AAS 08-008

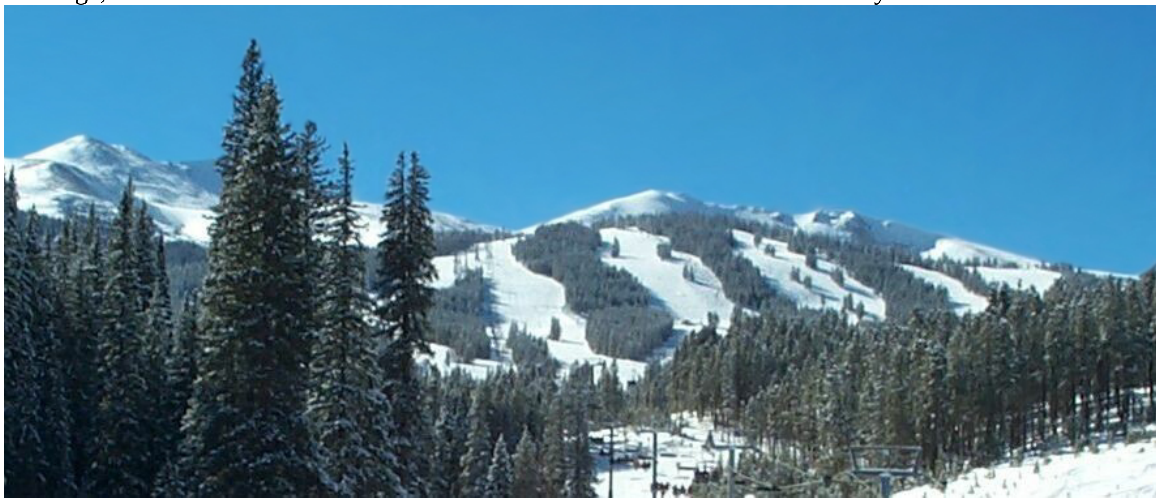
Autonomous Orbit Control Experience on TacSat-2 using Microcosm's Orbit Control Kit (OCK)

Yegor Plam, Richard Van Allen, James Wertz, Thomas Bauer
Microcosm, Inc.

31st ANNUAL AAS GUIDANCE AND CONTROL CONFERENCE

February 1-6, 2008
Breckenridge, Colorado

Sponsored by
Rocky Mountain Section



AAS Publications Office, P.O. Box 28130 - San Diego, California 92198

AAS 08-008

Autonomous Orbit Control Experience on TacSat-2 using Microcosm's Orbit Control Kit (OCK)

Yegor Plam, Richard Van Allen, James Wertz, Thomas Bauer
Microcosm, Inc. 4940 W. 147th Street, Hawthorne, CA 90250

ABSTRACT

Microcosm's patented Orbit Control Kit (OCK) derives from the company's long-term commitment to transfer to the spacecraft, from the ground, those operations that are better performed by an on-board system. This approach will lead to efficiencies in ground operations, lower costs, and reduced system risk. The OCK technology was developed largely to reduce the burden of constellation operations by putting straightforward, deterministic, and repetitive functions onboard the spacecraft. The results from the TacSat-2 mission demonstrate that the technology also provides a capability not previously available: controlling a satellite's in-track position (within about ±1 km for low Earth orbit missions) months, if not years, in advance with great ease and accuracy with simple geometric calculations, rather than complex orbital mechanics and propagation. This capability allows all system components to know factors such as the current locations 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 be over any location as far in the future as desired. For constellations, the technology eliminates the need for re-phasing as the in-track position is maintained with sufficient precision, along with the altitude, and is a major contributor to collision avoidance.

Microcosm has now updated and enhanced the OCK software for a flight demonstration on TacSat-2, which was launched in December 2006. The results have substantiated those from the previous University of Surrey UoSat-12 mission (1999), which showed that after only a few days, the technology was capable of maintaining in-track position to about ±1 km. In this paper the authors will describe the basic concept of autonomous orbit control and the implementation that has now been flight proven on two space missions. Next will be a discussion of the results of the multiple OCK experiments that have occurred on the TacSat-2 mission.

1. OCK OVERVIEW

Briefly, Microcosm's autonomous stationkeeping negates the influence of unwanted orbital perturbations. The patented (US[1], Europe) Orbit Control Kit (OCK) uses GPS data to compute the current orbit and generate delta-V requests required for precise stationkeeping. A delta-V request consists of the following information: time of the burn maneuver, magnitude of delta-V, and a flag indicating an in-track burn or a cross-track burn. It should be noted that OCK must be tuned to a specific orbit, based on altitude, eccentricity, and argument of perigee. A set of data defines a desired orbit, and it must include those perturbations which OCK should NOT attempt to negate. In general, the gravitational perturbations should be 'kept' and all others, primarily solar pressure and atmospheric drag, should be 'rejected'.

