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AeroAstro's Escort – A Microsatellite for On-Orbit Inspection of Space Assets

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Abstract. The recent tragic loss of the Space Shuttle Columbia highlights the need for the independent, in-situ inspection of operational satellites. To address this problem, AeroAstro has been designing an autonomous companion microsatellite named Escort™. Given the extremely high value of major operational satellites, AeroAstro believes that responsible stakeholders should insist on having a relatively low-cost Escort-like microsatellite accompanying their satellites. Other critical roles that Escort can fill include on-orbit inspection of a technology validation satellite, situational awareness of the "space neighborhood" around another satellite, and even aiding the deployment and periodic calibration of another satellite. Each Escort is intended to perform proximity operations around a much larger satellite after either releasing itself from its host or after being delivered to the vicinity of the target satellite by a transfer vehicle. Once near the primary satellite, Escort can maneuver autonomously or in a supervised manner, either to inspect from any angle and distance or to hibernate. AeroAstro is in the process of developing a variety of bus and payload technologies to enable the Escort concept. AeroAstro's patented RF Probe, in particular, can be used as a highly sophisticated diagnostic inspection tool to measure emissions from a communications satellites on-orbit.

Introduction

The recent tragic loss of America's first operational Space Shuttle, Columbia, dramatically highlights a problem that has plagued satellite operators since the dawn of the space age – the lack of an ability to independently observe, measure, or analyze satellite performance in-situ. AeroAstro has been studying an autonomous service companion vehicle, Escort, over the course of several years. It is posited that future missions may include multiple vehicles – a primary vehicle tasked with meeting specific mission objectives plus one or more Escort–like vehicles to make observations, assess performance, or provide calibration for the primary vehicle. In this paper, the rationale and design for Escort is described in detail, providing a status update of this ongoing development effort.

Escort is intended to perform proximity operations supporting large, sophisticated assets, such as commercial communications satellites, civilian scientific satellites, the Space Shuttle, or the International Space Station. Escort could be released from its primary satellite on orbit or may be delivered to the neighborhood of the primary by another transfer vehicle. Once in the vicinity of the primary vehicle, Escort can maneuver either autonomously or under human guidance to perform a variety of diagnostic functions. Potential uses for Escort include aiding deployment, providing calibration, monitoring performance, investigating anomalies, or monitoring the local space environment surrounding the primary satellite to provide situational awareness.

Escort, by design, is highly capable and extremely maneuverable. It can host a suite of sensors to monitor the primary vehicle's health or aid the primary in attaining or returning to operational status. The Escort inspection payload includes AeroAstro's patented RF (Radio Frequency) Probe as well as optical and/or infrared (IR) imagers. The RF Probe analyzes near-field RF signals emanating from the primary spacecraft using a calibrated wideband antenna and RF front end. The back end is an intelligent spectrum analyzer, incorporating extensive digital signal processing (DSP) capabilities for detection and characterization of signals to assess the state of the primary satellite. For example, the RF Probe may be used to measure gain patterns after antenna deployment or diagnose a malfunction by detecting the presence or absence of selected electromagnetic emissions. IR imagers can be used for thermal mapping to identify hot spots, while visible imagers can diagnose failed deployments, examine launch- or separation-related damage, or assess attitude control performance of the primary satellite. Extending the concept, Escort could carry optical sources to calibrate multi-spectral or hyper-spectral imagers, or may even be able to remedy a failure by nudging or heating a frozen deployment mechanism.

Several other important AeroAstro innovations, such as the S^3COUT (Small Smart SpaceCraft for Observation and Utility Tasks) modular architecture, the Miniature Star Tracker attitude sensor, and the SPORT™ (Small Payload ORbit Transfer) aerobraking vehicle, may be incorporated into or used in conjunction with Escort. This paper includes a review of AeroAstro technology efforts and shows how the Escort concept may ultimately benefit from these synergistic developments.

