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Autonomous On-board Orbit Control: Flight Results and Cost Reduction

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ABSTRACT

Microcosm, under Air Force Research Laboratory (Space Vehicles Directorate) and internal funding, developed and 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. Implementing autonomous orbit control significantly reduces operations costs, eliminates many of the traditional payload planning cycles, and creates added system robustness. In addition, 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. This paper provides results of the flight demonstration and discusses the cost reduction associated with implementing this technology.

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1. INTRODUCTION

By *autonomous, on-board orbit control*, also called *autonomous stationkeeping*[**], we mean the automatic maintenance by the spacecraft itself of all of its orbital elements. Because all the elements are controlled, the orbit is fully predictable and the position of the spacecraft at all future times is known in advance 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. On-board orbit control has three fundamental advantages:

1. It significantly reduces operations cost by eliminating the need for ground-based orbit maintenance
2. It decreases the scheduling and planning burden by knowing the precise future positions of the spacecraft (or all of the spacecraft in a constellation).
3. It offers 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 Sections 4 and 5, 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 example Chao and Berstein [1992], Collins, et al. [1996], Glickman [1994], Koenigsmann, et al. [1996a, 1996b], Wertz [1991, 1996, 1999, 2001], Wertz, et al. [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.

In the current implementation, orbit control consists of two principal software components. *Precision Autonomous Navigation*, PAN, provides on-board orbit determination (i.e., autonomous navigation) using a version of Microcosm's High Precision Orbit Propagator, HPOP. PAN uses 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, generates thruster firing commands that are implemented by the on-board Attitude Control System. PAN and OCK can be used independently or together, as PANOCK.

A major milestone in the development of on-orbit systems occurred in October, 1999, with the first flight demonstration of fully autonomous, on-board orbit control using OCK on the University of Surrey's UoSAT-12 spacecraft. The system configuration and results are described below.

2. THE UOSAT-12 ON-ORBIT DEMONSTRATION

A major milestone in the development of on-orbit systems occurred in October 1999, with the first flight demonstration of fully autonomous, on-board orbit control. The *Microcosm Orbit Control Kit* software was flown on the Surrey Satellite Technology Limited (SSTL) UoSAT-12 spacecraft, where it co-resided on a customized 386

[**] "Stationkeeping" here means maintaining the satellite within a pre-defined control box (analogous to geosynchronous stationkeeping), not simply altitude maintenance which does not control the in-track phase and, therefore, does not allow the future positions of the satellite to be controlled or known.

[†] The process of doing autonomous stationkeeping is covered by Microcosm patents No. 5,687,084 and 5,528,502.

on board computer, developed by SSTL, with their attitude determination and control software. For a discussion of the implementation see Wertz, et al. [2000]. UoSAT-12 was launched in April 1999. The OCK on-orbit demonstration was conducted Sept. 23 to October 22, 1999. Gurevich, et al., [2000] provides a detailed discussion of the software configuration, data flow, and flight results which are summarized below.

Figure 1 shows the results of the on-orbit demonstration. The vertical axis is time late crossing the ascending node, relative to the target time. The system maintained a 1-sigma error of ±0.12 sec (= 0.9 km) for the 29 day period. The system made 53 thruster burns with an average burn of only 1.4 mm/sec. This represents substantially less than 1 millionth of the orbital velocity of 7.5 km/sec.

Duration	29 days
Performance (1σ)	±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

