Boeing Low-Thrust Geosynchronous Transfer Mission Experience

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ABSTRACT

Since 2000, Boeing 702 satellites have used electric propulsion for transfer to geostationary orbits. The use of the 25cm Xenon Ion Propulsion System (25cm XIPS) results in more than a tenfold increase in specific impulse with the corresponding decrease in propellant mass needed to complete the mission when compared to chemical propulsion[1]. In addition to more favorable mass properties, with the use of XIPS, the 702 has been able to achieve orbit insertions with higher accuracy than it would have been possible with the use of chemical thrusters. This paper describes the experience attained by using the 702 XIPS ascent strategy to transfer satellite to geosynchronous orbits.

Keywords

XIPS, low-thrust, Boeing 702

1. INTRODUCTION

The Boeing 702 offers the option of XIPS orbit raising. Using XIPS to augment transfer orbit reduces the amount of propellant necessary to achieve the desired orbit, due to the high specific impulse (Isp) of the XIPS thrusters. Larger payloads can thus be accommodated, with greater flexibility in the choice and use of a launch vehicle. Chemical propellant is used to place the satellite into a 24-hour synchronous elliptical transfer orbit, and XIPS maneuvers are used to circularize the orbit and position the satellite in its final orbit.

2. XIPS ASCENT

2.1 Mission Design

For the 702 XIPS ascent phase, a "minimum time-of-flight" trajectory is targeted. Since there are many constraints that are difficult to implement quantitatively, the mission trajectory is optimized after the transfer orbit is somewhat manually constrained. XIPS ascent not only provides eccentricity reduction, but also is able to control the longitudinal drift rate, provide inclination reduction, and target other orbital parameters.

2.1.1 Mission Constraints

2.1.1.1 Chemical Initial/Final Orbit

The satellite is placed in an initial separation orbit by the launch vehicle. Depending on the launch vehicle provider, there may or may not be extensive input from Boeing to optimize the separation orbit. Thus, the chemical phase of the transfer orbit is designed to meet the final orbital targets, or as close as possible to those targets, but still meeting the constraints for XIPS ascent.

2.1.1.2 In-orbit testing/On-Station Longitude

The XIPS ascent transfer orbit needs to arrive at a geosynchronous orbit, and at the target longitude over the earth as requested by the customer. The transfer can be though of as roughly a rendezvous, since the satellite must arrive at a particular location (longitude) at the right time in the geosynchronous orbit.

2.1.1.3 Ground Station Availability/Ranging Geometry

To maintain orbit and attitude accuracy, it has been determined dual station ranging is needed. Normally, the stations used are the stations that will be used for on-station operations. Logistically, the stations are somewhat close together and close in longitude to the satellite. This lack of diverse geometry necessitates a longer duration of tracking data for high orbit accuracy. Additionally, the satellite must be in view from both ground stations the entire duration of XIPS ascent.

2.1.1.4 Other Constraints

Sun Angle – The satellite thrust vector must be close to normal to the line of apsides to avoid sun shining on the XIPS engines.

Eclipse – The satellite cannot operate when the sunlight is blocked by the Earth (in eclipse) in high power, and thus XIPS ascent maneuvers must not be performed during an eclipse.

Earth Acquisition – For satellites with earth sensors as a means of attitude knowledge, XIPS ascent must include coast phases periodically to turn and re-acquire the Earth to determine attitude. If this is not observed, the pointing error on the XIPS ascent maneuvers could be prevalent enough to miss orbital targets and thus unnecessarily increase the duration of XIPS ascent.

Communication Hinders – With many communication satellites, particularly with a nearby fleet of satellites of the same customer, communication hinder is a major concern. With C, Ku, and other bands, a satellite in transfer orbit can encounter a loss of telemetry or need to stand down from commanding due to interference with other satellites. This hinder coordination is paramount in avoiding interruption of service of other satellites, and can significantly affect the sequence of events during transfer orbit. If telemetry is not received for a significant duration of time, the orbit may not be able to be determined accurately, thus making it necessary to include a coast period after a lengthy maneuver to retain the orbit accuracy.

