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Space Administration

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ABSTRACT

Solar Electric Propulsion (SEP) technology is already being used for geostationary satellite stationkeeping to increase payload mass.[1] By using this same technology to perform part of the orbit transfer additional increases in payload mass can be achieved. Advanced chemical and N_2H_4 arcjet systems are used to increase the payload mass by performing stationkeeping and part of the orbit transfer. Four mission options are analyzed which show the impact of either sharing the orbit transfer between chemical and SEP systems or having either complete the transfer alone. Results show that for an Atlas IIAS payload increases in net mass (geostationary satellite mass less wet propulsion system mass) of up to 100 kg can be achieved using advanced chemical for the transfer and advanced N_2H_4 arcjets for stationkeeping. An additional 100 kg can be added using advanced N_2H_4 arcjets for part of a 40 day orbit transfer.

INTRODUCTION

Solar Electric Propulsion (SEP) is already being used for stationkeeping of geostationary satellites, most notably AT&T's Telstar 4. The next step is to use these types of thrusters to contribute to placing the spacecraft into geostationary orbit. For a given launch vehicle the fuel mass savings can then be directly used to increase the payload (e.g., number of communication transponders). Even a small increase in mass (100 to 300 kg) might have large revenue earning impacts. This study evaluated the mass impact of replacing some portion of a geostationary spacecraft's chemical apogee propulsion system with an N_2H_4 arcjet system with the N_2H_4 arcjet system also performing fifteen years of stationkeeping. No attempt was made to optimize the mission in this work. All the inputs as well as the results can be found in the text or Table 1. Each section of the paper describes a different portion of the Table. This paper describes the mission analyses, propulsion options, and the results for four geostationary insertion options.

MISSION ANALYSIS, OPTIONS AND ASSUMPTIONS

Mission Analysis

The approach is to consider various sub-GTO orbits (including GTO) as starting points for the SEP raising and plane changing. It is assumed that the launch vehicle, in this case the Atlas IIAS, places the payload satellite (including the necessary on board propulsion to achieve geostationary orbit) into some elliptical transfer orbit. Elliptical transfer orbits which have their apogee at geostationary altitude (36,000 km) shown in Fig. 1 are called geostationary transfer orbits (GTO) and are regularly used today. The transfer ellipse apogee can also be lowered (termed here as sub-GTO) to increase the SEP starting mass.

Whether the initial orbit is GTO or sub-GTO, the orbit transfer can be 'split' between the on-board chemical and SEP systems. While the SEP system can complete the mission alone, the transfer time is around 100 days (see Results section) and significant portions of this time are spent in the Van Allen belts. Avoiding the dense parts of the Van Allen belts (below ~10,000 km) and large radiation doses, is of primary concern. Consequently, perigees are used which are above these portions of the radiation belts.

Mission Options and Assumptions

The top portion of Table 1. shows the various missions used in this paper. While by no means exhaustive, they illustrate the potential system performance. The initial orbit defines where the spacecraft starts after separation from the Atlas IIAS

Centaur.[2] The on-board chemical system then transfers the satellite to the intermediate orbit where the SEP system takes over and completes the geostationary orbit insertion. Geostationary orbit is assumed to be a 35786 km circular orbit at 0° inclination.

The first cases, denoted as *baseline, advanced baseline and advanced+ baseline*, show the mission scenario of the launch vehicle placing the satellite into GTO and the on-board chemical propulsion system raising the perigee to equal the apogee (circularization) and changing the plane to 0°. This scenario is commonly used today. *Advanced* and *advanced+* denote the use of 574s and 622s arcjets, respectively, as explained the the systems assumptions section. In addition, all cases except the *baseline* use advanced chemical thruster technology. The next two cases, called *advanced high elliptic* and *advanced+ high elliptic*, again use a GTO orbit but this time the on-board chemical propulsion system only raises the perigee to 11,000 km and the changes the plane to 9°. As shown in Table 2, this division of plane change was found to roughly maximize the delivered mass in GEO using the on-board chemical and arcjet systems. The SEP arcjet system then delivers the spacecraft to geostationary orbit.