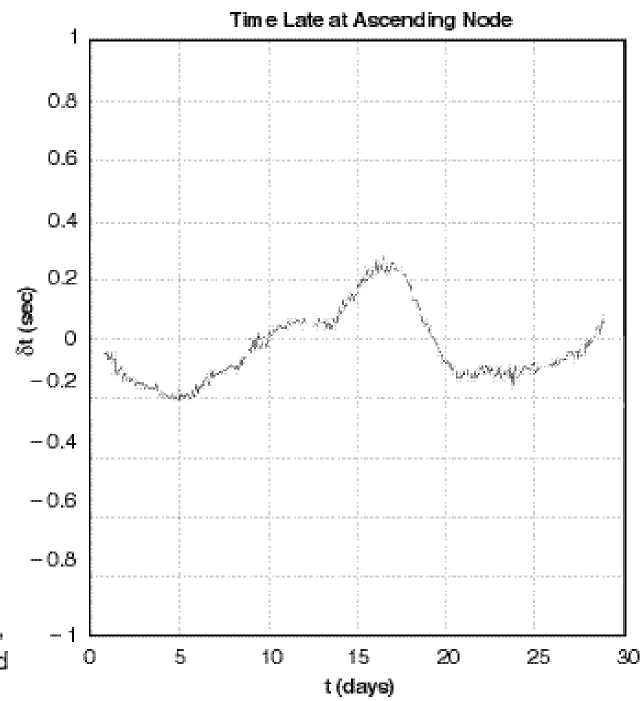

Figure 1. Results of UoSAT-12 Flight Demonstration. In-Track drift is essentially stopped entirely, even though the spacecraft drifted 4500 km in-track in the previous 9 months.

The OCK software demonstrated substantial robustness during the flight. At the beginning of the demonstration only 1 of 2 commanded thrusters was firing. This anomaly was undetected at the time. Consequently, the system initially had half of the intended thrust level. Midway through the demonstration the error in the spacecraft software (unrelated to OCK) was found and fixed such that both thrusters began firing. However, no adjustments were made to the flight software, either initially or when the error was corrected. This "half thrust/full thrust" was responsible for the dip and rise in the plot in Fig. 1. However, the system remained stable and fully controlled at all times.

A similar problem occurred with the GPS receiver which was also being tested at the time. We had anticipated and designed for outages of up to 5 minutes due to the GPS satellite geometry at the UoSAT-12 altitude. Because of the ongoing receiver testing, data outages of up to 8 hours occurred. Again the system processed the available data and continued to provide good control for the entire period.

In order to validate our system simulation we attempted to reproduce the on-orbit results by using real solar flux data for the period of the demonstration and a raw GPS state vector from the navigation software for initialization. The results are shown in Fig. 2. The simulation projected a total burn of 76.3 mm/sec vs. and actual total burn of 73.3 mm/sec. Thus, the two are in good agreement. (The thruster error described above was modeled in the simulation.)

Once the simulation had been validated, it was used to test the propellant savings. Specifically, another run was made with the stationkeeping burns turned off. At the end of the 29 days, the thrusters were fired in the simulation to restore the original altitude, but not the in-track phase. (Restoring the phase would have taken even more propellant.) Simply restoring the altitude required 85 to 100 mm/sec, depending on the conditions to be matched. This implies a delta V savings using OCK of 10% to 25% for the demonstration flight.

	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/s	

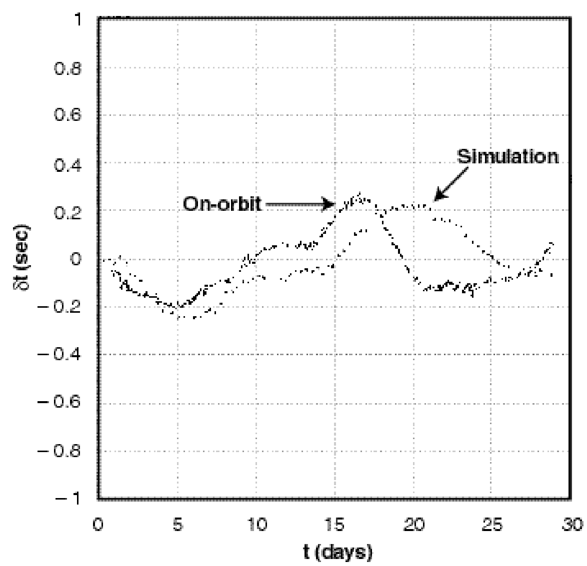

Figure 2. Simulation Results vs. On-Orbit Performance. The total delta V required was consistent between on-orbit data and the simulation to within 4%. Based on the simulation, the delta V required to restore the altitude (but not recover the in-track phase) was 85 to 100 mm/sec, implying a delta V savings with OCK of 10% to 25% for this period.

