MICROSAT CONSTELLATION CONTROL TECHNIQUES

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Abstract

The first air-launched constellation of seven small experimental communications satellites into an unexpectedly low earth orbit (246 nmi X 192 nmi) resulted in a set of tough flight control demands. In the abbreviated demonstration mission the flight operations team was challenged in rapidly propelling the spacecraft into a useful uniform distribution about the orbit plane and in maintaining the "stations" under adverse conditions. The constellation was injected in perfect order and began mission operations immediately. However, each spacecraft's attitude control system coupled with the force of heavy atmospheric drag to produce variable in-plane phase drifts that required constant observation and correction. The satellite UHF transponder payloads were operational until splashdown 190 days from launch.

Initial Deployment

As part of the DARPA LIGHTSAT Program, the UHF transponder-equipped near polar orbit constellation of seven small 49 pound satellites was designed to provide a nearly uniform swath over 3,000 nautical miles wide for the intended 392 nmi mean altitude circular orbit. At this height the instantaneous satellite footprints just overlap providing tactical "bent-pipe" communications for up to approximately three and one half hours at the equator, increasing with latitude. With the single plane constellation this communication opportunity is presented twice per day.

A major determinant in the choice of seven satellites for the constellation was the orbit of nearly 400 nmi (741 km) where the mission could last for three or more years and station-keeping demands would be modest. Computations showed that a single thrust parallel or anti-parallel to the orbital velocity each month for each satellite would confine the constellation phase drift to about 10°. Thus the phasing would be based on the nominal 51.4° satellite-to-satellite separation with drift from station allowed to accumulate up to 10° per satellite. The cold nitrogen thruster fuel load of 32 grams at 6,000 PSI would provide more than a 30% excess station-keeping capacity over three years.

The satellites were lofted by PEGASUS and deployed from the launcher carriage shown in Figure 1 so as to avoid collisions in the first orbits and to facilitate individual MICROSAT identifications. Initially, the satellites did not possess unique signatures, and the eventual USSPACECOM/NAVSPASUR ephemeris elements and resulting tracks would not be directly correlated with the satellite IDs.

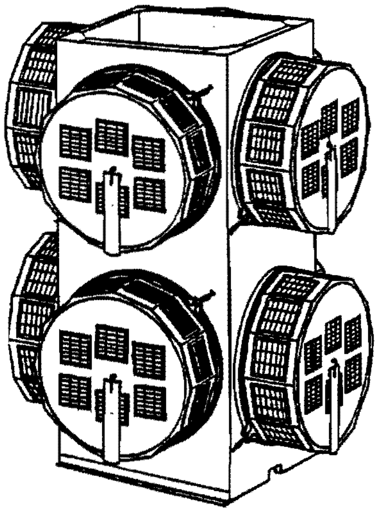

Figure 1. MICROSATs on the launcher carriage assembly attached to PEGASUS. All satellites but one were ejected in pairs (in opposite directions) to avoid destabilizing the vehicle.

Therefore, a unique deployment plan was devised whereby the satellites would be injected into two in-plane clusters consisting of four leading and three trailing satellites in a specific order based upon physics alone. Figure 2 depicts the deployment viewed from space along nadir 25 minutes after booster (PIK) burnout. Notice the initially retrograde motions of the satellites that soon develop into "forward" and "rearward" clusters as shown in Figure 3 that corresponds to 200 minutes beyond booster burnout. The deployment sequence consisted of a 40° yaw, a reciprocal (i.e., back-to-back, zero net momentum) satellite pair ejection of M4 and M6 followed by a 200 second delay during which a +45° rotation is performed, terminating with the second back-to-back ejections of M7 and M5. After 200 seconds and a -45° rotation M3 and M1 are similarly ejected. Finally, after an additional 200 seconds and a +45° rotation the unpaired M2 satellite was ejected. The ejection speeds with respect to the PEGASUS/carriage were approximately 1 ft/sec (FPS). The satellite-to-satellite collision probability for a CM-to-CM for the deployment was:

$P_c = 1.0$ for CPA = 35m; $P_c = 0.5$ for CPA = 22m; $P_c = 0.25$ for CPA = 17m; $P_c = 0.06$ for CPA = 5m; $P_c \approx 0$ for CPA < 4m

where a CPA of one meter or less could result in a physical collision.

