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AUTONOMOUS CONSTELLATION MAINTENANCE*†

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Abstract

Creating and maintaining the long term structure of a constellation can be a major element of cost and risk. Both can be substantially reduced by the use of straightforward, low-cost autonomous orbit maintenance. In most cases, this can be done with the computer, sensing, and thruster hardware already required on-board the spacecraft.

For most constellations, absolute stationkeeping (maintaining each satellite in a pre-defined mathematical box) has several advantages and no disadvantages compared to relative station-keeping in which only the relative positions of the satellites are maintained. These include a simpler, more robust control mechanism and less propellant usage. A secondary, but substantial, advantage of absolute stationkeeping is that the time history of the positions of all of the satellites are known in advance (i.e., before launch). This can be used to greatly simplify coverage analysis, hand-off, ground communications, and intersatellite links. Absolute stationkeeping is best implemented autonomously because it uses a large number of small thruster burns, rather than the small number of larger burns used in more traditional stationkeeping. Results of long term simulations show that in most cases position can be controlled indefinitely to within less than 0.2 sec (1σ), corresponding to an in-track position error of less than 1.5 km.

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The Need for Stationkeeping

Long term constellation maintenance is required to provide global coverage and avoid collisions among satellites. The system objective is to maintain the same relative position among the satellites in the constellation. We want to minimize both the propellant utilization and the cost and complexity required to do this.

The need for stationkeeping arises from two sources. First, at any given time each satellite will be in an orbit slightly different than intended. If left uncorrected, these small differences can accumulate with time to destroy the overall structure of the constellation. For example, a satellite whose period is 1 sec off the nominal value will, if uncorrected, drift in one month by 4,000 km relative to its desired position.

The second need for constellation maintenance arises from orbit perturbations. Without orbit maintenance, atmospheric drag will eventually bring down a low Earth orbit constellation and the satellites will reenter the atmosphere. Other perturbations result in differential satellite motion which has components which are cyclic with the orbit period and, also, ones which result in continuous secular drift. In general, we can treat each perturbation separately in deciding how best to deal with it. Ultimately, the implementation will be divided into the two major categories of in-track and cross-track stationkeeping.

In general, we can treat each individual perturbation in any of three ways:

Leave the disturbatance uncompensated

In this case, we increase the stationkeeping box size to incorporate variations resulting from the perturbations. This has no cost and uses no propellant. It is the best method for accommodating short period variations.

Negate the perturbing force

This maintains the orbit characteristics over time. However, it requires continuous propellant consumption and should be used only when necessary.

Control the perturbing force to be the same for all satellites in the constellation.

In this case, the satellites maintain the same relative positions but will not follow a perfectly circular or Keplarian orbit. This can be done for much less propellant usage than negating the disturbance and is the best approach if perturbations cannot be left uncompensated.

The principal orbit perturbations effecting low Earth orbit constellations and the recommended treatment for each are shown in Table 1.

Table 1. Principal Perturbations in Low Earth Orbit that Impact Constellation Structure and Recommended Treatment. See text for discussion.

Perturbation	Impact	Recommended Treatment
Atmospheric Drag	• Secular decay highly dependent on altitude	• Negated by In-Track orbit maintenance
J_2 (Oblateness)	• Secular node rotation proportional to cosine of the inclination • Secular phase rotation (perigee rotation for an eccentric orbit) • Changes shape of the orbit resulting in up to 15 km variation between satellites in a global constellation	• Controlled to the be same for all satellites by Cross-Track orbit maintenance • Controlled as part of In-Track maintenance • Uncompensated
Higher Order Harmonics (zonal)	• Small eccentricity oscillation	• e = 0.0013 can be maintained naturally (frozen orbit); can also be controlled as part of In-Track maintenance
Solar/Lunar	• Small secular drift in inclination and node • Low amplitude oscillations in inclination and node	• Negated by Cross-Track maintenance or compensated by inclination change • Uncompensated
Solar Radiation Pressure	• Small eccentricity growth	• Negated as part of In-Track maintenance

Absolute vs. Relative Stationkeeping

There are two principal stationkeeping trades involved in constellation maintenance:

- Whether to maintain the system altitude or allow the constellation to slowly "fall" to lower altitudes due to atmospheric drag.
- Whether to maintain an absolute pattern or only the relative locations of all satellites

Allowing the system to fall reduces the propellant requirement in the short term. Replacement satellites would be launched at a lower altitude. However, drag would continually increase as the altitude decreases and coverage holes would begin to appear or grow as the altitude decreases and the coverage of each satellite is reduced. Maintaining the altitude is the only way to give the system long term viability without having performance degradation grow with time. Consequently, for most constellations the only realistic approach is to maintain the system altitude over the long term.