Finally, the simulation was also used to predict the results over a full 11 year solar cycle. The simulation was run using Microcosm's High Precision Orbit Propagator (HPOP) using the JGM-3 gravity field (truncated to 21 x 21), MSIS-86 atmospheric model using historical F10.7 values plus random noise on the solar flux, solar radiation perturbations, and third body solar and lunar perturbations from the standard JPL ephemerides. The results are shown in Fig. 3. Although the atmospheric density changed by about two orders of magnitude, the OCK control gains were not changed for the entire run. The results show a 3-sigma time late over the entire period of ~0.08 sec (= 600 m).

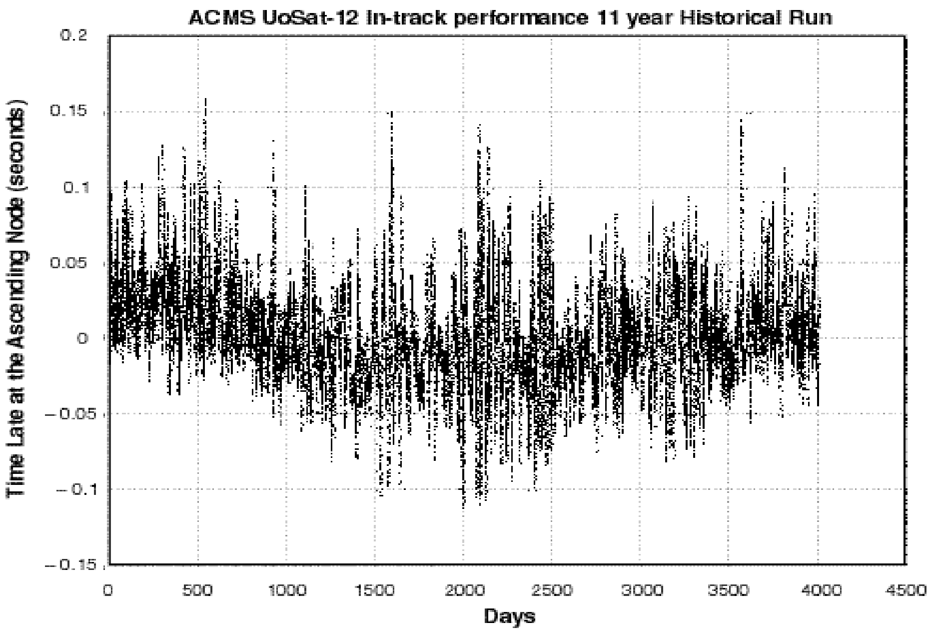

Figure 3. OCK Simulation Results Over an 11 Year Solar Cycle. The simulation included all normal perturbations (see text), including historical variations in solar flux which resulted in a variation by a factor of ~100 in atmospheric density. The OCK control gains were not changed over the entire 11 year run.

3. KEY CHARACTERISTICS OF AUTONOMOUS ON-BOARD ORBIT CONTROL

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

- All of the orbital elements of the spacecraft are controlled automatically, including specifically:
  - 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)
- This means that the spacecraft follows a fully predictable orbit pattern, such that
  - 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 sufficiently simple that it can be included in virtually any ground-based equipment that uses a general purpose microprocessor
- There is a longer planning horizon for all future activities
  - Payload planning

- Maneuver planning to achieve desired future coverage
- 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
  - The size and responsiveness of control actuators can be reduced
  - Restrictions on the timing of stationkeeping maneuvers can be reduced or eliminated

All of this is achieved using less propellant than more traditional orbit control techniques. There are two distinct mechanisms for propellant savings. First autonomous stationkeeping maintains the satellite at the top of its altitude range, rather than allowing it to drift down and then be reboosted. Because atmospheric density increases exponentially with decreasing altitude, this means that the satellite will be continuously maintained in the lowest possible drag environment, as was demonstrated by the UoSAT-12 performance.

