NOVEL ORBIT RAISING STRATEGY MAKES LOW THRUST
COMMERCİALLY VIABLE.

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ABSTRACT

A new technique for utilizing low thrust Electric Propulsion System (EPS) for orbit raising has been developed at Hughes Aircraft that makes it commercially viable and operationally feasible.

The proposed strategy [1] is radically different than other strategies that have investigated satellite injections into geosynchronous orbit using a variety of high performance, low thrust devices. This paper reports use of a novel, supersynchronous intermediate orbit using Xenon Ion Propulsion System (XIPS) producing hundreds of millinewtons of thrust and an $I_{sp}$ range of 4000-5000 seconds. Embedded in this strategy is a theory that demonstrates how a highly eccentric orbit can be transformed into a circular one by applying a constant force around the orbit in a specific inertial attitude (which appears exceptionally simple to implement) while maintaining the same orbital period. The scheme is applicable to satellites initially launched into sub/supersynchronous orbits or into standard geo-transfer orbits. An on-board Chemical Propulsion System (CPS) is used to transfer the satellite from its injected orbit to the supersynchronous intermediate orbit. The XIPS thrusters are then used to propel the spacecraft to its final geosynchronous orbit. For injecting massive spacecraft, several weeks or months of XIPS thrusting are required. Most, or all, of this time is spent continuously thrusting in a constant inertial attitude, in an orbit with a constant period of 24 hours and with decreasing eccentricity finally ending in the desired geosynchronous orbit.

NOMENCLATURE

TOD = Transfer Orbit Duration
$\Gamma$ = Thrust
$STD$ = Standard deviation
SMA = Semi Major Axis
XIPS = Xenon Ion Propulsion System
$I_{sp}$ = Specific Impulse
CPS = Chemical Propulsion System

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EPS = Electric Propulsion System
LV = Launch Vehicle
PVA = Perigee Velocity Augmentation

INTRODUCTION

Reference [1] describes in detail the strategy and the weight increase by using the proposed strategy which will be briefly repeated here. This paper will focus on the strategy's robustness and operations issues.

Low thrust high Isp orbit raising offers increased payload capability but suffers from long TOD and operational problems. The proposed strategy offers minimum TOD (not delta velocity) while showing exceptional operational features. We believe this orbit strategy is superior to other strategies from a total system standpoint. Key elements of the proposed strategy are:

Transfer Orbit Sequence using a Hybrid system (Figure 1).

1) The Spacecraft is injected to an optimized injection orbit by the LV.

2) A series of perigee burns are performed (using the on-board CPS) to raise the injected apogee to a highly eccentric supersynchronous orbit (Schematic number 1).

3) A series of apogee burns are performed using the CPS (Schematic number 2) to raise the perigee above the Van Allen belt while removing most of the orbital inclination.

4) The series of apogee burns are performed using XIPS to raise perigee to achieve exactly a 24 hour orbit period, and at the same time remove any remaining orbit inclination (Schematic number 3).

5) A continuous firing of the XIPS thrusters in a fixed orientation in space will lower apogee and raise perigee in such a way that the semi-major axis of all the intermediate orbits will stay at the geosynchronous one (i.e., the orbital period will be kept at 24 hours), until reaching the circular geosynchronous condition (Schematic number 4).
CHEMICAL PHASE

1: PVA burns raise apogee to a supersynchronous elliptical orbit

2: Apogee burns raise perigee and remove part of the inclination. The targeted perigee radius is above 15000 km

XIPS PHASE

3: EP thrusters are fired around apogee to remove the remaining inclination and at the same time raise perigee to a 24 hr orbital period

4: EP thrusters are fired Continuously to raise perigee and lower apogee. A 24 hr orbital period is maintained

Fig 1. Schematic of the Supersynchronous Transfer Orbit using a Hybrid System.
MISSION OPERATIONS

When using electric propulsion for orbit raising, the lengthy transfer orbit duration requires a different perspective when considering how to operate and control a spacecraft for extensive periods of time. Today's chemical transfer orbit mission operations calls for at least two ground stations with a large staff of around the clock positions to be filled, the spacecraft is ground tracked at any opportunity, hence, the cost for transferring the spacecraft to its final orbit is high. The new strategy introduced offers a significant cost savings in operating the spacecraft during the orbit raising phase, requiring only one ground station. This is partly because the long duration part of the transfer orbit is during the continuous firing of the electric thrusters. During this phase the orbital period stays constant (the longitudinal drift rate is zero), hence, one single ground station is needed to track the spacecraft. Furthermore, every orbit the spacecraft will be visible at this station for long periods of time (since around apogee the spacecraft travel's the slowest, and the supersynchronous orbit offers long arc's around apogee). Since the spacecraft is slowly reducing it's eccentricity, i.e. no large changes to the orbit's elements, it is not necessary to view the spacecraft constantly. This requires the spacecraft to have increased onboard autonomy which is provided in all modern spacecraft. Although the Hybrid strategy calls for some chemical firings, which might require more than one ground station (current practice), this phase is short (several days typically). Furthermore, the impact of errors during the chemical phase is substantially diminished since any errors from the chemical phase can be taken out efficiently by the XIPS thrusters. This in turn eliminates the need for "final trim" burns in the chemical phase.

