In-space Propulsion Influences on COMSAT Missions

IEPC-2007-027

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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The use of electric propulsion was evaluated for transfer of communication satellites from Geosynchronous Transfer Orbits to Geosynchronous Earth Orbits. Recent communication satellite designs, normal launch vehicle delivery orbits, and integrated electric propulsion subsystems (with input powers less than nominal satellites powers) were assumed to minimize required changes to present and near-term launchers and spacecraft. The "capture fraction" of recent communication satellites that could have been delivered was evaluated versus launcher delivery capability, launch site, and in-space propulsion characteristics. Electric propulsion greatly increased the capture fraction for small to mid-sized launchers. Insertion times at given launch sites were found accurately specified by the satellite power to mass ratios and the assumed electric propulsion specific impulse/efficiency characteristics. Insertion times less than 100 days were found for satellites with high power to mass ratios that used high thrust to power electric propulsion options. These results indicate that, where insertion times are acceptable, electric propulsion may provide major, near-term cost reductions for communication satellite missions. The influence of power for electric propulsion beyond that of satellite payloads and housekeeping was also assessed and insertion times less than a month will require powers significantly higher than presently installed.

Nomenclature

F_P = fraction of COMSAT BOL power added for quasi-stage
g = acceleration due to gravity, m/sec^2
I_{SP} = apogee engine specific impulse, sec
M_{BOL1} = initial estimate of COMSAT GEO BOL mass, kg
M_{BOLI} = adjusted COMSAT BOL mass with integrated EP, kg
M_{BOLQ} = adjusted COMSAT BOL mass with Quasi-stage EP, kg
M_{GTO} = calculated COMSAT GTO mass, kg
M_{GTO1} = cited COMSAT mass in GTO (from UCS data base), kg
M_O = BOL COMSAT mass, kg
P_D = reference Hall Effect Thruster discharge power, 4.5 kW
Pdiss = power dissipated from power processor, kW
P_{HET} = power into the HET subsystem, kW
P_O = BOL COMSAT power, kW

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α_{HET} = Hall Effect Thruster subsystem specific mass, 7.2 kg/kW
α_{PV} = solar array specific mass, 20 kg/kW
ΔM_{EPI} = mass penalty for integrated EP subsystems, kg
ΔM_{EPQ} = additional COMSAT BOL mass penalty for quasi-stage EP, kg
ΔV = launch-site-specific delta V from GTO to GEO, m/sec
η_C = reference Hall Effect Thruster magnet & cable efficiency, ~ 0.98
η_{PPU} = reference Hall Effect Thruster power processor efficiency, ~ 0.93

I. Introduction

A conjunction of developments has greatly increased the practicality and expectations for use of Electric Propulsion (EP) for energetic, Earth-orbit transportation functions with mission "delta Vs" equal to or greater than those for transfer from Geosynchronous Transfer Orbits (GTOs) to Geosynchronous Earth Orbits (GEOs). Key among these advancements are trends of beginning-of-life (BOL), GEO commercial communication satellite (COMSAT) power to mass ratios and masses, an increasingly competitive situation for COMSAT launchers, major advancements in space power technology, and the broad and increasing use of EP.

Figure 1 shows average, BOL communication satellite (COMSAT) on-orbit power to mass ratios and masses as a function of the year of launch. COMSATs considered herein were those in the Union of Concerned Scientists (USC) database[1] which met the conditions described later in section II-A and included nearly all recent COMSATs. Figure 1 shows that the average power to mass ratio of COMSATs has increased dramatically over the last two decades and the average mass has also risen strongly. As seen later, the transportation times with EP are directly reduced by higher power to mass ratios and the decreasing times implied by Fig. 1 are critical, positive factors regarding the use of EP for high-energy transfers of COMSATs to GEO. The increased masses with time also increase the leverage of EP, which grows with increasing mission energy.

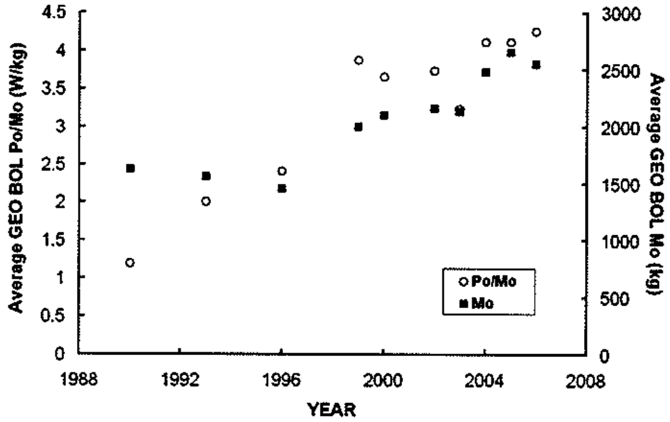

Figure 1. COMSAT Average P_0M_0 and M_0 Trends.