If the decision is made to maintain the altitude of the constellation, then the remaining principal trade is whether to maintain each satellite in a well-defined stationkeeping box, as is done for geosynchronous satellites, or whether to maintain only the relative orientation among the satellites. The goal of constellation maintenance is only relative stationkeeping. However, in looking at the implementation, there are substantial advantages to absolute stationkeeping and no significant advantages to relative stationkeeping. [Wertz,1992, 1996] These merits and demerits are summarized in Table 2.

Table 2. Advantages and Disadvantages of Relative vs. Absolute Stationkeeping. Assumes that the constellation is ultimately kept at a given altitude. If constellation is allowed to continuously decay, relative stationkeeping can reduce propellant utilization.

	Advantages	**Disadvantages**
Relative Stationkeeping	• Minimizes maneuver frequency	• Stationkeeping depends on interrelationship between all related satellites • Complex commanding may lead to command errors and greater collision risk • High operations cost • Different logic for system build-up than operations • Requires information transfer between satellites
Absolute Stationkeeping	• Minimizes propellant utilization • Simple commanding • Satellite positions known in advance • Satellites can autonomously maintain themselves in the pattern • Position of all other satellites known without requiring intersatellite communication • Easily monitored from the ground • Same logic for constellation build-up as normal operations • Fewer failure modes • Constellation pattern is purely deterministic	• More frequent stationkeeping burns

For in-track stationkeeping, each satellite must ultimately put in the delta V which atmospheric drag takes out. The only question is how this delta V is applied. With absolute stationkeeping it is provided by a large number of small burns, such that the phase in the orbit is continuously maintained. In relative stationkeeping, only the relative orientation between two or more satellites is maintained and the entire group is, from time-to-time, returned to its original altitude. Note, however, that atmospheric density decreases exponentially with altitude. Therefore, continuously maintaining the satellite at the higher altitude results in lower drag and, therefore, a small but noticeable propellant savings for absolute stationkeeping.

In addition, there is an inherent complexity to relative stationkeeping because each satellite must know not only its own orbit, but also that of the other satellites which it is maintaining itself with respect to. This represents both high operations cost and a very complex stationkeeping logic with the potential danger of breaks in coverage, satellite collisions, or other problems associated with the failure of a complex, interacting system. In absolute stationkeeping, constellation buildup is greatly simplified. Each satellite has an assigned slot defined before launch. The satellite is placed in that slot just as orbit rendezvous is done and as geosynchronous satellites are put in their location. Orbit maintenance is then begun, irrespective of whether the satellite is the first or last in the constellation.

With absolute stationkeeping the constellation pattern itself is fully deterministic. The intended position of each satellite at all future times is known. Consequently, we know in advance when they will pass over any given ground station, target, or communications location. The basic geometric conditions such as Sun angle, ground station angle, or intersatellite angles are all fully known in advance, such that activities can be planned at the convenience of the operations group and do not need to be updated over and over again as the constellation changes. We can, for example, pre-establish pattern boundaries as a function of time so that we know precisely which satellite will cover any ground location at any future time. This also makes the job of spacecraft requirement specification much easier. Each spacecraft needs only to meet its preassigned ground coverage pattern.

System Configuration

Constellation maintenance requires some type of onboard orbit control system consisting of sensing, logic, and actuation. Fortunately, the logic required for fully autonomous absolute orbit control is very straightforward. It is less complex than that required for relative stationkeeping and far less complex than that used in a typical attitude control system. Consequently, an autonomous orbit control system requires significantly less computer throughput than would be required for attitude determination, attitude control, or orbit determination.

