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Electric propulsion reliability: Statistical analysis of on-orbit anomalies and comparative analysis of electric versus chemical propulsion failure rates

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ABSTRACT

With a few hundred spacecraft launched to date with electric propulsion (EP), it is possible to conduct an epidemiological study of EP's on orbit reliability. The first objective of the present work was to undertake such a study and analyze EP's track record of on orbit anomalies and failures by different covariates. The second objective was to provide a comparative analysis of EP's failure rates with those of chemical propulsion. Satellite operators, manufacturers, and insurers will make reliability- and risk-informed decisions regarding the adoption and promotion of EP on board spacecraft. This work provides evidence-based support for such decisions. After a thorough data collection, 162 EP-equipped satellites launched between January 1997 and December 2015 were included in our dataset for analysis. Several statistical analyses were conducted, at the aggregate level and then with the data stratified by severity of the anomaly, by orbit type, and by EP technology. Mean Time To Anomaly (MTTA) and the distribution of the time to (minor/major) anomaly were investigated, as well as anomaly rates. The important findings in this work include the following: (1) Post-2005, EP's reliability has outperformed that of chemical propulsion; (2) Hall thrusters have robustly outperformed chemical propulsion, and they maintain a small but shrinking reliability advantage over gridded ion engines. Other results were also provided, for example the differentials in MTTA of minor and major anomalies for gridded ion engines and Hall thrusters. It was shown that: (3) Hall thrusters exhibit minor anomalies very early on orbit, which might be indicative of infant anomalies, and thus would benefit from better ground testing and acceptance procedures; (4) Strong evidence exists that EP anomalies (onset and likelihood) and orbit type are dependent, a dependence likely mediated by either the space environment or differences in thrusters duty cycles; (5) Gridded ion thrusters exhibit both infant and wear-out failures, and thus would benefit from a reliability growth program that addresses both these types of problems.

1. Introduction

The adoption of electric propulsion (EP) on board satellites has slowly but steadily increased over the last two decades. For example, a few hundred spacecraft have been launched to date with EP, and there are currently 128 active satellites in geosynchronous orbits (GEO) that use electrical propulsion (as of December 2015, excluding those with electrothermal devices), up from 28 such satellites in 2000. Electric propulsion is also used on-board spacecraft in all other orbits including interplanetary orbits. EP is principally used for station-keeping and orbit repositioning, tasks with little acceleration demands, in conjunction with traditional chemical propulsion for orbit-raising. The situation however may slowly change in the near future as low thrust orbit changes from geo-transfer orbits (GTO) to GEO have already been demonstrated, and at least one major orbit-raising from a transfer orbit to GEO using only electric propulsion has already been completed (in 2011, with the Advanced Extremely High Frequency 1 satellite, following the failure of its main Liquid Apogee Engine[1]). Furthermore, an announcement in 2012 by a major satellite manufacturer of the introduction of a fully electric satellite platform, and the acquisition of four of these platforms by a couple of satellite operators is an important new milestone for the EP technologies as it signals a changing attitude in the space community, traditionally and understandably risk averse, in its reliance on electric propulsion.

These recent developments are better appreciated when contrasted with the very slow, and at times hesitant history of development of EP. For instance, it is interesting to note that the inception of electric propulsion for space flight goes back a long way to Goddard in 1906:

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[1] The recovery of AEHF-1 is an important milestone in the history of EP: a major national security asset was rescued by its Hall thrusters (BPT-4000) when its chemical apogee motor failed. These Hall thrusters are based on models developed in the 1990's for the ambitious broadband satellite constellation Teledesic.

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> “[Goddard] experimented with an electric gas discharge in 1906. As he observed the very high velocities which were imparted to the charged particles while the temperature of the tube remained fairly low, the thought occurred to him that electrostatically repelled particles might be the answer to the problem of obtaining high exhaust velocities at bearable chamber temperature […]. The frequent recurrence of remarks concerning electrostatic propulsion in his notebooks from 1906 to 1912 reveals that ion [propulsion] had taken a firm foothold in [his] thinking”[24].

The idea of electric propulsion was also proposed more than a century ago by Tsiolkovsky in 1911:

> “It is possible that in time, we may use electricity to produce a large velocity for particles ejected from a rocket device […]. It is known at present that cathode rays […] are accompanied by a flux of electrons […], the velocity of which are 6000 to 20,000 times greater than that of the ordinary products of combustion.” (quoted in Ref. [6].

Little however was done with this idea of a “jet of charged particles” until Hermann Oberth (1894–1989) gave it a boost in 1929. In discussing the “electric spaceship”, Oberth identified one of the most important advantages of EP, namely the mass-saving it provides. Details of this early history of EP can be found in Stuhlinger (1964, first chapter) and Choueri [6]. More than 50 years after its inception and following the dawn of the space age with the launch of Sputnik in 1957, EP was ready for its maiden flight. The first technology demonstrations and operational experiences with electric propulsion on orbit occurred in the 1960's both in the U.S. and the Soviet Union. In the U.S., NASA and the U.S. Air Force tested electric thrusters on board spacecraft between 1962 and 1971 (first with the Space Electric Rocket Test, SERT-1 suborbital mission, then with the Applications Technology Satellites, ATS-4 and ATS-5 for NASA, and with three SCOUT missions for the Air Force). In the Soviet Union, the probe Zond–2 was the first to use plasma thrusters in 1964.