ERROR SENSITIVITY

The strategy described above assumes a keplerian motion (no perturbation) nor any errors on the state of the spacecraft, i.e. orbit and attitude. A study to assess the sensitivity of the transfer orbit TOD to these potential errors was evaluated. A high fidelity simulator [2] was designed that included eclipse outage, longitudinal and final orbit targeting. A Monte Carlo statistical analysis (1000 samples) was used to evaluate the achieved TOD sensitivity to any errors that might cause the orbit to deviate from it's nominal path, including:

1) Orbit uncertainty in terms of position and velocity.

2) Attitude uncertainty (imposed on the steering law).
3) Thrust uncertainty (as a percentage imposed on the nominal thrust magnitude).

The one sigma magnitude of the errors used in this study were: position 2.0 km, velocity 0.5 mps, attitude 5 deg, thrust 0.33%. These numbers are very conservative and were used to evaluate the strategy's sensitivity to large errors.

A case of a 70 day mission TOD (with no errors) using a series of 15 day auto flight intervals was analyzed. During each auto flight interval time it is assumed that the spacecraft has an autonomous guidance & control system to maintain a constant inertial attitude. By the end of the 15 day interval the mission is replanned and new errors are introduced to the state of the spacecraft.

Figure 2 depicts a histogram of all the samples showing a Gaussian distribution of all the errors analyzed. The abscissa variable is the mission TOD, expressed in days. The average mission TOD was 72.16 days. From the results it appears that the standard deviation for a mission using a 15 day auto flight interval is around 1.8 days. Shorter auto flight intervals did not substantially decrease the mission TOD's standard deviation, (10 day auto flight with somewhat lower attitude errors had a 1.1 days STD) indicating that the strategy can allow long autonomous flights with minor TOD increase. Further studies will examine longer intervals.

![Fig 2. Histogram for a 15 days interval auto flight orbit raising mission](image)
To better understand each source of error, each error was separately modeled. The simulator used only one source of error at a time while all the others were neglected. Figure 3 shows a histogram of the 15 day auto flight case for each source of error and total results for a 2 & 3 standard deviation dispersion. The figure of merit is the loss in TOD, ΔTOD, expressed in days.

![Figure 3. 15 days interval auto flight](image)

The results shown in Figure 2 & 3 are very encouraging (even with large error magnitudes used) and demonstrate the robustness of this orbit raising strategy to any possible errors. The 24 hour orbital period is closely maintained allowing daily opportunities to monitor the spacecraft.

**LONGITUDE CONTROL**

The constant orbital period (no longitudinal drift rate) that this orbit raising strategy maintains assumes no errors and no eclipse outage while continuously firing throughout the entire orbit. Figure 4 shows the evolving ground track of a satellite during the eccentricity reduction phase, indicating the wide longitude excursions early in the sequence (T=0.0) but also showing that the mean apogee radius longitude is centered around one longitude, in this case around 250°.
Fig 4. Longitudinal ground track during EP orbit raising phase with no errors.

The errors introduced to the state of the spacecraft (same as previous case) as well as assumed EP thruster eclipse outage will cause the orbital period to drift. In order to control and minimize the drift a "no burn gap" was added to the mission sequence. This gap, which can be near apogee or perigee can change the drift rate (induced drift rate) in both directions, i.e. westward or eastward. The size of the gap and its location depends on the desired drift to be compensated due to errors and eclipse outage. It was also determined that this "no burn gap" needs to occur only once every auto flight interval, presumably taking place on the first orbit after each spacecraft state adjustment. A Monte Carlo analysis showed a standard deviation of 2.5 deg from the target longitude, while all other orbital parameters have met their target (i.e. inclination & eccentricity), demonstrating the longitude control effectiveness. Fig 5 depicts the longitude control strategy with errors modeled, showing that the final longitude target of 250° was met. The small deviation in the error case is difficult to detect in this plot when comparing to Fig 4.
CONCLUSIONS

A new strategy that has been developed for low thrust orbit raising using high performance XIPS technology shows simple and robust operational features. The strategy is resilient to errors introduced to the spacecraft state while the attractiveness of daily viewing the spacecraft is retained. This strategy can not only produce very significant increase in launch efficiency but also has operational features which should lend themselves to cost-effective mission operations for multi-month transfer orbit missions.

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REFERENCES