The general structure of an autonomous orbit control system is shown in Figure 1. [See also Collins, *et al.*, 1996] One of the most interesting characteristics of autonomous orbit control is that it can make use of, but does not require, onboard orbit propagation. We have become accustomed to thinking of orbit determination, control, and orbit prediction in terms of a precision orbit propagator; it is easy to overlook the fact that it may not be necessary. Essentially, we use a sensor to determine when the satellite is correctly positioned in its stationkeeping box and apply the appropriate corrections to maintain the satellite there. This is equivalent to the attitude control process in which we simply sense the deviation from the desired attitude and apply the appropriate control torque. The typical attitude control system does not fly an attitude propagator. While attitude propagators are used on the ground to simulate and verify performance, they are only rarely used on-board the spacecraft. Similarly, we use precision orbit propagators to validate the performance of the orbit control system on the ground but may or may not choose to use them on-board depending, upon the details of our particular application.

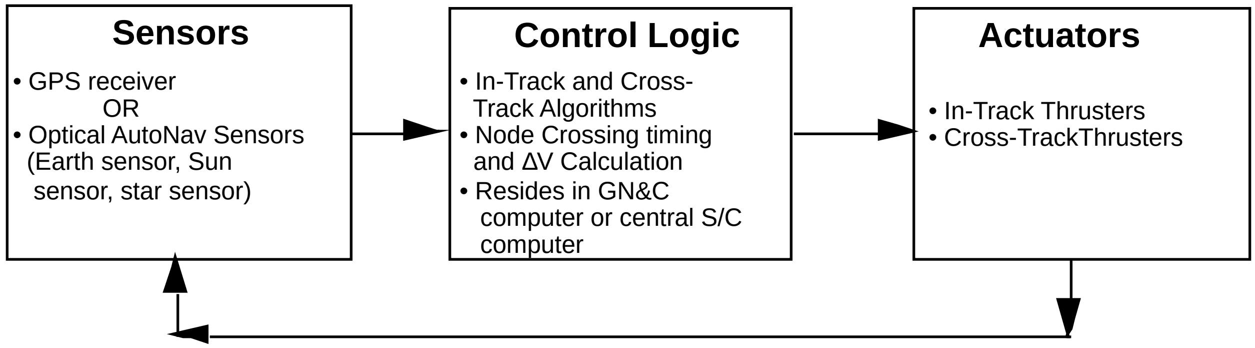

Fig. 1. Structure of Autonomous Orbit Control System.

While orbit propagation is not required, some type of position sensing is needed in order to provide the error signal for orbit control. For satellites in low Earth orbit, this error signal can be provided either by a GPS receiver or by optical autonomous navigation. (In principle, ground tracking could also be used for autonomous orbit control but this obviously negates many of the advantages of an otherwise autonomous system.) Whatever sensor we choose the error signal is simply the time difference between when a satellite is anticipated to across a reference plane and the measured time when it crosses that plane. An obvious choice for satellites at moderate to high inclinations is the time at which the satellite is at the ascending node, i.e., crossing the equator. Note that the node crossing time is a precisely defined mathematical function which is attached to some type of internal spacecraft clock which, from time-to-time, is synchronized with ground-based civil clocks, such as those provided by the GPS signal or other standard time sources. For example, when a leap second is inserted during some years, the orbit control logic will automatically correct for the additional 1 second on the appropriate orbit just as though there were additional drag during that orbit and the spacecraft was running a bit slow. This will cause a very small hiccup in the constellation pattern which will correct itself such that the constellation pattern continues to precisely follow the civil clock.

For absolute stationkeeping, the only actuators currently available are thrusters. However, either very low thrust chemical or electric propulsion can be used. The key characteristic is that the thruster impulse should be low enough that thrusting can be applied on a very regular basis (approximately every orbit). This requires a low level of thrust and is an ideal application for electric propulsion, although a variety of alternatives are also available. In practice, another key characteristic is to make the thrust levels low enough such that they do not disturb normal spacecraft operations. This means that thrusting can take place while the spacecraft payload is in its normal operating node.