Close Approach – Once the satellite is moving through the geosynchronous belt, it is necessary to determine if the satellite in transfer orbit will enter close proximity with other satellites. The XIPS ascent phase must be designed as such to avoid any close approaches, and if so, coordinate with other satellite operators. Close approaches are generally avoided by the design of both phases of the transfer orbit.

2.1.2 Star Tracker Implications

With the advent of star trackers aboard the 702 spacecraft, several constraints are positively affected. Earth acquisitions are no longer necessary since the star trackers are able to accurately determine the attitude of the spacecraft during all phases of the mission. This saves the period slews back to the Earth, and coast periods to determine the attitude, and re-plan the remaining segments of XIPS ascent. The duration increase due to the earth acquisitions were over 4%. With the use of star trackers, there is no need for earth acquisition, and therefore eliminates this increase in XIPS ascent duration. Additionally, with the increase in accuracy of the attitude determination, pointing error is reduced and increase in XIPS ascent duration is avoided. In previous missions (not flying star trackers), analysis defined budgeting a 2.4% XIPS ascent duration increase due to attitude pointing errors during ascent. With the use of star trackers, this increase in duration to the XIPS ascent phase is an order of magnitude smaller, at approximately 0.2%.

2.1.3 XIPS Trajectory Design

In addition to satisfying the previously mentioned constraints which could vary from program to program, the trajectory for 702 XIPS ascent is designed to be a 24-hour synchronous orbit. In other words, the initial semi-major axis of the XIPS ascent phase is targeted to be approximately 42164 km. This is to satisfy the continuous ground visibility requirement during XIPS firings without the extra cost of additional ground stations. The size of the initial eccentricity of XIPS ascent is limited by the allowable mission duration, although the apogee altitude could be a concern when it is significantly above the geosynchronous orbit at large eccentricity. To minimize hinders and close approaches, the argument of perigee is kept within ±45° of the nodal crossing. However, when a satellite is joining an existing fleet of the same communication band, hinders can sometimes be lengthy in duration since the angular separation between the satellites (with respect to the ground station) can be small. Additionally, the thrust vector is inertially fixed during each burn segment. This is primarily due to the sun constraints [9], which may be violated if the thrust vector is allowed to vary greatly during the transfer. Although the thrust vector can change between maneuvers, each of which can be multiple revs around the Earth, the thrust vector usually does not vary more than a few degrees from the previous maneuver unless there have been significant errors incurred from previous orbit determinations or misperformance in the XIPS thrusters.

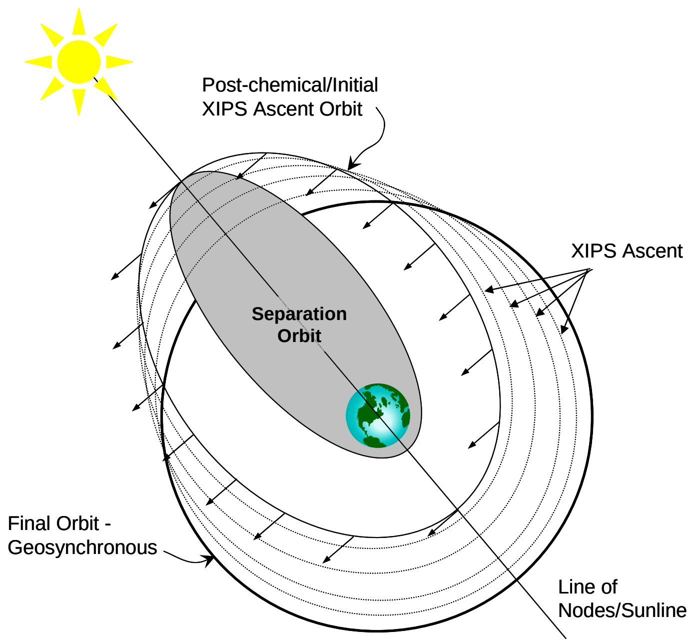


Figure 2-1: XIPS Ascent

2.2 Mission Operations

The XIPS maneuvers are planned using Boeing in-house software called XIPSTOP. This software is a non-linear root finding algorithm used to calculate the thrust vectors and burn times for the optimal two-burn transfer as an initial guess, and then computes an optimal multi-segment orbit transfer from the initial orbit to the final orbit[5]. XIPSTOP has the capability to optimize the mission in the presence of many mission constraints, but not all constraints involved.