Escort Mission

GEO Primary Satellites and Economics

The most probable primary satellite for an Escort microsatellite inspector is likely to be a large, geostationary Earth orbit (GEO) satellite (Figure 1), whose cost and complexity make the use of a small inspector satellite technically and economically advantageous. Currently, there are hundreds of geostationary satellites in operation, and hundreds more are expected to be launched in the next decade. The cost of these satellites is usually over $200M (US), not including the cost of launch and operations.

An Escort vehicle must be able to extend the expected lifetime of the primary satellite sufficiently to justify its cost. This trade depends on multiple factors, including the total value of the primary satellite, the probability of Escort extending the lifetime of the primary satellite, and the expected lifetime of the primary satellite. For Escort to be economically viable, the increase in the expected value of the primary satellite by incorporating an Escort co-launch must be more than the cost of the Escort satellite. It should be noted that as a result of AeroAstro's considerable efforts to develop low-cost, modular microsatellite bus architectures, the recurring cost of Escort missions could be consdierably less than $5M (US).

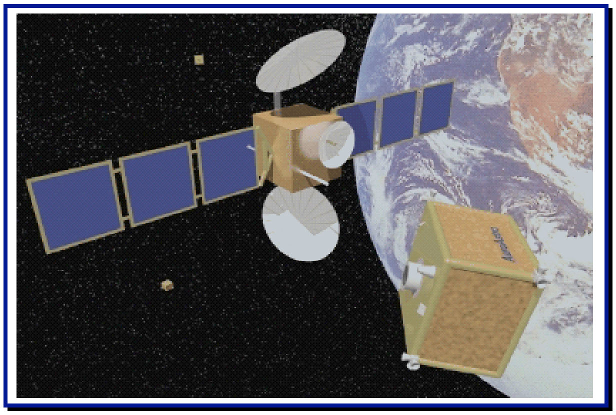

Figure 1. Escort Inspecting Primary Satellite.

To first order, the increase in expected value of the primary satellite is estimated by assuming that the value of the primary satellite is spread evenly over its expected lifetime. For example, if the satellite is valued at $400M (total fixed cost, including launch) and is designed to last 10 years on orbit, then the value of extending its lifetime by 10% (one year) is $40 M.

The expected increase in lifetime is determined by a combination of factors: the total expected lifetime of the spacecraft, the probability of Escort being able to detect and diagnose the problem, the probability of Escort being able to resolve the problem, and the remaining expected lifetime of the satellite. Equation 1 below shows the calculation for determining the expected change in spacecraft operational lifetime from using Escort, where L is the expected lifetime of the GEO spacecraft, Y is the fraction of its lifetime that is used up before the problem occurs, P_1 is the probability of the Escort inspection microsatellite being able to correctly detect and diagnose the problem, and P_2 is the probability of Escort enabling a fix that returns the satellite to normal operations.

$$\Delta L = P_1 P_2 L(1 - Y) \qquad (1)$$

For example, a spacecraft has an expected lifetime of 10 years (L=10), and during its seventh year of operation a problem occurs (Y=70%). Assume that the probability of Escort being able to correctly detect and diagnose this problem is 20% (P_1=0.2), and the probability of the problem being such that Escort can enable a solution that brings the satellite back into service is 40% (P_2=0.4). This means the increase in expected lifetime from using Escort is 0.24 years, using these assumed values. This calculation allows the customer or insurer responsible for the satellite to determine whether or not an Escort launch is economically advantageous given a set of conditions. It also gives metrics to judge whether or not Escort is useful for certain types of missions. In this example, an increase in expected lifetime of 0.24 years at a value of $40M per year, means the total cost of using Escort must be less than $9.6M in order to make economic sense.

Primary satellites can also benefit from Escort by using it to accelerate on-orbit calibrations and checkout after launch. If the time to map antenna gains and calibrate the antenna gimbaling system can be shortened by weeks or months using Escort, the satellite can be brought into service sooner, increasing its value by increasing its useful lifetime.