The next cases, termed *arcjet to GEO* and *arcjet+ to GEO*, have a mission scenario where the SEP system performs the whole perigee raise and plane change. No on-board chemical maneuvers are required for these cases.

The final two cases use a sub-GTO orbit and are called *advanced high circular* and *advanced+ high circular*. The on-board chemical system circularizes the orbit at 15,000 km and changes the plane down to 9°. (This choice of a 9° intermediate plane is made based on the data of Table 2.) The SEP system then completes the transfer.

Fifteen years of stationkeeping are assumed for every spacecraft. While the yearly ΔV varies with satellite station longitude, 50 m/s is chosen as representative.[3] The additional cosine losses encountered by not completing the whole burn at the orbit node (impulsive burn) are small and neglected.

The mission ΔVs (velocity or energy change required for orbit transfer) for the on-board chemical system are assumed to be impulsive. The transfer mission ΔVs for the SEP system differ from impulsive due to constant thrusting[4] and are obtained using the SECKSPOT[5] numerical optimization program along with various analytical spreadsheets. For the SEP portion of the mission the effects of shading, power degradation, and oblateness are considered. The SECKSPOT program determines optimal steering for a minimum time trajectory. The impacts of non-optimal steering and guidance, navigation, and attitude control limitations, while typically minor, are not considered here.

SYSTEM ASSUMPTIONS AND MODELING

Station Keeping and Final Orbit Delivery Propulsion

For this paper only state-of-art and advanced N_2H_4 arcjets[6] are considered for the SEP system. Fifteen years of north/south spacecraft stationkeeping is performed by four thrusters, one pair placed on the north face and the other on the south face (see Fig. 1). These thruster pairs are canted 17° from the vertical the minimize plume interaction with the array. To perform the north/south stationkeeping either the south or north pair is fired about the appropriate orbit node on the order of minutes. Four thruster I_{sp}s are assumed: 478s (state-of-art), 574s (advanced), and 622s (advanced+), all of which have been adjusted for the 17° thruster cant cosine loss. The input powers for the power processing units (PPUs) are 1.8 kW (state of the art) and 2.39 kW (advanced). Four PPUs support the four NSSK thrusters.

Four additional N_2H_4 arcjets are added for performing the perigee raise and plane change mission. These thrusters are assumed identical to the NSSK thrusters except they are placed about the chemical thruster on the aft portion of the spacecraft (see Fig.1). These thrusters share the NSSK PPUs. The input power for these thrusters is 2.39 kW and the I_{sp}s are either 574 s or 622 s. The combined arcjet and PPU efficiency is 32%. During perigee raising and plane changing four N_2H_4 arcjets are firing. Each thruster unit includes structure and controller and weighs 1.86 kg. Each PPU unit includes cabling and thermal system and weighs 6.08 kg. N_2H_4 arcjet thruster life is 1000 hours (41 days).

Chemical On-Board Propulsion

The assumed system is a state-of-art 314.5 s bipropellant system[7] for the *baseline* and an advanced 328 s bipropellant system[7] for the other cases in Table 1. Both systems have a dry mass of 23 kg and a tankage fraction of 0.08. This chemical system is deleted from the spacecraft for those missions where the arcjets complete the perigee raise and plane change entirely.

Power System

The GaAs solar arrays which provide payload power in geostationary orbit are assumed to provide the 9.56 kWs for four thruster operation during the SEP orbit transfer since the payload is inactive during this phase. The battery system is assumed to be capable of providing the 3.6 or 4.78 kW for two NSSK thruster operation while the payload uses direct solar array power as suggested by Free.[8] The arrays are assumed to be shielded with 12 mils front and 12 mils back.

RESULTS

The figure of merit of the advanced propulsion systems in this study is net mass delivered. Net mass refers to the useable satellite mass once the wet propulsion system is removed. The added net mass can be used for additional equipment including communication transponders, thus providing additional channels and increased revenue. Table 1 presents the results numerically while Figures 3 and 4 graph the net masses and EP trip times.

