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Initial Flight Results from UoSAT-12

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Microcosm, Inc.

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ABSTRACT

Microcosm, under funding from the Air Force Research Laboratory Space Vehicles Directorate, has developed the first on-orbit demonstration of autonomous, on-board in-track and cross-track orbit control. The flight demonstration was conducted on the Surrey Satellite Technology Laboratory's (SSTL) UoSAT-12 mission. The satellite is in a 650 km, near circular orbit at 65 deg. Navigation data is provided by an experimental GPS receiver built by SSTL. The first full orbit control test was initiated Sept. 23, 1999, and lasted for 29 days until other propulsion system experiments were initiated. During the test period, thrust calibration was initially off by a factor of 2 and was corrected midway in the testing. Due to active work on the GPS software, GPS data outages occurred that were as long as 8 hours, with as much as 11 hours out during a 24 hour period. In spite of these unexpected anomalies and lack of data, OCK maintained a time late at the ascending node to within a standard deviation of 0.12 sec, equivalent to ± 0.93 km in-track over the entire 29 day test run. This is in contrast to an in-track slippage of approximately 4,500 km over the preceding 4 month period. During the test period, OCK applied a total ΔV of 73.3 mm/sec in 53 burns. All burns were in the positive direction (i.e., provided drag make-up). The total ΔV was equivalent to or slightly less than that which would have been required to return the spacecraft to its initial altitude had all of the thrust been applied at the end of the test period.

INTRODUCTION

The Microcosm Orbit Control Kit (OCK)[1] is currently being flight-tested on board SSTL's ongoing UoSAT-12 mission. This demonstration validates the use of autonomous orbit control to maintain a spacecraft's long-term orbital position. The spacecraft orbit position, in terms of orbital phase and "longitudinal phase," is controlled individually or within a larger constellation. OCK[2] technology opens the door to significant simplification of day-to-day operations of constellations, large and small, and the associated cost benefits. In addition, OCK can greatly simplify mission planning and operations for single satellite missions.

OCK continues Microcosm's long-term commitment to transfer those operations that can be properly carried out by an onboard system from the ground to the spacecraft. This approach leads to efficiencies in ground operations, lower cost, and reduced system risk and will allow resources to be utilized on problems at which human operators excel, such as on-orbit anomalies and one-of-a-kind operations such as check-out. For further discussion of the history of OCK and its applications to constellation management and orbit control see Wertz [1996], Königsmann et al. [1996], Collins et al. [1996], and Wertz et al. [1998].

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[1] Microcosm holds US and European patents for doing autonomous onboard orbit control.

[2] OCK consists of software developed under Phase 1 and 2 Small Business Innovative Research (SBIR) contracts sponsored by the Air Force Research Laboratory, Albuquerque, NM.

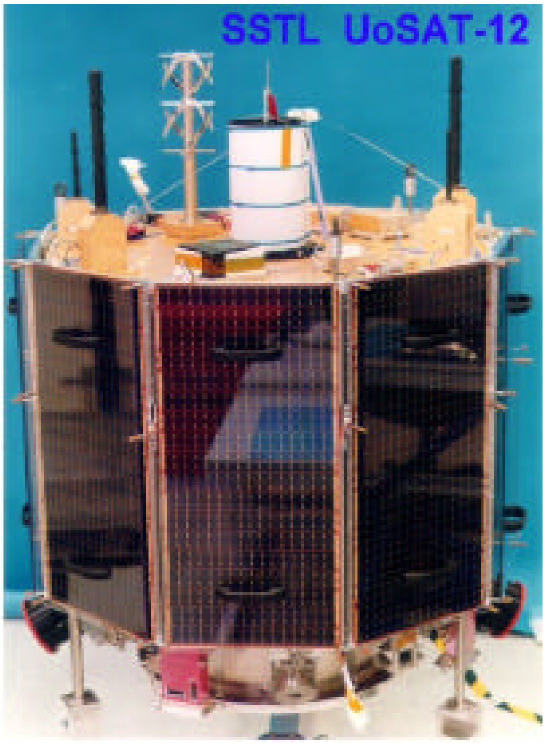

Figure 1 UoSAT-12

ARCHITECTURE

The Microcosm OCK software is flying 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. 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. GPS is a relatively low-cost solution to acquiring the needed navigational input to the Microcosm OCK controller. This approach enables absolute orbit control instead of having to do relative orbit control for a constellation of Earth-orbiting satellites.

