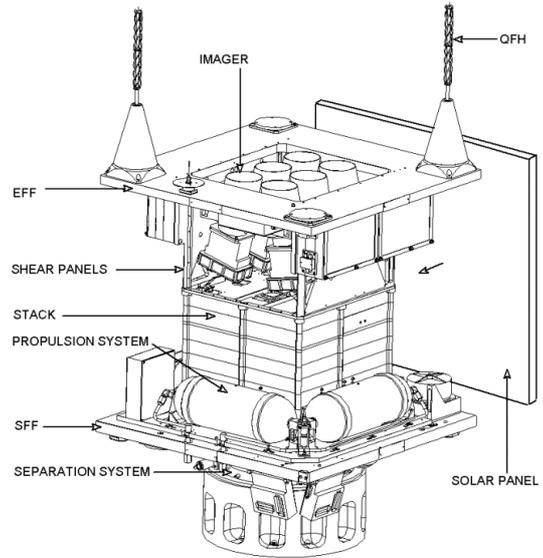


Figure 2 - Cutaway view of a DMC spacecraft

A block diagram of the system is shown in Figure 3. It shows that each spacecraft has two imagers linked to solid-state data recorders, which is downloaded to the ground station via an S band communications system. The spacecraft has a 6 meter deployable boom to give it gravity gradient stability.

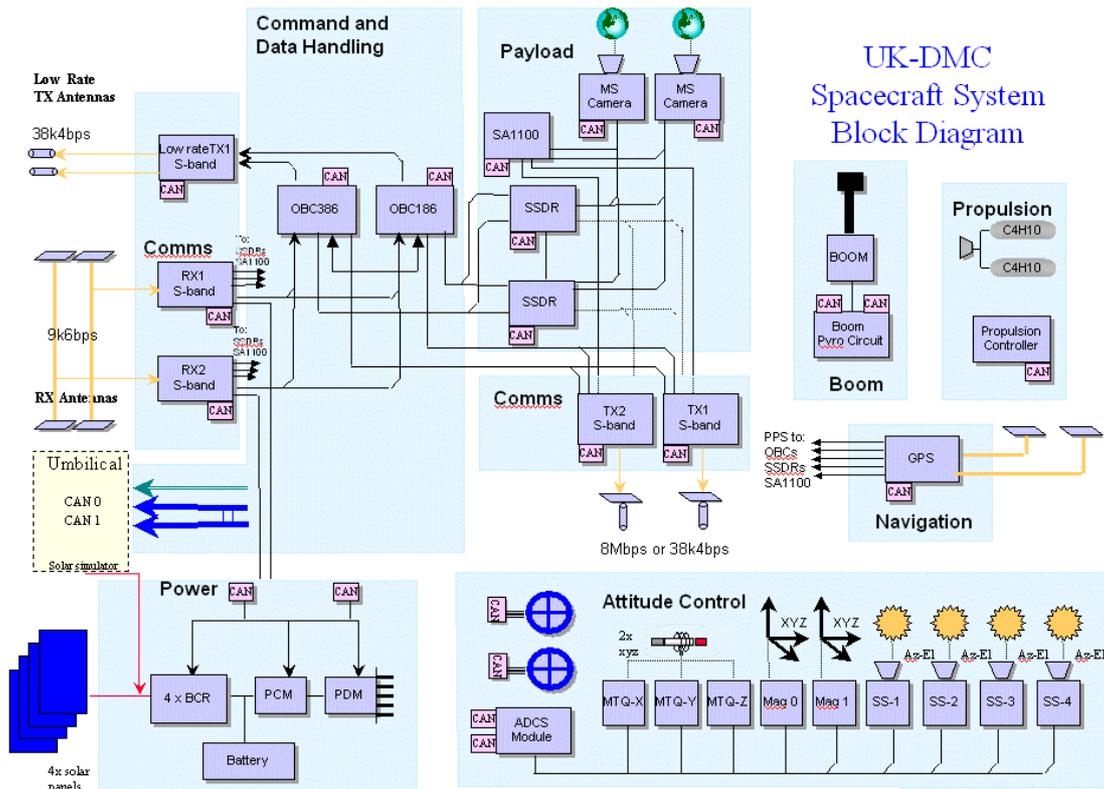


Figure 3 - System block diagram of a DMC Spacecraft

The key technologies required to form the DMC constellation are :-

- The propulsion system, capable of giving the spacecraft a delta V of up to 25 msec^{-1} .
- A full attitude control system giving 0.3° pointing knowledge and 0.5° pointing control.
- Orbital position and timing functions are supplied by the GPS system.

C. Propulsion System

The propulsion system for the DMC spacecraft (Figure 4) stores butane propellant in two propellant tanks. The outlet of one of these tanks is connected to series solenoid valves, which isolate the single resistojet thruster. The system is operated by opening the Flow Control Valves and allowing the propellant to flow under its own vapour pressure, approx 2 bar absolute. The propulsion system can be seen fitted to the DMC spacecraft in Figure 2.

