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Gwynne Gurevich, Robert Bell, and James R. Wertz
Microcosm, Inc.
El Segundo, CA

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AUTONOMOUS ON-BOARD ORBIT CONTROL: FLIGHT RESULTS AND APPLICATIONS

Gwynne Gurevich, Robert Bell, and James R. Wertz
Microcosm, Inc., El Segundo, CA 90245
web address: ggurevich@smad.com

ABSTRACT

Microcosm, under Air Force Research Laboratory (Space Vehicles Directorate) and internal funding, developed and recently flew the first fully autonomous, on-board orbit determination and in-track and cross-track control system. Results show the technology maintaining in-track position to ± 1 km indefinitely while using less propellant than traditional orbit maintenance. This technology provides a capability never previously available: specifying a satellite's position months, if not years, in advance with great ease and accuracy with simple geometric calculations rather than complex orbital mechanics and propagation. This will allow all system components (ground based and on-orbit) to know factors such as the current location of all satellites in the system, location and direction to the nearest satellite, parameters of current or future ground passes, when satellite transitions occur, and when a given satellite will next be over any location for all future times. For constellations, the technology eliminates the need for re-phasing as the in-track position is maintained as well as the altitude. Implementing autonomous orbit control significantly reduces operations costs, eliminates many of the traditional payload planning cycles, and creates added system robustness. This paper provides results of the flight demonstration and discusses additional applications of this technology.

1. INTRODUCTION TO AUTONOMOUS ORBIT CONTROL

By *autonomous, on-board orbit control* we mean the automatic maintenance by the spacecraft itself of all of its orbital elements, such that the position of the spacecraft is maintained indefinitely to within the accuracy of the control box. In the most typical case of a spacecraft in a near circular low Earth orbit, the most important elements to control are the period of the orbit and the in-track phase.

However, the eccentricity, argument of perigee, inclination, node, and node rate are also controlled in the Microcosm implementation. On-board orbit control has the following fundamental advantages:

1. Significantly reduced operations cost by eliminating the need for ground-based orbit maintenance.
2. Reduced scheduling and planning burden because the precise future positions of the spacecraft are known at all times.
3. Provides a new and unique capability in that even very simple ground equipment that remains out of contact for extended periods can know where each of the satellites is and when they will next be within contact.

These benefits, discussed in more detail in Sec. 4, are achieved using less propellant than typically required by the normal process of ground-based orbit maintenance. In addition, it may be possible to reduce both the mass and cost of the spacecraft bus since both the size of the thrusters and the maximum disturbance torques can be substantially reduced.

Microcosm has been working on autonomous on-board orbit control for over a decade. (For background on the development of orbit control see, for Chao and Bernstein [1992], Collins, et al. [1996], Glickman [1994], Koenigsmann, et al. [1996a, 1996b], and Wertz, et al. [1996, 1998].) This work has been funded by internal R&D and over 15 contracts from various organizations. Development leading to the current on-orbit demonstration was funded by two SBIR contracts from the Air Force Research Laboratories, Albuquerque, NM.

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In the current implementation, orbit control consists of two principal software components, PAN and OCK. *Precision Autonomous Navigation*, PAN, provides on-board orbit determination (i.e., semi-autonomous navigation) using a version of Microcosm's High Precision Orbit Propagator, HPOP, and GPS measurements over an extended period. It is not needed for orbit control, but serves to fill in inevitable GPS coverage holes and provides precise, continuous orbit determination. *The Orbit Control Kit*, OCK, determines where the satellite should be and generates thruster firing commands that are implemented by the on-board Attitude Control System, ACS. PAN and OCK can be used independently or together, as PANOCK [Collins, et al. 1996].

In September-October, 1999, OCK provided the first flight demonstration of fully autonomous, on-board orbit control on board the Surrey Satellite Technology Limited UoSAT-12 spacecraft. The system configuration and results are described in Section 3.0.

1.1 The Controlled Orbit Concept

In normal orbit maintenance, the orbit elements are maintained only in an average sense. We need an orbit propagator to predict where the satellite will be at any future time. The prediction is limited in that the actual future position of the satellite will depend on drag and other variables which are poorly known in advance (i.e., not predictable). Orbit propagation is inherently inaccurate in terms of predicting future positions of spacecraft primarily because of the difficulty in being able to predict the future atmospheric density and, therefore, the level of drag.

In contrast, a *controlled orbit* is one which maintains all of the elements of the orbit, including the in-track phase. An orbit propagator is not needed to determine future positions, and indeed will not work over an extended period, since small burns are being made on a regular basis to force the satellite to stay within its stationkeeping box. This means that the future position of the satellite is determined by a simple mathematical projection, rather than a complex and uncertain orbit propagator. A relatively simple orbit propagator can be used to determine the position of the stationkeeping box, if it is desired to know the position of the satellite to a higher level of accuracy than an analytic model allows. Even in this case, the orbit propagator would not be run from the current time to some future time, but only for one orbit corresponding to the time at which the information was needed.

In many respects, an orbit controller is similar to the attitude control system. For most satellites, we know where a satellite will be pointed at any future time (within the ACS accuracy) because the attitude control system is maintaining that pointing, regardless of the disturbance torques. We can at best crudely estimate the sum of all of the disturbance torques which the spacecraft feels over an extended period of time. However, irrespective of the magnitude or sequence of these torques, we expect the spacecraft to be pointed accurately at any given future date. Similarly, in a controlled orbit, we do not know all of the orbit perturbations that the satellite will need to overcome. Atmospheric drag will vary in unpredictable ways; there may be a propellant leak or an explosive bolt which will change the orbit. Irrespective of these effects, if the orbit control system is operating, the spacecraft in a controlled orbit will always be at a well defined position, just as the spacecraft attitude will be.