After these early experiments, enthusiasm for electric propulsion in the U.S. seems to have dwindled, and there was a 20 + year hiatus before the Air Force resumed on orbit experimentation with EP thrusters. In the late 1990's the Air Force Research Laboratory began the development of a low power Hall thruster targeting reliable high efficiency propulsion for the emerging micro-satellite market [16]. NASA continued to test EP on orbit but with a meager half a dozen flight experiments over the next two decades. The situation in the U.S.S.R. however was different, the enthusiasm for EP persisted and about 40 flights carried electric thrusters during the two-decade hiatus of the Air Force. As a result, EP matured earlier in the Soviet Union, and this may explain in part some of the reliability implications that will be seen later in this work. Japan also began experimenting with EP on orbit in the late 1970's and early 1980's, and was soon followed by China and Europe. Beyond its government support, commercial interest in EP developed slowly in the early 1980's, with a launch rate in the low single digit per year until the mid 1990's. A detailed review of the flight experience with EP can be found in Pollard and Janson [20]. These launch rates are better understood when contrasted with the launch rate of non-EP spacecraft: an average of over a 100 such spacecraft were launched per year[2] between the early 1960's and 1990's [14], thus making EP during that time period occupy a very small niche market compared with chemical propulsion (CP).

It is against this background that the observations in the first paragraph in this Introduction have to be understood, namely that the late 1990's truly represent an inflection point in the adoption of EP, and the fact that the 128 satellites in GEO currently use EP is an important achievement for this 100 + year old idea.

It is worth reflecting, even if briefly, on the reasons for this sluggish development and belated market adoption of EP—technologies over a century in the making and with over 50 years of flight experience. Understanding the past can be informative about the extent and sustainability of the growth of EP adoption in the future:

1. First, with its minute thrust, EP was significantly behind the development priority of chemical propulsion before and early after the advent of the space age, and it carried little weight between the powerful advocates of liquid and/or versus solid propellant;
2. Second, given its level of thrust, EP was not suitable for operating in the atmosphere, and as such, it offered little appeal for weapon systems. Consequently, development funds for EP were minute compared with the interest in and support for chemical propulsion;
3. Third, one of the main advantages that EP provides over chemical propulsion, namely mass savings, had a low valuation in government procurement of spacecraft, until the late 1980's (given the geopolitical and military imperatives at the time). More generally, the advantages of EP did not seem appealing enough at the time to outweigh the drawbacks and technical uncertainties associated with it;
4. Fourth, the power available for spacecraft in terms of generation and storage (solar panels and batteries) was rather small (<1 KW) and below a meaningful threshold for practical EP adoption;

All the above conspired synergistically to delay the development and adoption of EP and kept it stuck in the slow maturation lane. The situation began to change in the 1980's and 1990's for the following reasons:

5. In the 1980's and early 1990's, the mass savings afforded by EP were increasingly recognized as important in the commercial space market, not only for the cost savings they led to but also for the increased payload capacity which can replace the mass of propellant saved. Given the large revenues communication satellites were reaping and the growing demand for their services, more payload capacity–as enabled by EP replacing chemical propulsion–would translate into more revenues. As a result, the value equation for EP began to change.[3] **New trade-offs would be enabled by the adoption of EP, including extending lifetime of the spacecraft on orbit and increasing its payload capacity, therefore modifying its value profile** (raising and extending the value delivery potential of the system);
6. While this value argument explains in part the inflection point in the adoption of EP in the 1990's, one reason for **the reluctance of its broader and enthusiastic adoption remained: the absence of a solid track record of on orbit performance and (demonstrated) field reliability.** Given the high cost of access to space and the quasi-unavailability of on orbit maintenance to compensate for subpar (hardware) reliability, **the risk aversion of the space community is understandable and it explains in part the slow uptake of EP even after the value argument won the day.**

With a few hundred spacecraft launched to date with electric propulsion, it is now possible to conduct an epidemiological study of EP's on-orbit track record of anomalies and failures. No such study has been conducted to date that included the global set of EP missions. The first objective of the present work is to undertake such a study and to analyze EP's track record of on orbit anomalies and failures (and identify different

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[2] The yearly launch rate fluctuated widely, and a sharp drop off for defense and intelligence spacecraft occurred in the late 1980's, from about 70 launches per year to about 30 per year in the early 1990's. A similar drop off occurred for science missions, albeit earlier starting in the 1970's. Commercial satellites exhibit a very different pattern, with a slow but steady growth until the mid 1990's [14].

[3] A value analysis of EP would integrate the various benefits, costs, and drawbacks (including the much longer flight time to achieve final orbit and the corresponding revenues forfeited for example for a communications satellite), and benchmark the resulting net value against that of a system with chemical propulsion. Satellite operators will make value-informed decision regarding the adoption of EP, and it is important to understand under what conditions, and for what missions and markets, would EP tip the value balance in its favor. See Geng et al. [12]; and Brathwaite and Saleh [2] for examples of satellite value analysis in a commercial and government context.