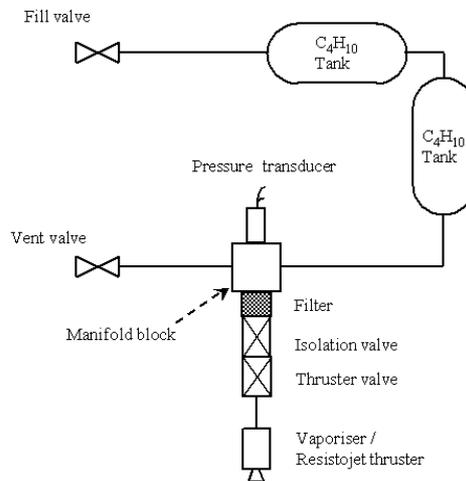


Figure 4 - DMC Propulsion System Schematic

The propellant used in this system is butane. It stores in the liquid phase, at density greater than twice that of nitrogen compressed to 200 bar. Hence to get the same overall performance from a nitrogen system an extra two propellant tanks would be required in the same area of the spacecraft. The fact that butane can be used is primarily due to the resistojet thruster, which in this case also acts as a vaporiser to ensure that none of the liquid phase propellant is expelled. The low power resistojet thruster design and qualification are described in detail in reference 1. The thruster design is shown in sectioned view in Figure 6.

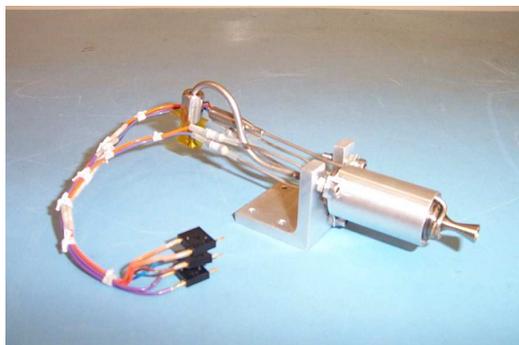


Figure 5 - Flight thruster

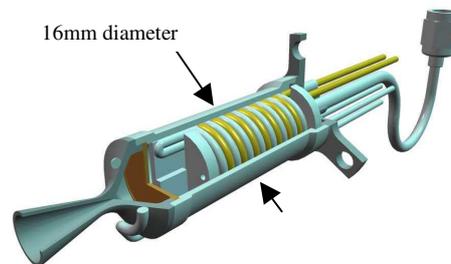


Figure 6 - Sectioned view of thruster

The thruster has a standard convergent / divergent nozzle with a throat diameter of 0.42mm. This is approaching the lower limit of that which can be machined with a regular machine shop capability, (any smaller requires costly machining techniques). The throat is protected with a 10 micron filter disc immediately upstream. Consequently no special cleanliness precautions are required when winding the heaters on the bobbin.

The thruster is made of conventional materials, with all the machined parts being stainless steel. The heaters and propellant feed tube are brazed into the chamber and the case is welded closed.

The thruster is fitted in a remote valve configuration. The flow control valves being located on the main propulsion panel, inside the spacecraft. The thruster has no thermal insulation, however it has a simple aluminium heat shield around the chamber as can be seen on the AISAT-1 flight unit shown in Figure 5.

D. Attitude Determination and Control System

ADCS block diagram can be seen in Figure 3. The system is controlled by the ADCS module, which is linked to the spacecraft's OBC via the CAN bus. It receives inputs on the spacecraft's attitude from 4 two axis sun sensors and 2 three axis magnetometers. It controls the attitude using 2 reaction wheels and 3 redundantly wound torque rods.

Orbital knowledge is gained from an on board GPS system. To assess the performance of the orbital manoeuvres the GPS system was operated for 3 orbits prior to propulsion firings, during the firing, and for 3 orbits after the firing.

E. Thruster alignment

The thruster is mounted on the space facing facet of the spacecraft, next to the separation system, with the thrust vector in the $-X$ direction. To minimise the disturbance torques on the spacecraft during the thruster firings, the thrust vector had to be aligned with the spacecraft's centre of gravity. In the $X Y$ plane the thruster bracket could be rotated to align the thrust vector through the measured C of G. The tip mass on the boom was selected such that the spacecraft's C of G in the Z axis was at the same height as the thrust vector once the boom was deployed.

With the thrust axis aligned along the velocity vector, the spacecraft's velocity could be increased by simply firing the thruster. To decrease the velocity the spacecraft ADCS is required to yaw the spacecraft 180° before the firing (using the Z reaction wheel), and return the spacecraft to its nominal position after the firing.

Of the four DMC spacecraft BilSat-1 was slightly different in as much as its boom deployment was not baselined. Hence to align the thrust axis through the C of G the thruster required adjustment capability in all three axes. The consequence of this was that the thruster was not aligned along the velocity vector, and a pitch manoeuvre of $+50.5^\circ$ (to increase velocity) or -129.5° (to decrease velocity) was required before each propulsion firing, and a reverse manoeuvre to return the spacecraft after the firing. This pitch manoeuvre was performed using the pitch reaction wheel.

III. ALSAT-1 In flight performance

A. Orbit injection

The first DMC spacecraft ALSAT-1 was launched on 28th November 2002 on a Cosmos launch vehicle from Plesetsk Cosmodrome in Russia. It was targeted for a circular 686 km orbit. However launch injection errors were outside the 3 sigma levels and the final orbit ended up with an apogee of around 745 km. Due to the fact that 3 further DMC spacecraft were to be launched to form a complete constellation, the orbit had to be recovered to be very close to its intended level.