2. CHARACTERISTICS OF A CONTROLLED ORBIT

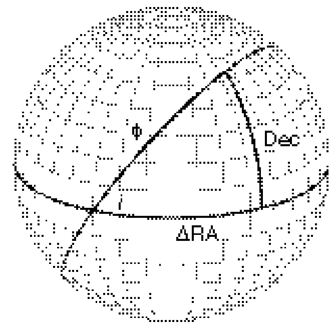
2.1 All Orbit Elements Controlled

The most fundamental characteristics of orbit control as implemented by Microcosm is that it autonomously controls **all** of the orbit elements. Specifically, the controlled elements are:

- Period (and, therefore, the semimajor axis)
- Eccentricity
- Argument of Perigee
- In-track phase (i.e., mean and true anomaly vs. time)
- Longitude of the ascending node
- Node drift rate (and, therefore, the inclination)

Note that it is the period rather than the semimajor axis which is being controlled because this is the fundamental quantity of interest for most satellite applications. Using OCK, a spacecraft will have a predetermined and precisely known average period for the life of the mission, if desired. Controlling the orbit period effectively controls the future times at which the spacecraft crosses the ascending node. Controlling the eccentricity and argument of perigee controls how the satellite moves within the orbit and, therefore, the true anomaly as a function of time, or the phase of the spacecraft in its orbit. These elements constitute *in-track stationkeeping* and determine the position of the spacecraft in the orbit plane.

- **Controlled orbit (UoSAT-12 circular orbit with 650 km altitude)**
  - $P = 5865.633$ sec
  - $\dot{\Omega} = -2.883449759$ deg/day
  - $i = 66.00$ deg
- **Start = 1:00 UT, 9/1/1999**
  - $(RA_0, Dec_0) = (1.15, 2.37)$
  - $\Omega_0 = 0.10$ deg
  - $\phi_0 = 2.59$ deg
- **Estimate the satellite location at 1:00 UT, 9/1/2009**
  - $\Delta T = 3653$ days $= 315{,}619{,}200$ sec $= 53{,}808.2079$ orbit periods
  - $\dot{\Omega} = \Omega_0 + 3653 * \Omega = 266.86$ deg; $\phi = \phi_0 + 360 * 0.2079 = 77.44$ deg
  - $RA = \Omega + \Delta RA = 328.14$ deg; $Dec = \text{asin}(\sin\phi * \sin i) = 63.08$ deg



$\tan \Delta RA = \tan\phi \cos i$

$\sin Dec = \sin\phi \sin i$

Fig. 1. Representative Hand-calculator Estimate of Satellite Position 10 years in Advance. For the 10-year projection shown this simple algorithm produced an error of 9 km relative to a high precision orbit propagation using historical daily variations in atmospheric drag, 70 x 70 geopotential model, solar-lunar perturbations, and OCK control algorithms.

Cross-track stationkeeping controls the orientation of the orbit plane–either in inertial space or with respect to the surface of the Earth. For many spacecraft it is desirable to control the longitude of the ascending node or at least the node drift rate. This is particularly important for a Sun synchronous orbit or whenever the satellite needs to be maintained relative to other satellites, as in a constellation. The node drift rate is controlled by controlling the orbit inclination.

Depending on the specific mission, cross-track orbit control may or may not be required and can be incorporated or omitted as desired. Cross-track control requires that in-track control be done since the node drift rate depends on both the inclination and the altitude. However, in-track control can be applied without cross-track control. Many missions may not need cross-track control because there is no natural long-term perturbation tending to change the node drift rate. Consequently, if the orbit initialization is sufficiently accurate and the cross-track stationkeeping box is large enough, there will be no need for cross-track control and both the cross-track control mode and, possibly, a set of thrusters can be omitted from the spacecraft.

2.2 Determining Position for all Future Times

Using OCK, the computation of future positions to the accuracy of the stationkeeping box is exceptionally straightforward. As illustrated in Fig. 1, the position of the spacecraft ten years in advance can be computed to an accuracy of the order of 10 km using a hand calculator with no memory. Consequently, virtually any user equipment which has a general-purpose microprocessor can easily calculate the future positions of one or more satellites as far in advance as we like. For example, the time table of future passes can be delivered with the software and hardware for a scientific instrument or business groundstation that will be making use of satellites for data transmission. For systems which do not provide continuous coverage this can be used to tell when satellites will be within communication range. For systems with continuous coverage, having the user equipment know where the satellites are can allow, for example, use of a directional antenna to significantly reduce transmit or receive power.

2.3 Disturbance Torques During Orbit Maneuvers

After a spacecraft has achieved its orbital position, by far the largest disturbance torque it will see comes from thruster firings. The magnitude of this disturbance torque typically determines both the size and speed of the attitude control actuators. Frequently, gyros are included in a spacecraft design solely to accommodate stationkeeping maneuvers and other thruster firings. With autonomous orbit control much of this complexity can be eliminated.

In the traditional process of ground-based orbit control, a primary objective is to maximize the time between stationkeeping maneuvers. This reduces the amount of commanding required and the potential for operator error or other problems associated with spacecraft commanding. When the process becomes fully autonomous and implemented on board, this is no longer an important consideration. For example, we would not design an on-board attitude control system to minimize the number of times we applied torque to the reaction wheel.

Instead, we will design the system to minimize disturbances or maximize system accuracy.

The same process occurs with orbit-control. Because the commands are done on board, we will use a large number of much smaller thruster firings to provide orbit control. This provides us with a much finer granularity of control and has the secondary advantage of minimizing the disturbance torque. Generally, the largest thruster firing we would like is a few times the minimum impulse bit of the thrusters being used. This is, by definition, the smallest levels of thrust the propulsion system can efficiently provide and, therefore, the smallest disturbance torque. There is no need for off-modulating the thrusters as is often done to counterbalance torque. Since only a few impulse bits are being used, they are already adjusted as finely as possible.

All of this implies a very different orbit control process from the traditional ground control mechanisms. The orbit control system becomes similar to the attitude control system in that commands are computed and executed on board and, except for monitoring performance and equipment, has little interaction with the ground. From an applications perspective, this means that in many cases we will not need to cease payload operation during stationkeeping. The normal control system will absorb the small disturbance torques involved and the payload operation can continue right through stationkeeping maneuvers. This eliminates a control mode and significantly simplifies the planning and scheduling process. It also reduces the outage times for systems which would like to have nearly continuous payload operations.

2.4 Propellant Utilization

In most applications, autonomous on-board orbit control uses less propellant than traditional orbit maintenance. There several reasons for this as described below.