Escort also reduces costs by diagnosing problems that can be prevented in other satellites and by reducing the manpower required in trying to analyze and resolve problems from the ground. As Escort is able to analyze the on-orbit operation of a satellite, the data that is gathered can be used in the design and planning of future satellites to prevent the same problems from occurring. It can also prevent operational mistakes, which may threaten the welfare of similar satellites already in orbit, from being repeated. In addition, Escort's unique ability to analyze and gather data from the primary satellite saves time and manpower for engineers on the ground, further reducing costs.

The economic model used is conservative, because it uses a low estimate of the primary satellite's value. A GEO satellite's true value in orbit is actually more than the cost of replacement, which is all that this model assumes. A more accurate calculation of the true value would also include the opportunity cost of lost functionality or business if the satellite is out of service or in a diminished capacity. Calculation of the opportunity cost is satellite specific and beyond the scope of this paper. In addition, the model assumes the remaining lifetime of the satellite is not extended beyond the satellite's original expected lifetime, which is frequently exceeded in practice.

Other Primary Satellites

There are high-value satellites in orbits other than GEO – in particular, there are many in low Earth orbit (LEO), including weather satellites, the Space Shuttle, and the International Space Station (ISS). AeroAstro has considered the design changes that would be required to convert an Escort primarily deigned for GEO over to LEO operations. In summary, it was found that the GEO environment is more stressing than LEO on the following Escort subsystems and features: communications, thermal, radiation tolerance and eclipse duration. Because the LEO environment is more benign than GEO, no major changes in the abovementioned subsystems or features are required. However, since communications gaps are to be expected in a LEO orbit, Escort would require greater autonomous capabilities, but these requirements are not beyond what it should be able to handle with limited operational modifications.

AeroAstro has also considerd the use of the baseline GEO Escort in the highly elliptical geosynchronous transfer orbit (GTO) and found that its applicability to this orbit is feasible. Other types of orbits for primary satellites include highly elliptical Molniya and Tundra orbits, medium Earth orbits (MEO), and even interplanetary orbits, all of which remain to be investigated for compatibility with the Escort design.

Inspection Capabilities

To be technically valuable, Escort must provide the appropriate data gathering capabilities to diagnose failure modes and enable solutions. Several geostationary satellites fail on orbit each year for a variety of reasons, and many of their failure modes could be better diagnosed using the tools provided by Escort, particularly the RF Probe.

Table 1 is a partial list of failure modes for geostationary satellites. Data that would be useful in diagnosing and correcting these failures include: thermal mapping of the satellite structure, detailed and overall visual inspection from all angles, mapping of RF emissions at a variety of frequencies, occurrence of electro-static discharge (ESD), and the radiation environment.

Table 1. Some Failure Modes of GEO Satellites.

Failure Mode	
Separation Failure	Radiation Damage
Separation Collision	Electronics Failure
Orbit Insertion Failure	Human Error
Launch Vibration Damage	Loss Of Power
Antenna Deployment Failure	Mechanical Structure Failure
Solar Array Deployment Failure	Broken Wiring Or Loose Connector
ADCS Component Failure (Star, Earth, Sun, Magnetic, Or Inertial Sensor, Wheel)	Flake Of Metal Loose In Electronics
Thruster Stuck Closed/Open	Mis-wired Cable
Propellant Leak Or Freeze	Loss Of Communications
Thermal Too Hot/Too Cold	Damaged Batteries
Thermal Blanket Torn	Charger Malfunctioning
Deterioration Of Thermal Coatings	Orbit Raising Propulsion Failure
Battery Short Circuit	Solar Aray Gimbal Failure
Software Failure	Antenna Gimbal Failure
Space Junk Collision	Timing Failure
Electro-Static Discharge	Damage Prior To Launch

In order to collect data useful for diagnosing and resolving on-orbit failures, Escort can carry several payloads to inspect the primary satellite and the environment around it. An IR and visual camera can be used to inspect the thermal environment of the satellites and look for any damage or Attitude Determination and Control Subsystem (ADCS) anomalies.