Perturbations from solar pressure and atmospheric drag are undesirable for two reasons. First, they are the main cause for orbital decay and the need for periodic orbit raising maneuvers. Second, they can not be modeled precisely enough to predict satellite position far into the future, which makes them good candidates for 'negation' by autonomous stationkeeping.

The gravitational perturbations, on the other hand, do not cause orbit decay and can be modeled precisely enough by numerical means to enable prediction of satellite position far into the future. A number of orbit propagators exist today with this capability. Furthermore, it would be ill-advised to try to negate orbit perturbations due to the tesseral harmonics of the Earth's geopotential field. An attempt to do so would most likely result in making minute burns in the in-track and counter in-track directions on every orbit, which would be a very fuel-wasteful process.

There are some terms that must be defined so that future discussions are clear. These are:

1. Time-late (orbital): the difference between the actual orbital period and the desired orbital period. The actual orbital period is the time between two successive ascending nodes, as determined from GPS data fed to OCK.
2. Time-late (cumulative): cumulative time-late is the integral of all orbital time-late measurements since the crossing of the Reference Node. OCK strives to drive the cumulative time-late to zero and to keep it there. This action permits creation of a schedule for ascending node crossings indefinitely into the future which, combined with management of eccentricity and argument of perigee, results in a "frozen orbit", permitting creation of a schedule for ground contacts indefinitely into the future.
3. Reference Node: an ascending node, the crossing-time of which is taken as the time from which to start measuring time-late. Nominally, it is the 1st or 2nd ascending node that OCK detects after it begins to receive GPS data.
4. Schedule Reset: an event which re-starts cumulative time-late from the time of the last (current) ascending node. This ascending node becomes the new Reference Node. It should be done only when the spacecraft is at the desired altitude.
5. Shadow Mode: operating OCK nominally, without allowing the requested burns to execute. This mode is used for initial testing of the basic functionality of the OCK on-board software, prior to allowing requested burns to be executed.

---

[1] US Patent numbers 5,528502 and 5,687,084

2. TACSAT-2 ON-ORBIT DEMONSTRATION

The operational constraints of the TacSat-2 mission placed some interesting requirements on OCK. In addition to the anticipated modifications driven by the specifics of the TacSat-2 commanding, the flight software interface, and telemetry structure, OCK software was modified to accomplish four main objectives:

1. Do not allow time-late to exceed 0.2 seconds (actually ±0.1 seconds). This time-late limit was driven by the need to maintain a communication link during ground passes with open-loop tracking;
2. Allow mission operations to designate certain orbits as “no-burn” orbits (e.g., every 5th orbit), driven by the need to dedicate a certain number of orbits to battery charging or for other spacecraft activities;
3. Provide a mechanism in OCK to autonomously reset schedule after recovery from prolonged burn outages;
4. Maintain altitude for a non-nominal orbit over an indefinite amount of time.

Requirements 1 and 2 can conflict, given the combination of the high-drag orbit (415 km altitude) and low ballistic coefficient. However, ±0.1 seconds of time-late is a relatively easy goal, so the majority of modifications were in the OCK simulation software (not the flight software), used to select the gains of the PID controller.

Because of a variety of operational issues unrelated to OCK, testing of OCK did not start until approximately six months after the mission started. At that point, a series of three short validation tests, lasting up to several days, were performed. These short duration tests were followed by one extended test that lasted two weeks.

Test 1

The first live test on TacSat-2 lasted one day, starting on April 3, 2007 when it was taken out of Shadow Mode (burns are calculated, but not executed) and ending on April 4, 2007. For this test, the desired period was intentionally chosen to be enough different from the “current” period to make sure that OCK determined that at least some maneuvers were required during the short time allocated for the test. In fact, all of the maneuvers that occurred were at the maximum allowed of 15 mm/s.

An investigation of the results, based on data derived from telemetry of several relevant subsystems [OCK, Autonomy Flight Software (ATE), and Hall Effect Thruster (HET) propulsion] was conducted. The results are presented graphically in Figure 1.