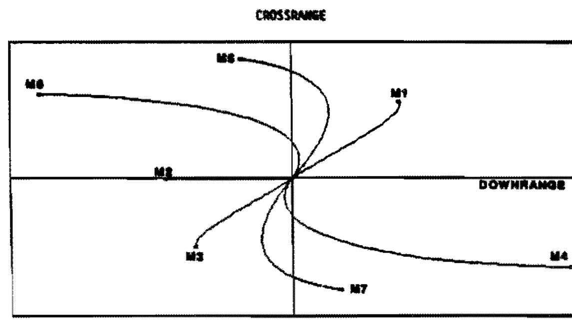

Figure 2. View toward earth, PEGASUS at center of figure showing the MICROSAT tracks up to T = 25 minutes past the second PIK burnout. The full-scale downrange is ± 0.5 km with the full-scale crossrange of ± 0.25 km.

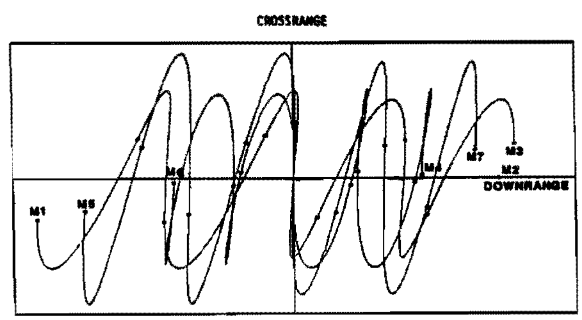

Figure 3. View at T = 200 minutes with downrange scale now ± 10 km and track symbols every 50 minutes.

The two clusters thus formed diverge at a rate of about 3.7 km/hr. The individual clusters disperse at a rate of about 1.2 km/hr. Figure 4 was used by USSPACECOM/NAVSPASUR and DSI in eventually making the track-to-satellite correlations. It shows the expected formation and dynamics of the satellite clusters. Despite the small size of the 12 sided truncated cylindrical MICROSATs (19 x 7.5 inches), NAVSPASUR resolved individual satellites within two days. (See Figure 5)

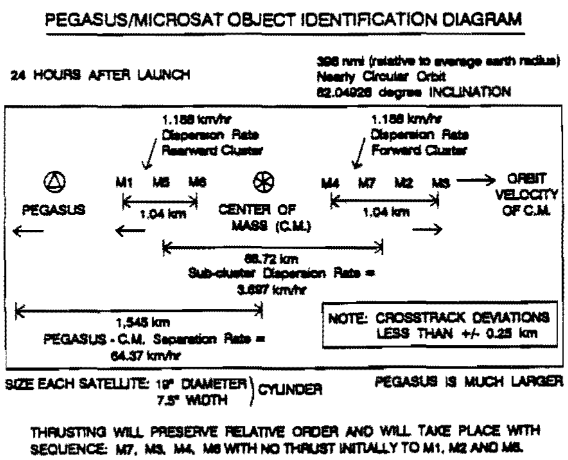

Figure 4. Expected early formation of the MICROSAT constellation before initial thrusting.

Achievement of the Constellation

Due to PEGASUS launch anomaly on 17 July 1991, the intended altitude was not realized. The actual orbit achieved had a mean altitude of approximately 217 nmi and an eccentricity of 0.0073, but with the intended 82° inclination. New thrust-to-station calculations were quickly made, and each satellite was fired sequentially onward toward its intended destination.