Stationkeeping. As discussed in Sec. 3.0, we were able to model the on-orbit performance of UoSat-12 and reproduce the actual propellant utilization to within a few percent. We then used the same atmosphere model, allowed the spacecraft to "decay" in the computer, and determined the ΔV and propellant requirement to return to the original altitude, but not the original in-track phase. Even without maintaining phase, the process of allowing the satellite to decay for a month and then restoring the altitude required 10% or more additional propellant.

The need for additional propellant when longer times are allowed between altitude maneuvers in low Earth orbit comes from the general characteristic of atmospheric density. Specifically, at any given altitude and solar intensity level, the density of the atmosphere decays exponentially with altitude. This exponential change in density is characterized by the atmospheric scale height. (See, for example, Wertz [2000]). At satellite altitudes, the scale height is typically 50 to a few 100 km. This means that the atmosphere will be noticeably denser with even small drops in altitude. Consequently, when the satellite is allowed to decay, it will spend more of its time in a lower, denser portion of the atmosphere. Using frequent small burns maintains the satellite continuously at the upper-bound of its altitude range. In general, the ΔV that the spacecraft must supply is equal to the ΔV taken out by drag since the last stationkeeping maneuver. In most applications, the savings by doing maneuvers more frequently is not large. Nonetheless, there can be a small benefit in terms of propellant utilization due to continuously maintaining the satellite at its higher altitude as demonstrated by the UoSat-12 mission.

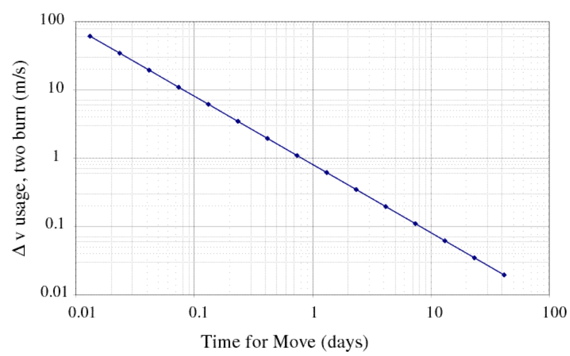


Fig. 2. Delta V Required to Move a Satellite 35 km In-Track as a function of Time Available for the Move. Increased time available for the move can dramatically reduce the delta V and, therefore, propellant requirements.

Avoidance of Physical or RF Interference. If the spacecraft is ever required to do an avoidance maneuver to avoid collisions or RF interference, then the propellant required to do this is inversely proportional to the time available before the maneuver. This is shown in Fig. 2. A very general characteristic of in-plane rephasing is that the longer the time available to do the rephasing, the less propellant it requires. Moving the spacecraft quickly is exceptionally demanding in terms of propellant utilization. Consequently, there is a significant propellant advantage to knowing where your spacecraft will be as far in advance as possible.

Rephasing to Meet Mission Needs. Similar to the avoidance of physical or RF interference, rephasing the satellite to meet specific mission needs can be done at far lower propellant cost if done far in advance. For example, if we would like to "reposition" the spacecraft with respect to a future pass over Hawaii, this could be done at virtually no propellant cost a few weeks in advance or at an extremely high propellant cost a few hours in advance. If we are able to look ahead in our planning activity, we can dramatically reduce the propellant utilization required for repositioning. This planning may, of course, require coordination with multiple users and many different organizations. Consequently, a planning and scheduling process that works well in advance of real time provides many mechanisms for optimizing the mission at very low propellant cost. This gives us both a new level of capability and a significant mechanism for reducing propellant use whenever maneuvers are required for meeting planned or unforeseen mission needs.

For constellations, the issue of rephasing is especially important. The potential of having to rephase a large number of satellites simultaneously and maintain continuous knowledge of their location and potential interactions represents an extremely complex, uncertain, and expensive task. Using OCK entirely eliminates the need for rephasing. Because each orbit is maintained with the same fixed period, the constellation structure is maintained indefinitely with no additional computations or thruster firings other then the ongoing orbit control process.

3. RESULTS OF UoSAT-12 FLIGHT DEMONSTRATION

3.1 Implementation on UoSAT-12

The Microcosm OCK software was flown on the Surrey Satellite Technology Limited (SSTL) UoSAT-12 spacecraft, where it co-resides on a customized 386 onboard computer, developed by SSTL, with their attitude determination and control system software (See Fig. 3.) The inputs for OCK are generated by the SSTL-built 12-channel L1-code GPS receiver (SSTL model SGAR 20) with an output frequency of 1 Hz. For a further discussion of the UoSAT-12 implementation, see Wertz, et al. [2000].

The baseline OCK software was created using ANSI C. The operating system used was SCOS (Spacecraft Operating System), created by BEKTEK. The following estimates of memory, throughput and system services required are based upon actual execution on the 386/387 processor. Memory required is 120K using a 16 bit processor. Throughput is <20 milliseconds per 60 second interval with a 200MHz processor. The system services required include system time, and I/O (from GPS and to the ACS or thruster interface software). The use of the math co-processor provides higher fidelity output, but is not necessary as a suite of math libraries is available with the OCK code.

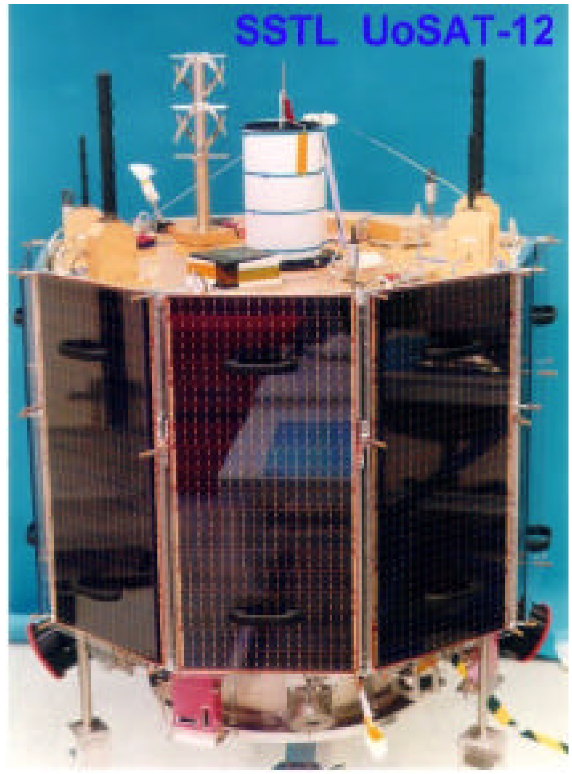


Fig. 3. UoSAT-12. The Surrey Satellite Technology Limited satellite was launched in April, 1999. The OCK on-orbit demonstration was conducted September 23 to October 22, 1999.