Table 1. contains the results of this analysis. Note the *baseline* mission where the orbit transfer is completed solely by the on-board chemical system and the stationkeeping performed by the arcjet system.

The next two cases, *advanced baseline* and *advanced+ baseline*, show the impact of upgrading the propulsion systems while preserving the baseline mission scenario. Up to 100 kg of additional payload is achievable for a state of the art mission.

The remaining cases show the impact of using different mission scenarios as discussed in the mission options section. The *high elliptic* cases split the transfer mission between the chemical and arcjet systems using a high elliptical orbit which avoids most of the radiation belts. For an approximate 40 day trip time, 70 to 100 kg additional payload is delivered compared to equivalent technology using the normal mission scenario. The cost of this 40 day transfer is not considered here.

The *arcjet GTO to GEO* and *arcjet+ GTO to GEO* cases show a mission scenario where the arcjet system transfers the spacecraft without a chemical on-board propulsion system. While this technique can add over 100 kg over the normal mission scenario, the trip time approaches four months and there is additional time spent in the radiation belts.

The last two *high circular* cases show missions using a high circular orbit which again avoids the worst portions of the radiation belts and completes the transfer in just over 40 days. Unfortunately, no additional net mass is provided, since the additional starting mass is more than overcome by the higher chemical and EP ΔVs.

With a mission life of 41 days of constant thrusting, only the arcjet GTO to GEO cases would require extra thrusters. While this additional mass is neglected in Table 1, the impact would only be four extra thrusters (not PPUs) and would be less than 10 kg total.

The degradation to the arrays is estimated to be around 3% for the high elliptic and high circular mission scenarios, and 15 % for the arcjet GTO to GEO transfer. No radiation dose calculation on the payload has been made. While not considered in Table 1, some part of this loss of array power might be charged to the propulsion system. This loss in net mass fraction should be less than 20 kg for the 3% degradation cases.

CONCLUSIONS

Additional net mass can be delivered to geostationary orbit to increase the payload mass and communication satellite revenues by using advanced on-board chemical and electrical propulsion. Up to 100 kg additional net mass is achievable with advanced chemical propulsion for orbit transfer and advanced arcjets for NSSK. To achieve 200 kg net gain, a portion of the transfer must be completed by the higher performing arcjet system using available payload power. While transfers performed by arcjets alone provide even more payload, the transfer time is tripled and much more radiation is encountered.