Thruster Sizing and Delta V Requirements

In low Earth orbit, both the size of the thrusters and the total propellant requirement are dominated by the requirement to overcome atmospheric drag. To provide margin thruster firings at solar maximum should cover a small fraction (<1%) of a full orbit. On the other extreme, the firing must be long enough that the thruster is able to maintain reasonable efficiency when it is providing a delta V every few orbits. Thus, the maximum thruster size should be such that the smallest efficient thruster pulse provides a delta V, that it is no more than 2-3 times the minimum delta V per orbit at solar minimum (altitudes over 800 km or upper limit 20 times the minimum delta V is reasonable). Similarly, the minimum thruster should be such that the delta V applied over one minute (~1% of the orbit period) is larger than the maximum delta V expected at solar maximum. Representative values of these delta V perameters for various low Earth altitudes are given in Table 3.

The total propellant budget for the constellation maintenance activity will be approximately proportional to the total delta V required over the life of the spacecraft. This in turn is fixed nearly entirely by the delta V loss due to drag over the spacecraft lifetime. If the total spacecraft life is a few years or less then the worst case would be for the satellite to be active entirely at solar maximum. If the satellite lifetime is ten years or more, then it is reasonable to average the propellant utilization over both solar maximum and solar minimum. Again, representative values are provided in Table 3. A sample calculation for both thruster sizing and the total delta V and propellant budgets is given in Table 4 for two mission profiles.

As discussed in the Control Strategy section below, the situation for cross-track control is very different than in-track in terms of propellant utilization. There is no fundamental cross-track disturbance to be overcome. Consequently, the cross-track component oscillates slowly with very small errors due to both measurement and thrust errors. Propellant utilization is no longer fixed by the environment, but depends on the measurement system, the thrusters used, the control requirements, and the (initial) orbit insertion error. We have inserted "<10 m/s per year" in the table as a representative value of the amount needed for control to approximately 1 km in cross-track.

Table 3. Delta V Estimates for Thruster Sizing and Propellant Budgets for Autonomous Orbit Control. In-track numbers assume a ballistic coefficient of 100 kg/m^2. In-track range is from solar minimum to solar maximum. Data based on Wertz and Dawson [1996].

	Delta V per orbit		**Delta V per year**	
Altitude (km)	**In-Track (m/s)**	**Cross-Track (m/s)**	**In-Track (m/s)**	**Cross-Track (m/s)**
200	$2.86 \times 10^{-1} - 5.65 \times 10^{-1}$	< 0.002	$1.70 \times 10^{+3} - 3.36 \times 10^{+3}$	< 10
400	$1.20 \times 10^{-3} - 1.23 \times 10^{-2}$	< 0.002	$6.80 \times 10^{0} - 7.01 \times 10^{+1}$	< 10
600	$2.79 \times 10^{-5} - 8.09 \times 10^{-4}$	< 0.002	$1.52 \times 10^{-1} - 4.41 \times 10^{0}$	< 10
800	$4.98 \times 10^{-6} - 8.27 \times 10^{-5}$	< 0.002	$2.60 \times 10^{-2} - 4.32 \times 10^{-1}$	< 10
1000	$1.99 \times 10^{-6} - 1.51 \times 10^{-5}$	< 0.002	$9.97 \times 10^{-3} - 7.54 \times 10^{-2}$	< 10
1500	$4.05 \times 10^{-7} - 2.15 \times 10^{-6}$	< 0.002	$1.84 \times 10^{-3} - 9.77 \times 10^{-3}$	< 10

Table 4. Sample calcuation of thruster sizing and propellant requirements for autonomous constellation maintenance. See text for discussion.

Parameter	**Mission A**	**Mission B**
Assumptions:		
Altitude	400 km	800 km
Spacecraft life	2 years at solar max	10 years
Ballistic coefficient	100 kg/m^2	100 kg/m^2
Mass	1000 kg	1000 kg
Isp	300 s	300 s
Minimum effective impulse	50 ms	50 ms
Thruster Size		
Minimum	0.20 N	1.4 mN
Maximum	70 N	0.2 N
Delta V Budget		
In-Track	140 m/s	0.84 m/s
Cross-Track	20 m/s	< 100 m/s
Total	160 m/s	< 100 m/s
Propellant Budget		
Total stationkeeping budget	3.0 kg	0.29 kg

Navigation and Attitude Requirements

As will be shown later, the autonomous orbit control system has an inherent accuracy on the order of 0.2 to 0.4 sec (1σ). In order to achieve this accuracy, we need to maintain a navigation accuracy on the order of 20% of the stationkeeping accuracy or better. This implies a navigation (i.e., node crossing time) accuracy requirement of better than 0.04 to 0.08 sec which corresponds to an in-track position requirement of 300 to 600 m. This is well within the capability of both GPS and autonomous navigation systems.