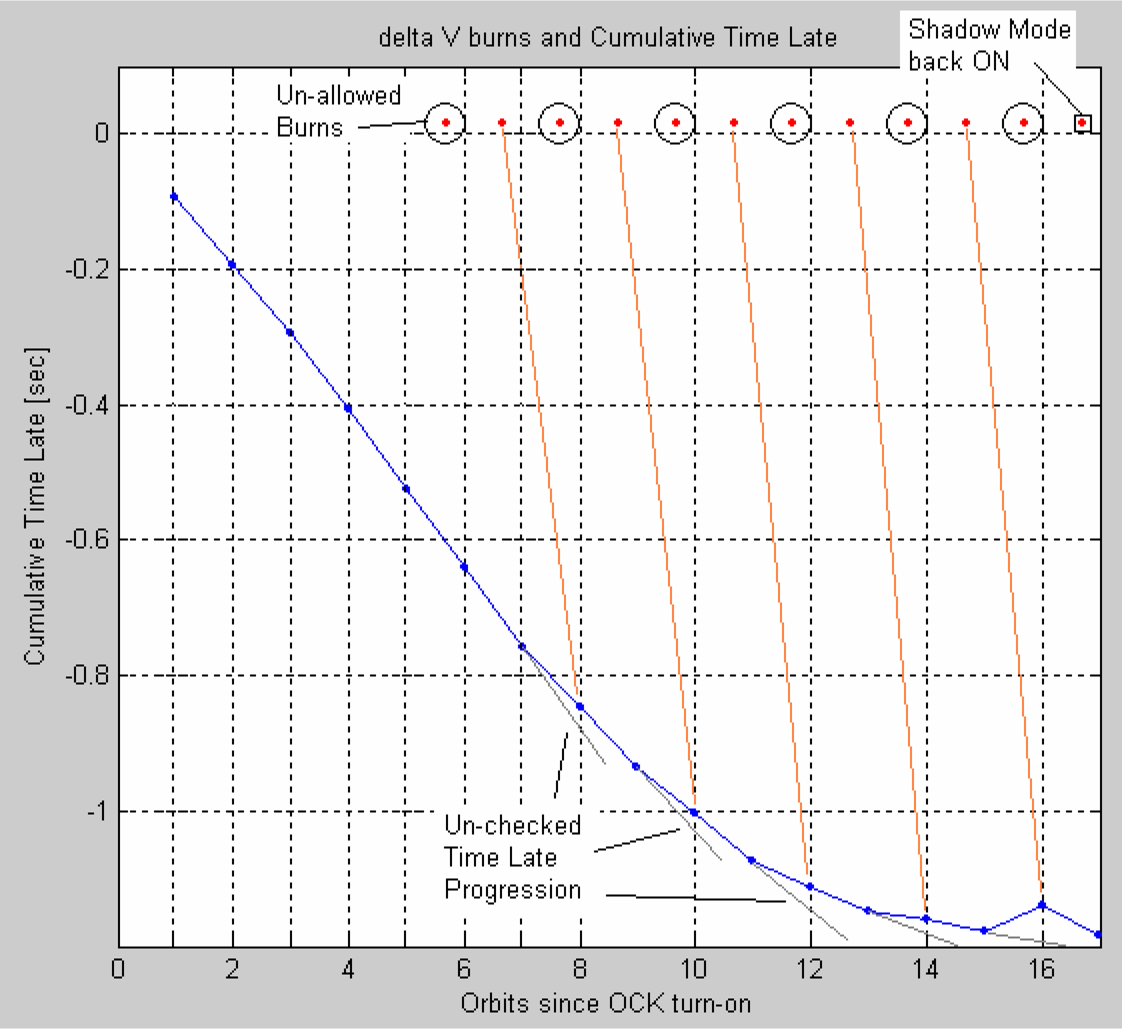


Figure 1. Delta V burns and CTL for Test 1.

In general, it can be concluded that there were five (5) burns executed from OCK burn requests, which resulted in a definite "corrective action" of the CTL. Note that only 5 of 11 OCK burn requests were passed on to the propulsion system due to system constraints. These limitations were placed on OCK because of spacecraft power limitations. Specifically, the 7.5-min burn (approximately 15 mm/s) is the longest burn that HET, an electric thruster, is allowed to execute in the dark (which clearly impacts OCK, since it needs to be able to command the burn anywhere), and the "every-other-orbit limit" is a way to give the spacecraft enough time to re-charge the batteries before another, possibly long-duration, burn.

The orange lines in Figure 4 show which burn is responsible for which CTL data point. As can be seen, in the absence of propulsive maneuvers, the CTL increases in magnitude in a linear fashion. Each corrective burn, however, is seen to decrease the slope of this curve, which suggests that the orbital period is changing and getting closer to what OCK was targeting as the desired orbital period.

At the start of the test, the slope of the CTL curve is negative because the actual orbit is lower than the operator-specified desired orbit; thus the actual orbital period is shorter than the desired orbital period. At the end of the test, the slope of the curve becomes positive, which is an indication that the semi-major axis was increased to the point where the orbital period became slightly longer than that of the desired orbit. <u>This effect is exactly what needs to happen in order to drive CTL to zero, the ultimate goal of OCK</u> [Note that a horizontal "slope" of the CTL "curve" indicates that the actual orbital period is equal to the desired (i.e., specified) orbital period.].