The Microcosm OCK approach employs absolute control rather than relative control. Absolute orbit control maintains each satellite in a "box" which will keep a predictable, regular position relative to users on the ground and will keep the satellite orbit from decaying. (For a discussion of absolute vs. relative orbit control, see Wertz [1999, 2000].) In the Microcosm OCK implementation, each satellite maintains its own position and velocity relative to a pre-defined stationkeeping box which has a very predictable periodic motion in an inertial reference frame. In this way, the position of one satellite in the constellation does not determine the fate of the rest of the satellites. If one satellite "dies" prematurely, this has no detrimental effect on the other satellites in the constellation, since each maintains its own state relative to its uniquely defined orbit control box. Another benefit of absolute control is that the satellites will have a longer life than those in systems employing relative control. In a relative control implementation, the entire constellation typically decays as quickly as the slowest falling member, to maintain the desired uniform distribution of satellites.

ALGORITHMIC OVERVIEW

The Microcosm OCK project is validating two different high-accuracy in-track orbit controllers as well as a single cross-track controller. Additionally, the use of a general filter for GPS inputs assures that a consistent and continuous data set is provided to the control software and provides improved accuracy of node crossing detection when possible. Nominally, UoSAT-12's attitude determination and control system provides a fresh GPS state vector, with GPS time, every ten seconds. The filter's role is to aid OCK through "back-filling" of skipped vectors and, as best it can, aid in reducing the vector-to-vector noise that is encountered.

The filter has four operational modes:

1) *Pass Through Mode,* where GPS solutions are converted to ECI and passed on to Orbit Control,
2) *Sample Mode,* where every n^{th} GPS solution is converted to ECI and passed to Orbit Control (the sample rate is defined by the user),
3) *Short Term Average Mode,* where n GPS solutions, taken over a $n \times 10$ sec time period, are propagated to a common epoch and averaged to produce a state estimate for Orbit Control, and

4) *Long Term Average Mode*, where, in addition to the short term average, a long term average based on the last *m* short term average estimates is produced. Long term averages are only used for testing the filtering technique and are not used by Orbit Control.

The filter has been tested using data from a high precision orbit propagator with noise added to simulate GPS selective availability and with on-orbit GPS data. Preliminary results show that the filter can reduce position noise by a factor of about 2. Results with simulated data show that the filter provides accurate data during short GPS unavailability to allow orbit control processing to continue.

In the implementation of both of the in-track controllers, the basic measurement to be controlled is the deviation in the time of crossing from South to North of the Earth's equator from the desired or expected value. Thus, the system controls a pre-defined period (and, specifically, the orbit phase) and longitudinal phase, rather than any particular set of orbital elements. In essence, the end-user is uninterested in whether a spacecraft can hold its orbital elements x, y, z to some prescribed level of accuracy; they are more interested in whether or not a telephone signal will get through. By use of OCK, this problem is now reduced to a timing problem.

This approach allows the controller freedom from particular force models' differences with reality and negates the need for onboard propagation. Therefore, great savings in onboard processing requirements are accrued without impinging on accuracy. 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. 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, that is, the non-axially symmetric terms in the expansion. Each technique provides a different level of fidelity based on the complexity of the implementation. Since different filtering techniques are employed, the nature of the signal fed to the in-track controller is different between the two.

In addition, onboard targeting of frozen orbit conditions is used to better control the "orbit average" performance of the controller. Frozen orbit conditions are those where the natural rotation of the argument of perigee and the oscillations in the orbital eccentricity are essentially frozen out through the playing off of J_2-derived perturbations against perturbations from higher odd-numbered zonal coefficients. 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 calculated on board and are used to facilitate this feature.

In terms of cross-track control, an analogous process to in-track control has been implemented. The longitudinal phase of the orbit is controlled and not the orbital inclination. This means that any secular drifts in the placement of a constellation's orbital plane are removed slowly over time until the desired longitudinal position and, importantly, "longitudinal speed" are maintained. From a constellation operator's point of view, the control of the longitude of a spacecraft with respect to other planes and within a plane can be as important to coverage as in-track slippage and altitude decay.