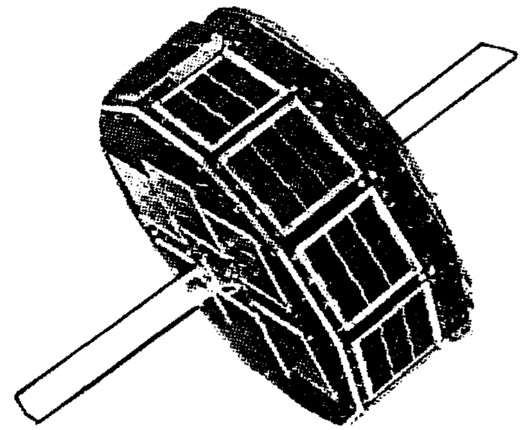

Figure 5. A MICROSAT showing solar cells mounted on top, bottom and sides. The protrusions are the omni-directional blade antennas which are aligned with the orbit normal. The NiCd batteries of 50 Watt-hr capacity deliver 10 Watts to the digitally controlled UHF FM transmitter. The systems could handle voice and clear or encrypted data (up to 4.8 kbps). The central processor was a low power 80C86 operated by VRTX/C-language software.

The objectives were dual: first thrust each satellite in such a manner as to confirm or resolve its identity; and second swiftly accelerate the transit to station so that the system could be immediately used in an optimal manner (i.e., without undue footprint overlap which would result in a user keying up more than one satellite at a time). The ephemeris data was obtained (usually once per day) and the tracking diagram updated. Positive identification was achieved for each apparent satellite track (initially based on presumption) by single satellite thrusting which tied the physical track with the exact MICROSAT name (ID). Figure 6 shows how this was applied in the case of M4 and M7 which were very close and possibly not actually resolved on day 12 when a -2 FPS thrust was applied to M7. The departure of this track from its previous direction clearly identifies the now sharply diverging track. By an analysis of the kinetics it turned out that the actual thrust was -2.67 FPS.

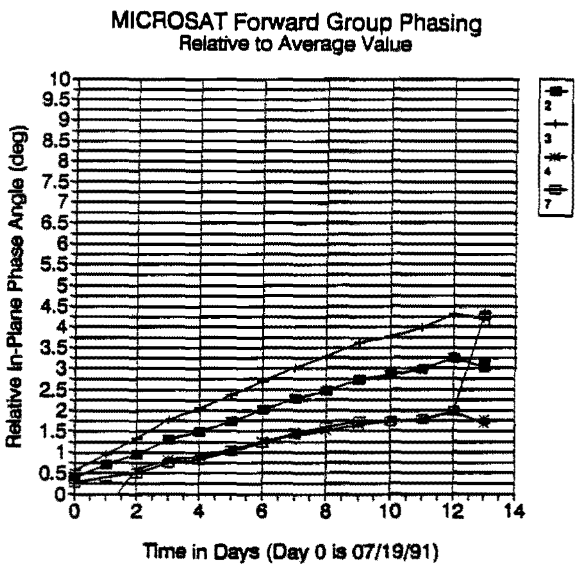

Figure 6. Illustration of track correlation. Theoretically M4, M7, M2, M3 comprise the forward cluster and here M7 is given a retro-thrust of -2 FPS forcing it into a lower, faster orbit and therefore, moves ahead in the formation.

Due to the low orbit, it was decided to bunch the satellite together in order to maintain a small footprint overlap (i.e., 5 - 10%) with a long period of continuous "bent pipe" (i.e., transponder) communications and also to accept the resulting gap in in-plane coverage. Thus, the satellites were thrust toward orbital stations separated by 38° by means of impulses ranging between +/-6 FPS generated by the onboard nitrogen gas thrusters. Multiple small thrusts were used where possible and the 38° stations were generally achieved after 60 days with errors of -3° to +7° in orbital phase.