Orbit maintenance requires that in-track thruster firings be made in the direction of the velocity vector and that cross-track firings be made at right angles to this direction i.e., toward the orbit poles. However, the delta V values are extremely small, consequently, small variations in the direction of the firing are equivalent to a small unmodeled perturbation and are corrected on subsequent firings. Thus, the only substantial attitude requirement is to maintain the efficiency of thruster firings by providing them in approximately the correct direction. Fortunately, the thrust component along the desired axis is proportional to the cosine of the error and, consequently, is relatively insensitive to small errors in the thrust direction. A random fluctuation in attitude of less than 1 deg is very adequate to ensure high efficiency and even larger errors could be tolerated, if necessary.

Orbit Control Strategy‡

The specific orbit control strategy depends on the nature of the dominate perturbing forces. In low Earth orbit, this strategy is different for in-track and cross track control [Königsmann, et al., 1997].

In-track Control

In low Earth orbit, the dominant perturbing in-track force is atmospheric drag. Although, the stationkeeping strategy is made more complex by the effect of gravity harmonics, the fundamental strategy is most easily understood by looking simply at the effect of drag.

It is convenient to think of orbit maintenance in terms of a stationkeeping box moving in a purely drag free orbit and the satellite itself moving within that box. As drag slows the satellite the semi-major axis will be reduced, the period will be shorter, the satellite will move more rapidly, and will drift toward the front of the box. As the satellite moves forward, we must provide thruster firings from time-to-time to provide additional velocity to the satellite thereby raising the orbit, causing the satellite to slow down, and pushing it toward the rear of the box. Thus, the basic operation is to measure where the satellite is relative to the stationkeeping box and fire thrusters in the direction of motion as necessary to continually push the satellite toward the rear of the box as drag proceeds to move it forward. A key issue is to make thrusters firings sufficiently small that they never push the satellite beyond the rear of the stationkeeping box, thus requiring thruster firings opposite to the direction of motion. This limits the size of the delta V that can be applied during any one firing.

In addition to maintaining the altitude, we also need to maintain the eccentricity typically at or near 0. (One can choose to use a frozen orbit which maintains a level of ~0.0013 naturally. However, since orbit control is being continually applied, the frozen orbit is not necessary.) If thruster firings were to be applied only at one location in the orbit, such as near the ascending node, then eccentricity would build up and a substantial breakdown in the constellation pattern would occur. Consequently, it is necessary to distribute firings at various locations throughout the orbit. This can be conveniently accomplished in either of two ways.

The first approach to eccentricity control is to estimate the location of apogee and to always fire at apogee so as to raise perigee. For an orbit which is nearly circular, apogee will, of course, be poorly defined. However, this simply serves to distribute the firings around orbit, since they are done at that position closest to the sensed apogee. If the orbit remains nearly circular, this will distribute firings throughout the orbit, if at any time a significant eccentricity builds up, then the logic will continue to raise perigee to recircularize the orbit.

The second approach to eccentricity control is to fire the thrusters at alternate locations approximately 180° apart in the orbit. This allows us to maintain the eccentricity by continuously raising and circularizing the orbit. While any two locations 180° apart could be selected, an obvious choice is to fire the thrusters at the ascending and descending nodes. Thus, if thruster firings are occurring on every third orbit, then firings at the ascending node could be at the first, seventh, thirteenth, and nineteenth orbits, while firings at the descending node would be at the fourth, tenth, and sixteenth orbits. It is this process

‡ U.S. Patent No. 5,528,502 issued June 18, 1996. Patent allowed in Europe. A similar strategy was developed independently by Glickman, [1994.]

of alternating the node that was used to generate the performance results in the next section.