FLIGHT SOFTWARE

The Microcosm OCK software, while originating from two different SBIR programs, is a single computer software configuration item (CSCI) consisting of four computer software components (CSC) as shown in Figure 2.

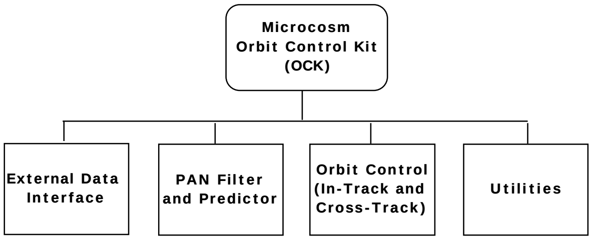

Figure 2 Microcosm OCK CSCI and CSCs

The general input, processing, and output flow, shown in Figure 3, demonstrates how compact the software is. The OCK software executes in under 100 msec when called at a 10 sec time interval.

Originally, the Microcosm OCK software was to reside on an Intel 186 processor with no math co-processor. Much of the accuracy associated with the OCK implementation was dependent on double precision arithmetic that would not be available without a co-processor. Low level testing was performed to see how single precision would effect accuracy, timing and code size. The results confirmed that the accuracy of the overall system would be substantially affected by the lack of double precision arithmetic.

In addition to the initial arithmetic constraints, the Intel 186 onboard computer (OBC) would only allow an executable of less than 64 Kbytes. The size of the code needed to be minimized, implying that using software solutions for improved arithmetic would not be acceptable. A version of the OCK software is available for an Intel 186 processor without a math co-processor, with slightly reduced accuracy.

When the Intel 386-based OBC became available, the OCK software could now make use of a math co-processor and/or expand to provide double precision arithmetic in software. Both of these implementations are also available. The OCK software based on the 386 OBC with math co-processor is ~65 Kbytes and the OCK software with its own software based arithmetic libraries is ~75 Kbytes. The use of the math co-processor provides higher fidelity output.

INTEGRATION

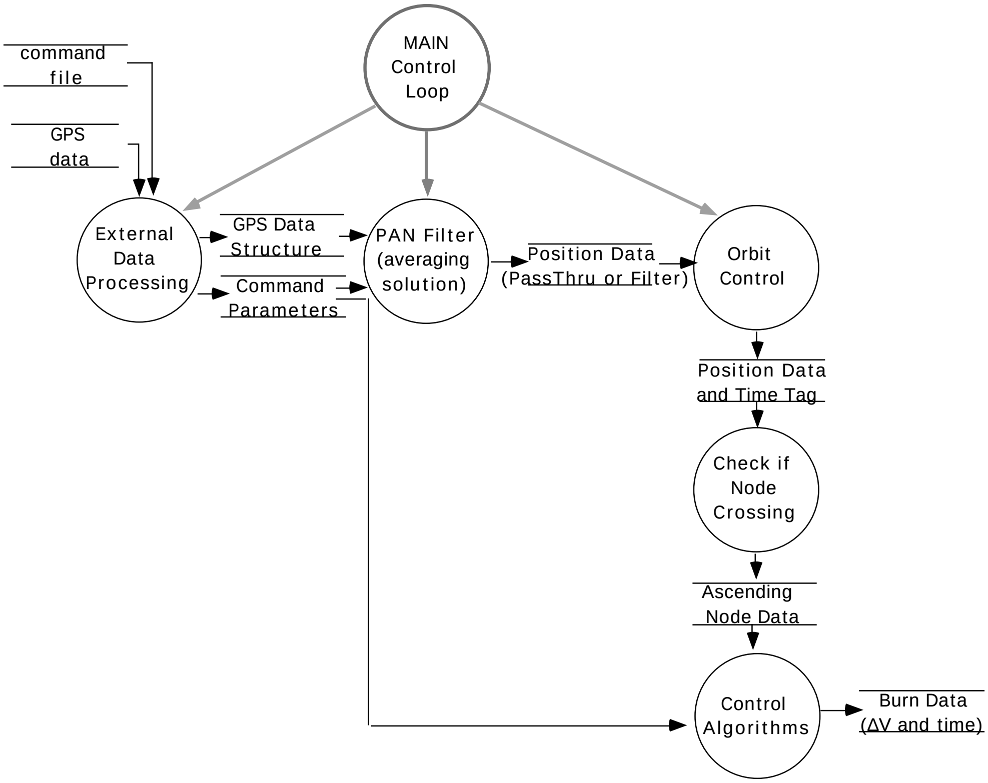

Figure 3 Microcosm OCK Data Flow

Figure 4 Integration on Engineering Model at SSTL's Facilities.