The second propellant savings comes about if maneuvers are required at any time, such as for debris avoidance or to provide better coverage of a ground target. As shown in Fig. 4, the critical issue for propellant utilization is to do the maneuver as far in advance as possible. With autonomous stationkeeping we know the position of our satellite as far in advance as needed. Consequently, maneuvers can be done as soon as the need becomes known and, therefore, significantly reduce the propellant required.

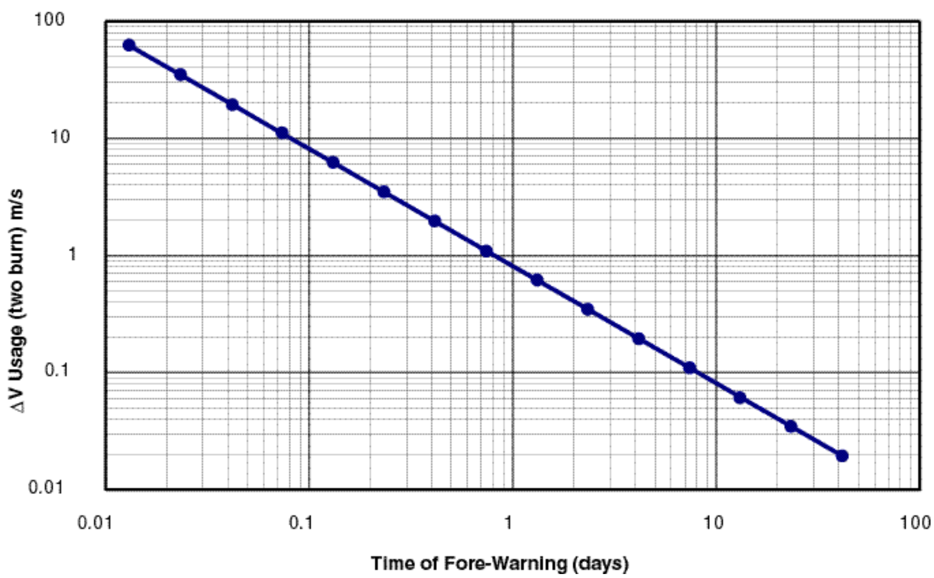

Figure 4. Delta V Required to Move a Satellite 35 km In-Track as a Function of the Time Available for the Move. Increasing the time available can dramatically reduce the delta V and, therefore, the propellant requirements.

4. COST REDUCTION ENABLED BY AUTONOMOUS STATIONKEEPING

In spite of the significant advantages, the most substantive benefit of autonomous stationkeeping 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. The costs here include: ground collection of navigation data, ground based orbit determination, preferred orbit position determination, thruster command generation, command uploads, verification of command uploads, verification of command execution. Basically, the ground operations required for orbit maintenance is reduced to occasional monitoring. In addition, the ground based systems to perform this work is no longer required as a primary system. A backup system can likely be developed for significantly less money.

- The cost of planning and scheduling (often representing 50% of operations cost) is reduced for several reasons:
  - Replanning and rescheduling as an event approaches due to drift in orbital elements is eliminated. Since orbital position is known for the life of the mission, the need to update planning based upon better ephemeris prediction is no longer needed. Atmospheic drag no longer plays a role in mission planning.
  - Planning and scheduling can be done on a business basis as convenient for the users (i.e., at monthly, quarterly, or annual meetings), rather than as dictated by astrodynamics.
  - Because the impact of the burns is minimal (the burns are very small), there is no interaction between timing of stationkeeping maneuvers and the payload event planning. Most payloads will be able to continue observations through the stationkeeping maneuver.

- The cost and complexity of transmitting spacecraft ephemerides to various users is eliminated. The spacecraft ephemerides can be provided to users on a floppy disk at the beginning of the mission.