The relatively sustained and significant COMSAT market has contributed to an extremely competitive situation for launch vehicles. Figure 2 shows COMSATs launched from four sites in the last six years. Other COMSAT launch sites, such as in China, India, and the Pacific region, are becoming used and should be included in future analyses of the types presented herein. Also, multiple new launcher options are under development which may soon be available for COMSAT launches. In-space propulsion can dramatically affect the fraction of the COMSAT market captured by specific launcher/launch site options and is, therefore, a key competitiveness consideration for specific COMSAT missions. The competitive condition is, similar to the case for initial acceptance of EP for station keeping, favorable for acceptance of EP for high-energy, GEO insertions.

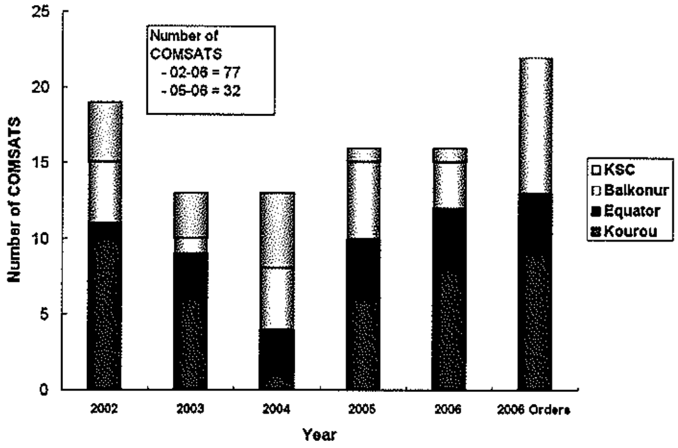

Figure 2. COMSAT Launched by Year and Launch Site.

Spacecraft power has always had a predominant influence on the performance and acceptance of EP. This is especially so for primary propulsion functions due to the increased leverage of power system characteristics on the overall mission cost and performance. There have been rapid and significant improvements in all space power characteristics relevant to primary propulsion with

EP.[2-4] In particular, and likely benefiting from very large terrestrial photovoltaic programs and competitions between different space solar array concepts, major advancements have occurred for space solar array specific costs and masses, environmental (including both radiation and plasma) robustness, packing density in launch fairings, and cell/array efficiencies. A review of space solar array characteristics is beyond the scope of this paper. However, the dramatic advancements in space solar arrays, such as that shown in Fig. 3 for solar cell efficiency increases with time, have materially improved the potential performance and enhanced the expectations for use of high-power electric propulsion.

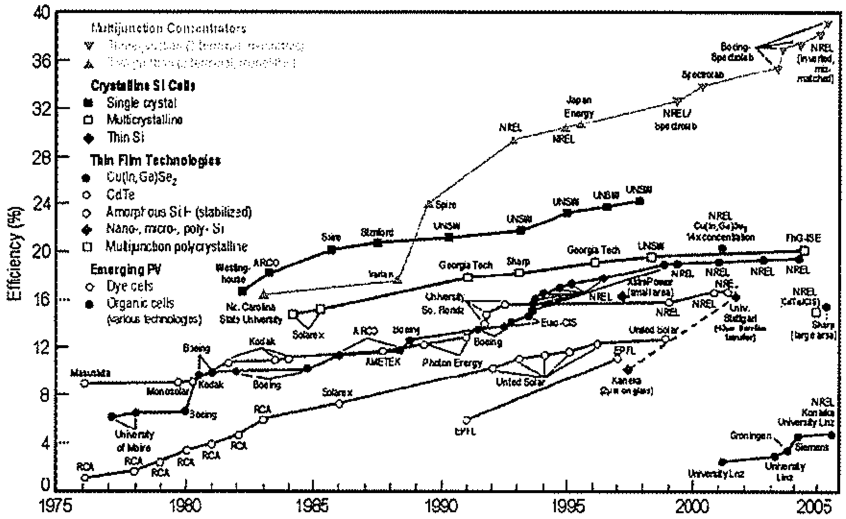

Figure 3. Solar Cell Efficiencies versus Time.[2]

As shown in Fig. 4, EP has been broadly accepted for operational applications for multiple propulsion functions. EP is now routinely used for stationkeeping on spacecraft produced by an international set of satellites suppliers. In some cases EP is also used for final GEO insertion (the so-called "apogee topping" maneuver). Planetary missions have also been successfully performed by several countries and additional planetary missions using EP are firmly planned. The Earth-orbit Transfer function on Fig. 4 is defined as missions with delta Vs provided by EP about equal to or greater than GTO to GEO transfers and is the application most relevant to the missions discussed herein. The SMART-1 mission used EP for transfer of a scientific satellite from an Ariane 5 GTO to the Moon.[5,6] This was the first planned use of EP for high-energy, Earth-orbit transportation and it very successfully demonstrated the functions required for low-thrust transfers and, importantly, the robustness of standard spacecraft designs for Earth-orbit environments, including effects of an extraordinary solar storm.[7] The Advanced Extremely High Frequency (AEHF) satellites will soon use EP for high-energy transfers to GEO. These applications are notable in that they will use EP transfers of over 100 days for Earth-orbit transportation of very high-value assets.[8]