The Microcosm OCK software was developed for implementation on prototype hardware being developed at SSTL in Guildford, England (see Figure 4). Early in the development process an interface control document (ICD) was created between the SSTL shell software which calls OCK and the OCK software itself. This ICD was necessarily adhered to by both sets of team members. When changes were needed by one team member, the implications were discussed and both team members agreed upon a solution. Often this interaction took several days, and even weeks, since the groups were 8 time zones apart.

When the OCK software was ready for final integration on the hardware, a trip was made to SSTL. Prior to any "hands-on" work, the ICD was re-addressed, questions were resolved, and details were firmed up. Each team member made changes to the application software as required. The OCK software was loaded onto the OBC and execution began. The interface between the OCK software and the SSTL shell was proven early in the integration process.

The 386-based OBC is a new product for SSTL and the kernel functions that support the hardware were worked concurrently with the hardware development. Thus, the kernel support for the floating-point math co-processor was not available during early integration. The Microcosm OCK software was tested using the software implementation of the double precision functions and compared to similar baseline test cases. This integration was successful (see Figure 5).

Prior to uploading the Microcosm software to the spacecraft, the software was re-tested on the SSTL OBC using the math co-processor. The integration process for the Microcosm OCK software was quite successful based on strong adherence to an established ICD and regular communications between the team members. The total effort for hardware/software integration in the laboratory was less than a man-month performed over a two-week calendar period.

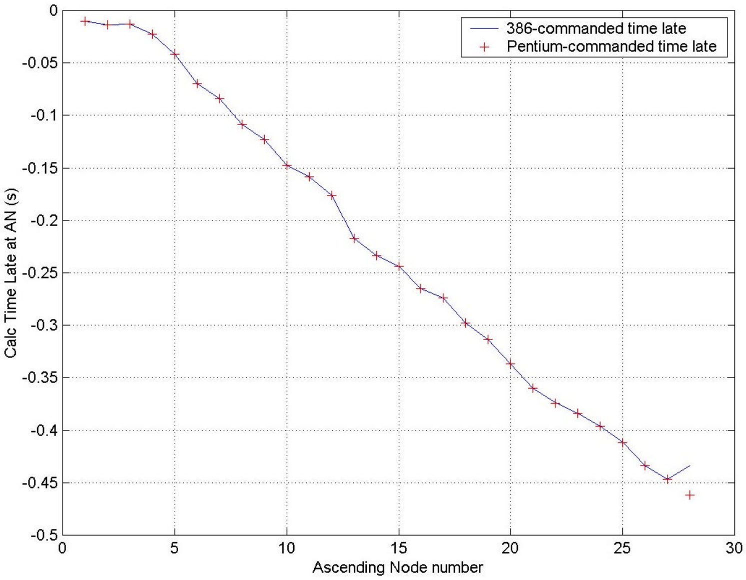

Figure 5 Sample Integration Results.
Note strong correlation between reference and 386-derived results.

EARLY RESULTS: PAN FILTER

The precision autonomous navigation (PAN) element pan was uploaded to UoSAT-12 and commenced operations on September 22. Results from the complete run are given below. These represent PAN's best estimates of the orbit's mean elements and show the level of noise to be expected from the proprietary method used. The need for orbital elements on board the spacecraft is as a check value for orbit control burns. They also provide information on the orbit's relative orientation with respect to the desired orientation. The actual values sometimes differ strongly from NORAD-derived data – the only "truth" model available to the project. This is to be expected given the differences in averaging models. NORAD apparently uses an amalgam of Brouwer's and Kozai's theories when it creates Two-Line Element (TLE) sets whereas OCK uses a time-averaged (orbital frequency) osculating to mean equinoctial conversion before the final "mean" Keplerian elements are created. This difference in techniques has significant implications for the absolute values of the calculated elements. It is the broad agreement with trends in both data sets that is important, not the disagreement in absolute values. OCK requires stability in the answers it receives on eccentricity and argument of perigee and not on their absolute values – these can always be offset from the "real" (read NORAD) values in the telecommanded-desired values.