B. Orbit correction manoeuvres

Following a series of propulsion checkout firings, the orbit correction manoeuvre series began on 26th March 2003 and lasted through to 30th April. An average of 5 x 3 minute firings were performed per day, giving a total of 168 firings. The orbit apogee was reduced from 745.5 km to 693.61 km, which is equivalent to a total delta V of 14.5 m/sec. This is sufficient to keep the LTAN (Local Time of Ascending Node) at greater than 10:00am throughout the mission life, and hence meet the mission specification, despite the large initial injection error. This will allow the imaging to be performed with constant shadow length, for easy comparison, over the mission.

Figure 7 and Figure 8 show the details of the orbital parameters and how they changed during the sequence.

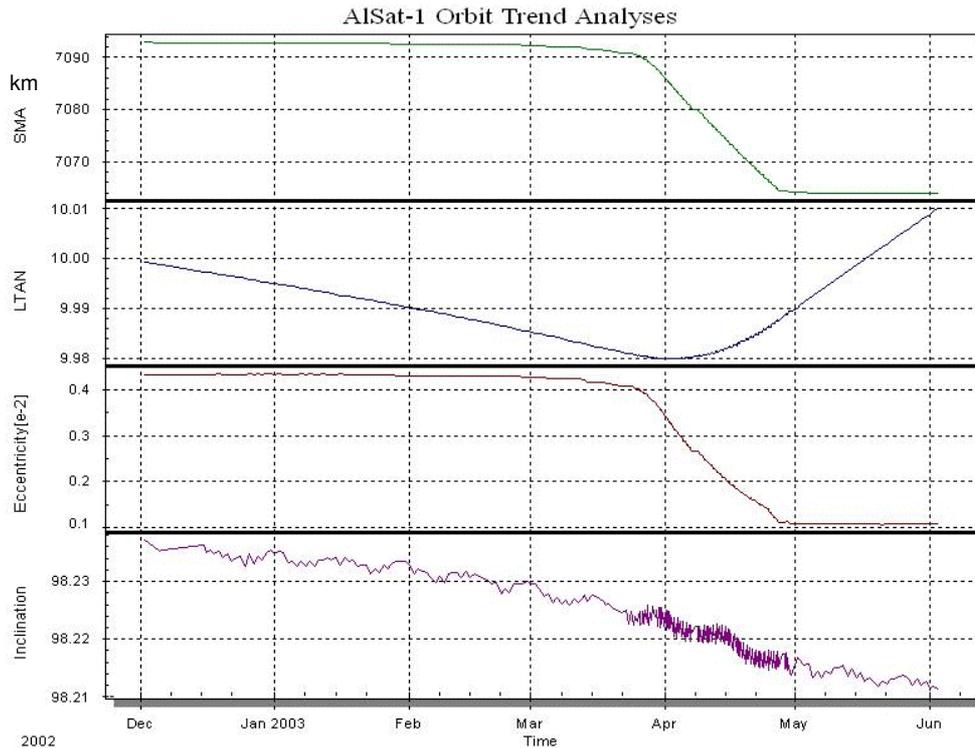


Figure 7 - ALSAT-1 orbital parameters over the first 6 months in orbit

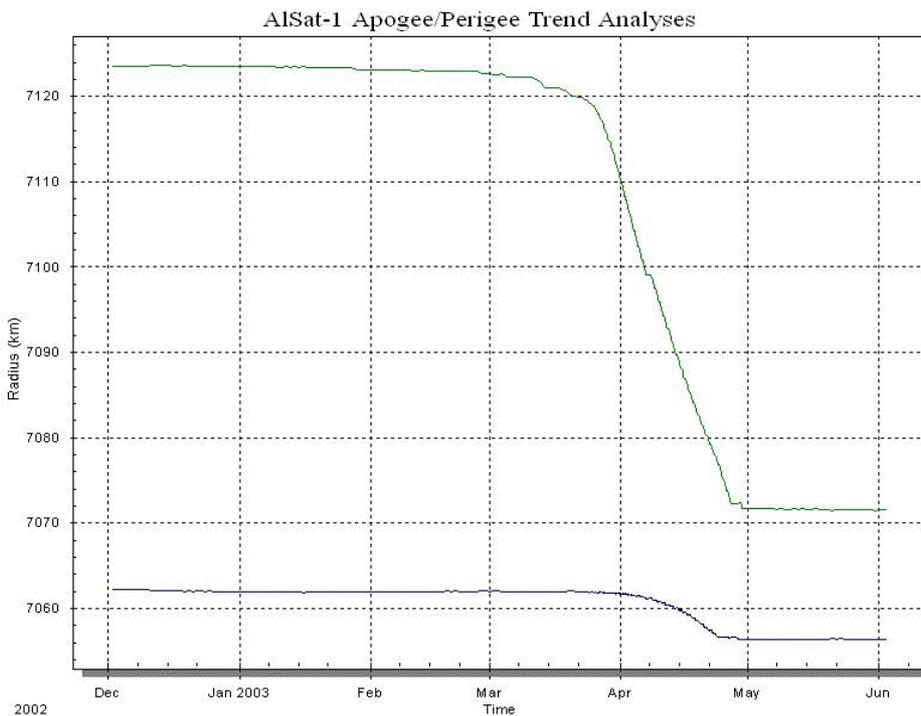


Figure 8 - ALSAT-1 orbital radius over the first 6 months in orbit

During the series of 3 minute firings, the imager was used sparingly, hence the power saved by not having the payload on was used for propulsion. Both thruster heaters were used simultaneously for the pre-heat and firing. The thruster pre-heat was performed for 6 minutes (at 30 Watts total power) allowing the thruster temperature to rise to over 300°C. Once the propellant flow began, the thruster would start to cool down. By the end of the firing the chamber temperature was typically 200°C. Models of the thruster operation predict average specific impulses of 100 seconds during these firings. However the specific impulse figure cannot be fully confirmed, as it is difficult to accurately gauge the amount of butane consumed. The mass flow rate is calculated using parameters measured during ground test.