AeroAstro's patented RF Probe is designed to inspect the operation of the communications system as well as check for anomalies within the satellite's other electronics. The RF Probe can be used to diagnose a host of problems, ranging from a processor stuck in a continous loop to a mispointed antenna.

Electro-static discharge (ESD) and radiation sensors monitor the environment around the satellite and notify ground controllers of conditions that could cause data corruption or hardware damage. A description of how each sensor is used, problems it can diagnose, and possible corrective actions are contained in Table 2.

Figure 2 is a collection of pictures from NASA, demonstrating the type of information that can be obtained using cameras in space. Escort's imaging system will be even more capable due to the fact that it can move around the target satellite freely and take pictures from a variety of distances and angles. The pictures show micrometeoroid damage on Hubble, similar to the type of visual inspection Escort could provide on other satellites.

The operational requirements of Escort depend on its mission and the instruments being used for inspection. Depending on the problem being diagnosed, Escort may need to vary its operational parameters, such as distance from the target satellite, duration of operation, and orientation. With each parameter being varied, the operational risk incurred must be balanced against the value of the data being gathered. Ground controllers can gradually begin using more and more aggressive maneuvers to collect data on a target satellite if the data collected does not enable an effective solution.

Table 2. Capabilities of Escort Payload.

Sensor	Inspections Enabled	Potential Problems Diagnosed	Corrective Actions Possible
IR Camera	• Thermal mapping	• Failed heat pipes • Alpha degradation	• Change heater control plan
Visual Camera	• Macro-scale damage • Micro-scale damage • ADCS anomalies	• Damaged solar arrays • Failed deployment (solar arrays, antenna reflectors, etc.) • Separation failure • Micrometeorite strikes • Damaged optics • Damaged antenna • Frayed or cut wiring • Erroneous spin rate • Pointing inaccuracies • Propellant leak • ESD arcing • Blanket damage	• Use images to determine whether or not to use thruster assisted deployment or switch to redundant units
RF Probe	• Mapping of antenna gains • Transponder anomalies • Inspection of waveguide assemblies • Inspection of spacecraft processors and clocks	• Antenna gimbal misalignment • Transponder malfunction • Processor stuck in continuous loop	• Re-point antenna • Use Inspector as a data relay • Streamlined in-orbit tests (calibration of gimbaled antenna) • Alerts operators to switch to redundant systems
ESD Sensor	• Sensing of ESD in real-time	• Possible arcing across satellite bus, damage to electronics	• Monitor compromised equipment • Shut off compromised equipment, switch to redundant systems
Radiation Sensor	• Sensing of radiation environment in real-time	• Exceed Total Ionizing Dose (TID) for susceptible hardware	• Check memory • Temporarily shut down sensitive equipment • Off-point solar arrays • Check for Single Event Upsets (SEU) and failures

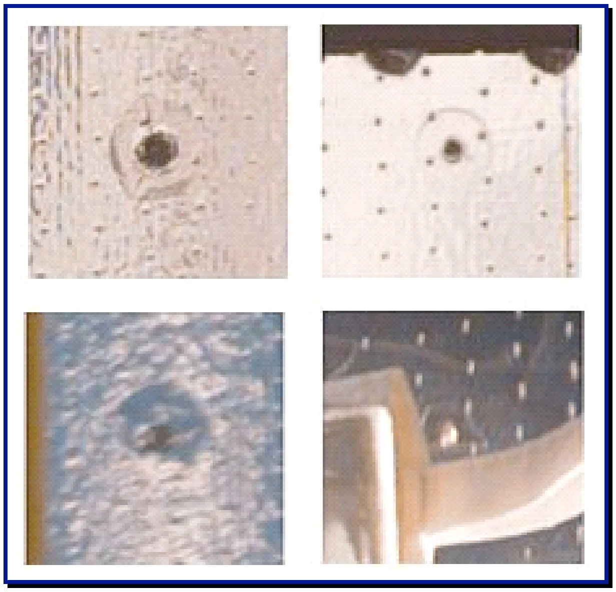

Figure 2. Pictures of Satellites Taken in Space.