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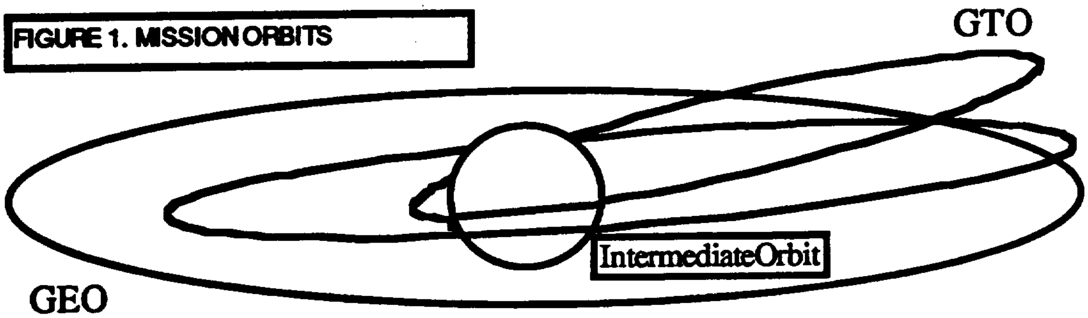
Table 1. Mission Options and Results	Baseline	Advanced Baseline	Advanced+ Baseline	Advanced High Elliptic	Advanced+ High Elliptic	Arcjet GTO to GEO	Arcjet+ GTO to GEO	Advanced High Circular	Advanced+ High Circular
Initial orbit (Atlas IIAS delivery orbit)	GTO: 167 x 35786 km@ 27°	GTO: 167 x 35786 km@ 27°	GTO: 167 x 35786 km@ 27°	GTO: 167 x 35786 km@ 27°	GTO: 167 x 35786 km@ 27°	GTO: 167 x 35786 km@ 27°	GTO: 167 x 35786 km@ 27°	Sub GTO: 167 x 15000 km@ 27°	Sub GTO: 167 x 15000 km@ 27°
Intermediate orbit	none	none	none	High Elliptic: 11000 x 35786km 9°	High Elliptic: 11000 x 35786km 9°	none	none	High Circular: 15000km 9°	High Circular: 15000 km 9°
Final Orbit	GEO	GEO	GEO	GEO	GEO	GEO	GEO	GEO	GEO
Propulsion Systems									
Chem Transfer System (Initial to Intermediate orbit)	Biprop	Adv Biprop	Adv Biprop	Adv Biprop	Adv Biprop	none	none	Adv Biprop	Adv Biprop
Mission ΔV	1806 m/s	1806 m/s	1806 m/s	968 m/s	968 m/s	0 m/s	0 m/s	1762 m/s	1762 m/s
Isp	315 s	328 s	328 s	328 s	328 s	-	-	328 s	328 s
Fuel Mass	1588 kg	1539 kg	1539 kg	931 kg	931 kg	-	-	1965 kg	1965 kg
System Wet mass	1738 kg	1685 kg	1685 kg	1029 kg	1029 kg	0 kg	0 kg	2145 kg	2145 kg
EP Transfer System (Intermediate to Final orbit)	None	None	None	N2H4 AJ Adv.	N2H4 AJ Adv.+	N2H4 AJ Adv.	N2H4 AJ Adv.+	N2H4 AJ Adv.	N2H4 AJ Adv.+
Mission ΔV	0 m/s	0 m/s	0 m/s	1369 m/s	1369 m/s	3074 m/s	3070 m/s	1491 m/s	1492 m/s
EP Transfer Time	0 days	0 days	0 days	38 days	42 days	108 days	119 days	42 days	46 days
Isp	-	-	-	600 s	650 s	600 s	650 s	600 s	650 s
Fuel Mass	-	-	-	550 kg	512 kg	1458 kg	1369 kg	603 kg	562 kg
System Wet mass	-	-	-	596 kg	556 kg	1567 kg	1473 kg	653 kg	609 kg
NSSK EP SYSTEM	N2H4 AJ SOA	N2H4 AJ Adv.	N2H4 AJ Adv.+	N2H4 AJ Adv.	N2H4 AJ Adv.+	N2H4 AJ Adv.	N2H4 AJ Adv.+	N2H4 AJ Adv.	N2H4 AJ Adv.+
NSSK ΔV for 15 years	750 m/s	750 m/s	750 m/s	750 m/s	750 m/s	750 m/s	750 m/s	750 m/s	750 m/s
NSSK Isp (@ 17° cant)	478 s	574 s	622 s	574 s	622 s	574 s	622 s	574 s	622 s
EP PPU Input PWR	1.80 kWe	2.39 kWe	2.39 kWe	2.39 kWe	2.39 kWe	2.39 kWe	2.39 kWe	2.39 kWe	2.39 kWe
EP Fuel Mass	295 kg	255 kg	236 kg	262 kg	248 kg	265 kg	256 kg	261 kg	247 kg
EP system Wet mass	367 kg	338 kg	319 kg	346 kg	330 kg	349 kg	340 kg	345 kg	330 kg
Resulting Masses									
Mass in Initial Orbit	3583 kg	3583 kg	3583 kg	3583 kg	3583 kg	3583 kg	3583 kg	4660 kg	4660 kg
Mass in Intermediate Orbit	1996 kg	2044 kg	2044 kg	2653 kg	2653 kg	3583 kg	3583 kg	2695 kg	2695 kg
BOL Mass@ GEO	1996 kg	2044 kg	2044 kg	2102 kg	2140 kg	2126 kg	2214 kg	2092 kg	2133 kg
EOL Mass @ GEO	1701 kg	1789 kg	1808 kg	1840 kg	1893 kg	1861 kg	1958 kg	1831 kg	1886 kg
Combined NSSK & Transfer Propulsion Systems Wet Mass	2105 kg	2024 kg	2004 kg	1971 kg	1915 kg	1917 kg	1812 kg	3143 kg	3084 kg
Final Net Mass	1479 kg	1560 kg	1579 kg	1612 kg	1669 kg	1667 kg	1771 kg	1517 kg	1576 kg
Added Net Mass over Baseline	0 kg	+81 kg	+100 kg	+133 kg	+190 kg	+188 kg	+292 kg	+38 kg	+97 kg