IV. DMC-2 launch

On 27th September 2003, Nigeriasat-1, Bilsat-1 and UK-DMC were launched on a Cosmos launch vehicle from Plesetsk, Russia. The target orbit was that of AISAT-1 to minimise the amount of propellant required during constellation forming operations.

The achieved orbit injection was excellent. The orbit was altitude of 685.2km with an inclination of 98.2°. This meant that the three spacecraft had a semi major axis of just 300m lower than AISAT-1 and a difference in inclination of just 0.005°. They were phased 165° behind AISAT-1.

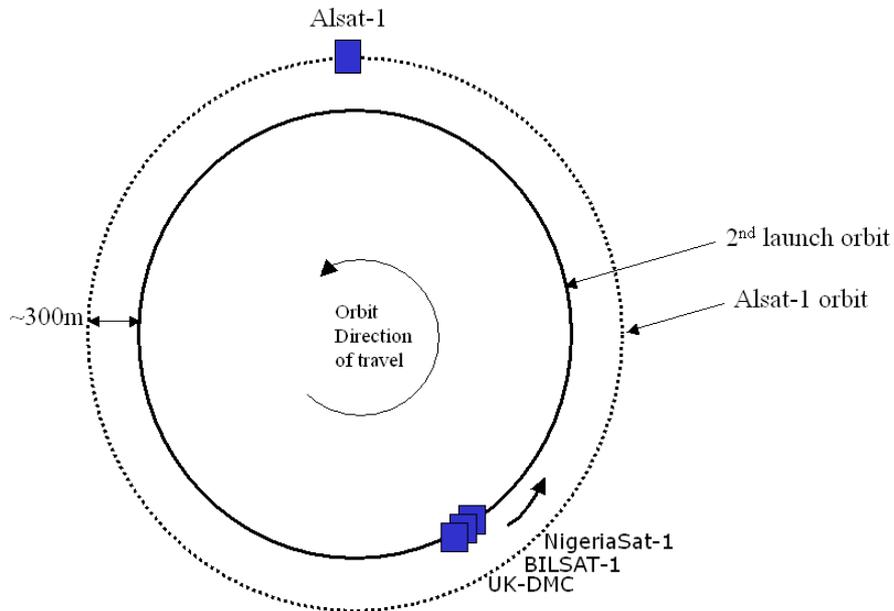


Figure 9 - Orbit phasing after second launch

V. Strategy for forming constellation

The strategy to correctly phase the constellation was to change the relative speed of the satellites by changing their orbital heights. The spacecraft were allowed to drift into their correct positions and their heights were returned to the nominal altitude. Figure 10 shows the phasing strategy employed.

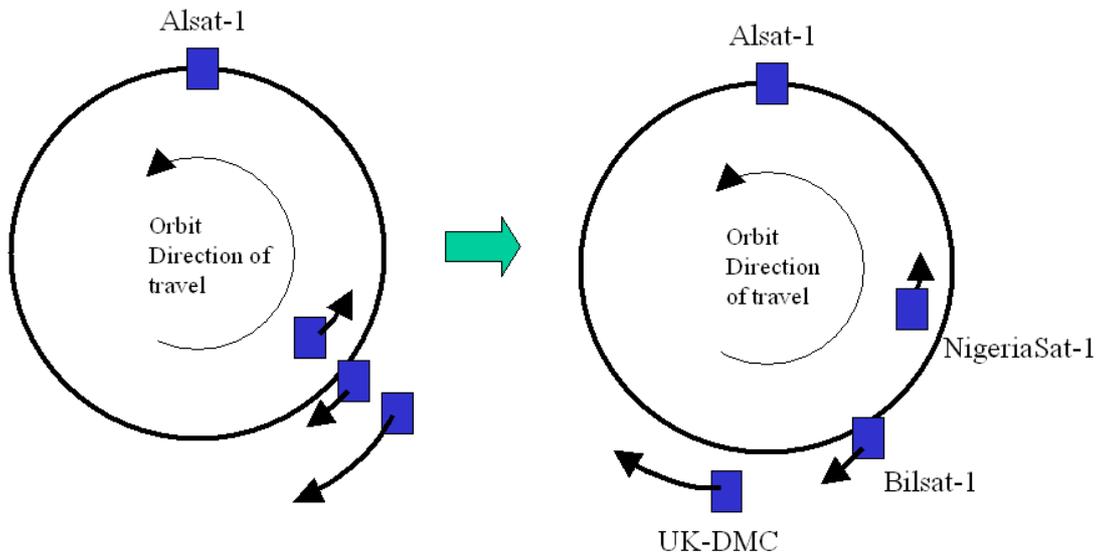


Figure 10 - Phasing strategy

To enable the constellation to be formed in a reasonable period a 90 day drift time was set. This determined the drift rate and hence the altitude changes required to form the constellation. One of the requirements during phasing was to minimize the propellant consumption on each spacecraft. Alsat-1

had already expended a significant quantity of propellant to correct injection errors from the first DMC launch and hence the other spacecraft were to be phased around it, to conserve its remaining propellant.