2.2.1 Sensor Constraints

Before the use of star trackers, staring Earth sensors have been used to determine attitude. With the earth sensors, constraints on the Earth disk radius were enforced during specific coasts to ensure good earth chords, thus ensuring good attitude determinations. Another constraint enforced for an earth calibration has been the minimum and maximum sun-satellite-earth angle. Now that most Boeing 702 satellites are being equipped with star trackers, this constraint is no longer necessary to enforce.

2.2.2 Eclipse Constraint Options

Additionally, there is a capability to develop a mission in eclipse season, where the maneuver segments will coast through eclipses, to observe eclipse constraints. XIPSTOP will observe eclipse constraints by coasting during the eclipse, though the user must insert coast segments in order for XIPSTOP to perform the coast. Additionally, there are two different options for balancing the coast phases caused by the eclipse constraints. One method is to insert a coast phase 180 degrees opposite the eclipse coast. This will allow the XIPS ascent plan to remain relatively stable with a nearly-constant thrust direction, fixed inertially. However, removes valuable burn time from the ascent plan, and may lengthen the overall duration more than necessary. Another option for balancing this eclipse coast phase is to re-optimize the thrust vector for each maneuver, such that the burns still observe all the other constraints. This method, which requires a small reorientation between maneuvers, in some circumstances will result in a faster ascent plan than the balance coast method. This is due to the fact that the thrust vector is burning in a slightly off-nominal direction, but is burning continuously (with the exception of the eclipse coast). In general, during pre-mission analysis, both methods should be evaluated to determine which one is more optimal for overall XIPS ascent duration.

2.2.3 Orbit Determination and Maneuver Reconstruction

For recent Boeing 702 XIPS transfer missions, orbit determination has been accomplished primarily by a Kalman filter, verified by a weighted least-squares method. The data used to compute the real-time orbit is as follows: XIPS on-board telemetry (latch valve status, etc.), dual-station range and the XIPS maneuver segment plan. From the latch valve status, the Kalman filter can determine the status of the thrusters (on/off), and automatically reconstructs a maneuver immediately after it is determined the thrusters are off. From this reconstruction, a determination can be made as to the thrust and gimbal angles, based on the maneuver plan and the actual orbit determined. Two pieces of information are critical to the success of the real-time Kalman filter convergence. First, a good estimate of the initial orbit is essential in providing the Kalman filter the necessary start. Without a good apriori state, obtained from a pre-XIPS ascent orbit determination, the Kalman filter may likely diverge. Another vital component during XIPS transfer is the knowledge of the thruster performance of previous burns. With this XIPS thruster data known by the Kalman filter, there is less chance for the solution to diverge due to corrupt or outage of tracking and telemetry data. This additional information has improved the accuracy and stability of the Kalman filter solution through the XIPS ascent phase for several 702 missions.

2.3 Mission Performance

Below is a table summarizing recent missions using XIPS to perform the orbit transfer and station changes.