- Lower propellant usage (and, therefore, longer spacecraft life and lower cost per year) for several areas:
  - Normal stationkeeping activity
  - Rephasing to avoid debris or RF interference
  - Planned or unplanned rephasing to meet mission needs, such as coverage of a specific event

- Spacecraft cost and weight is reduced due to
  - The implementation of smaller thrusters.
  - The maximum disturbance torques are reduced, which typically dictate both the size and responsiveness of attitude control components.
  - There is potential to eliminate cost and complexity of a separate ACS stationkeeping mode and even separate stationkeeping ACS hardware (i.e., gyros).

A key issue is the reduction in the disturbance torque environment. Normally, thruster firings represent the largest disturbance torque on the spacecraft and may interfere with payload operations. Consequently, there is often a planned “stationkeeping mode” in the spacecraft control system in which normal operations are stopped, the thrusters are fired, and then operations are resumed. Clearly, such an activity needs to be coordinated with the users so as to minimize the adverse impact.

In contrast, autonomous stationkeeping can use thruster burns that are very small, typically only several times the minimum impulse bit of a small thruster. In most cases, this can be made small enough that the disturbance torque is absorbed entirely by the control system and is effectively unnoticed by the spacecraft. (This is essentially comparable to the spacecraft control system; i.e., the payload doesn't care when the control system chooses to command the reaction wheel to speed up to maintain the stability of the platform.) This not only eliminates the need for a separate stationkeeping mode, it also eliminates interference with the payload and the need to coordinate payload operations and stationkeeping activities.

5. MISSION FEATURES ENABLED BY AUTONOMOUS STATIONKEEPING

5.1 General Features

A summary of the representative mission features enabled by autonomous stationkeeping is shown in Table 1 and discussed below. As discussed in Sec. 5, most of these features are available at no added cost to the mission and, in many cases, cost less than more traditional approaches.

Table 1. Representative Mission Features Enabled by Autonomous Stationkeeping.

1. **"Random Walk" LEO Orbit**
   – With preassigned "random" burns, you know where your assets will be at all future times, but no one else does
      * Two separated burns between observations leaves a discontinuous trail which is difficult to identify
2. **Advanced Mission Planning**
   – Tell your customer in southern France all the passes available for pictures (including viewing angle and Sun angle) for the next 10 years
3. **Advanced Mission Control**
   – Use a burn of 1 m/sec to have the satellite fly directly over the target on a defined pass two months in the future
4. **Collision Avoidance**
   – If Ellipso is built, their satellites will fly through your constellation 500 times a day for the life of the mission
   – You can tell them where your satellites will be months in advance
5. **More GEO Satellites**
   – Can pack multiple satellites from different organizations into a single GEO orbital slot
6. **Open Loop Rendezvous**
   – With a target vehicle in a controlled orbit, the chaser will know where it is at all times — even when they have not been in communications for an extended period
7. **Complete Coverage Analysis for Constellations**
   – All users know where all of the satellites are all of the time with no comm link
8. **Eliminate Constellation Rephasing**
   – All satellites in the constellation are maintained in phase with each other at all times; no rephasing for the life of the constellation
9. **Eliminate DSN Tracking**
   – With a spacecraft in a controlled orbit about Mars, observation and communications times and geometry will be known in advance without DSN tracking

Ground Track Maintenance. Because all of the orbital elements are controlled, either the spacecraft ground track or its track in inertial space can be made to follow a predefined pattern, such as a repeating ground track orbit. This provides two major features of importance to the mission designer. As discussed above, we can predict the characteristics of any future spacecraft pass or determine when specific conditions will occur, such as when the spacecraft will next pass within 10 deg of straight overhead at Kansas City between 9:00 am and 11:00 am local time. In addition, we can use a very small delta V sufficiently far in advance to change the conditions of a specific ground pass to match our needs. Thus, a small change in orbit period can move next Friday's Kansas City pass from 15 deg off the zenith to 10 deg off the zenith. This is a level of control that has not previously existed at low cost and which 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. 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 satellite tracking much more difficult.