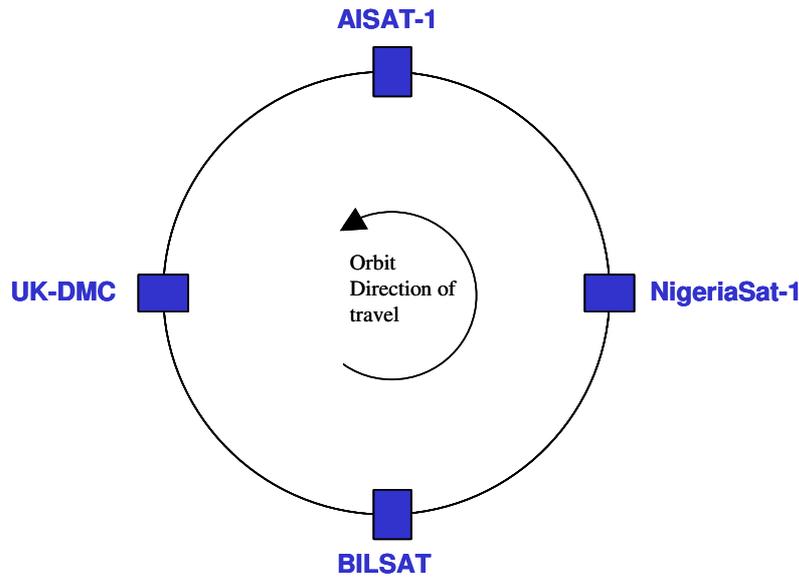


Figure 11 - Final constellation spacecraft spacing

Observation of actual orbit evolution of Alsat-1 indicated that the Alsat-1 inclination had dropped slightly faster than predicted. With this latest observed Alsat-1 inclination, the long-term prediction of the LTAN for Alsat-1 after approximately 5 years is in the order of 5 - 10 minutes earlier than for the other members of the DMC. This is illustrated in Figure 12.

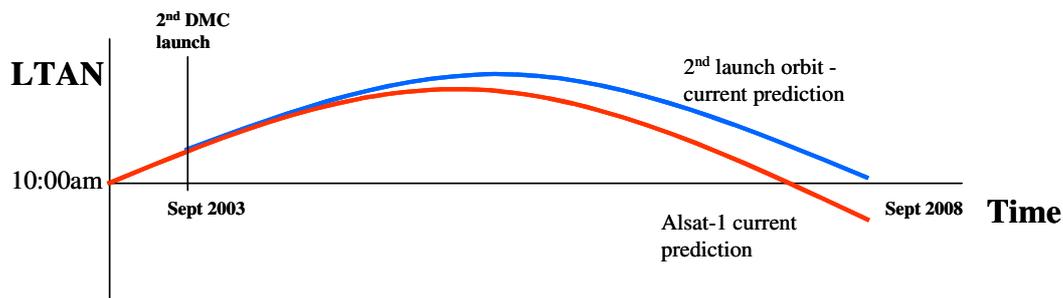


Figure 12 - Predicted LTAN Profiles

Whilst this did not impact mission performance within the target 5 year lifetime of the constellation, it was beneficial to the long-term orbit profile of the DMC mission for Alsat-1 to trim its inclination to be close to that of the satellites on the second launch rather than vice versa. This would result in a raising of the DMC orbit LTAN curve, extending the lifetime of the DMC orbit within the chosen LTAN window (greater than 10:00am). This would be particularly beneficial in the event of the DMC lifetime exceeding five years. The estimated DeltaV required from Alsat-1 to trim its orbit inclination was $\sim 0.6\text{ms}^{-1}$.

Table 1 gives an approximate DeltaV capacity vs. requirements based on the proposed strategy.

	Estimated Remaining DeltaV (ms^{-1})		Estimated Required DeltaV (ms^{-1})			Estimated Spare DeltaV (ms^{-1})
	Excluding margins	Including margins	Inclination adjustment	Phase Acquisition	Phase Maintenance	Excluding Margins
Alsat-1	5	9	0.6	-	-	4.4
BILSAT-1	13	16	-	0.45	< 3	> 9.5
NigeriaSat-1	19	24	-	0.77	<< 3	> 15.2
UK-DMC	19	24	-	1.35	<< 3	> 14.6

Table 1 - Propellant Status and Potential Requirements Summary

V. Phase Acquisition

The phase acquisition manoeuvres took place between December 2003 and March 2004. The DMC phase acquisition sequence can be seen below in Figure 13. As shown in Figure 10 the UK-DMC had the furthest to drift and hence its altitude was raised the highest, to give it a higher drift velocity with respect to AISAT-1.

