Overview of Hall Current Thruster Integration Activities at Lockheed Martin Space Systems Company

Vadim Khayms, vadim.khayms@lmco.com
Keith Kannenberg, keith.kannenberg@lmco.com
Bill Meyer, bill.meyer@lmco.com.com
Lance Werthman, lance.werthman@lmco.com

Lockheed Martin Space Systems Company, 1111 Lockheed Martin Way, Sunnyvale, CA 94086

Integration of Hall Current Thrusters on geostationary communication satellites requires a detailed understanding of the potential effects induced by the thrusters on critical satellite subsystems. Some of the concerns related to the thruster plume include: erosion and sputtering of spacecraft surfaces, re-deposition of sputtered materials and surface contamination, transmission of bus and payload signals through the thruster plume, electromagnetic interference due to thruster radiated and conducted emissions, differential surface charging and electrostatic discharges, and attitude control disturbances due to thruster body torques and plume impingement onto spacecraft surfaces. In addition, the use of low-thrust propulsion requires the development of new orbit transfer and station-keeping algorithms that take full advantage of the high performance offered by electric thrusters. This paper summarizes some of the work currently pursued at the Lockheed Martin Space Systems Company in addressing a number of these integration issues. Specifically, our progress in the following areas will be reported[1]: Hall thruster plume characterization and modeling, sputter rate database development and spacecraft-level assessment of erosion and contamination effects, preliminary analysis of the changes in the optical properties of solar arrays and optical solar reflectors due to ion impingement, spacecraft charging and methods for mitigating the risk of electrostatic discharges, modeling and assessment of signal propagation through the thruster plume, and the progress in the work on station-keeping algorithms and the development of a software tool for orbit transfer optimization.

Introduction

In an effort to increase payload capability of the future commercial and military spacecraft, a program was initiated at Lockheed Martin several years ago to investigate Hall Current Thruster (HCT) technology. Lockheed Martin and General Dynamics entered into a long-term agreement in the Fall of 2000 to develop and qualify flight versions of the BPT-4000 Hall thruster, a power processing unit (PPU), and a Xenon flow controller (XFC). Hardware qualification is expected to begin in 2002. In parallel with the development of flight hardware, Lockheed Martin has been pursuing a number of internal integration studies. The main emphasis of this comprehensive Hall Thruster Propulsion System (HTPS) development and integration program has been to gain quantitative information on the effects of the ionized thruster plume on various spacecraft subsystems and to help mitigate risk associated with the introduction of this new propulsion technology on future spacecraft. Some of the major highlights of this effort are discussed in this paper.

Significant progress has been recently made in the area of plume effects and surface interactions. A detailed characterization of the thruster plume was performed as part of a series of vacuum chamber tests at the Aerospace Corp. [1]. In parallel, a software tool was developed at SAIC to help predict the ion plume distribution of a Hall thruster in a space-like vacuum environment [2]. A comprehensive sputter rate database was developed for a wide range of important spacecraft materials, characterizing sputter rate variation with plume angle of incidence and ion energy [3]. A simplified model was developed to predict erosion rates of various spacecraft surfaces exposed to the thruster plume using the results of the plume model in combination with the sputter rate database [4]. The model was subsequently validated through a series of sample exposure tests at the Aerospace Corp. [3] and used to generate sputter rates for a variety of specific spacecraft configurations. In addition, experimental characterization of optical properties was performed on a number of samples exposed to a calibrated ion beam to determine how various changes in surface topology induced by ion sputtering affect optical transmission, absorption, and emissivity [3]. Simplified models of the surface roughness, as seen with an Atomic Force Microscope, were used to explain the observed changes in the optical properties and to evaluate the consequences of ion sputtering on the design and performance of thermal radiators, solar arrays, and other optical instruments. As part of an overall spacecraft-level assessment of erosion and contamination effects, the impact of surface erosion on the charging of spacecraft surfaces was examined. Several strategies to actively control spacecraft charging have been proposed and are currently being evaluated. Other on-going efforts include development of tools to analyze the effects of the plume on the propagation of communication signals [5]-[7] and to optimize low-thrust trajectories. Our current status and recent progress in these and other areas of HTPS integration are discussed briefly in this paper.

Hall Thruster Plume Characterization

The accuracy of our sputter models and the ability to correlate them to the results of sample exposure tests rely heavily on the knowledge of the HCT plume properties. To that end, a series of plume characterization tests was conducted at the Aerospace Corp. to measure the ion flux, ion energy, and charge-state distributions in the plume of the BPT-4000 Hall thruster as a function of its operating conditions. A brief description of the test and some of the results are summarized in this paper. Additional information can be found in Ref [1].

The ion flux and the ion energy distributions were measured at a distance of 1 meter away from the thruster exit plane using a pair of Faraday probes, one collimated and one uncollimated, and an electrostatic deflection analyzer, respectively. The probes were mounted on a rotating arm and measurements were taken as a function of the plume angle with respect to the thruster centerline at power levels ranging between 2.0 kW and 4.5 kW and discharge voltages ranging between 200 V and 500 V. For the purposes of subsequent spacecraft-level analyses, the distributions of low-energy charge-exchange species that are typically found in the wings of the thruster plume, were of primary interest. To better characterize this portion of the plume, the two Faraday probes were configured as retarding potential analyzers (RPAs) for some of the measurements. In those cases, the probe collectors were biased at various voltages to collect the ion flux while screening out the low-energy ion population.