3.2 Flight Results

Microcosm demonstrated an orbit two different high-accuracy in-track orbit controllers, one cross-track controller, and the PAN filter. Nominally, UoSAT-12's attitude determination and control system provides a GPS state vector, with GPS time, every ten seconds. The role of PAN is to aid OCK through "back-filling" of skipped vectors and to reduce the vector-to-vector noise.

The general input, processing, and output flow is shown in Figure 4. In the implementation of the in-track controllers, the basic measurement to be controlled is the deviation from the expected value in the crossing time from South to North of the Earth's equator. This data is supplied to the OCK software in the form of ECEF GPS state vectors and their associated epochs, which are then processed within OCK to extract the relevant information.

The in-track controllers differ in their filter implementation for tesseral correction. Both filter types reduce the effects of high-order terms in the Earth's gravitational field by removing the majority of the effects of the tesseral and sectoral terms. Onboard targeting of frozen orbit conditions is used to better control the "orbit average" performance. A proprietary method is used to continually move the orbit toward frozen orbit conditions and, once achieved, hold it there. Orbit-averaged mean elements are also calculated on board.

An analogous process to in-track control has been implemented for the cross track control. However, the longitudinal phase of the orbit is controlled and not the inclination. This means that any secular drift in the placement of a constellation's orbit plane are removed over time until the desired longitudinal position and, importantly, "longitudinal speed" are maintained.

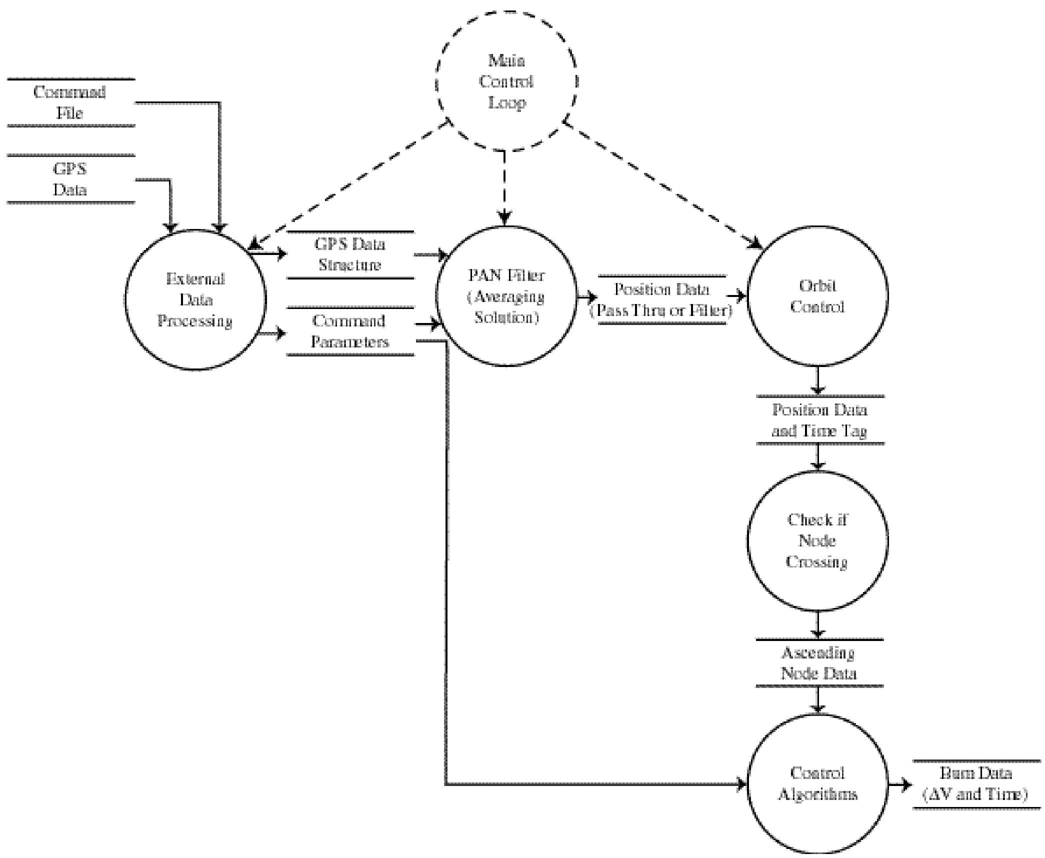


Fig. 4. OCK Data Flow. OCK uses inputs from a GPS receiver (or autonomous navigation system) and outputs delta V commands needed for orbit maintenance.

Duration σ	29 days
Performance (1)	±0.12 sec = 0.9 km
No. of Burns	53
Maximum burn	2.7 mm/s
Minimum burn	0.053 mm/s
Mean burn	1.4 mm/s
Sum of burns	73.3 mm/s
GPS availability	5% of key measurements not received
GPS outages	Up to 8 hours
Thrust Profile	Half thrust for 12 days, then full thrust restored

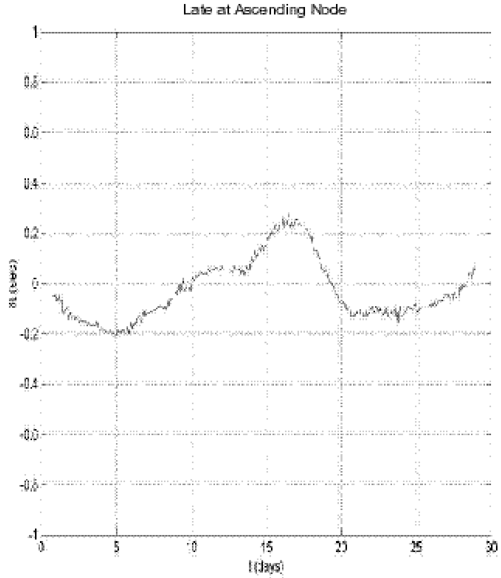


Fig. 5. OCK On-Orbit Performance. During the preceding 4 months, UoSAT-12 had slid in track over 4000 km or approximately 500 sec. Once OCK began, satellite decay effectively stopped.