Escort Technology

Overview

AeroAstro has been developing a variety of technologies that could be effectively used to make an Escort microsatellite smaller, cheaper, and more capable. The key technologies that will enable the Escort concept are a modular satellite architecture, an avionics subsystem, the RF Probe payload, Nitrous Oxide propulsion, and a lightweight, inexpensive star tracker. All of these technologies are funded through Phase I or Phase II Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) contracts and are briefly described below.

Architecture and Integration

AeroAstro is developing a modular architecture for small satellites, S^{3}COUT (or SCOUT). The SCOUT modular architecture is intended to exhibit the following attributes:

- **Small and Lightweight** to maximize utility within the limited performance envelope of modest launch vehicle capabilities, especially for secondary payloads
- **Universally Compatible** to enable using as many different launch vehicles as possible, with particular emphasis on secondary payload accommodations
- **Low Cost** to assure that assets can be readily expended as necessary, and also to be economically viable
- **Rapid Response** to allow swift reactions with readily available assets to rapidly changing situations
- **Flexible** to permit a modest complement of off-the-shelf modules to address a wide-ranging set of mission requirements
- **Field Configurable** to enable just-in-time integration and configuration of modules to meet different mission requirements as they develop
- **Modular** to achieve the conflicting goals described above
- **Scaleable** to tailor the capability to a range of applications
- **Extensible** to allow the system to adapt to future needs

These characteristics of SCOUT are intended to enable a low-rate mass-producible small satellite architecture that is complementary to similar rapid response small launch vehicle concepts under development. SCOUT will also enable access to space in general even for users who do not require rapid response simply by bringing down the costs of small satellites.

The SCOUT architecture is currently baselined for use on Escort. It should be noted that an Escort could also be built without using the SCOUT architecture. For example, a different stackable modularity concept developed by AeroAstro, called SpaceFrame, which aggregates more components into a single module, could be used.

Alternatively, a totally non-modular Escort could be developed, since modularity tends to increase the size and mass of satellites compared to those developed to a point-design.

Avionics

The SCOUT avionics architecture is designed to allow the most efficient and most capable transfer of data and power between stackable modules along a common "spinal column." The core or "heart and brain" of the avionics architecture is based on a SCOUT module from another AeroAstro program, entitled Short Duration Mission Avionics (SDMA), which is based on standard VME (Versa Mode European) form factors. SDMA allows for three different avionics cores, which are themselves modular:

1. A single VME card for simple Field Progammable Gate Array (FPGA) based power, control, and telemetry functionality

2. The above card, plus a second VME card with a Central Processing Unit (CPU) for greatly increased computational power and associated data storage
3. The above cards, plus a third card dedicated solely to solid state memory for significantly increased data storage

As with the overall architecture, the Escort design is baselining the avionics architcture from SCOUT.

RF Probe

Perhaps the most interesting and innovative aspect of the Escort concept is AeroAstro's patented RF Probe. The RF Probe is used to analyze near-field RF signals emanating from the satellite being inspected by Escort. The signals are acquired through a calibrated wide-bandwidth antenna and RF front end. The back end is an intelligent spectrum analyzer with extensive DSP capabilities. This allows for detection of signal level, quality, and classification of an inspected satellite's transponders, antennas, waveguides, and emitted RF noise. Compared to RF inspection of targets using ground stations, Escort and the RF Probe enable inspection with approximately seven orders of magnitude greater signal sensitivity.

The RF Probe is a key technology in the Escort design.