The developments cited above provide strong bases for selection of EP for Earth-orbit transportation of COMSATs to GEO. This use of EP, with and without a separate chemical propulsion subsystem for part of the transfer, has been extensively studied. Many evaluations, particularly the earlier examples, assumed Low Earth Orbit (LEO) starting orbits, often with EP powers much higher than typical of present COMSATs.[9-12] GTO and other initial orbits have also been assumed in many recent analyses.[13-16] In general, the prior studies evaluated the effects of EP on the GEO payload with specified masses in the orbits where EP operation was initiated. The analyses herein adopt alternate approaches to maximize relevance to near-term acceptance and use of EP for high-energy, Earth-orbit transfers. The GEO payloads are the COMSATs from the UCS data base[1] with BOL powers and masses obtained as discussed in detail below. Also, "integrated" EP subsystems are assumed with input power levels of 0.95 of the BOL

Prime / Propulsion Functions	Alcatel - Alenia	Astrium	Boeing	ISAS	Lockheed	Loral	Mitsubishi	Orbital	Russian	Spectrum Astro	Swedish Space Corporation
Stationkeeping & Orbit Insertion	X	X	X		X	X	X	X	X		
Planetary ΔV				X				X		X	X
Earth - Orbit Transfer					X						X

Figure 4. EP Application on Operational Spacecraft.

COMSAT powers. Use of recent COMSAT designs and integrated EP should minimize impacts on present spacecraft designs. Launcher GTO delivery capabilities necessary to deliver the specific COMSATs were then calculated for different launch sites as a function of the characteristics of the chemical and electric in-space propulsion subsystems. It was then possible to evaluate the COMSAT market capture of launchers as a function of their GTO delivery capability and launch site. Knowledge of the capture capability and the associated delivery times may then be useful to providers of COMSAT services, launchers, and spacecraft.

II. Analyses

The overall goals of the analyses were to quantify the COMSAT market capture potential of launchers, and the associated trip times from GTO to GEO, as a function of GTO delivery capability, launch site, and chemical and electric transfer propulsion characteristics. Figure 5 shows the overall approach which will be briefly described below.

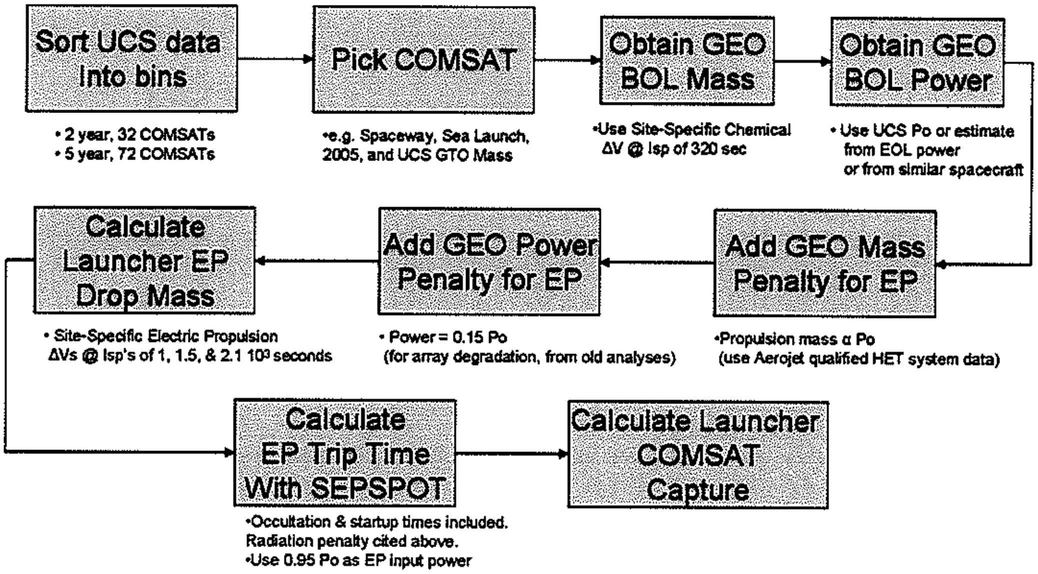

Figure 5. COMSAT Mission Capture and Insertion Time Calculation Flow.