System Scheduling and Mission Planning. These are areas previously dominated by astrodynamics. Planning is traditionally done as far in advance as feasible in terms of future orbit propagation. If preliminary plans are done, say, two months in advance, they will be redone two weeks in advance and then updated again several days before the event and finally on the morning of the event as orbit predictions become better and better. Autonomous stationkeeping effectively eliminates all of the replanning cycles.

With autonomous stationkeeping, planning and scheduling are done on a business basis, not as astrodynamics dictates.

For example, we can do planning at regular meetings of the user group on a monthly, quarterly, or annual basis. Plans are updated as the needs of the users change and as convenient for dissemination. Thus, we might put out a detailed weekly plan three weeks in advance to allow time for convenient distribution and potential coordination and input among the users.

User Equipment Able to Know Future Positions. This has potential applicability for military, commercial, and scientific systems. As discussed in Sec. 6.1, user terminals, such as remote weather stations or bookstore computers with daily receipts, can be delivered to the user with the entire spacecraft ephemeris already in memory. Consequently, data can be transmitted autonomously when the satellite is overhead. Similarly, worldwide science groups can do observation planning based on advance knowledge of where the satellite will be and the detailed lighting and viewing conditions then. As a representative military application, a submarine can break through the ice for a brief period to send a 1-way message, knowing that the satellite will be there to receive it. All of this provides a new level of utility while substantially reducing the cost and complexity of providing needed ephemeris information to the user community.

Of course it may be necessary to change the position of a satellite in its orbit from time to time. This could come about because of changing mission requirements, failure of on-orbit equipment, or the replacement of an old satellite with a new one in a different orbit. In any case this is easily accommodated within the autonomous stationkeeping process in that all of the data needed to predict satellite future positions can be provided with less than 10 parameters in a look-up table.

Avoiding Collisions and RF Interference. There is a substantial body of literature on collision avoidance and debris mitigation. (See, for example, Chobotov, et al. [1997], Jenkin [1993a, 1993b, 1995], Johnson and McKnight [1991], and Simpson [1994].) The problem is most severe for satellites in GEO or in other high density regimes. However, it can also be a problem for general satellite orbits. If the Ellipso constellation is built, its satellites will fly through your constellation or single satellite orbit 500 times per day for the life of the mission. RF interference with higher or lower spacecraft can pose outage problems that may be critical with respect to business interruptions or obtaining important scientific data.

The fundamental problem with avoiding both collisions and RF interference is to know about it as far in advance as possible. This allows coordination with other system operators and, as discussed above, allows avoidance maneuvers to be done as fuel efficiently as possible.

If both systems involved are using autonomous stationkeeping, the problem is straightforward and can be done as far in advance as desired, say on a monthly or annual basis or at industry conferences which both groups attend. Very minor amounts of propellant would be required. If only one of the two is using autonomous stationkeeping (e.g., potential collisions with debris) the problem is more complex. In this case, we can plan as far in advance as propagation of the debris orbit will allow. This is not as desirable as two fully controlled orbits, but it still better to know in advance where your satellite will be.

Finally, a system using autonomous stationkeeping may choose to make the future positions of its satellites public. For example, this could be done on a system website. This allows any other satellite users or potential users to calculate as far in advance as possible when potential collisions or interference could occur. This provides the maximum possible warning and permits advance coordination, even between competing organizations. While such coordination might prove challenging from a political perspective, it is in the best interests of both organizations to avoid the potential for either collisions or RF interference.

5.2 Applicability to Constellations

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. Microcosm's implementation of orbit control provides this relative control by doing absolute control for each of the satellites in the constellation. (See Wertz [1999, 2001] for a discussion of absolute vs. relative orbit control.)