Propulsion

With VACCO, AeroAstro has been developing Nitrous Oxide (N_2O) hot gas monopropellant propulsion technology for small satellites. There are numerous advantages to this propulsion method:

- The low propellant storage pressure (~800 psia) allows non-conventional shaped tanks that can fill up more of the available envelope volume than would be possible using a spherical or cylindrical tank, as is required for more common high pressure cold gas or hydrazine systems.
- Nitrous Oxide is non-toxic, low-cost, and storable.
- The specific impulse (Isp) of at least 120 seconds is considerably higher than cold gas, and may be as high as 200 seconds.
- For volumetric efficiency the propellant is stored within the tank as a liquid that is pressurized by its own vapor – no diaphragm is needed.

Propellant in either gaseous or liquid state enters a micro plenum chamber within the tank through a valve. The pressure and temperature within the plenum is controlled such that all the propellant inside transforms to a gaseous state. MEMS (Micro Electro-Mechanical Systems) valves are used throughout the system – they are immersed in the propellant along with an electronics driver board on which the propellant feed system is also built. The feed system channels propellant from the plenum to individual hot gas thrusters.

The N_2O hot gas monopropellant propulsion technology is being considered for the Escort attitude control system.

Star Tracker

AeroAstro is developing a lightweight, inexpensive, low-power, coarse star tracker. This star tracker features a CMOS (Complementary Metal-Oxide Semiconductor) imager instead of the more traditional CCD (Charge Coupled Device) imager. The CMOS imager requires much less supporting electronics and is more radiation tolerant. This star tracker also features pinhole optics. The absence of a lens and baffle assembly greatly reduces cost and volume of the star tracker at the expense of performance. The miniature star tracker is so small and consumes so little power that some of the disadvanages of no baffling can be overcome by using several orthogonal star trackers.

The coarse star tracker is baselined for Escort, keeping cost, mass, and power consumption to a minimum.

Escort Design

Overview

A variety of different modular and non-modular small satellite architectures could be used to build Escort. One concept for a very short-duration Escort that is powered solely by primary batteries and that is built in a totally non-modular fashion was depicted in Figure 1. Another concept for an Escort that is built using the SCOUT modular architecture is shown in Figure 3.

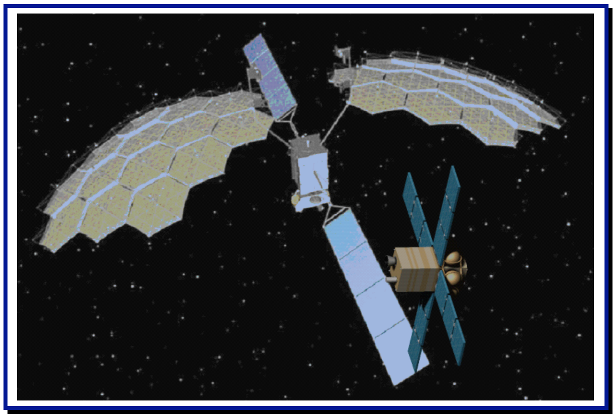

Figure 3. SCOUT-Based Escort Inspecting a Primary Satellite.

Since the layout, structure, and power system of Escort could vary widely depending on customer requirements, only some general concepts regarding a few selected subsystems are presented below.

A common theme among all of the Escort designs considered by AeroAstro is that the Escort is not equipped for large-scale orbit transfers or rendezvous. The Escort should either be released from its primary satellite or should be transferred to the primary's orbit and rendezvoused with it by a separate transfer vehicle, such as SHERPA, which is also being developed by AeroAstro. Escort is also not designed for re-docking with its primary satellite or for performing any sort of robotic maintenance or servicing. It is anticipated that as Escort technology matures and evolves through actual operational utilization, it will steadily gain more advanced capabilities that will allow future derivatives to perform robotic maintenance and servicing.