A. COMSAT Data Set

The UCS web-site spacecraft data sets[1] were the primary sources of COMSAT information. In all cases, data were checked against other, public, web-based sources which resulted in a small number of modifications of the UCS data bases. The UCS data set includes only active spacecraft so that the number of spacecraft cited as launched in a given year decreases with time. The masses delivered to GTO were always provided and in many cases the BOL or end-of-life (EOL) power was also given. When power data were not available, estimates were made as discussed below. On the basis of available data, COMSATs were limited to those launched from Baikonur, the Equator, Kourou, or the Kennedy Space Center (KSC); provided by Western primes; planned solely for civil communications; and operated in GEO. These constraints eliminated a very small number of COMSATS launched from other sites, in non-GEO orbits, or used for non-civil sector functions. However, most COMSATs were included and the number recently launched per year is shown in Fig. 2. As seen in Fig. 1, critical COMSAT characteristics vary with time. UCS data from 1990 to 2006 were used to generate Fig. 1 However, as a compromise between sample size and relevance to present COMSAT designs, the set of 32 COMSATs launched in 2005 and 2006 was used for all other analyses presented herein. It is important to note that all calculations shown used the characteristics of the individual COMSATs as a starting point. This approach was taken to maximize the relevance of the results to near-term COMSAT designs. While EP transfers can provide non-incremental increases in GEO masses, exploitation of those benefits may require significant changes to present COMSAT concepts.

B. Integrated Electric Propulsion

COMSATs were launched from four sites and, to be relevant to decision makers, it was necessary to normalize the information to allow estimates of the market capture and trip times for specific launcher GTO delivery capabilities and launch sites. The following describes the approach used to obtain those data for the integrated EP options. The approach for evaluation of a "quasi-stage" EP approach will then be discussed.

The initial COMSAT mass in GEO was the payload of interest; but was almost never available and an initial estimate for a selected COMSAT BOL mass was obtained using the equation:

$$M_{BOLI} = [\mathrm{Exp}\ -(\Delta V/gI_{SP})]\ M_{GTOI} \qquad (1)$$

The delta V in Eq. (1) is that associated with both the actual launch site and a chemical propulsion apogee system. The delta Vs used herein are in Table 1 and were taken from data cited for specific missions and reflects the nominal values required after the various launchers dropped the COMSATs into the associated GTOs. It is recognized that in practice different GTOs are employed from given launch sites and, in a few cases, EP has been used for "apogee topping". However, details of GTOs and such EP applications are rarely available for specific launches and typical, single values of delta Vs are therefore used for the calculations of market capture. For the reference cases, chemical "apogee" propulsion was assumed with an I_{SP} of 320 seconds. Of course, different chemical apogee engines with slightly different Isps were used on different COMSATs. However, details of chemical apogee propulsion are seldom provided for specific launches and the global mission impact due to use of different, state-of-art, chemical apogee systems is very small.

Table 1. Delta Vs for GTO-GEO transfers

Launch Site	Inclination (Degrees)	GTO – GEO ΔV (m/s) Chemical	GTO – GEO ΔV (m/s) Electric
Baikonur	~46	1837	2647
Equator	0	1478	2187
Kourou	7	1502	2215
KSC	28.5	1831	2641

The BOL COMSAT power was a key parameter for the analyses. The USC data base or web data often provided spacecraft BOL or EOL power levels. In all cases where only the EOL power was given, the BOL power was estimated by increasing the EOL power by 15% to account for degradation during the GEO mission. The degradation is, of course, a function of the solar cell technology and GEO lifetime and a 15% degradation was used as representative of the different, recent GEO spacecraft situations. Where no power data were available, the BOL power was estimated using available data from similar spacecraft from the same manufacturer. The input power to the integrated EP system was then assumed to be 0.95 of the BOL COMSAT power. This approach constrained the EP power level to less than that installed for GEO COMSAT operations and also accounted for housekeeping power to the COMSAT during the transfer to GEO.

It was then necessary to adjust the initial COMSAT BOL mass to account for propulsion and power penalties associated with use of integrated EP. The propulsion subsystem penalty was taken to be the BOL power times a representative specific mass of a Hall Effect Thruster (HET) subsystem. A HET approach was chosen to maximize the thrust to power ratio options available in order to minimize EP transfer times. The qualified, Aerojet BPT-4000 subsystem[17], with additions for gimbals and structure, was used to calculate a reference HET subsystem specific mass and Table 2 provides the values used. For the integrated EP subsystems it was assumed that all the electric propulsion elements except the power processor radiate directly to space and so do not impose a thermal control penalty. The power processor was assumed to use the COMSAT thermal control system and involve no additional penalties, beyond a fraction of the 0.2 structure allocation, as the rejected heat that requires a radiator is of the order of 0.05 that of the operational COMSAT. The thruster specific impulse and associated efficiencies were obtained from an on-going United States Air Force program being conducted by Aerojet. Specific impulse values of 1000, 1500, and 2100 seconds were selected for analyses as they covered the range of available data and provided evaluation of different thrust to power options.

Table 2. Reference 5 kW HET System Masses.