What OCK is trying to achieve is not merely to get to the right altitude, but to get to (and then maintain) a specific station within the desired orbit. Because the spacecraft spent time in a lower orbit, Figure 4 shows that it "overshot" its specific station. Thus, it must spend some time in a higher altitude orbit in order to "slow down" and allow the in-track position of its station to catch up to it.

For this first test of OCK, the combined restrictions of the 24 hour time limit, the 15 mm/s delta-V limit (7.5 minute burn time limit), and the every-other-orbit burn limit, prevented OCK from fully demonstrating the capability to drive CTL to zero during this first test. However, this first test was a success in the following ways: 1) OCK was able to compute correct delta-V burns based on the GPS data; 2) OCK's delta-V requests were successfully received by the autonomy software (ATE); 3) the requests were converted into HET burn commands when allowed; 4) the burn commands were routed to the HET subsystem; 5) the burns were executed at the correct time; and 6) the burns were executed for the correct durations. The overall effect was an adjustment of the orbit "in the right direction".

Test 2

Test 2 was another short-duration test, lasting approximately 36 hours. It was started on June 8, 2007 and terminated on June 10, 2007.

Although of similar duration to Test 1, Test 2 was intended to have one key difference: the Desired Orbital Period was to be chosen to be as close to the actual period as possible. By having the desired orbit period nearly equal to the actual orbit period, OCK was immediately "in the zone", allowing immediate demonstration of station keeping within a short demonstration time period, rather than orbit raising, as turned out to be the case in Test 1.

There are two ways to set a desired orbital period that is (approximately) equal to the actual period: a) compute orbital period from recent telemetry and upload this value as one of the Operating Parameters, and b) execute the Accept Current Orbit feature of OCK (which had not been tested on-orbit prior to this). Option (a) was successfully implemented.

Figure 2 illustrates the progression of CTL, along with HET burn requests and executions and quality of GPS data. The quality of GPS data may be considered as "acceptable" when the plot of |R| resembles a "nice" sine wave. Any obvious excursions from the sine wave pattern indicate "poor" GPS data. More specifically, as GPS lock is lost for any significant amount of time, the final position and velocity solution provided to OCK by the TacSat-2 attitude control and determination system (ADCS) J4 propagator diverges. The ADCS J4 propagator was meant to "fill in" between 10 second Integrated GPS Oscillation Receiver (IGOR) GPS updates and does a poor job of propagating for longer durations. For example, the GPS outage on orbit 20 lasted about one-quarter of an orbit, approximately 23 minutes.

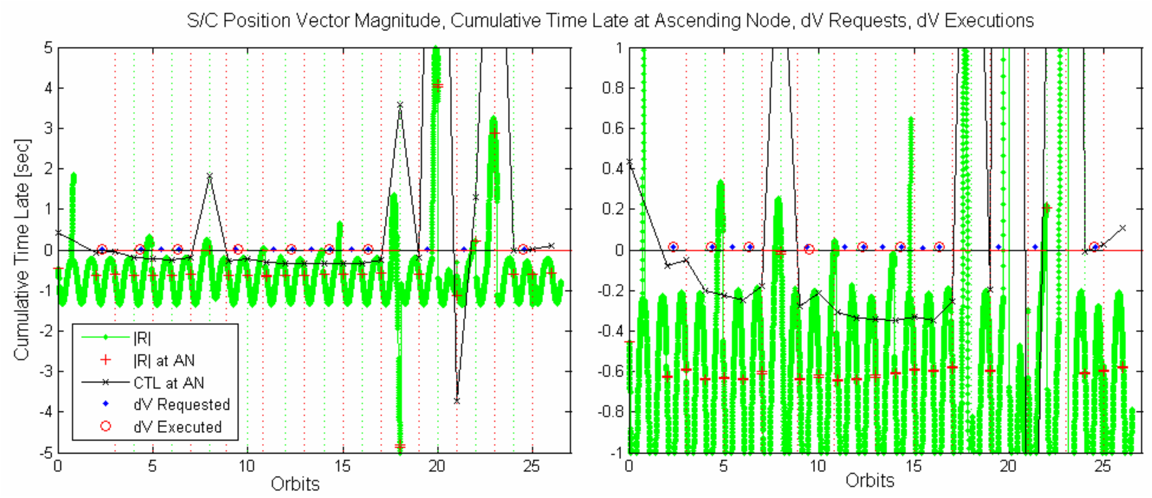


Figure 2. CTL and Other Data Relevant to Live Test 2 (Full View and "Close-up").