Finally, Figure 11 shows the NORAD-derived estimate of UoSAT-12's ballistic coefficient for the duration of the run. This shows some alarming effects as NORAD's filtering technique attempts to track the – apparently – continuously maneuvering spacecraft. NORAD's solution suggests that the spacecraft has become alternately draggy, drag-free and "negatively-draggy", i.e., gaining altitude – and all within the space of days! Note that the OCK run began on Day of Year 267 and ended on Day of Year 296.

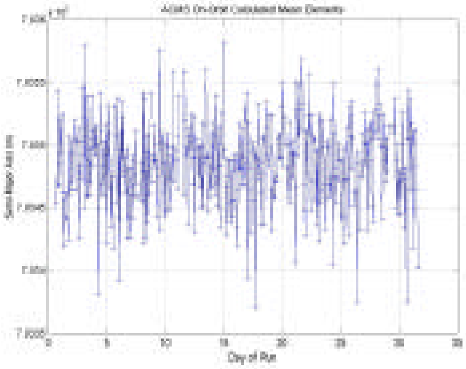

Figure 6 Semimajor Axis Measured On Orbit

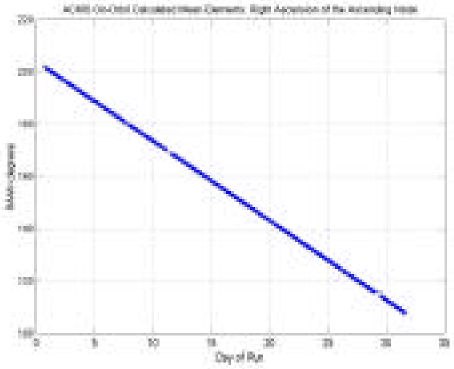

Figure 9 Right Ascension of the Ascending Node Inclination Measured On Orbit

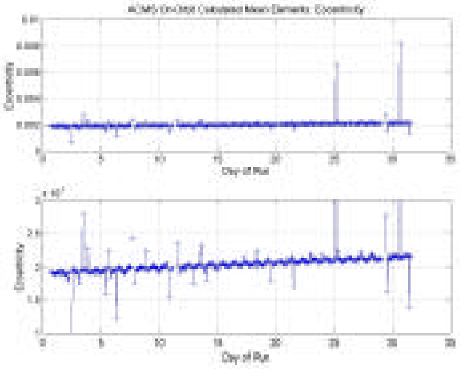

Figure 7 Eccentricity Measured On Orbit with Enlargement of Detail

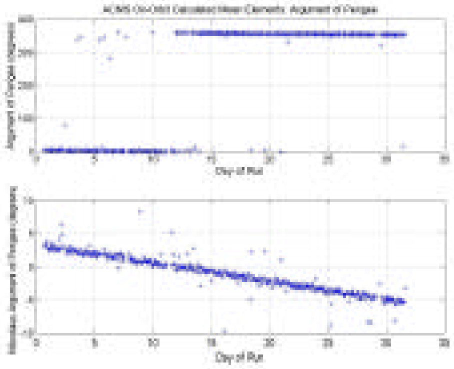

Figure 10 Argument of Perigee Measured On Orbit with Enlargement of Detail (Modulo 360 Degrees)