System Element	Mass (kg)	Comments
Thruster	12.3	Includes cable and brackets (Ref. 17)
Power Processor (PPU)	12.75	(Ref. 17)
Propellant Management	0.5	(Ref. 17)
Gimbal	4.1	Estimated @ 33% of thruster
Structure	5.93	Estimated @ 20% of subsystem
Total HET subsystem	35.6	

An arbitrary 15% solar array mass penalty, at an assumed specific mass of 20 kg/kW, was also added to account for degradation of the array during the transfer with EP. This penalty is conservative, especially due to the advances in solar array environmental robustness and assumption of GTO start orbits where the total time spent in the Van Allen belts during EP transfers to GEO has been calculated to be less than one day.[13] For reference, the degradation of the SMART-1 solar arrays due to Van Allen Belt effects[6] was about 0.08 and lower degradations are anticipated with next-generation solar arrays.

The integrated EP mass penalty added to the COMSAT BOL mass then was obtained via use of Eqs. (2-5):

The total power of the reference HET subsystem was:

$$P_{HET} \approx (P_D)/(\eta_{PPU}\eta_C) \approx 5\text{kW} \quad (2)$$

The specific mass of the reference HET subsystems was then:

$$\alpha_{HET} \sim 7.2 \text{ kg/kW} \quad (3)$$

The specific mass of array power was assumed to be:

$$\alpha_{PV} \sim 20 \text{ kg/kW} \quad (4)$$

As a penalty of 15% of the initial power, P_O, was assumed, the overall penalty added to the BOL dry mass of the COMSAT for integrated EP was:

$$\Delta M_{EPI} \approx [3 + 7.2]\, P_O \quad (5)$$

The total power of the COMSAT was used to calculate the EP mass penalty and the slight overestimate of EP mass due to the assignment of 0.05 P_O to housekeeping functions was ignored.

The final GEO BOL mass was then calculated as:

$$M_{BOLI} \approx \Delta M_{EPI} + M_{BOL1} \quad (6)$$

It is noted that no penalty was taken for the xenon propellant tank of the EP subsystem. This was assumed as the approach used did not take a credit for elimination of the dry mass of the chemical apogee subsystem that was part of the initial mass delivered to GTO. It was assumed that in first order, the dry masses of the propellant tanks of the chemical and EP subsystems would be equal. This was approximately the case for the lowest EP Isps evaluated due to the roughly compensating effects of the differences in propellant masses and ratios of tank to propellant masses for present chemical and electric propulsion subsystems. For the highest EP Isps considered, however, the xenon tanks would be considerably lighter than those of the chemical apogee subsystems. The other dry masses of the chemical apogee system, such as the thrusters, pressurant tanks, propellant and pressurant lines and control components, associated thermal management, and etc, were not considered. In an actual application, the chemical apogee subsystem would likely be eliminated for both cost and performance reasons. Therefore, not assuming a credit for the chemical apogee subsystem dry mass is conservative with respect to the performance EP transfers.

After the GEO BOL mass is estimated the associated GTO mass may be calculated for a given launch site (with an associated GTO-GEO delta V) and transfer propulsion specific impulse:

$$M_{GTO} \approx \mathrm{Exp}\ (\Delta V/gI_{SP})]\ M_{BOLI} \tag{7}$$

Herein, GTO masses were calculated only for the Kourou and Kennedy Space Center launch sites. These sites were selected to illuminate the effects of launch site inclination. The delta Vs were taken from Table 1 for the appropriate launch sites and propulsion approaches. The GTO mass in Eq. (7) is that required of a launcher to deliver the selected COMSATs to GEO from the launch-specific GTO with a transfer subsystem of the specified Isp.

In the case of an assumed chemical apogee transfer approach, no changes were assumed to the spacecraft and the GTO masses were varied only to be consistent with the different delta Vs for chemical propulsion shown on Table 1.

The GTO masses required for each of the 32 COMSATs launched in 2005-2006 were calculated for Kourou and KSC launches. The mission capture of the 32 COMSATs launched in 2005-2006 may now be calculated as a function of launcher GTO delivery mass capability and transfer propulsion characteristics.

The transfer times with EP were calculated using the SEPSPOT[18] code. SEPSPOT is a time optimal trajectory tool for geocentric attitude constrained analyses. In initial analyses, occultation and EP startup times were included. The startup penalty was imbedded in the SEPSPOT code and was representative of engine conditioning times when condensable mercury propellant was used with ion thrusters. The startup times are, therefore, longer than appropriate for inert gas propellants but were used for convenience. Transfer times were first calculated for situations that represented extremes of COMSAT and EP subsystem characteristics. It was found that occultation and startup times increased transfer times, relative to times calculated without those penalties, by a maximum of 7 percent. To expedite analyses, therefore, most trip times presented were obtained via SEPSTOP analyses that did not include occultation or startup penalties modified which were then increased by 7 percent. Although available, the array degradation feature of SEPSPOT was not used as it did not reflect recent solar array degradation characteristics. Instead, as cited above, an array mass penalty was added to the BOL mass of the COMSATs.