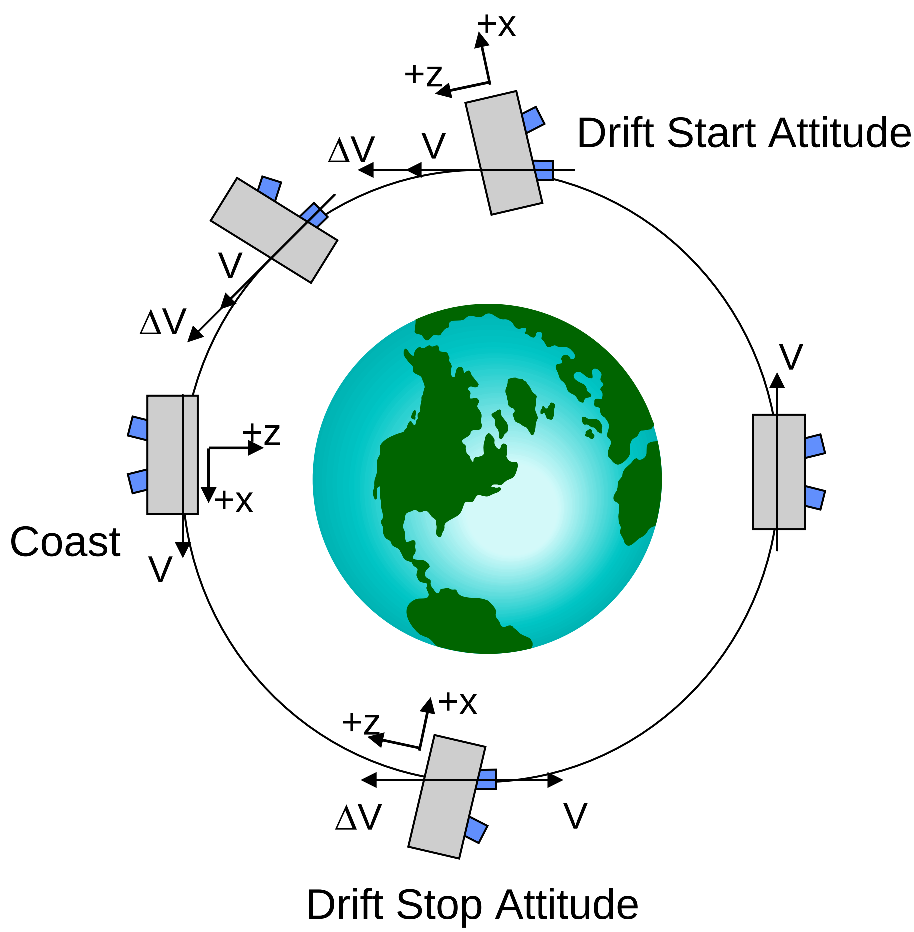
Program	Ascent Duration (Days)	Station Change	Comments
Program 1	29	21 degrees	XAM (XIPS Ascent Mission) Observed partial lunar eclipse, demonstrating capability for spacecraft to suspend and resume maneuvers
Program 2	33	11 degrees	XIPS recovery due to chemical burn abort No decrease in S/C life due to XIPS recovery
Program 3	40	12 degrees	XAM demonstrated capability to adjust to a nominal drift rate after chemical phase
Program 4	20	N/A	XAM eclipse constraints (planned burns through eclipse)
Program 5	22	N/A	XAM observed earth acquisition constraints
Program 6	36	19 degrees	XSC (XIPS Station Change) observe drift rate, eclipse, and collocation constraints
Program 7	21	7 degrees	XAM precise orbital insertion eliminated need for initialization, only 1 stationkeeping maneuver for 4 week period in-orbit testing XSC high and low power modes, observed eclipse and collocation constraints
Program 8	4 (burn-in only)	5 degrees	XAM observed XIPS thruster burn-in requirements, provided precise orbital insertion, eliminating the need for stationkeeping maneuvers through IOT
Program 9	74	N/A	XAM performed 30 day continuous burn, no eclipses, demonstrated use of star trackers on Boeing 702's
Program 10	61	N/A	XAM performed 27 day continuous burn, no eclipses, star trackers, precise orbital insertion eliminated need for stationkeeping maneuvers during PIOT
Program 11	4 (burn-in only)	4 degrees	XAM drift rate adjustment, completed orbit circularization XSC observed close proximity constraints, communications constraints with other fleet satellites

3. SPECIAL TOPICS

Though the main objective of the XIPS system is for stationkeeping and transfer orbit, XIPS has also been used in other situations successfully.