Cross-track Control

In low Earth orbit, cross-track orbit control is inherently different than in-track control in that there is no dominant perturbation which must be negated. A cross-track error in a low Earth orbit satellite is equivalent to an error in inclination and ascending node. A small error in the location of the node does not grow and is not a long term problem. Unfortunately, the oblateness of the Earth causes the location of the node to drift continuously and the rate of node drift is proportional to the cosine of the inclination. Consequently, small variations in the inclination result in differences in the node drift rate. While we typically do not care what the node drift rate is, it is important that all satellite orbits drift at the same average rate in order to maintain the constellation structure. Thus, variations in inclination will result in a long term deterioration of the constellation. Consequently, the node drift rate must be maintained by maintaining the inclination at an appropriate value.

The orbit inclination is inherently stable over the satellite lifetime. There are no major perturbations which cause a continuous secular inclination drift equivalent to the secular node drift or orbit decay due to drag. Consequently, there is no long term perturbation to be negated and cross-track maintenance is simply a matter of controlling the average value of the inclination to maintain the constellation structure. Thus, we watch the node drift rate over time and make corrections by correcting the inclination. This process removes small errors in-orbit insertion and in the measurement process. Consequently, the cross-track delta V requirements are small and thruster firings can be both small and infrequent. Nonetheless, some level of cross-track control will be required both to maintain the node drift rate and to avoid coupling between cross-track and in-track perturbations.

Representative System Performance

The in-track performance of the system depends primarily on whether the constellation is above or below approximately 800 km. Below this altitude, drag is a strong perturbative force. Thus, the control system is continuously pushing against drag and frequent thruster firings are required to maintain the altitude. Since the thruster firings are always in the direction of motion, the propellant utilization does not depend on how often the thrusters are fired. The system is simply putting back the delta V that drag takes out. The absolute pattern is maintained by the process of doing this more-or-less continuously rather than waiting for a long time and then assign a large burn to regain the lost altitude.

Typical in-track performance of the system is shown in Fig. 2. Here the vertical coordinate is the time late in arrival at the ascending node. This is the measurement which is being used for control. However, thruster burns are made at both the ascending node and descending node in order to maintain the eccentricity.

At altitudes above 800 to 1000 km, atmospheric drag becomes extremely small. In this case there is no continuous strong perturbation to balance and the orbit control system is softer and uses much less propellant. Representative results for a satellite at 1500 km are shown in Fig. 3. Because drag is extremely low, negative burns (i.e., opposite the direction of motion) will occasionally be required to maintain active control. However, the total propellant requirement is extremely small.

At all low Earth orbit altitudes, the cross-track control is similar to the high altitude in-track system. There is no large secular term to overcome and the system is pushed slowly back-and-forth by the control system with very little propellant utilization. Typical performance results are shown in Fig. 4.

Conclusions and Implementation Status

A variety of low earth orbits have been simulated. Results of long term (approximately one year) simulations show that the in-track position can be controlled indefinitely to within less than 0.2 sec (1σ) in most orbits with the equipment normally available in LEO constellations. This corresponds to an in-track position of less than 1.5 km. Absolute stationkeeping to this accuracy minimizes the propellant utilization and requires providing the satellite only as much delta V as is removed by atmospheric drag. In this sense, the in-track control can be regarded as optimally efficient in propellant utilization. Cross-track orbit control requires a somewhat different strategy and cross-track position can be maintained in the long term to within an error of < 1 km (1σ).

Perhaps the largest single difficulty to be overcome in autonomous constellation maintenance is that orbit control is traditionally done from the ground, not on-board the spacecraft. It is this tradition, more than any physical impediment, which must be overcome [Wertz, 1991]. It is interesting to note that the consequences of failure are far less catastrophic for an orbit control system than for a failure in the spacecraft attitude control system. If the