3.2.1 In-Track Performance

Fully autonomous, onboard orbit control was activated on September 23 at 14:29:41 UT. The controller first commanded a burn of 1.386 mm/s some 8 hours later. This burn was executed as planned by the UoSAT-12 ADCS system. OCK then commanded 52 subsequent burns over the next 29 days totaling 73.3 mm/s of expended Δ*V*. The results are shown in Figure 5.

Examination of these charts shows the slow "sinking" of the deviation from expected crossing time (the "time late at the ascending node"), over the first five days. This was expected and represents the controller reacting to the building of the time late due to the effect of drag. As can be seen up to about day 12, the magnitude of the burns increases before starting to level off as the time late ceases to increase and returns to close to the desired zero level. This zero level conforms to the spacecraft being exactly on time within the control accuracy.

Near day 12, SSTL staff identified a problem resulting in the spacecraft software preventing one of the two thrusters from activating. This imbalance was detected in anomalous attitude motions. OCK compensated for the lack of restorative impulse by increasing its demanded Δ*V*. Hence, the "sink" upon initialization was more than one would have expected from simulation results alone. The second thruster's non-performance was rectified, but no change was made to the OCK filter. OCK's internal integral term had built up to a significant level. Thus, when, from the perspective of OCK, the Δ*V* was effectively doubled – or, alternatively, drag halved – it proceeded to overshoot into positive time late and subsequently rebounded into negative territory over the next ten days or so. Nonetheless, in spite of doubling the thruster response in the middle of the flight demonstration, OCK maintained the in-track error to within less then ±1 km.

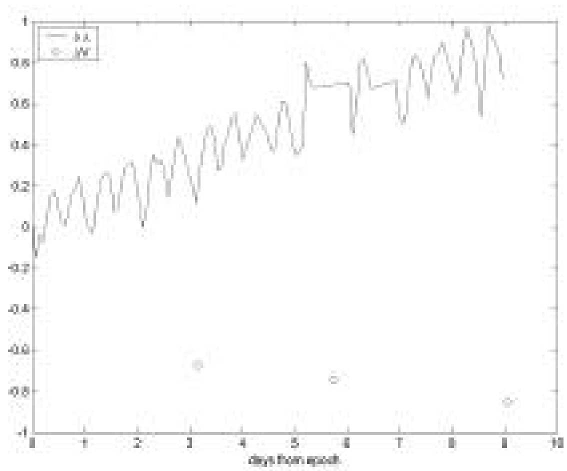


Fig. 6. OCK Cross-Track Results. The targeted node drift rate was intentionally set well off the actual node drift rate so that the system would be required to fire in the cross-track direction, which it did correctly.

3.2.2 Cross-Track Performance

A short nine-day cross track experiment was performed to validate the cross track control algorithms. Though there was insufficient time to validate the long-term performance of cross track control onboard UoSAT-12, the experiments showed (1) that the cross track controller works as expected, and that (2) the algorithms are robust in the presence of missed node crossing data. Indeed, it takes several

	On-Orbit	Simulation
Atmosphere	Real	MSIS
F10.7	Real	Measured
Duration (days)	29	29
Performance (sec, 1σ)	± 0.12	± 0.14
Performance (km, 1σ)	± 0.9	± 1.02
No. of Burns	53	48
Maximum burn (mm/s)	2.7	4.9
Minimum burn (mm/s)	0.053	0.19
Mean burn (mm/s)	1.4	1.6
Sum of burns (mm/s)	73.3	76.3
ΔV to restore altitude	85 -100 mm/sec	

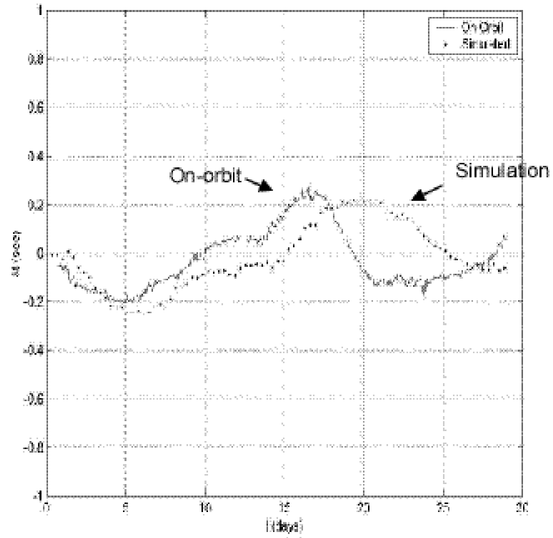


Fig. 7. Simulation Results vs. On-Orbit Performance. The total required delta V was consistent between the simulation and actual flight to about 3 mm/sec (= 4%). Using the simulation, the delta V required to restore the altitude was 85 to 100 mm/sec, implying a delta V savings using OCK of 10% to 25%.

days to measure the mean cross track rate and even longer to nullify and stabilize the longitude error. Because of the short duration available for the cross track demonstration, the desired longitude rate was deliberately set far from the actual longitude rate in order to determine (1) if the controller recognized the longitude error, and (2) if the control ΔV is properly placed to correct the errors. Had the desired longitudinal rate been set at the rate observed on-orbit, no firings would have occurred.

The results of the cross-track demonstration are shown in Figure 6. The ±2 mdeg noise level on top of the mean longitude error is typical. This error is due in part to GPS Selective Availability and the interpolation method used to determine the node crossing time and longitude. Figure 6 shows a growing longitude error, indicating an Eastward longitude drift. The controller correctly fired three times in the negative direction to reduce the inclination and hence reduce the longitude rate.

The nature of the curve changes during day six and seven. Several node crossings were missed during this time period when the spacecraft ADCS experienced technical difficulties that resulted in poor GPS reception. During day six and seven, 78.4% and 47.2% of the GPS solutions were invalid, respectively. Cross track control merely waits for the Next valid node crossing measurement and proceeds.

This element worked as expected.