3.1 XIPS Station Change

In several situations, XIPS has been used to relocate the spacecraft from one geosynchronous longitude slot to another. With the flexibility of XIPS, a relocation maneuver sequence can be planned in either high power or low power, depending on the specifics of the relocation. XIPS Station changes have been executed successfully for at least 7 Boeing 702 missions, moving the satellite from as little as 0.5° to over 20° in longitude with high accuracy. The fundamental difference between the XIPS ascent transfer and the station change is the attitude pointing. With a station change, the thrust vector is closely aligned with the velocity or anti-velocity vector, whereas the XIPS ascent maneuvers are inertially fixed. It is important to note that the station change also has a targeted eccentricity, so that at the conclusion of the maneuver sequence, there is no net change in eccentricity. Below is an illustration of the typical station change.



3.1.1 Time Constraint

If a minimum duration transfer is required, then a XIPS high power station change can be used. The minimum time of flight transfer would be one in which the spacecraft spirals out from the circular orbit, coasts if necessary, and spirals back in for orbital insertion at the new desired location (specifically longitude). This method is approximated by a XIPS station change by a drift start maneuver, a touchup maneuver (usually waived), a drift stop maneuver, and a final touchup for orbital insertion. The XIPS high power station change has been executed successfully numerous times to provide the customer with a minimum downtime of service.

3.1.2 Power/Eclipse Constraint

In the event the satellite will experience an eclipse during the relocation maneuver sequence, two options can generally be implemented. If time of flight is of concern, the XIPS station change can be performed in high power mode, but it is necessary to coast during the eclipse to observe power constraints. Additionally, a XIPS station change can be executed in low power mode, and can continue to perform maneuvers during the eclipse periods. Depending on the specifics of the relocation, it may be more optimal to operate in high or low power when eclipses are present in the relocation sequence. For example, if the high power scenario requires an extended coast period to successfully relocate the satellite and observe the eclipse constraint, then it may be faster or more efficient to perform the relocation in low power mode and have the ability to perform the maneuvers during the eclipse.

3.1.3 Proximity Constraints

In many instances, the satellite is relocated to or from a longitudinal slot that is very close in proximity to other satellites. To ensure adequate safety in this situation, proximity estimates are performed before and during the XIPS station change sequence. If the satellite is estimated to encounter the proximity threshold, coordination with the operators of the other satellites is carried out to avoid collusion.

3.2 XIPS Recovery

In general, XIPS has been used primarily for orbit circularization, station changes, and stationkeeping. However, there have been circumstances that have provided Boeing the opportunity to exercise the flexibility of XIPS by using it to recover a mission from sub-nominal performance from other systems. In the event that other components of the transfer mission encounter problems, such as underperformance from the launch vehicle or chemical thrusters, XIPS can recover the mission with relatively minimal impact to the lifetime of the spacecraft. From historical experience, a lunar flyby mission was performed to achieve the desired geosynchronous orbit after the launch vehicle underperformed [6]. Had the spacecraft been equipped with the 702 XIPS thrusters, the mission may have been salvaged with greater remaining life, shorter duration, and much less complex mission operations (all which correlate to a more cost-effective and reduced-risk recovery mission).

4. CONCLUSIONS

From previous accounts, the XIPS system has been very reliable and repeatable. As of 2002, over 7000 successful hours of operation in stationkeeping mode had been accomplished [4]. Since then, at least six more Boeing 702 satellites have successfully utilized the XIPS system for *both* ascent and stationkeeping, some of those also using XIPS for station change as well. This bringing the total in-orbit operational hours accrued to over 35,000 hours, with 8000 of those hours being accrued in XIPS ascent, each with different mission plans and durations.

Using electronic propulsion has had a great increase beginning in the commercial satellite industry, but now also in the military and civil space applications [3]. In some instances, it has been evaluated that a faster transfer is worth the additional propellant spent to arrive at the desired orbit, touting other types of propulsion over XIPS [2]. However, in the case of non-perishable payloads being delivered to distant orbits, a low-thrust transfer has significant advantages. XIPS has been assessed for Interplanetary Missions with NASA by JPL [7, 10]. With low-thrust transfers to either Earth-Moon libration points or interplanetary destinations, XIPS existing technology offers the capability to achieve a safe and accurate mission with significant fuel or payload mass savings. Coupled with other techniques, such as variable specific impulse (or engine throttling), XIPS could prove to be an even more optimal option for scientific missions or payload delivery missions where orbital accuracy and fuel savings are important.

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