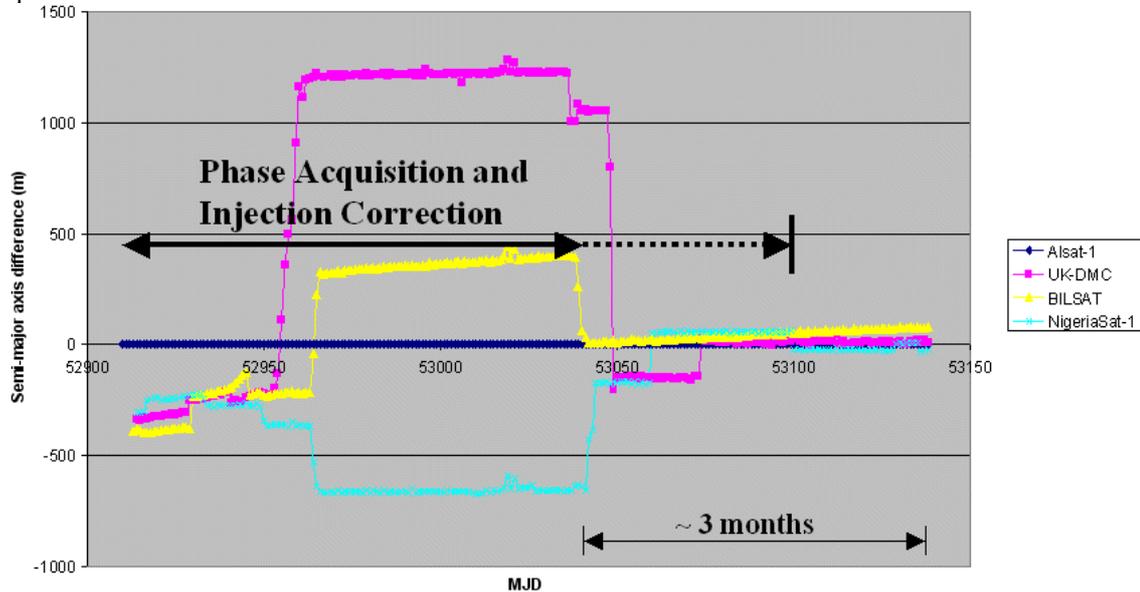


Figure 13 - DMC phase acquisition Semi-Major Axis profile with respect to Alsat-1

Due to slightly different timings of arrival, BILSAT was the first to perform its final phase acquisition firing.

UK-DMC slightly overshot its phase position due to practical operational difficulties (predominantly lack of availability of the SSTL groundstation). Hence it can be seen that UK-DMC performed a small correction manoeuvre to arrive on station approximately a month later. This was similar for NigeriaSat-1 with additional correction required. However, this was very small and the phase overshoot was negligible.

VI. Constellation maintenance

It had been previously agreed by the consortium partners that, unless new circumstances dictated otherwise, BILSAT, NigeriaSat-1 and UK-DMC would acquire and maintain phase around Alsat-1. This was due to the large amount of propellant already used by Alsat-1 in the correction of the injection error for the first DMC launch.

NigeriaSat-1 and UK-DMC are physically very similar to Alsat-1 and hence have a very similar (almost identical) drop rate. BILSAT-1 is more physically different and hence has a different drop rate. From the start of April the semi-major axis drop rates for each of the satellites had been fairly steady. The drop rates over this period are estimated as:

	Semi-Major Axis drop rate (m/day)
BILSAT	0.91
NigeriaSat-1	1.56
UK-DMC	1.56
Alsat-1	1.56

Table 2 - DMC Relative Semi-major Axis Drop Rates

This is illustrated in Figure 14, which covers the 3-month period following station acquisition for BILSAT.

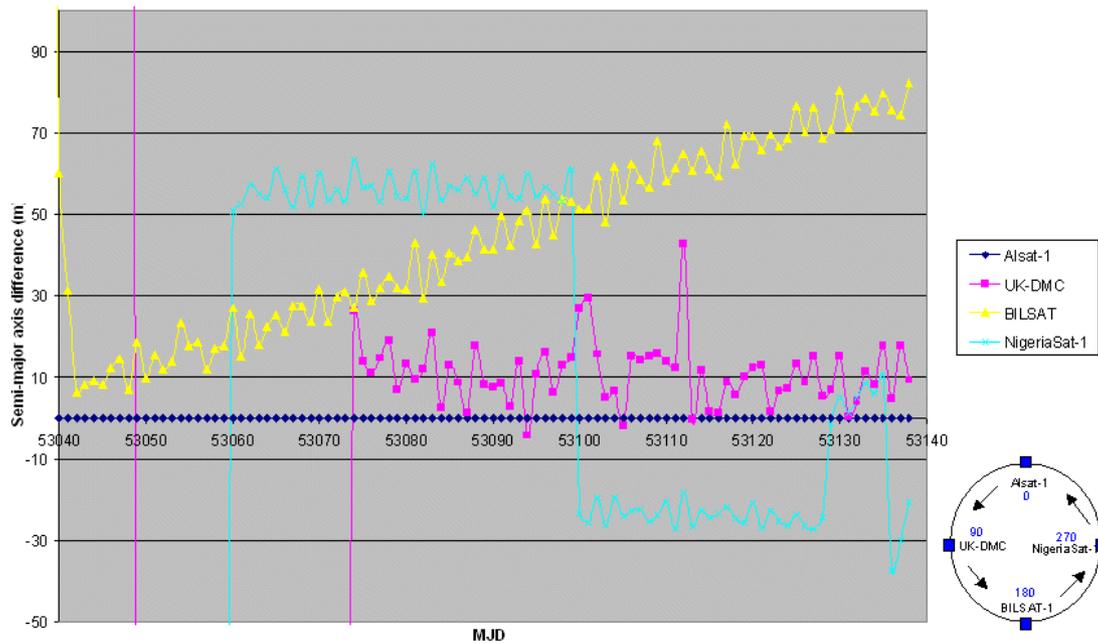


Figure 14 - Satellite Semi-major axes with respect to Alsat-1

Figure 15 shows the evolution of satellite phase with respect to Alsat-1 over the same period. The relatively large divergence of BilSat-1 is clear during this observation period. From commencement of nominal phase maintenance operations a much tighter phase window will be maintained.