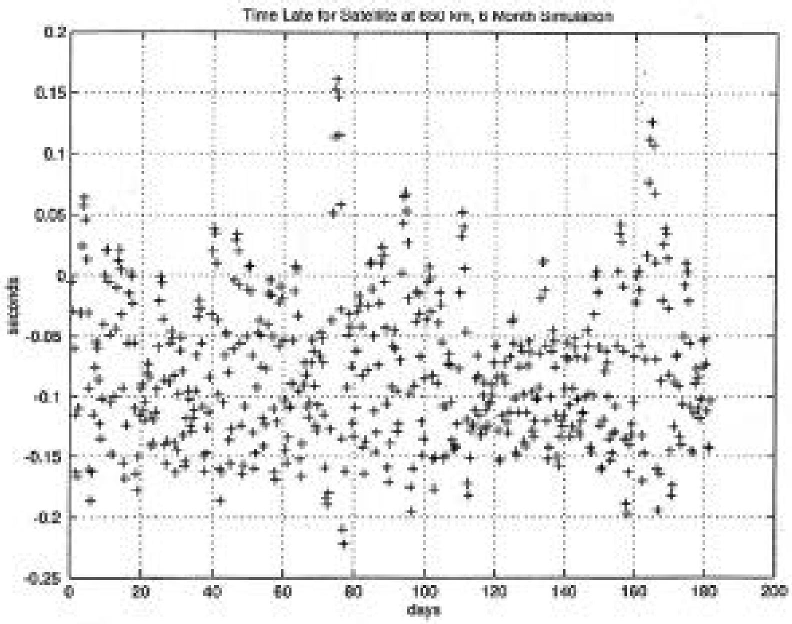

Fig. 2. Representative In-Track control accuracy for a 6-month period for a satellite at 650 km. The vertical coordinate is the time late at the ascending node.

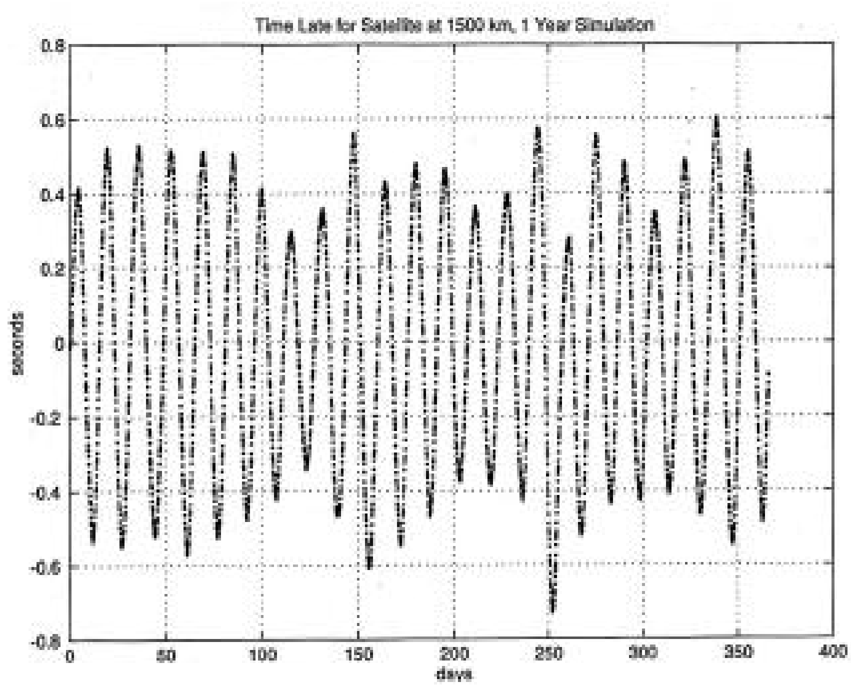

Fig. 3. Representative In-Track control accuracy for a 1-year period for a satellite at 1500 km. At this altitude, the satellite is in a region of extremely low drag and oscillates slowly about the nominal value.