3.3 Post Flight Analysis

3.3.1 Validation of System Simulation

In order to validate the orbit control simulator, a test was performed with the intent to reproduce the on-orbit results of the in-track controller from UoSAT12. A raw GPS state vector obtained from the navigation software on UoSAT12 was used as the initial state for the simulation. In addition, historical solar flux values were obtained for the period of the on-orbit experiment and used in the simulation. A plot of the time-late results for both the simulation and the on-orbit experiment are shown in Figure 7. As discussed above, an error aboard UoSAT12 during the experiment resulted in a thruster failure. As a result, the thruster output was only half that which was commanded for the first 13.5 days. Afterwards, full thrust was restored. This thruster error was also modeled in the simulation and shows a similar behavior to the on-orbit results. As can be seen in the figure, the simulated and on-orbit results compare quite favorably. Though not overlapping, they both exhibit the same trends in time-late, both in the magnitude of the time-late deviations and the timing of the events. The median (1-sigma) time-late differences between the experimental and simulated results are ±0.12 sec and ±0.14 sec respectively. The mean burns are 1.4 mm/s and 1.6 mm/s respectively. In addition, the total fuel consumption differs by only 3 mm/s or 4% of the total burn. These results indicate that the simulator reproduces a realistic space environment for the testing of orbit control and that the simulated results are statistically the same as those that would be obtained on-orbit.

3.3.2 System Robustness

The system as demonstrated maintained control during significant GPS outages. OCK also maintained stability during the "halving" and then the effective "doubling" of the expected thrust levels.

Further examining the ramifications of the controller's behavior is instructive:

1. The controller dealt with an effective doubling of the ballistic coefficient upon initialization and controlled the time late to an acceptable level.
2. Upon "re-instatement" of the second thruster the controller "hiccoughed" as to be expected but never lost control.

Thus, the controller has demonstrated its ability to overcome pre-launch mis-modeling of the spacecraft as well as unforeseen variations in the atmosphere.

3.3.3 Fuel Consumption

To first order, the required ΔV is a function only of the perturbations which are being overcome (atmospheric drag in LEO) and does not depend on many small burns vs. fewer large burns. When overcoming drag, orbit control must put back whatever ΔV drag takes out.

In low-Earth orbit, atmospheric density increases exponentially with decreasing altitude, doubling with every 30 to 50 km drop. This implies that loss due to drag is minimized by maintaining the satellite at its operational attitude, rather than allowing it to decay and then re-boosting Autonomous orbit control typically maintains the altitude to ~100m and nearly eliminates the excess drag losses due to orbit decay incurred by traditional orbit maintenance methods.

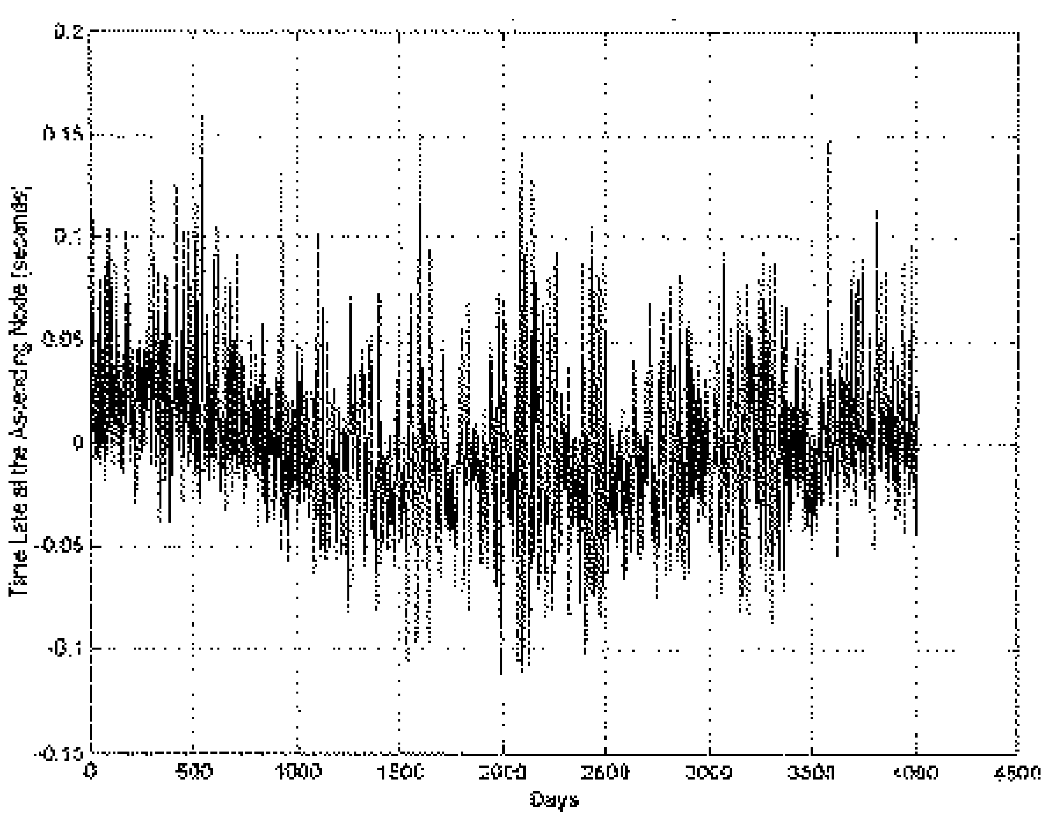


Fig. 8. OCK Simulation Over an 11 Year Solar Cycle. Simulation includes daily variation in the F10.7 index, 21 x 21 geopotential model, solar-lunar perturbations, and solar radiation pressure. The OCK gains were not changed for the entire 11 year run.

3.3.4 Long-Term Behavior

As shown in Fig. 8, ground-based simulations of in-track control run for 11 years, shown a 3-σ time late at the ascending node for a nominal LEO (650 km altitude close circular) spacecraft of ~0.08 sec. These simulations were run using Microcosm's High Precision Orbit Propagator (HPOP) using the JGM-3 gravity field (truncated to 21 × 21), MSIS-86 atmospheric model using historical F10.7 plus random noise solar flux, solar radiation perturbations, and third body lunar and solar perturbation from the standard JPL ephemeris. Given the excellent agreement between expected and achieved results, we expect that forthcoming on-orbit implementations can produce similar levels of performance.