C. Quasi-stage System

Some calculations were made where power, equal to F_PP_O, was added to the installed COMSAT power levels in order to evaluate EP transfer times with increased COMSAT power to mass ratios. It is important to note that the added power is not available for GEO payloads as that would require an increase in the COMSAT mass and reduce the overall power to mass ratios to near original values. Consistent with an assumed 15 percent degradation in the Van Allen Belts, addition of a power of F_PPo will require a mass of 1.15 F_PP_O. Also, the additional power will require more propulsion mass. Unlike the case for Integrated EP, it was assumed that a separate thermal rejection system would be required for additional power. Detailed analyses of thermal systems are beyond the scope of these analyses; but, based on Ref. 19, a mass of 31 Pdiss was assumed to account for the thermal rejection system for the PPU.[19]

From the above, the quasi-stage concept requires an additional mass beyond that of the integrated EP approach of:

$$\Delta M_{EPQ} \approx \{1.15\ \alpha_{SA} + \alpha_{HET} + 31\ \eta_{PPU}\}\ F_P\ P_O \tag{8}$$

The BOL COMSAT mass for the quasi-stage is then:

$$M_{BOLQ} \approx \Delta M_{EPI} + M_{BOLI} + \Delta M_{EPQ} \tag{9}$$

The GTO masses, capture fractions, and trip times are then calculated as described for the Integrated EP approach.

III. Results and Discussion

Figure 6 shows the reductions in GTO mass requirements for Kourou and KSC launches resulting from the use of integrated EP, rather than chemical apogee propulsion with an Isp of 320 seconds. The benefits, with three values of Isp of EP, are shown versus the mass required in the respective GTOs if chemical apogee propulsion were used. Each datum was derived from a specific COMSAT launched in 2005-2006, with some excluded for clarity, and the lightest and heaviest COMSATs are represented by the extreme values of GTO masses. As an example, use of EP enabled reductions of KSC GTO masses of about 900 to 1300 kg, at 1000 and 2100 seconds Isp, respectively, for a COMSAT that required a GTO mass of about 4000 kg with chemical apogee propulsion. Overall, for EP Isps from 1000 to 2100 seconds, respectively, integrated EP allowed fractional GTO mass reductions of around 0.2 to 0.3 at

Kourou and 0.25 to 0.35 at KSC. The lower leverage of EP at Kourou is due to the reduced delta Vs for GEO insertions that result from the lower inclination of the launch site. The expected decrease in launcher requirements to deliver COMSATs from Kourou relative to KSC is also reflected on Figure 6. The data of Figure 6 may also be used to contrast launcher requirements for specific COMSAT opportunities with both chemical and EP transfers to GEO. Although derived from specific COMSATs, the data of Figure 6 are general and may also be used to evaluate the impact of integrated EP on dual-launch scenarios. However, in-space propulsion effects on dual launches are dependent on details of the spacecraft support systems in launch fairings and were not treated herein.

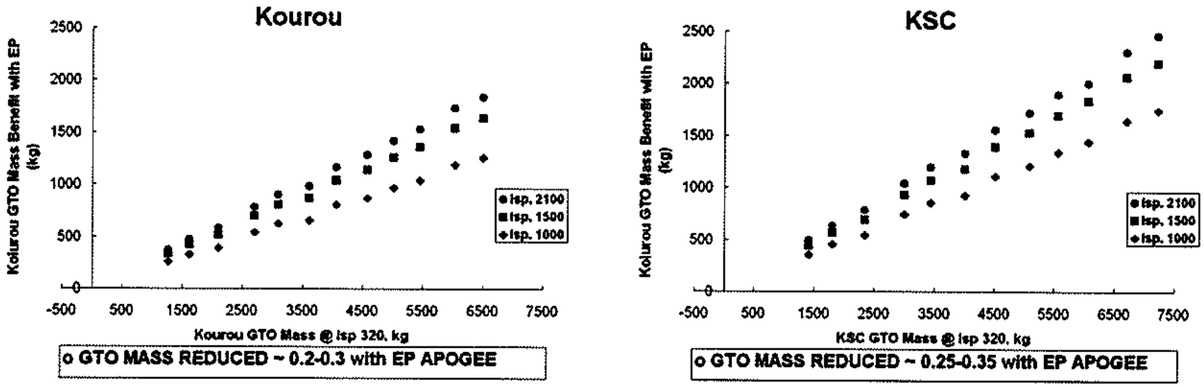

Figure 6. Mass Benefits with Integrated EP for Kourou (left) and KSC (right).