Legend:

|R| - position magnitude, biased and scaled to fit within the vertical scale of the plot (green line)

|R| at AN – |R| at the ascending node, marks ascending node on the plot timeline (red plus sign)

CTL at AN – cumulative time late at the ascending node (black "x")

dV Requested – delta-V burn requested by OCK (blue diamond)

dV Executed – delta-V burn executed by HET (red circle)

The bad quality of the GPS data at some ascending nodal crossings prevented OCK from correctly computing and thus, correcting the CTL at, and immediately after, those ascending nodal crossings.

However, because OCK works with CTL, it was able to recover after each instance of bad GPS data on the very next orbit (unless the next ascending node crossing was also "bad"). For example, computations of CTL on orbit 25 were not affected by the erroneous computations (due to bad GPS data) on orbits 18 through 24. Thus, it is important to note that bad GPS data inputs only affect OCK negatively for the duration of the bad GPS data.

Figure 2 also illustrates that every other orbit was an "exclusive reservation" orbit, during which no OCK burns were allowed. It should also be mentioned that the burn executed during the exclusive reservation, specifically during orbit 9, is a HET-experiment burn, not an OCK-requested burn. This burn was executed off the velocity vector (for the purpose of imaging the exhaust plume). It affected the CTL, but did not affect the overall OCK station keeping process.

Although, as shown by Figure 2, the CTL was controlled to within 0.3 seconds, in fact, CTL was driven to near-zero by the end of the test. However, the frequency of bad GPS data, and its impact on OCK's performance, demonstrated the level of dependency OCK has on good position and velocity information, particularly in the vicinity of the nodal crossings. If a "bad GPS data flag" had been available, OCK might have been able to avoid requesting burns based on erroneous input data. As will be discussed later, an enhancement to OCK was implemented to allow for ignoring bad GPS data, independent of external information, for the TacSat-2 mission.

Test 3

The third test of OCK began on August 31, 2007 and ended on September 2, 2007. The large break in time between Tests 2 and 3 occurred because of a wide range of other tests and operational exercises associated with the basic TacSat-2 mission that took place in the June-July 2007 timeframe. Further, Test 3 was used as a validation that upgrades to the autonomy software (ATE) did not adversely impact OCK's ability to command maneuvers. Only a few OCK initiated maneuvers occurred during the two day time period, which verified that the ATE modifications were transparent to OCK, but did nothing to further validate OCK's ability to drive CTL to zero.

Test 4

The fourth test began on September 21, 2007 and ended on October 6, 2007. It was the first test of OCK during which no other maneuvers (e.g., HET tests or manual orbit maintenance maneuvers) were allowed that might have corrupted the interpretation of the results. As was the case for all previous tests, the primary GPS receiver was not operational, so OCK input data was obtained from the IGOR experiment GPS antennas – both intended to be pointed toward the Earth's horizon, rather than towards zenith, which provided good data periodically. This calendar period was selected to maximize the quality of GPS reception data at the ascending nodal crossings in order to properly test OCK functionality. Determination of good periods of GPS reception was key to the OCK test and was made with the assistance of Tim Rood of Advanced Solutions, Inc. and Wayne Fornwalt of Broadreach Engineering. There were occasional periods during which no GPS data was provided to OCK and also periods during which bad GPS data was passed to OCK, without a flag that indicated the data were bad.

During the two week period, there were 76 burns requested and 43 executed over 216 orbits. The average delta V for these burns was 6.3 mm/s, which translates into 1.25 mm/s/orbit. CTL at the ascending node after 2 weeks was 0.01 sec (equivalent to an in-track position accuracy of 75 meters).

Figure 3 depicts the results over the two week period. Blue lines on the figure represent the $\underline{+}0.1$ sec tolerance band of CTL. The black "curve" is the measured CTL (note the spikes that are indicators of bad GPS data, long straight lines between "x" symbols are indicators of GPS outages). OCK burn requests are shown as blue dots – not all burns that were requested were executed because of various operational constraints. The scale is in m/sec for burns. Finally, red circles around blue dots indicate an executed burn.

After an initial transient, OCK got "on station" inside the $\underline{+}0.1$ sec CTL band in less than one day and maintained station in spite of operational interference (sun-pointing and imaging). During the two week period, the OCK commanded delta-Vs ranged from 0.5 mm/s to 15.5 mm/s and averaged 6.3 mm/s (1.25 mm/s/orbit or 19.3 mm/s/day). OCK was not impacted by nominal errors in GPS data. However, as can be seen from the data, OCK was impacted by large errors in the GPS data (i.e., bad GPS data) at the ascending nodes. For test days 10 to 14, the adverse effect on CTL was mitigated by reducing the maximum delta-V allowed from 15 mm/s to 7 mm/s. OCK was also impacted by prolonged GPS data outages that occurred during test days 7 and 8. However, similar to the initial transient, OCK recovered fully in one day (day 9) and maintained station even with intermittent bad GPS data.