FIGURE 1. MISSION ORBITS



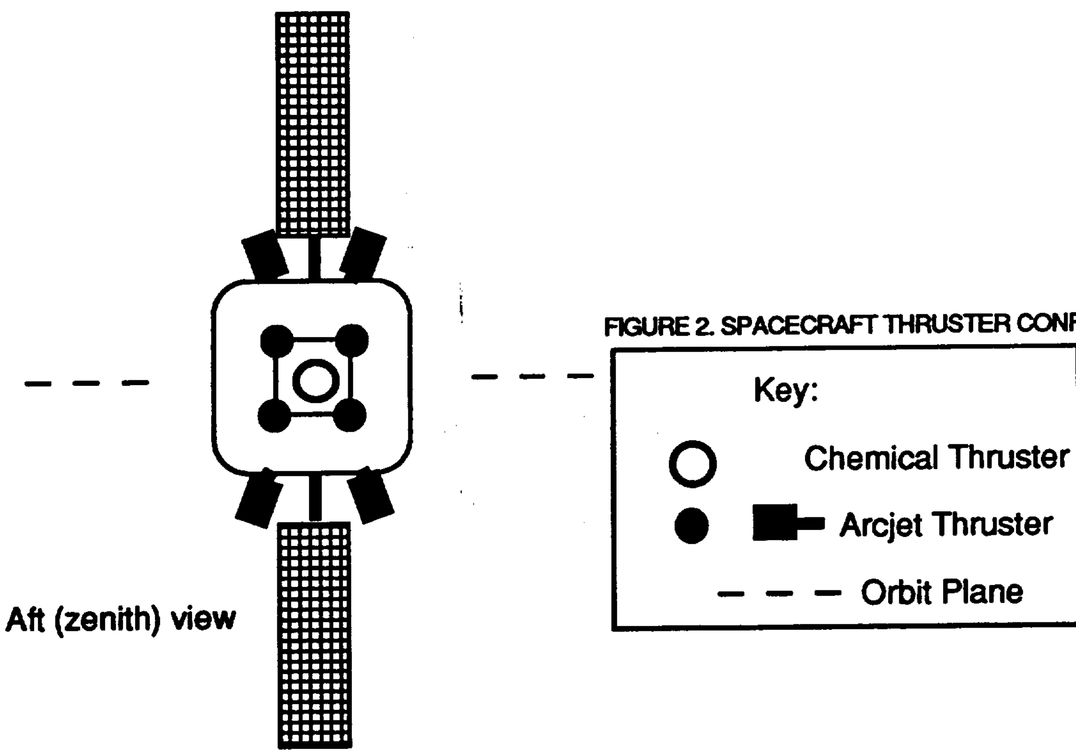


FIGURE 2. SPACECRAFT THRUSTER CONFIGURATION

TABLE 2. MISSION PLANE CHANGES

Intermediate Inclination	Initial Mass in Intermediate Orbit	Delivered Mass in GEO with 600 s AJ	Trip Time
27°	2751 kg	1789 kg	68 d
21°	2725 kg	1913 kg	57 d
12°	2608 kg	2020 kg	41 d
9°	2554 kg	2025 kg	37 d
6°	2497 kg	2011 kg	34 d
0°	2374 kg	1940 kg	30 d

Figure 3. Net Mass Delivered (EOL Mass in GEO less Propulsion System) vs Mission / Propulsion Options