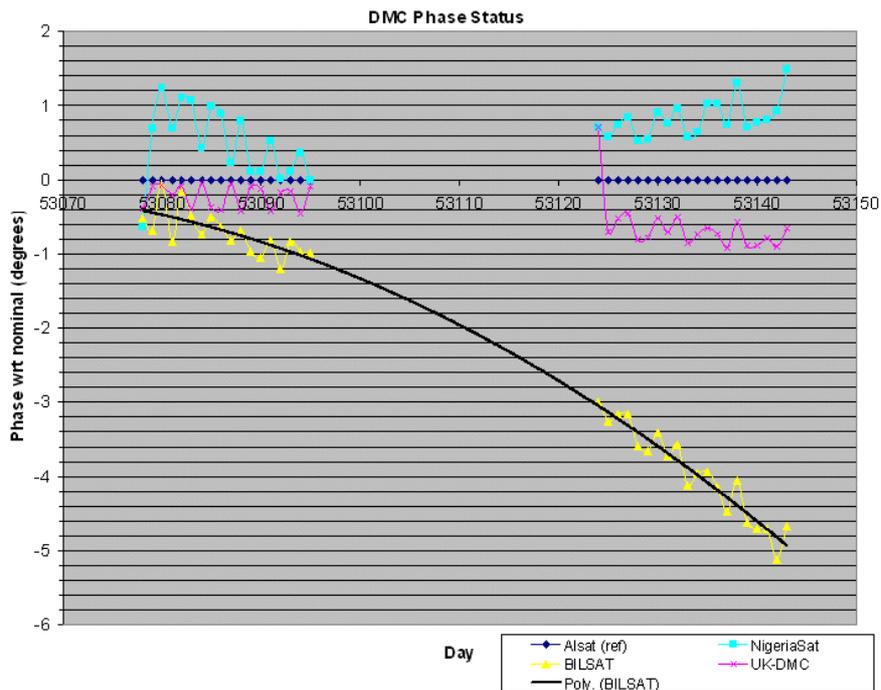


Figure 15 - Satellite Phase with respect to Alsat-1

B. Phase Control Approach for NigeriaSat-1 and UK-DMC

For UK-DMC, NigeriaSat-1 and Alsat-1, the differences in semi-major axes shown in Figure 14 are very small, in the order of <25m. It can be seen from Figure 15 that over significant time (e.g. several months), a phase drift in the order of 1 degree has occurred as a result of these differences. This is very acceptable for the mission.

It would be an acceptable solution for the mission to perform firings to alternately raise and lower the semi-major axis above and below the Alsat-1 semi-major axis, allowing the satellite phase to drift one way and then the other between firings.

However, Figure 14 indicates that the drop rates for NigeriaSat-1, UK-DMC and Alsat-1 are, in practice, extremely close. This presents a potential opportunity for the mission that is considered worth exploring. With a near identical drop rate, assuming that phase is correct to start with, the only firings that would be necessary, in theory, would be firings to correct previous firing errors. If the semi-major axes are perfectly aligned then, theoretically, no firings would ever be needed. Of course in practice this will not be the case as there is a finite achievable accuracy to the control of semi-major axes, and also the drag drop rates will not be *exactly* identical, just very close. However, by attempting to align semi-major axes as closely as possible, there may be an opportunity to minimise the frequency of firings and propellant use for UK-DMC and NigeriaSat-1.

It is proposed that the first UK-DMC and NigeriaSat-1 firings should be made to equalise semi-major axes with Alsat-1. The result should be observed. If the actual deltaV achieved was slightly more than planned, this would result in the phase gradually moving back towards its nominal value. Hence no further firing should be performed until phase is at its nominal value. If the deltaV achieved was slightly less than that planned then a further very small firing should be considered to ensure that the phase drift over the following weeks and months is in the right direction.

The relative semi-major axes should be compared when the satellites are at their nominal positions and a decision made as to whether a small firing is desirable to more closely align the semi-major axes.

As a general routine, if phase is within an acceptable window, a firing should be considered to correct for any appreciable semi-major difference and hence equalise with Alsat and arrest any phase drift. The differences in semi-major axis involved are very small and it is questionable whether such control will be achieved. However, it is proposed that the first few station-keeping firings attempt to follow this method. If successful it will both save propellant and greatly reduce the frequency of necessary firings.

It is proposed that this inspection of semi-major axis and phase position be made once per month as well as shortly before and after any planned firing. Firings would be expected to be necessary much less frequently than once per month (e.g. perhaps only every 6months or even less), but this will depend on actual achieved semi-major axis control accuracy for each firing.

In summary, for UK-DMC and NigeriaSat-1 the phase accuracy is currently very good and more than acceptable for the mission. The above procedure outlines an approach that serves to test the limits of achievable phase accuracy with minimal operational effort, and at the same time to establish whether there exists an opportunity to save propellant and minimise the frequency of station keeping firings throughout the mission.