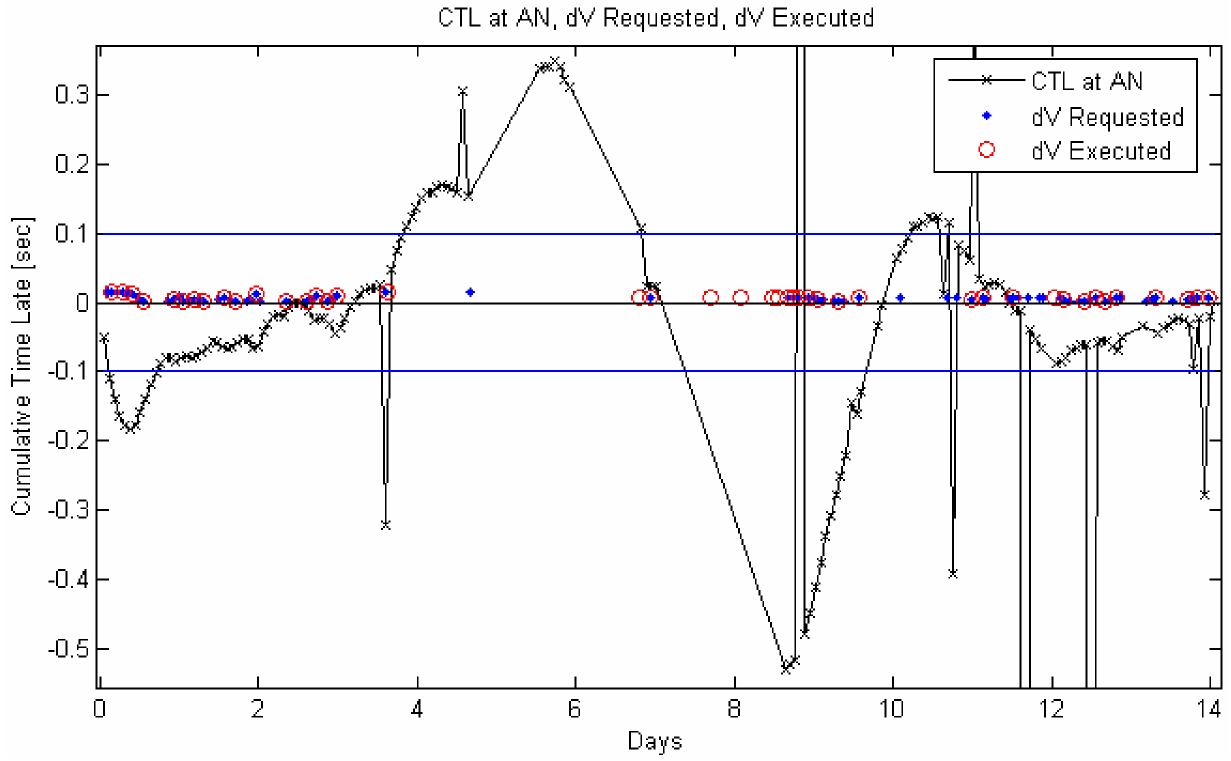


Figure 3. TacSat-2 Two Week OCK Test Results (Test 4).

A segment of the two week test results has been expanded and the performance of OCK during the first three days of the two week test period is shown in Figure 4. As was mentioned previously, it is now easier to see the initial CTL half-day transient that occurred because of the difference between the target orbit period and the initial actual orbit period. In less than one day (actually 0.75 days), OCK corrected CTL to within 0.1 second and drove CTL to less than 0.05 sec in two days and maintained it, even with operational interference that resulted in numerous burn requests being blocked by higher priority operations. In-track position accuracy was better than 380 m, and pointing accuracy was better than 0.053 deg directly overhead (410 km altitude).

Figure 5 highlights a section of the two week test results, during which there was a lot of bad GPS – days 11 to 14. OCK still managed to maintain CTL at less than 0.1 sec even when burdened with a combination of overlapping bad GPS data and operational interference (i.e., other experiments). In-track position accuracy was maintained at better than 760 m, with pointing accuracy directly overhead from a ground station maintained at better than 0.1 deg. OCK commanded delta-Vs ranged from 1.2 mm/s to 7.2 mm/s and averaged 5.6 mm/s. Over-reaction to bad GPS data was mitigated by decreasing the maximum allowed OCK delta-V at Day 10, which was done with a near real-time adjustment via a single and simple command from the ground.