The speed impulse necessary to adjust a satellite by a phase shift of γ in a time T is given by

$$\Delta V = \frac{1}{3}\,\frac{\sqrt{M_e G}\;a^{-1/2}}{T\sqrt{M_e G}/\gamma(a^{-3/2}) + 1}$$

where a is the nominal semi-major axis. Substituting $a_{nmi} \approx 3{,}444 + ALT_{nmi}$ and adjusting for units of ΔV in FPS, the expression reduces to

$$\Delta V(FPS) = -\frac{4.0914 \times 10^{-4} \times (ALT + 3{,}444) \times \gamma_{deg}}{T_{days}}$$

For example, to change a satellite's phase by 100° in 60 days requires a ΔV of 2.5 FPS assuming an altitude of 217 nmi. To advance the satellite requires a retro thrust. Once the period of T_{days} is reached and the desired station thus achieved, a braking impulse of the same magnitude is required. This must equalize the altitude of the given satellite with the mean constellation altitude.

Such balance is never possible in LEO operations and therefore vigilance is required in the provision of essentially constant control. Since the orbits are of low eccentricity it is not important that the impulses be imparted at either perigee or apogee. This is not so of major thrusts, i.e., where $\Delta V/V_{orbit}$ is not very small.

Thrust Operations

MICROSATs are spinners equipped with active ACSs as reported in reference (1). The satellite spin axis is maintained normal to the orbit plane and internal magnetic torquers provide both precession and spin control. Precession was normally held to within the intended $\pm$ 5° limit, a detail of importance due to the unexpectedly low orbit as explained below. The spin was nicely maintained at 3 RPM. In order to fire a thruster the attitude dynamics and stability of the satellite had to be known and judged satisfactory else the thrust would be ineffective, somewhat out of plane, and potentially in the wrong direction should the spin sense be incorrectly interpreted. Spin sense was not directly available from telemetry but was deduced by a comparison of the magnetometer telemetry with the results of simulated orbit and IGRF geomagnetic field models.

The nitrogen jet nozzle was mounted radially to provide thrust orthogonal to the spin axis in the orbit plane. Ground control would issue a thrust command to deliver a specified impulse to be delivered at a specified future time. Onboard, the thruster software measured the gas temperature and pressure and solved Van der Waals equation to obtain the mass of the gaseous nitrogen remaining in the tank. The performance of the valves had been extensively characterized and a parametric description was held in computer ROM memory. This permitted the shape of each pulse (including the impulse associated with the often significant pulse tail) to be calculated and the thrust centroid to be aligned with the $\pm$RAM direction as the satellite rotated. An error in spin sense knowledge would result in a reciprocal thrust. The thruster system therefore determined the proper valve orders and synchronized with the last nadir crossing time and current spin rate as determined by the ACS. Thrusts produced by this system on orbit were well within expectations based upon pre-flight laboratory analysis. However, the system could not deliver impulses less than $\pm$0.86 FPS at maximum gas pressure (6,000 PSI). A smaller "microthrust" capability would have been useful especially if satellite tracking could be accomplished more frequently than once per day.

The satellite constellation relative phase diagram (Figure 8) was used as the primary tool for prediction of drift. Due to the low orbit the data obtained at the rate of once per day exhibits considerable non-linearity and sometimes "noise" as well. With the very short predicted lifetime of about six months, the long gentle slopes associated with the intended monthly station-keeping at the 400 nmi level were not possible. The situation was changing at a rate equal to or greater than the incoming ephemeris (i.e., tracking) data and predictions for the long term were impossible. Drag levels on the order of 400 times those expected coupled with the ACS in a unique manner greatly impacting flight operations. The MICROSAT ballistic coefficient $B = m/(C_D A)$ for a satellite showing no roll/yaw error is approximately $B_{max} = 101.4$ Kg/m^2. Should the satellite yaw or roll 90 degrees, the coefficient becomes $B_{min} = 60.6$ Kg/m^2. Thus, a MICROSAT precessing its spin axis slightly ($\pm 5°$) off the orbit normal will present an intermediate B-value. The effective variation raises and lowers the orbit and therefore continually affects phasing. Figure 7 shows the early history of the "rear" cluster of satellites (M1, M5 and M6) especially the behavior of M6 which took longer than the other MICROSATs in initial ACS stabilization. As a result of ACS activity, this satellite begins to descend in orbit thus gradually leaving the rear pack as its relative phase advances.