C. Phase control approach for BILSAT

For BILSAT, there is a significant natural change in semi-major axis relative to Alsat-1, which causes an accelerating drift in phase with respect to Alsat-1.

However, this also means that for BILSAT there is therefore a natural stability mechanism in that small over-firings will be compensated for, over time, by the natural drag differential to Alsat-1. This means that there is little point in trying to equalise the BILSAT semi-major axis with the Alsat-1 semi-major axis.

It is currently proposed that routine firings are performed by BILSAT every 2 months. It is estimated that over the course of 2 months BILSAT will drift in the region of 50m in semi-major axis with respect to Alsat-1, due to natural differential drag effects. Hence, if at the start of a two-month period BILSAT is 25m below Alsat-1, at the end of the two-month period BILSAT will be 25m above Alsat-1.

Also, assume that at the start of the 2 month period BILSAT is ~ 0.4 degrees *behind* nominal phase position. For the first month or so (whilst the semi-major axis is below that of Alsat-1) BILSAT will drift (relative to Alsat-1) forwards in the orbit to be at approximately 0.4 degrees *ahead* of nominal phase position. At this point the BILSAT semi-major axis should be approximately equal to that of Alsat-1. In the second month, the BILSAT semi-major axis will be greater than that of Alsat-1 and hence BILSAT will drift (relative to Alsat-1) backwards in the orbit to be at approximately 0.4 degrees *behind* nominal phase position (and approximately 25m above Alsat-1 in semi-major axis), which was the starting point for the two-month period. The cycle can then be repeated routinely. This 'sawtooth' procedure is illustrated in Figure 16.

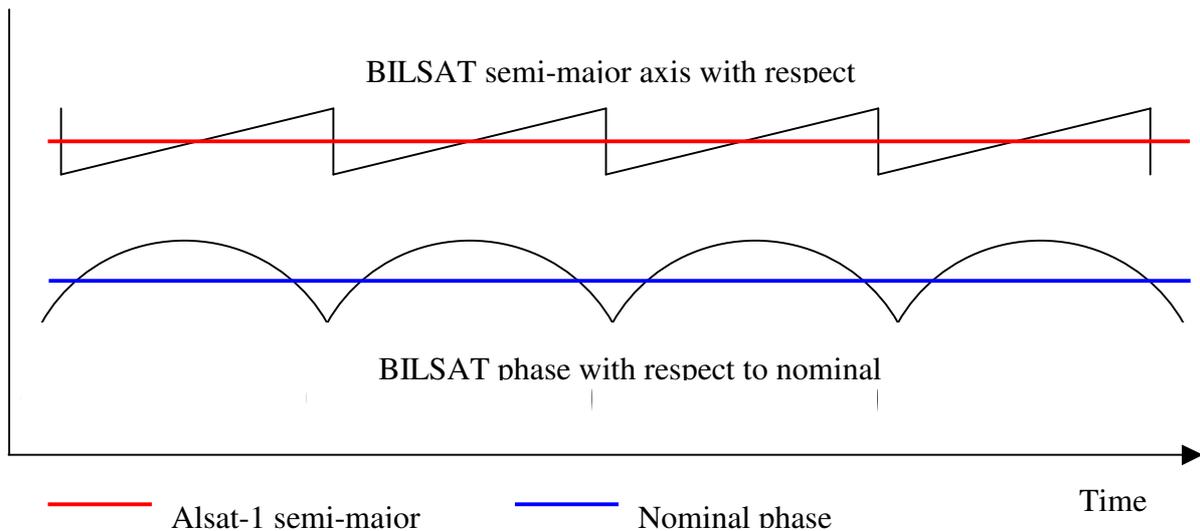


Figure 16 - Proposed BILSAT Phase Maintenance Pattern

Of course there are however, many uncertainties and this is only a baseline estimation. The frequency of firing and phasing accuracy will almost definitely differ from this depending on accuracy of individual firings as well as actual solar activity.

The suitability of this approach and these target numbers should be periodically reviewed. A window of 0.4° is not a strict requirement (3° to 4° in fact would be more than reasonable to satisfy the mission) and is chosen primarily by the judgement that a firing every 2 months seemed like a reasonable frequency for firing purposes. The window could be relaxed and potentially less frequent (larger) firings performed if desired.

VII. Conclusions

SSTL along with its consortium partners have successfully launched, formed and are maintaining a constellation of four small spacecraft, which allows daily revisit optical imaging over any point on the earth.

As part of the forming process AISAT-1 performed a major orbit change manoeuvre, lowering its apogee by 50 km, to correct launch vehicle injection errors. The other three spacecraft were later launched into the AISAT-1 orbit. The constellation was formed by using the onboard propulsion systems to modify the relative drift rates, by modifying their altitudes. When 90 degrees spacing was achieved between each spacecraft, the altitudes were brought back to the same level to keep the spacecraft in their selected positions.

This work has demonstrated that small spacecraft, of less than 100 kg mass, can possess the capability to form and maintain themselves in constellations.

VIII. References

1. "The Development Of A Family Of Resistojet Thruster Propulsion Systems For Small Spacecraft", D.Gibbon, A.Baker, I.Coxhill, M.Sweeting, 17th Annual AIAA / USU Conference on Small Satellites, Logan, Utah, USA, Aug 2003, SSC03-IV-8

IX. Acknowledgements

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Further information on SSTL can be found at web site www.sstl.co.uk.