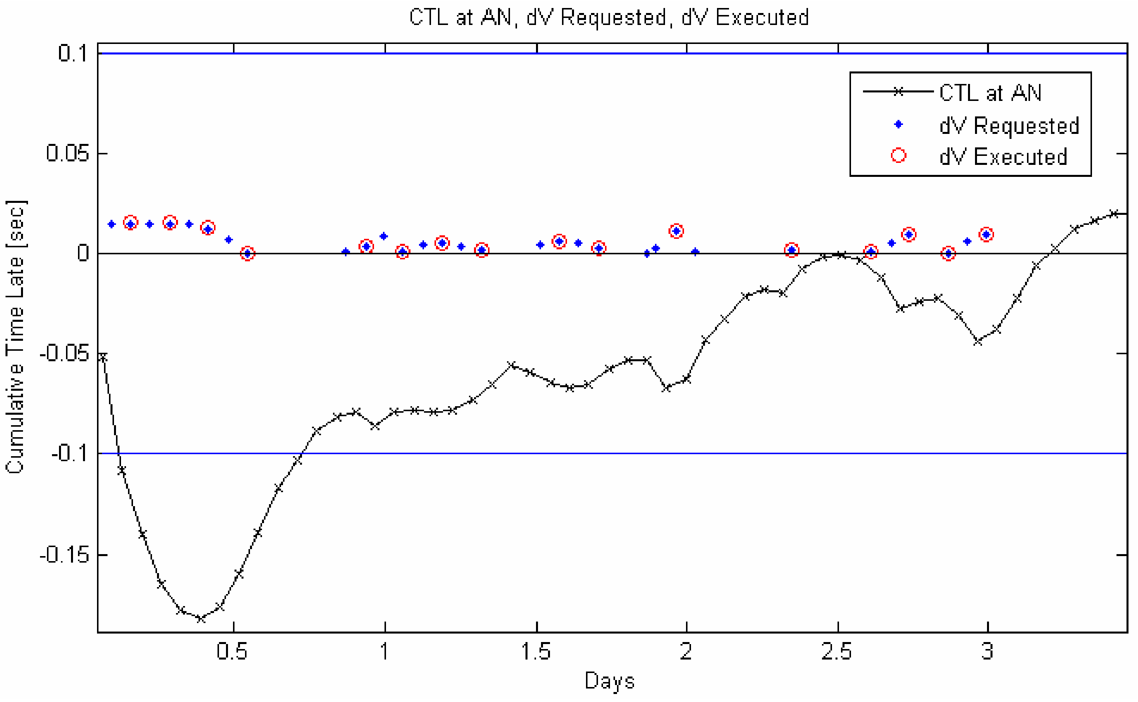


Figure 4. OCK Performance During the First Three Days of the Two Week Test (Test 4) with Good GPS Data.