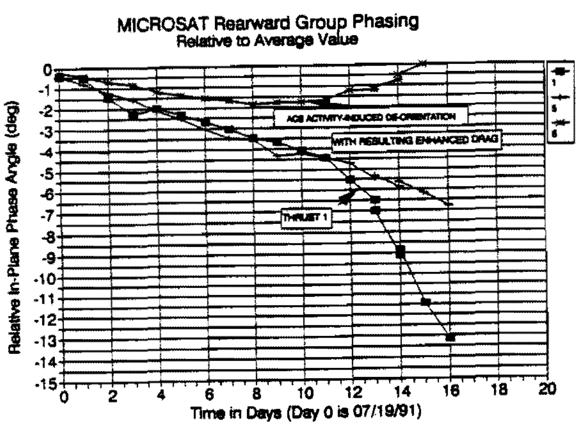

Figure 7. Tracking data for the rear cluster (M1, M5, M6) illustrating the enhanced drag coupling effect for M6 due to temporary sluggishness of the ACS in aligning the satellite spin axis with the orbit normal.

Thrusting was not attempted until satisfactory attitude stability was achieved. Due to such unexpected effects, several crossovers were permitted and the ordering of satellites in the constellation was thus modified several times during the mission. Figure 8 shows the first 130 days of flight. The ripples in the curves represent actual motions of M6 at the center of the constellation. Intervals of poor communications due principally to extreme ground interference with our antenna near Washington D.C. contributed on several occasions to undesired satellite drift past the intended station. The requirements to have accurate smooth track data, a stable ACS, and clean communications opportunities at the necessary time would not have been a problem at 400 nmi. However, with the low orbit, achievement of all three of these objectives became increasingly difficult as the short mission proceeded. As time progressed and the altitude dropped, these effects escalated until control became nearly impossible due to the extreme drag and ACS coupling with it. The thrusts required to overcome drag induced de-phasing eventually approached the limits of control. For example, Figure 9 shows M1 about four months into the mission when the ACS was shut down for about three hours. The resulting re-acquisition process was very sluggish due to the presence of the tremendous disturbance torques. The orbit began to decay at a rate of -2.1 nmi/week. The ACS became stable only after two weeks when thrusting was again enabled. A series of five forward thrusts was undertaken in order to restore the proper altitude(a pre-requisite to phase stability) but in this episode the satellite had already moved 53° in relative phase. The drift rate between the center of mass and a given satellite is governed approximately by

$$\frac{d\theta}{dt}\ (°/day) = -\frac{3}{2}\,\frac{\sqrt{M_e G}}{a_{nmi}^{5/2}}\,\Delta a_{nmi} \times 86{,}400 \times \frac{180}{\pi}$$

$$= -1.86 \times 10^{8}\left(\frac{\Delta a_{nmi}}{a_{nmi}^{5/2}}\right)$$

where G is the universal gravitation constant, M_e is the mass of the earth, and a_{nmi} is the mean semi-major axis in nmi. At 180 nmi, for example, a ≈ 3,624 nmi. Thus $d\theta/dt = -2.36\Delta a_{nmi}$. If a satellite is one nmi low, then $d\theta/dt$ = +2.36°/day. This is the approximate situation depicted in Figure 9 applied to an average altitude loss for M1 of about 3.5/2 = 1.75 nmi. Thus in two weeks this yields 58°, in close agreement with the measured value of 53°. Drag induced discrepancies in altitude must constantly be corrected in order to maintain proper phasing. The capacity to both make a proper determination of the decay rate and order thrusts required time, perhaps two days. The effective reaction time is eventually a limiting factor in very low altitude orbit control.