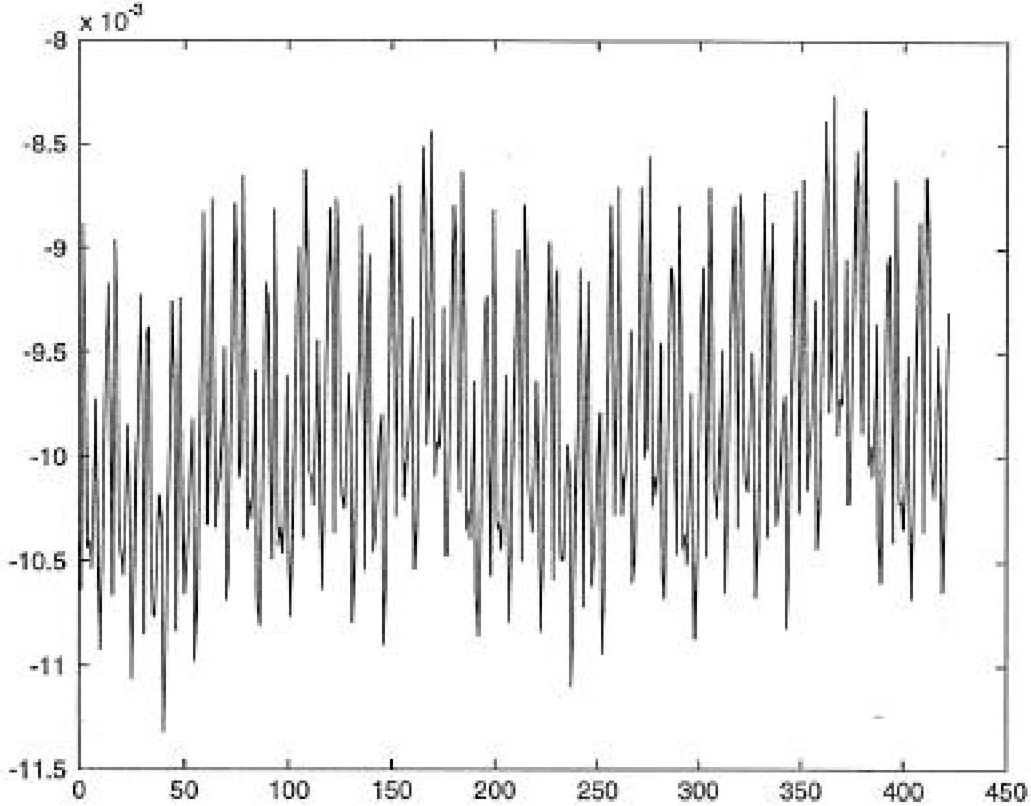

Fig. 4. Representative Cross-Track performance applicable to most low-Earth orbit altitudes (1-month simulation). Here the vertical coordinate is the horizontal error in node crossing location in degrees. The mean error for this period is 0.01 deg or approximately 1 km.

attitude control system fails for even a brief period, the spacecraft will typically tumble, pointing the solar arrays away from the sun, communication antennas away from the Earth, and sensitive instrumentation to orientations which are potentially damaging. Such a control system failure may or may not be recoverable. Nonetheless, virtually all spacecraft have fully autonomous, on-board attitude control.

On the other hand, failures in an autonomous orbit control system are remarkably benign. If one of the very low thrust firings fails to occur, or is in a direction 180° opposite the intended direction, the impact is sufficiently small that it would not even be noticed for some time. The spacecraft would simply drift slowly from its assigned position in the stationkeeping box. Under most circumstances there would be ample time to assemble a crew, evaluate the failure, send correcting commands, and recover the orbit position (assuming there was some fix or backup method available). All of this could reasonably be expected to be done with absolutely no interruption in service or long term damage to the space system or any of its subsystems or components. In this respect, orbit control system failures are far more benign than corresponding failures within the attitude control system. Nonetheless, there is a strong bias within the world-wide community against on-board orbit control simply because the traditional approach is to provide orbit control from the ground.

Because of this tradition of ground control, on-orbit verification of autonomous orbit control is key to its implementation in future constellations. Microcosm is currently developing flight code for fully autonomous orbit control in low Earth orbit under contract to U.S. Air Force Phillips Laboratory. Three near-term candidate space missions have been identified and negotiations are currently ongoing for providing on-orbit validation. A subset of the flight code was flown on the unsuccessful SSTI Lewis mission. (The orbit control code was never executed and was unrelated to the failure.) The first on orbit test of the Microcosm Autonomous Orbit Control System is anticipated within the next 18 months. However, this is subject to variations in flight test schedules.

Autonomous orbit control and constellation maintenance has the potential to dramatically reduce both the cost and risk of constellation operation. In addition, by creating a purely deterministic constellation pattern, it can greatly simplify payload and user operations as well. Test code has been operated under a wide variety of circumstances and flight code is now under development. The key remaining obstacle is on orbit verification in order to overcome the long standing tradition of orbit control from the ground.

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