4. APPLICATIONS

We begin by discussing the applicability of autonomous, on-board orbit control to typical single satellite missions. Sec. 4.2 then describes the use of orbit control for low Earth orbit constellation maintenance. Finally, Sections 4.3 and 4.4 discuss orbit control applications in two specialized areas -- geosynchronous orbit and satellites orbiting other planets or moons.

4.1 Single Satellite Missions

Ground Track Maintenance. Because all of the orbit elements can be controlled, either the spacecraft ground track or its path in inertial space can be made to follow a pre-defined pattern, as in the case of a repeating ground track. However, it does not need to be a repeating ground-track and can be changed at the convenience of the user by straightforward changes to the orbit control parameters. This provides two features of importance to the mission designer. We can, for example, predict the characteristics of any future spacecraft pass or determine when specific events will occur, such as next time at which Hawaii will be seen at an elevation angle greater then 50 deg (see Sec. 2.2). Similarly, we can change the pattern to provide appropriate coverage for specific future events. For example, we can provide a very small ΔV sufficiently far in advance and change the conditions of the ground-station pass over Hawaii two weeks ahead such that it passes at an elevation angle of 60 deg, rather than 40 deg. This can be useful in creating scenarios required for specific applications. As discussed in Section 2.4, the process of doing this far in advance greatly minimizes the propellant needed for scenario control. This, in turn, can open a new set of observation methods and long-term asset utilization.

Random Walk Orbit. Related to ground track maintenance is the idea of a "Random Walk Orbit" for which future positions are precisely known by the ground system or end users, but unpredictable by others. This is done by executing a series of more-or-less random, pre-defined maneuvers throughout the mission life. This produces a series of connected, controlled segments. The sequence of controlled orbits is known to the end users so that they can predict where the satellite will be with only a minor modification to the prediction approach shown previously in Fig. 1. However, this prediction will not be possible for those that do not know the maneuver sequence. In addition, if the satellite makes two maneuvers between successive attempts to track the satellite, then the satellite observations become difficult to correlate. That is, propagating backward in time from the current observation will not find any point at which the current and the "old" satellite were ever at the same place at the same time. This tends to dissociate a satellite from its prior observations and makes ground tracking much more difficult.

System scheduling and mission planning. Mission planning and scheduling are traditionally dominated by astrodynamics. Planning is done as far in advance as feasible in terms of future orbit propagation. If preliminary plans are done, say, two weeks in advance, then an updated plan will be created several days in advance, and final updates will be made as close to the event as possible so that the predicted positions can be as accurate as possible. Autonomous on-board orbit control effectively eliminates all of the replanning and rescheduling process and allows these activities to be done on a convenient business basis rather then as astrodynamics dictates. For example, we may choose to do long-term planning on an annual, quarterly, or monthly basis as convenient for the user group. These plans are updated as the needs of the users change and the detailed schedule of events is prepared in a manner convenient for operations and dissemination. For example, we may choose to make a detailed weekly plan three weeks in advance in order to distribute the information to various user groups for potential input and changes.

User Equipment Able to Know Future Positions. An example of a military application for this capability would be a submarine leaving port and surfacing six months later knowing the exact time for transmission to a satellite overhead, without requiring the establishment of two-way communications. As another example, a scientific spacecraft with a large user community can distribute software to the whole community which incorporates the future ephemerides of all satellites in the system. Consequently, each of the users can do their own planning either for potential spacecraft commanding or for determining when data appropriate to their interests will be collected. All of this provides a new level of utility for low-cost, simple ground equipment.

Of course it may be necessary, from time to time, to change the positions of satellites in orbit. This could be due to new mission requirements, failure of on-orbit spacecraft, or the replacement of an old satellite or constellation with a new one in a different orbit. This can be easily accommodated within the orbit control process in that all of the data necessary to predict future positions of a satellite can be provided with less than 10 parameters in a look-up table.

Avoiding Collisions and RF Interference. Substantial work has been done in recent times on the problem of collision avoidance and debris mitigation. [Chobotov, et al. 1997; Jenkin, 1993A, 1993B, 1995; Johnson and Mcknight, 1991; Simpson, 1994] This is particularly a problem for satellites in geosynchronous orbit or in high density regimes. However, it can also be a problem for general satellite orbits. RF Interference with higher or lower satellites can also pose outage problems which may be critical to either avoiding business interruptions or obtaining important scientific data.

The fundamental problem associated with avoiding both collisions and RF interference is knowing as far in advance as possible when and where potential events will occur. This is critical to coordinate planning among different system operators and to allow any required maneuvers to be done with minimum propellant. (See Section 2.4.) If the potential problem is with another active satellite then it is important to work with the other operations group so that appropriate coordinated actions can be taken. If both satellites are using a fully controlled orbit, then the advanced computations are trivial and can be done as far in advance as desired, say on a monthly or annual basis. In this case the coordination becomes straightforward and extremely small amounts of propellant would be required to avoid any problems.

If only one of the two systems is using a controlled orbit, then the problem is more complex. This would occur, for example, with a satellite in a controlled orbit and a potential collision with inactive debris. In this case, we can plan as far in advance as the propagation of the debris particle will allow. While this is not as desirable as two fully controlled satellites, it is still better to know in advance where your satellite will be.

A controlled satellite or constellation may choose to make the future positions of all of its satellites publicly known. For example, this might be included on a system website. This allows other satellite users to calculate as far in advance as possible when potential collisions or interference could occur and to provide the maximum possible warning. This may involve coordination between two competing organizations. Nonetheless, it is in the best interest of both organizations to avoid any potential for either collisions or RF interference, if it is feasible to do so.

4.2 Constellation Maintenance

For single satellite missions, the use of orbit control can reduce cost and enhance performance. These are importance for most missions, but can be truly critical for constellations where retaining the structure of the constellation (at minimum cost and risk) is fundamental to the definition of the constellation and, therefore, its mission performance.

Essentially all of the applications for single satellite missions are germane to constellations as well. However, there is the additional requirement to maintain the overall constellation structure -- i.e., the relative positions of all of the satellites in the constellation. Some work has been done on methods for providing only relative orbit control for constellations. [Burgess, 1996] Microcosm's implementation of orbit control provides this relative control by doing absolute control for each of the satellites in the constellation. As discussed by Wertz [2000], absolute control uses less propellant than relative control and is far less complex to implement. This absolute control has a few added benefits: the configuration and logic does not need to change during constellation build up as it would for a relative constellation and there is no need to perform coverage analyses based upon the "new" constellation configuration as it decays. (See Wertz [2000], for detailed discussion of absolute versus relative orbit control.)