Attitude Determination

The Escort mission demands a variety of attitude determination sensors:

- **Star tracker**, for when the primary satellite is temporarily out of view
- **Sun sensor**, for when the Escort is in hibernation or battery charging mode
- **Imager**, for attitude determination relative to the primary satellite
- **Body rate sensors**, for when the Escort needs to detumble and to propgate the attitude between environmental sensor updates

Without advanced technologies, such as AeroAstro's coarse star tracker or medium sun sensors, or MEMS rate sensors produced by a variety of manufacturers, a sufficiently compact yet capable attitude determination suite would not be possible. It is also fortunate that the imager, which can be used for attitude determination, serves a dual purpose as a payoad sensor.

As many as four coarse star tracker apertures and two processors should be used to prevent sun, Earth, moon or primary-induced loss of lock. The attitude sensor selection is insensitive to orbit selection, making it useful for both LEO and GEO, and it is also capable of recovering from a lost-in-space mode.

Attitude Control

A variety of different attitude control designs were evaluated, as shown in Table 3. Bang-bang thrusters were selected, because they provide the best attitude control capabilities and could be used for translational control, which is required by the Escort mission.

A typical baseline imager for Escort has an approximatley 5° full-angle field of view (FOV). Requirements for attitude pointing control are set based on being able to image a certain percentage of the intended FOV.

For example, to image 70% of the intended 5° FOV, pointing control accuracy of ±1.5° is required. Requirements for attitude rate control are set based on a requirement not to blur the images. Based on typical imager integration times, the attitude rate control requirement is likely to be on the order of ±0.1°/sec. By rule of thumb, the requirements for attitude pointing and rate knowledge are simply set to one-third of the control requirements, which should be sufficient assuming that all numbers are quoted at three sigma. These requirements can be easily met using the selected suites of attitude sensors and actuators.

The attitude control momentum impulse requirement is calculated by assuming that Escort has to continuously fight the maximum possible environmental disturbance torque and also continuously perform a bang-bang attitude limit cycle. Over the approximately 100-day active life of a typical Escort in GEO, the limit cycle impulse is approximately two orders of magnitude larger than the disturbance torque impulse and the total impulse is on the order of 5,000 Nms.

Table 3. Attitude Control Trade Study.

Figure of Merit	Spin Stabilized	Momentum Bias Wheels	Reaction Wheels	Bang-Bang Thrusters
Imager Complexity	High	Low	Low	Low
Pointing Stability	Moderate	Moderate	High	Low
Slew Capability	Low	Moderate	High	High
Power Draw	Low	Moderate	High	Low
Mass	Low	Moderate	High	Low
ADCS Complexity	Low	Moderate	High	Low
Cost	Low	Moderate	High	Low

Table 4. Propellant Trade Study.

Propellant	Dry Mass	Propellant Mass	Thruster Size	Tank Size	Cost
N_2 Cold Gas	Low	High	Small	Large	Low
N_2H_4 Monopropellant	High	Low	Large	Small	High
Pulsed Plasma	Low	Very Low	Large	Large	High
N_2O Hot Gas	Low	Medium	Small	Small	Low

Propulsion

To provide a high level of inspection capability, Escort needs to be highly maneuverable in both attitude and translation. In order to provide fully uncoupled six-degree-of-freedom control, at a minimum, a classic twelve-thruster topology should be used. A propellant trade study was conducted, and the results are presented in Table 4. AeroAstro's N_2O hot gas technology was selected. The thrust in a N_2O thruster is set by adjusting the chamber geometry; a 0.1 N thurst level was selected. The minimum on-time was selected to be long enough for the gas to fully ignite, thereby allowing a higher Isp. The resulting propellant efficiency was found to be greater than what could be achieved by reducing the on-time and accepting a lower Isp closer to that of cold gas, due to incomplete combustion.