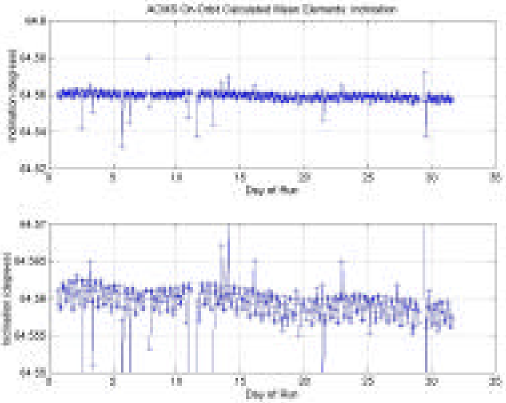

Figure 8 Inclination Measured On Orbit with Enlargement of Detail

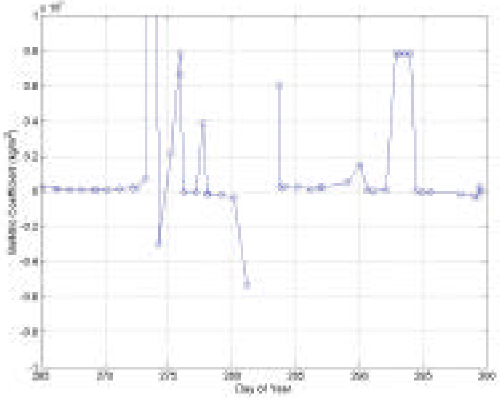

Figure 11 NORAD-Estimated Ballistic Coefficient

EARLY RESULTS: OCK SWITCH-ON AND RESULTS

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 12 and Figure 13.

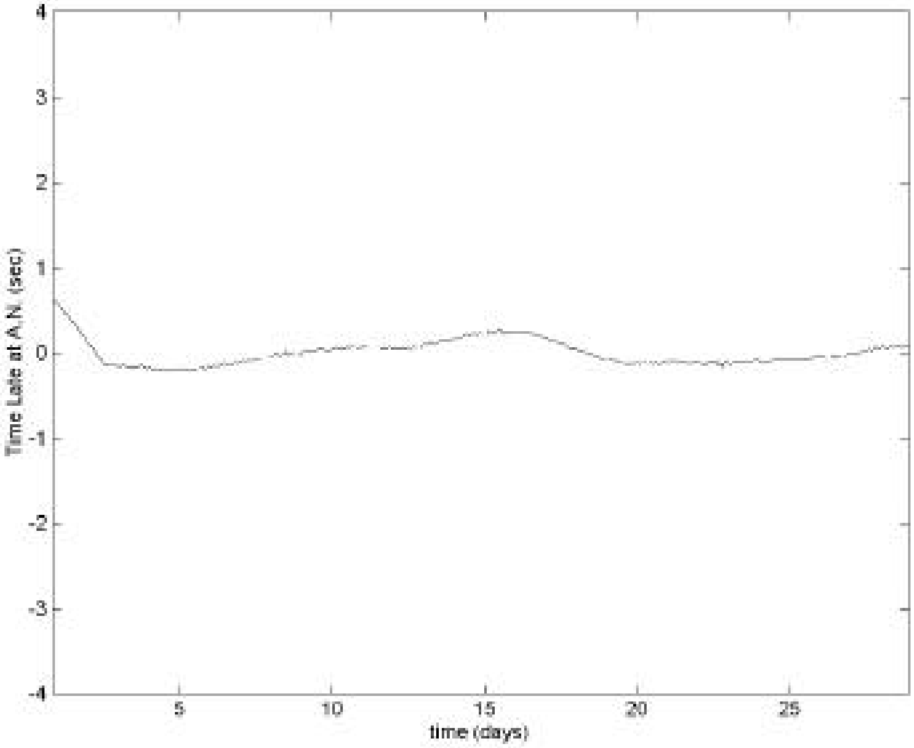

Figure 12 On-Orbit Time Late at The Ascending Node
The steep drop off for the first few days represents the time late prior to OCK being switched on at 14:29:41 UT, September 23, 1999.

Examination of this chart shows the slow 'sinking" of the "time late at the ascending node," or deviation from expected crossing time, over the first five days. This was expected and represents the controller reacting to the building of the time late due to the effects of drag. As can be seen up to around 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 to the level of control.

Near day 12, SSTL staff identified a problem with one of the two thrusters that were being used to effect the velocity change. Essentially, the software was preventing the second thruster from activating. This imbalance was detected in anomalous attitude motions. OCK compensated for the lack of restorative impulse by upping its demanded Δ*V*. Hence, the 'sink" upon initialization was a little further than one would have expected from simulation results alone. The second thruster's non-performance was rectified on approximately day 12, but by then 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 – we proceeded to overshoot into positive time late and subsequently rebounded into negative territory over the next ten days or so.

Examining a little further 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.

OCK is expected to show a variation in the time late signal of < 0.2 sec (3 σ) after the controller has had time to settle. Short runs, as depicted in the figures, will have larger standard deviations. If allowed to run for an extended duration then these data would improve over time towards the value of < 0.2 sec.