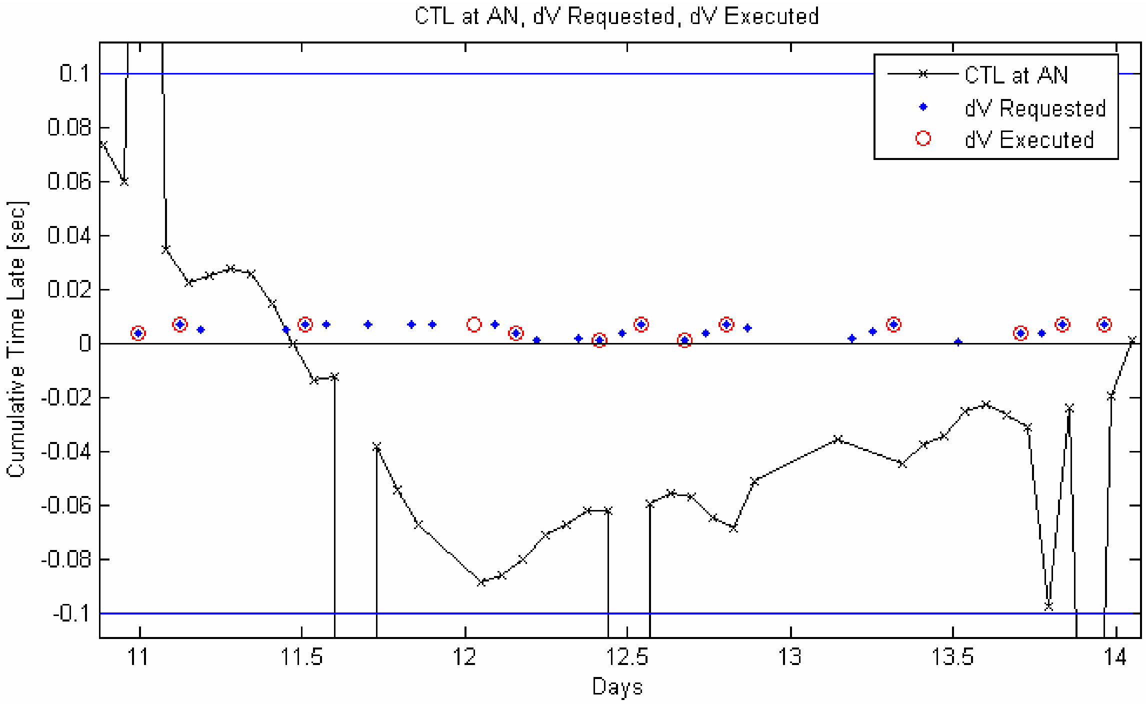


Figure 5. OCK Performance During the Last Four Days of the Two Week Test (Test 4) with Bad GPS Data.

In spite of both GPS data gaps and bad GPS data, after two weeks, the ability to maintain CTL to < 0.1 sec (< 750 m in-track) at the ascending node was demonstrated.

The most obvious problem illustrated by the results of Test 4 is the OCK algorithm's lack of notification when the GPS input data are bad. It is important to have a bad GPS data flag that can be used by OCK, and other spacecraft systems, to ignore bad GPS data. An enhancement to OCK to ignore obviously bad GPS data was developed as a result of this experience, although it is expected that for future missions, a bad GPS data flag will be routinely available.

3. CONCLUSIONS

1. Autonomous onboard orbit control has been further validated on TacSat-2 (2007) after its initial validation on UoSat-12 (1999). Similar to the experiment on UoSat-12, OCK managed to maintain very accurate in-track position over an extended period of time on TacSat-2, in spite of a variety of off-nominal events.
2. In addition, OCK has now been demonstrated to perform as predicted across a wide range of altitudes/atmospheric densities (between 400 km and 600 km altitude, mean density decreases by a factor of approximately 26, Reference 12).
3. The greatest return on investment when using OCK will be on constellations, where constellation maintenance is a significant cost and performance component, and on small, low cost missions that need at least some orbit control. This impact is especially true relative to "responsive space" class spacecraft, which are likely to be in low altitude, high-drag orbits and to carry observation equipment of considerable tactical and strategic value and, in addition, to have the requirement of ground contacts with mobile field stations.
4. Various enhancements to make OCK more robust have been identified as a result of flight testing on TacSat-2: addition of a bad GPS data flag, an orbit propagator, a CTL "reasonableness" filter, a descending node calculation, and eccentricity/argument of perigee algorithms based on the full eccentricity vector and mean elements.

In summary, autonomous, on-board orbit control can fundamentally change the way space missions operate. It is a key component in increasing spacecraft utility and in decreasing operational complexity.

4. REFERENCES

1. "Satellite Autonomous Orbit Maintenance System," U.S. Patent No. 5,528,502, issued June 18, 1996 to Microcosm, Inc.
2. "Satellite Autonomous Orbit Maintenance System," U.S. Patent No. 5,687,084, issued Nov. 11, 1997 to Microcosm, Inc. (four related patents issued in Europe.)
3. Conger, R. E., Gurevich, G. E., Wertz, J. R., "Autonomous On-Board Orbit Control," Paper No. 2002-1976, 20th AIAA International Communications Satellite Systems Conference (ICCSSC), May 13–15, 2002.
4. Charles J. Finley, Lt Lisa Baghal, Lt Jennifer Guarnieri, Air Force Research Laboratory, Bianca Prumo, Brian Buckley, Interface and Control Systems, "TacSat-2: Taking Operationally Responsive Space from an Idea to a Reality," RS5-2007-6002, 5th Responsive Space Conference, Los Angeles, CA, April 23-26, 2007.
5. Koenigsmann, H., Gurevich, G. E., Wertz, J. R., "Autonomous Orbit Control: Initial Flight Results from UoSat-12," AAS 00-071, AAS Guidance and Control Conference, Breckenridge, CO, February 2–6, 2000.
6. Wertz, J. R., "Implementing Autonomous Orbit Control," AAS Paper 96-004, 19th AAS Guidance and Control Conference, Breckenridge, CO, February 7–11, 1996.
7. Wertz, J. R., Bell, R., Gurevich, G. E., "Autonomous On-Board Orbit Control: Flight Results and Applications," AIAA 2000-5226, AIAA Conference and Exposition Long Beach, September 19–21, 2000.