Lacking sufficient fuel to correct this large 53° phase error (via a sojourn to a higher orbit) the original station for M1 was abandoned and two other satellites were repositioned to give M1 another's slot. This altitude restoring sequence cost over 11 ft/sec or roughly 11 months of the initial fuel allocation.

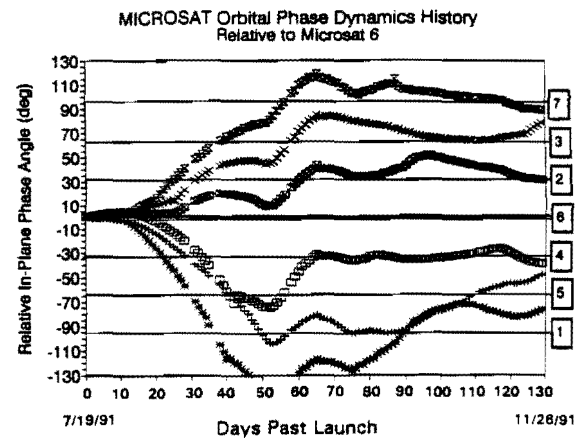

Figure 8. Constellation history for the first 130 days of the flight. The spacing was gradually reduced as the mean altitude decreased.

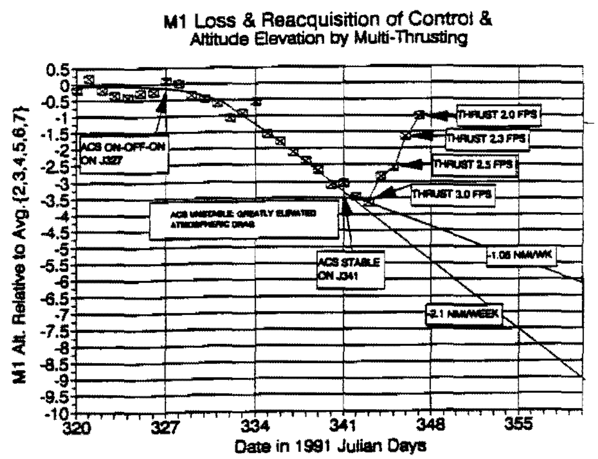

Figure 9. Illustration of criticality of proper ACS function in terms of station-keeping and thruster fuel consumption.

Final Assessment

Figure 10 lists the fuel history for each of the MICROSATs over the 190 days of the quickly decaying orbit. An average of 9.6 thrusts were applied to each satellite. The thrusts realized were generally within about 20% of those intended, but the exigency mandated by the low orbit necessitated larger pulses than otherwise would have been undertaken. The optimum procedure to correct orbit phasing is to thrust in smaller steps thus asymptotically approaching the key stopping point. Any insufficiency in providing timely and accurate stopping thrusts will result in overshoot or undershoot with generally continuing drift.

MICROSAT NITROGEN FUEL REPORT

	M1	M2	M3	M4	M5	M6	M7
DAY 0 Pressure (PSI)	5151	5403	5361	5841	4762	5734	5580
DAY 306 Pressure (PSI)	1139	3028	1787	2601	686	2207	2070
% REMAINING	22	56	33	43	14	38	37
% USED *	78	44	67	57	86	62	63
Cumulative DELTA V Commanded (FPS)	32.0	12.2	23.6	12.8	28.8	18.0	12.8
No. of Thrusts	15	7	11	6	12	8	8

Figure 10. MICROSAT actual fuel consumption table for the entire mission of 190 days.
* Approximate - based strictly on pressure.

Despite the hardships imposed by the low orbit, the satellites performed their communications missions satisfactorily and many "firsts" in LEO communication satellite constellation operations were accomplished in 190 days. The flight control function encompassed more than 550 scheduling operations all carried out on the single 286 PC-based ground station, which also served as the primary graphic display terminal for all spacecraft telemetry.

Detailed analytic support was carried out on a 386 PC utilizing daily ephemeris data sent via modem directly from NAVSPASUR, Dhalgren together with the actual telemetries. All seven satellites were mission-functional until splashdown.