A detailed ΔV budget was assembled that included the following entries:

- Initial separation
- Coupled radial and in-track maneuvering
- Cross-track maneuvering
- North-South station-keeping
- East-West station-keeping
- Orbit translation bang-bang limit cycle
- Disposal to Super-GEO
- Attitude control compensation for thruster offset disturbance during translational maneuvers

The maneuvering (relative to the primary satellite) budget allowed for a single 100-meter amplitude radial maneuver per day and also a single 100-meter amplitude cross-track maneuver per day. The station-keeping budgets were conservative and assumed unusally tight orbit control. The thruster offset was conservatively large to also include the effects of center of mass uncertainty, thruster misalignment uncertainty and thrust balancing uncertainty. The total resulting ΔV was approximately 35 m/s.

The dry mass for a typical Escort is approximatley 40 kg. Based on this dry mass a propellant budget was assembled by adding up the following:

- Attitude control momentum impulse propellant
- ΔV propellant
- 30% mass margin propellant
- Pressurant propellant

The total mass of N_2O propellant required is then on the order of 5 kg.

Escort Operations

To minimize propellant usage, Escort spends most of its time passively orbiting its primary satellite. Alternatively, Escort can also lead or trail the primary satellite separated by a fixed true anomaly. The primary satellite is assumed to be in a circular GEO orbit, and Escort is slightly offset from that orbit.

A slight true anomaly offset will cause Escort to lead or trail the primary. A slight apogee and perigee (or semi-major axis and eccentricity) offset will cause Escort to orbit relative to the primary in the radial and in-track directions. A slight inclination offset will cause Escort to orbit relative to the primary in the cross-track direction.

The dynamics of orbits relative to a primary satellite are somewhat counter-intuitive. The radial and in-track motions are inexorably coupled: the in-track radius of the relative orbit will always be twice the radial radius. The cross-track radius is uncoupled and can be independently controlled. Another counter-intuitive point is that the smaller the radius of the Escort's orbit relative to the primary, the slower the Escort moves relative to the primary. This has advantages from the standpoint that it is safer to move slower when the Escort is closer to the primary, and also that features on the primary will still be passing through the Escort FOV slowly enough to be inspected.

Based on preliminary discussion with stakeholders, the minimum distance between the center of Escort and the center of the primary is expected to be on the order of 100 meters. The maximum distance is expected to be on the order of 1,500 meters. The typical maximum length dimension of a large primary is on the order of

50 meters. The typical smallest feature size of interest is on the order of 1 centimeter. The simple imager payload baseline is capable of meeting both the 50 meter and 1 centimeter requirements within the specified operational distances to the target. The imager is also capable of recording short movies at a variety of resolutions for up to several hours.

Downlinking the recorded imaging and RF Probe data from such a small spacecraft as Escort in GEO can be quite time and energy consuming. Therefore, depending on the power architecture, it may be necessary to temporarily suspend normal payload data acquisition during downlink periods. As a result, the Escort concept of operations evolves into a "campaign" mode where Escort acquires payload data for a limited duration and then transitions to a different mode to downlink the data and simultaneously charge its batteries. Each such campaign can be repeated up to several times per day. The nominal concept of operations has each human operator shift of say 6 or 8 hours conducting a single full campaign within their shift duration.

When it is not needed, Escort can also be put into a hibernation mode by slowly spinning it up in a stable sun-pointed attitude. Hibernation should preferably be in a leading or trailing orbit – whichever will result in the absence of East-West station-keeping to cause the Escort to slowly drift away from its primary. The total lifetime of Escort in GEO from a radiation dosage point of view is on the order of 1 year; the propellant is sized for approximately 100 days of activity.

Conclusion

The importance of Escort missions and their capabilities for inspection have been hilighted. It is evident that Escort has the potential to add substantial value to exiting large satellite systems by performing in-orbit inspection, diagnostic, deployment and calibration functions and also by providing near-field situational awareness. In extreme cases where human space flight is involved, it is even possible that Escort could be a life-saving technology.

A very cursory overview of Escort technology has been presented. The vast majority of details regarding the various potential Escort designs have been omitted. AeroAstro is currently baselining the use of the SCOUT modular microsatellite architecture for development of Escort.