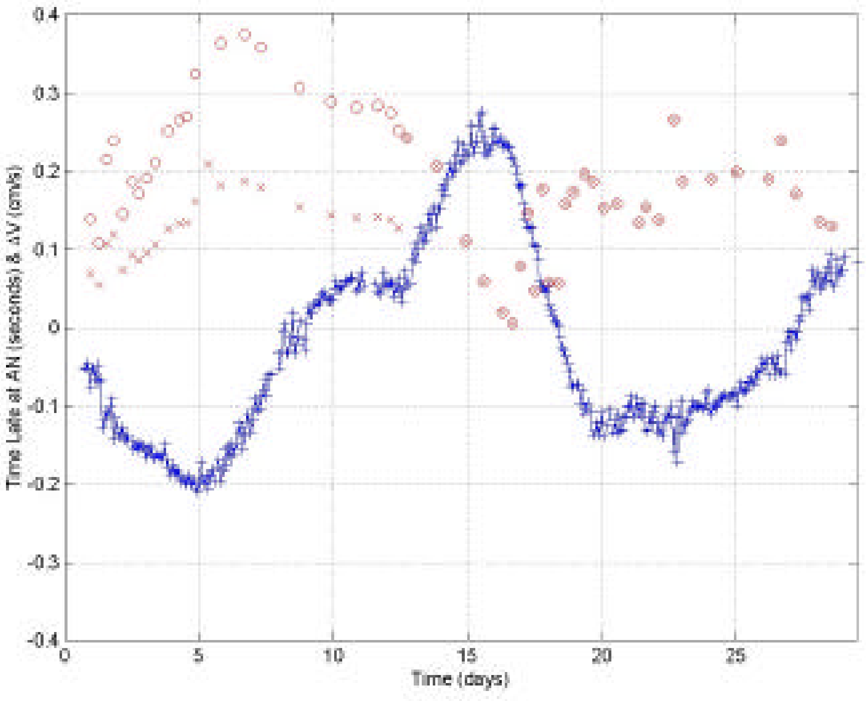

Figure 13 On-Orbit Time Late at The Ascending Node and Commanded and Actual In-Track Burn Magnitudes
Solid line and plus signs depict measured time late; empty circles depict commanded ΔV; crosses depict actual ΔV.

NAVIGATION PERFORMANCE

The performance of the SSTL GPS receiver was excellent while good data was flowing to OCK. However, for a significant fraction of the run data was either unavailable from the receiver or was deemed by PAN to be unreliable and was therefore discarded. The SSTL GPS receiver is a prototype unit and the positioning and communications software was in a state of flux throughout the run. In addition, the UoSAT-12 receiver did not benefit from having EDAC protection that will be available on future versions. Later data runs showed much greater reliability as the software matured. Consequently, we feel certain that there will be a more stable data stream from similar runs in the future. However, this data was the data available to OCK and hence provided a much needed “work-out” of the data checking capabilities resident in our code. Figure 14 shows the number of frames that were dropped in any single day but does not differentiate between long-term outages and singly dropped frames. Since OCK received data at 10 sec intervals multiplying the number of frames that were dropped translates this into fractions of a day. As one can see, on two occasions almost a half-day was lost to outages.

Despite these outages, OCK continued to work through them, inhibiting burns when the age of the last good GPS vector exceeded a pre-set limit. This limit was set empirically from simulation work before the run and put a limit on the accuracy or usefulness of a vector from the simple onboard predictor. This tool was only meant to take OCK through short duration outages (few minutes) and therefore, while very helpful in that area, was unsuccessful in taking OCK through many hour outages.