A key issue for constellations is mitigating the impact of higher order harmonics on the constellation structure. Because of these higher order harmonics due to the nonuniform mass distribution of the Earth, satellites with the identical mean semimajor axes but different node crossings (i.e., in different orbit planes) will have slightly different orbit periods. If the spacecraft altitude is controlled using the same process for all of the satellites, then an occasional "rephasing" or "rebaselining" will be required to maintain the constellation structure. OCK overcomes this problem by continuously maintaining the orbit period, rather than the semimajor axis, such that the mean period will be the same for all satellites in the constellation over its full lifetime. This maintains all of the satellites in the constellation "in synch" and ensures that the constellation structure will be fully maintained over the lifetime of the satellites without periodic rephasing or readjustment.

The collision avoidance problem is particularly severe for constellations because there are a very large number of potential collision opportunities within a confined constellation structure. (See, for example, Wertz [2000].) This implies that we need to design the constellation to avoid collisions and then to control each spacecraft to follow that design within the accuracy of the defined stationkeeping box. This is a significant advantage of full orbit control in the constellation management problem.

As with single satellites, a constellation may or may not require cross-track control. This depends on the stationkeeping box requirements, the accuracy of orbit initialization, and the lifetime of the constellation. OCK can be implemented either with or without cross-track control as appropriate to each specific mission. For a more extended discussion of all aspects of constellation maintenance and control, see Wertz [2000].

4.3 GEO Applications

For GEO, the use of continual orbit maintenance can shrink the size of the stationkeeping box, allowing more vehicles to be placed into a traditionally single GEO slot. The potential economic benefit of this scenario is substantial. First, the vehicles could potentially be smaller to achieve the same capacity at GEO (less transponders per vehicle). Smaller vehicles can use significantly cheaper launch vehicles. The system robustness is higher given this scenario as a launch failure does not eliminate all capability. The system is also more robust to on-orbit failures (i.e., not all capacity is eliminated if one spacecraft fails. In addition, producing many vehicles that are exact duplicates will reduce the non-recurring costs via economics of scale. Note that because the orbit maintenance is done on-board (for free in a recurring sense), the operations costs are reduced for GEO applications as well.

Finally, because the thrust is reduced (more frequent, but smaller, maneuvers), it is possible to eliminate an ACS mode, and potentially, the need for expensive ACS components, such as gyros and reduce weight in the process. Also, the thrusters can be smaller, again reducing the vehicle weight.

In GEO the perturbing forces are only very weakly dependent on the size of the stationkeeping box. Consequently, there is no propellant loss or savings by using a larger number of smaller burns. Thus, the principal advantages are the smaller stationkeeping box, smaller disturbance torques, and the potential for fully autonomous operations. For further discussion, see Chao and Bernstein [1992].

4.4 Other Planetary Applications

The Deep Space Network, DSN, is normally used to support operational missions around other planets. However, DSN costs are very high and scheduling the network to provide timely support can be difficult because of potentially conflicting priorities. The level of DSN support required is greatly reduced and many of the problems alleviated by the use of autonomous orbit control around other planets.

Consider, for example, the benefit of OCK on a Martian orbiting system. The satellites will not need DSN assets for orbital maintenance. In addition, because OCK maintains orbital position, the vehicles' position far into the future can be determined and thus, planning for operations that do require the DSN can be done far more effectively. Operations times can be known enough in advance that DSN service can be counted on. Other operations, such as a rover communicating with an orbiter can be easier to plan. Finally, because the system has been shown to use less propellant when drag is present, spacecraft weight can be decreased, a very important benefit for interplanetary applications.

5. CONCLUSIONS

The UoSAT-12 technology demonstration mission showed that autonomous, on-board orbit control works successfully and is robust to both thrust variations and data outages. Further, it maintained all of the spacecraft elements using 10% to 20% less propellant than would have been expected using traditional, ground-based orbit control.

Autonomous, on-board control offers several technical capabilities not previously available to space missions:

- The position of the spacecraft at all future times is known as far in advance as desirable

- The ground track (or inertial track) of the spacecraft can be made to follow a predefined pattern which can be changed at the convenience of the user

- The process for computing future positions is simple and can be included in any ground-based equipment that uses a general purpose microprocessor

- There is a longer planning horizon for dealing with the potential problems of RF or physical interference with other spacecraft or debris

- Disturbance torques are much lower than with more traditional orbit control processes, such that the size and responsiveness of control actuators can be lessened and restrictions on the timing of stationkeeping maneuvers can be reduced or eliminated

In spite of the significant technical advantages above, the most substantive benefit of, on-board orbit control is in reducing both cost and cost risk. Costs can potentially be reduced in the following principal areas:

- The operations cost of orbit maintenance is essentially eliminated (i.e., reduced to occasional monitoring)
- The cost of planning and scheduling (often representing 50% of operations cost) is reduced
- The cost and complexity of transmitting spacecraft ephemerides to various users is eliminated
- Lower propellant usage (and, therefore, longer spacecraft life and lower cost per year) for several areas:
    - — Stationkeeping
    - — Rephasing to avoid collisions or RF interference
    - — Rephasing to meet coverage needs

- Lower spacecraft weight, due to the decreased use of propellant and the decreased size and possible elimination of some ACS components.

The impact of these performance enhancements and cost and risk reduction areas will depend on the details of the specific mission. The least impact will be on missions which have no orbit control requirement (and, therefore, no propulsion system) and on large, single spacecraft, such as Space Telescope, in which orbit operations is a very minor element. The greatest impact will be on constellations, where constellation maintenance is a significant cost and performance component and on small, low cost missions which need orbit control and require significant knowledge of spacecraft position for payload planning purposes. In addition, this technology enables some missions and mission elements, such as automated one-way data transmission, which would otherwise not be possible.

In summary, autonomous, on-board orbit control can fundamentally change the way space missions operate. It is a key component in extending the philosophy of "faster, better, cheaper" to 21st century ground operations.

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