Substantial work has been done on methods for providing only relative orbit control for constellations. (See, for example, Smith, et al. [1999].) ORBCOMM has implemented this successfully by using differential drag produced by changing the orientation of the solar arrays [Burgess, 1996]. The fundamental objective of most relative control approaches is to reduce the overall propellant utilization and, therefore, extend the life and reduce the cost/year of the mission. However, as implemented in OCK, absolute orbit control uses less propellant than the traditional process of ground-based relative control. In addition, the process of developing and implementing a relative orbit control scheme adds significantly to the complexity of the system and, therefore, to the non-recurring development cost and cost risk. For example, a proposed genetic algorithm for relative orbit control has execution times of 12 to 24 hours using 6 parallel processors in a silicon graphics multi-processor workstation to optimize 4 burns in a 3-month run for 1 satellite [Smith, et al. 1999]. OCK will obtain a more fuel optimal solution using more than 1000 times less computational resources Equally important, OCK transforms the process from a astrodynamics problem to a business problem that can be addressed on a business basis.

Table 2 summarizes the principal application areas of autonomous stationkeeping to constellation maintenance. Most of the individual entries have been discussed elsewhere. However, a key issue for constellations is mitigating the impact of higher order harmonics on the constellation structure. Because of these higher order harmonics which are due to the nonuniform mass distribution of the Earth, satellites with the identical mean semimajor axis 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 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.

Table 2. Autonomous Stationkeeping Reduces Cost, Risk, and Cost Risk For Constellation Management. The last 4 columns show areas of cost and risk reduction using autonomous stationkeeping. NR-$ = Saving in Non-recurring Cost; R-$ = Saving in Recurring Cost; Fuel = Propellant Savings; Risk = Risk Reduction

Issue	**Problem**	**Impact of Auto. Stationkeeping**	**NR-$**	**R-$**	**Fuel**	**Risk**
Stationkeeping	Very Ops intensive; risk of errors	Automated on board to minimize cost and risk	**X**	**X**	**X**	**X**
Collision Avoid. (internal)	Risk of collision cascade	Minimizes risk; allows emphasis on exceptions	**X**	**X**	**X**	**X**
Collision Avoid. (external)	Advance warning may be short	Maximizes warning/planning time; minimizes prop. usage	**X**	**X**	**X**	**X**
RF Interference	May cause outages	Minimized by adv. knowledge	**X**	**X**	**X**	**X**
Coverage	Operational req. to maintain	Minimizes stationkeeping box and maximizes coverage	**X**	**X**	**X**	
Propellant Management	Consumable use limits life	Minimizes propellant usage			**X**	
Higher order harmonics	Small period diff's in each plane	All sats have identical average period	**X**	**X**	**X**	**X**
System Initialization	Create pattern with only a few sats	Each sat has assigned place from launch of 1st sat	**X**	**X**		**X**
Satellite Loss	Service outage	Advanced planning possible	**X**	**X**		**X**
Operations	Historically high cost & cost risk	Eliminates multiple planning cycles, most stationkeeping	**X**	**X**		**X**

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 [2001].

6. CONCLUSIONS

The impact of autonomous stationkeeping performance enhancements and cost and risk reduction areas will, of course, 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, nonetheless, need at least some orbit control. In addition, this technology enables some missions and mission elements, such as automated one-way data transmission, which would not otherwise 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 satellite operations.

7. ACKNOWLEDGEMENTS

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On-Board Orbit delta-V Determination Determination. 1998. Autonomous Constellation.Â When this third generation GPS receiver is coupled with autonomous on-board maneuver planning and orbit control software, and formation control algorithms, formation flying becomes feasible. In addition to relative and absolute positioning, GPS provides low cost, spacecraft timing systems, vehicle attitude determination and attitude control, and autonomous data transmissions over ground stations.Â create an extensive flight simulation environment. The third prong in the NASA testbed strategy is an extensive on-orbit campaign of demonstration missions. Flight planning, aircraft sizes and infrastructure are optimised and where necessary increased. New operators have evolved from the general aviation market segment. Seamless door-to-door travel of passengers and freight is the norm.Â Air transport is at the heart of an integrated seamless, energy efficient, diffused intermodal system taking travellers and their baggage from door-to-door, safely, affordably, quickly, smoothly, seamlessly, predictably and without interruption. Choices are offered between customised products and services offering levels of facilities, quality of service, on-board comfort, journey time, optional rescheduling and price. Passage through the airport is streamlined and rapid.