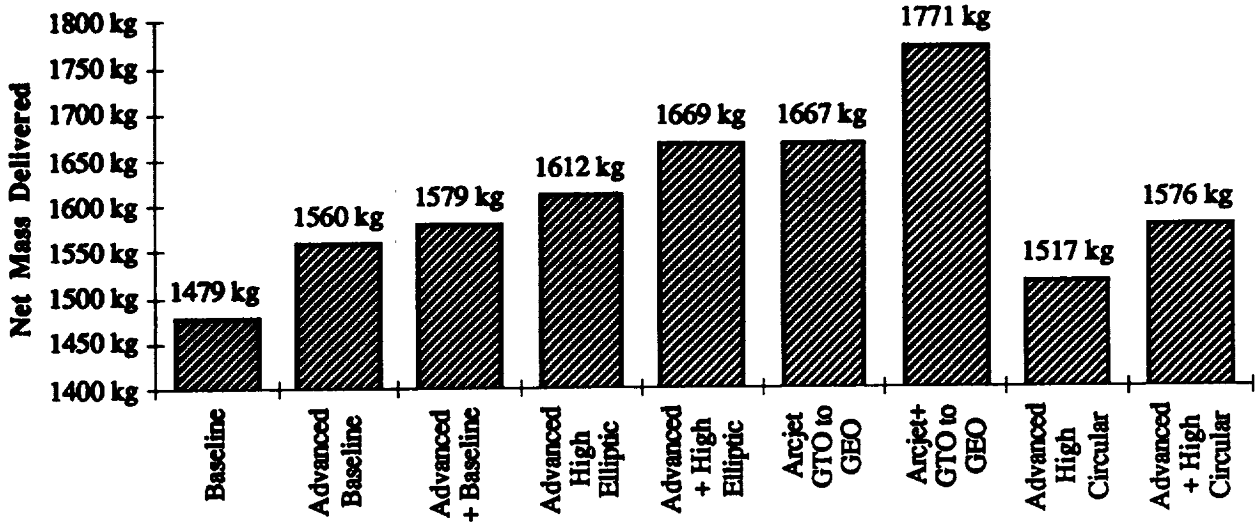
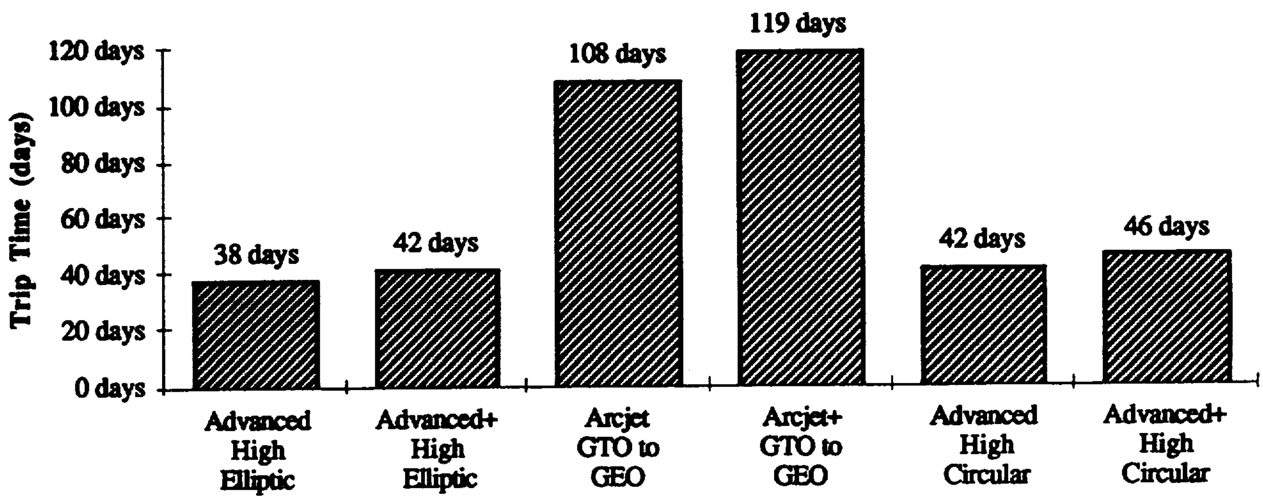


Figure 4. EP Transfer Trip Time vs Mission / Propulsion Option



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