Figure 7 shows the capture fraction of launchers versus GTO drop mass capability for launches from Kourou and KSC, respectively, with chemical and integrated electric propulsion. The capture fraction is defined as the fraction of the 32 COMSATs launched in 2005-2006 that could have been delivered with the specified launch site, GTO delivery capability, and transfer propulsion characteristics. It is seen that from both launch sites integrated EP provided significant gains in capture fraction of recently launched COMSATS for launcher GTO delivery capabilities between about 2500 and 5000 kg. Capture of the entire, recent COMSAT market with chemical apogee propulsion required Kourou and KSC launcher GTO masses of about 6500 and 7500 kg, respectively. Integrated EP enabled capture of the full set of COMSATS with Kourou and KSC GTO delivery capabilities, respectively, of about 4400 and 5000 kg. These data suggest that the leverage of integrated EP is, for launches of single COMSATs, greatest for small to mid-sized launchers. This may offer an opportunity for significant cost reductions for COMSAT missions. However, many relevant costs are generally not public; so no attempt was made herein to quantify the resource implications of the calculated performances.

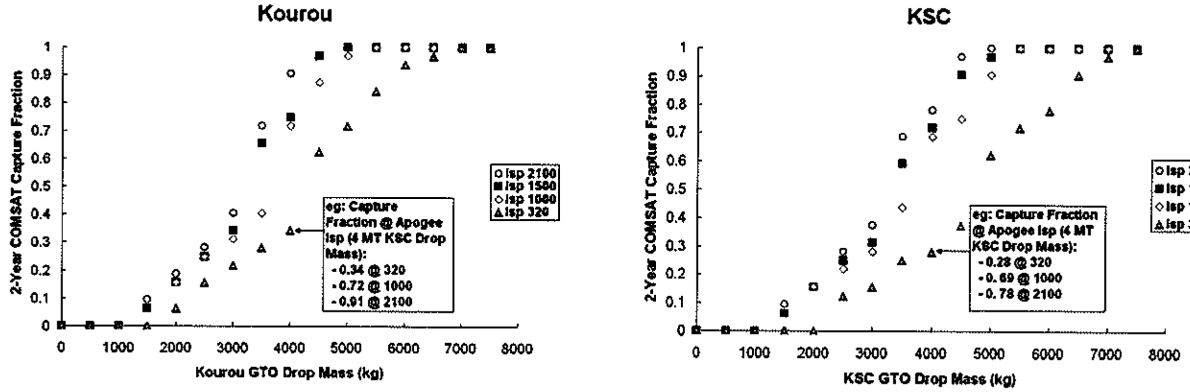

Figure 7. COMSAT Mission Capture with Integrated EP for Kourou (left) and KSC (right).

Transfer times to GEO with integrated EP are shown in Fig. 8 for the full set of recently launched COMSATs. A specific COMSAT is represented by a value of BOL power to mass ratio which ranged from slightly less than 3 to over 6 W/kg for recent COMSATs. Insertion times are shown for values of integrated EP Isps of 1000, 1500, and 2100 seconds. For a specific launch site and specific impulse (and associated system efficiency) the insertion time is very closely specified by the BOL power to mass ratio of the COMSAT. Therefore, the trend in average COMSAT power to mass ratios shown in Fig. 1 has enabled major decreases in potential COMSAT insertion times to GEO with EP. As expected, insertion times at Kourou are shorter than those at KSC due to the reduced delta Vs required for the GTO to GEO transfers. Figure 8 also shows the transfer times become less sensitive to power to mass ratio as that parameter increases. That has important implications for the attainment of short transfer times of order month or less, which will be discussed below.

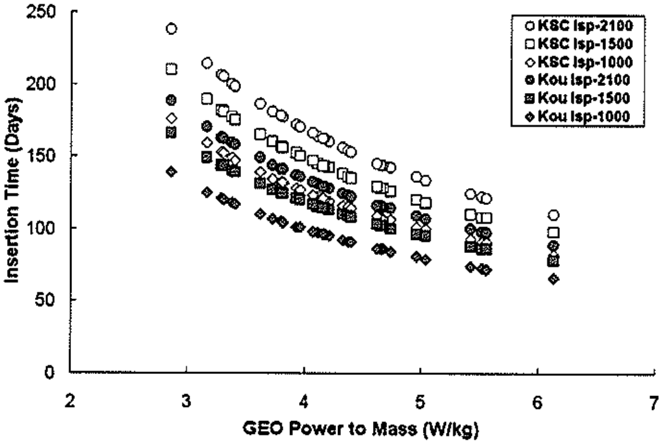

Figure 8. COMSAT Insertion Time with Integrated EP.