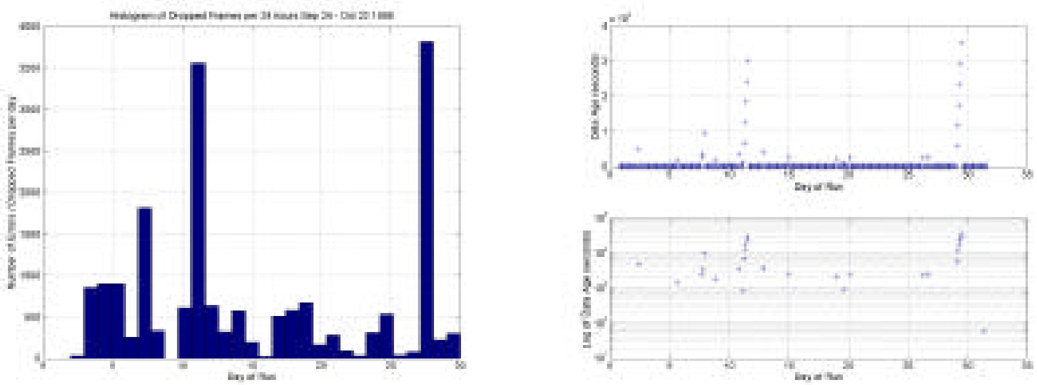

Figure 14 Histogram of Dropped Data or Bad Data Frames and Age of Last Good Vector Prior to Ascending Node.

SUMMARY OF PRELIMINARY RESULTS

OCK operated continuously for 29 days and demonstrated accurate autonomous in-track orbit control under the adverse conditions of long GPS outages and an initial halving of thrust followed by a return to full thrust midway into the run. Due to navigation drop-outs 21 ascending nodes were missed out of a total of 418 (i.e., 5% were dropped). The standard deviation of the time late was 0.1237 sec representing a 3σ value of 0.3711 sec. Multiplying these time late data by the orbital velocity of 7.531 km/s gives an estimate of the in-track slippage over the entire length of run.

Length of Run	29 days
Number of Burns	53
Maximum burn size	2.7 mm/s
Minimum burn size	0.053 mm/s
Mean burn size	1.4 mm/s
Standard deviation of burn size	0.564 mm/s (1σ)
Sum of burns	73.3 mm/s

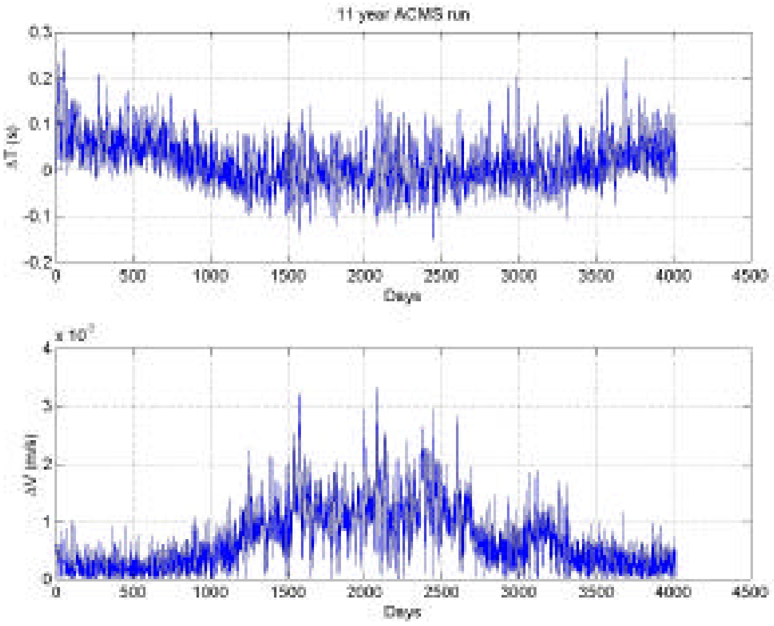

Figure 15 Simulated OCK Performance (Integrated Time Late at the ascending Node and Associated Propellant Usage) over a Full 11-year Solar Cycle
UoSAT-12 Configuration shown.

Ground-based simulations of both in-track control implementations, run for durations of 11 years, suggest a 3 σ time late at the ascending node for a nominal LEO (650 km altitude close circular) spacecraft of ~0.12 sec and ~0.08 sec respectively. 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, it is expected that forthcoming on-orbit implementations can produce similar levels of performance.

CONCLUSION

The Microcosm OCK project, consisting of two SBIRs sponsored by USAF AFRL (Albuquerque), has produced flight code demonstrably capable of *autonomously* controlling constellation members” in-track and cross-track positions indefinitely to approximately 1 km. Therefore, a ground user can predict the position of the same spacecraft any time into the future with 1 km accuracy. The tasks of orbit prediction, re-prediction and re-re-prediction, and all the associated burden of planning and re-planning of activities, can be automated to the level of a simple spreadsheet operation.

ACKNOWLEDGEMENTS

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