Some reductions in integrated EP insertion times from those shown on Fig. 8 should be available with little effort in the near term. First, it was previously noted that no credit was taken for removing the majority of the chemical apogee subsystem dry mass and that would likely be done to improve both mission costs and performances. These masses, while not predominant, represent an influential fraction of COMSAT BOL dry mass. Use of integrated EP could also gain from more accurate and less conservative assumptions than used herein regarding startup times after occultations and array mass penalties to account for degradation. The transfer time reductions available from refined assumptions are not large but could be expected to improve insertion times by a few percent. As indicated on Fig. 1, there is a steady upward trend in average power to mass ratio of COMSATS. This trend may be expected to continue and would naturally provide reduced insertion times. Preliminary estimates of the potential impacts of these three pathways were made and insertion time reductions of up to nearly 10 percent from those of Fig. 8 appeared possible. More invasive steps to reduce insertion times include redesign of busses to eliminate the large structural penalties associated with accommodation of the large chemical propellant and pressurant tanks; use of part (in particular power processors) of an electric propulsion stationkeeping subsystems, if used; and use more efficient GTOs (such as supersynchronous apogees); and direct drive. Very preliminary estimates of the effects of such changes indicated that additional reductions in insertion times of about 10 percent may be possible. Overall then, insertion time reductions of about 10 percent of the values shown on Fig. 8 should be available in the near term with little effort. Additional trip time reductions with integrated EP would require more complex and invasive steps.

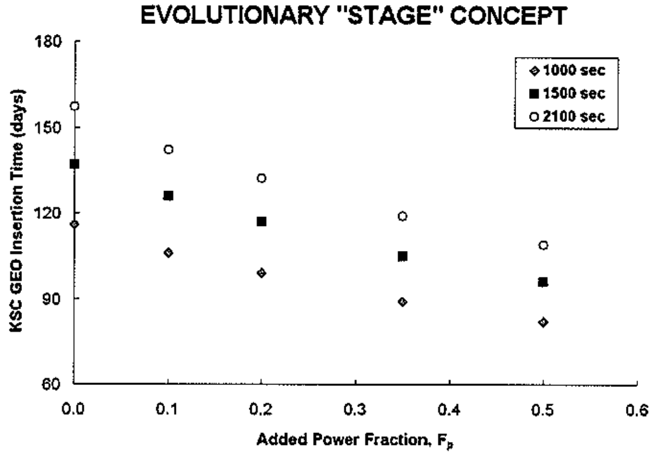

Figure 9. COMSAT Insertion time from KSC with added Power Fraction.

A quasi-stage concept was evaluated as a possible evolutionary path to classical stages for EP Earth orbit transfer that could enhance both mass delivery performance and insertion times. As described above, power was added to the COMSATs to be used for the EP transfer but the power isn't available for normal, on-orbit payloads. Added solar array power decreases the overall COMSAT power to mass ratio as the specific power of the added power is much higher than that of a full COMSAT, which contains many payload and buss elements with rather low specific powers. A COMSAT with a BOL power to mass ratio of about 4 W/kg was selected as that was approximately the average value for recent COMSATs (Fig. 1). Figure 9 shows the GEO insertion times for that COMSAT as a function of the added power, expressed as a fraction of the original BOL power. An upper bound of added power of half the installed power was arbitrarily selected to illustrate the situation. It is seen that the insertion times dropped slowly with increasing added power. However, Fig. 9 indicates that enablement of insertion times of order month or less requires additional powers significantly greater than installed on present COMSATs. Classic EP stages use such an approach and are thereby able to reduce insertion times to values well below those attainable with any integrated EP concept.

IV. Conclusions

Multiple recent and on-going developments have significantly increased the practicality and expectations for the use of EP for energetic, Earth-orbit transfers. These developments include trends of COMSAT power to mass ratios and masses, an increasingly competitive launcher situation, major advancements in spacecraft power systems, and the broad and increasing acceptance of EP for multiple propulsion functions. The use of electric propulsion was evaluated for transfers of COMSATS from GTOs to GEOs. Recent communication satellite designs, normal launch vehicle delivery orbits, and integrated electric propulsion subsystems (with input powers less than nominal satellites powers) were assumed to minimize required changes to present and near-term launchers and spacecraft. The "capture fraction" of recent communication satellites that could have been delivered was evaluated versus launcher delivery capability, launch site, and In-space propulsion characteristics. Electric propulsion greatly increased the capture fraction for small to mid-sized launchers and may provide interesting benefits to dual-launch options. Insertion times were found accurately specified by the power to mass ratio of the satellites and the assumed electric propulsion specific impulse/efficiency characteristics. Insertion times less than 100 days were found for satellites with high power to mass ratios that used high thrust to power electric propulsion options. These results indicate that, where insertion times are acceptable, electric propulsion may provide major, near-term cost reductions for communication satellite missions. The influence of power for electric propulsion beyond that for satellite payloads and housekeeping was also assessed and insertion times less than a month will require powers significantly higher than presently installed.

Acknowledgments

The authors acknowledge the support of the In-space Propulsion Project under NASA's Science Mission Directorate in determination of the COMSAT insertion times via use of the SEPSPOT low-trust trajectory code.

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