The ion energy distribution was measured using both the retarding potential analyzer and an electrostatic deflection analyzer. Although the energy distribution was mainly used for sputter rate calculations, it also provided additional qualitative insight into the production of charge-exchange ions. Multiply charged species, that underwent charge-decreasing collisions, generated peaks in the energy distribution at potentials (ratios of energy to charge) that were higher than the nominal thruster discharge voltage. In addition, it was also confirmed that at angles larger than 80º. with respect to the thruster centerline, the ion population was dominated by ions with energies below 50 eV. Ions collected at these angles are believed to be background or thruster neutrals that lost a single electron in collisions with primary ions and were accelerated in the plasma potential.

The distribution of charge states in the plume was obtained by means of a time-of-flight spectrometer that could disperse ions with a specified energy to charge ratio in time based on the ion charge. As a result, relative proportions of the individual species (Xe^{+}, Xe^{++}, Xe^{+++}, etc) were obtained as a function of the plume angle over a range of ion energies between 100 and 300 eV. It was concluded, based on the results of these measurements, that the relative proportions of multiply-charged species were insensitive to the plume angle and remained reasonably constant over the energy range of interest.

Numerical Simulation of Thruster Plume

Analyses of surface effects require a detailed description of the thruster plume. Since experimental measurements in most ground tests include secondary effects that do not appear in space, a numerical plume model was developed to simulate on-orbit conditions. This model simulates the expansion of the ion plume into a vacuum for different thruster operating conditions. The output of this model is a map of plume properties that can be used for subsequent analyses. Several operating conditions of interest to Lockheed Martin have been successfully simulated [2].

The Hall thruster plume is composed of three components: the primary beam of high energy ions, which supply the majority of thrust, slow moving, low energy ions generated by charge exchange, which produce a backflow, and off-axis, mid-range energy ions produced by elastic scattering. The plume model accounts for these components and computes each with appropriate numerical techniques. As a result, the model predicts the ion density in the plume and captures the form of the ion energy distribution. In particular, it was found that the inclusion of elastically scattered ions was necessary to produce the correct energy distribution at angles greater than 45º from the thrust axis.

To validate the model, predictions have been made for chamber conditions, including the effects of observed back-pressure. These predictions were then compared with measurements of the HCT plume. Good agreement has been found between the numerical results and experimental data for both ion density and energy distribution. The agreement lends confidence to the use of the model to predict plume properties on-orbit.

Development of a Sputter Rate Database

Proper assessment of the numerous plume impacts on the performance of critical spacecraft components, such as solar arrays and optical solar reflectors, requires accurate knowledge of the sputter rates as a function of ion impingement angle and energy. Although some sputter rate data are available in the literature, most of the reported rates are either for pure metals only or for materials exposed to ions at unrealistically high energies. Since most of the damage to spacecraft surfaces is caused by low-energy charge-exchange plasma that is typically found in the wings of the thruster plume, the sputter rate values were primarily needed in the energy range between 50 and 300 eV.

In an effort to improve accuracy and, therefore, the predictive power of our erosion models, several spacecraft materials were selected to undergo sputter rate measurements. Among these materials were indium tin oxide (ITO), MgF_2, silver, gold, and borosilicate glass. For each of the materials, sputter rates were obtained at incidence angles 0º, 20º, 40º, 60º, and 80º and ion energies 50, 100, 300, 500, and 2,000 eV. In order to rule out any facility- or instrument- related uncertainties and gain additional confidence in the results, sputter rate measurements were made at two different test facilities following two different test protocols. A subset of these measurements was repeated at identical test conditions at both facilities for comparison purposes. The objective was to identify possible sources of measurement uncertainty and to achieve the desired level of confidence in the resulting empirical relations for the sputter rates as a function of incident angle and ion energy. Sputter rate measurements obtained at the two facilities produced similar results at near-normal incidence. However, at larger incident angles significant discrepancies were observed. These discrepancies were attributed to the increased surface roughness that became more pronounced at larger angles and affected sputter rate measurements. An explanation of the nature of these discrepancies and a comparison of representative sputter data taken at the two facilities can be found in Ref. [3].

Spacecraft-Level Erosion and Sputter Model

The thruster plume model and sputter database have been used to predict the erosion of spacecraft surfaces due to plume impingement. A model has been proposed to predict the variation of sputter rates with the energy and incident angle of ions that uses sputter yield measurements as input. Combined with a description of the energy distribution in the plume this model can be used to predict the erosion of exposed surfaces. Comparisons with the results of controlled exposure tests have shown that this model yields accurate predictions [4].

When combined with a geometric model of a spacecraft, this erosion model can be used to predict erosion rates over spacecraft surfaces. Plume properties at any point on the spacecraft are determined using the thruster plume model and combining contributions from multiple thrusters. The spacecraft itself is assumed to have no effect on the structure of the plume with the exception of line of sight shadowing, an assumption that is accurate for surfaces that are sufficiently far away from the thrusters.

Several spacecraft configurations have already been analyzed to determine the extent of erosion caused by the plume and to predict contamination due to the redeposition of sputtered material. In the future, the model will be used to assess possible damage to surfaces and to predict changes in relevant properties of critical optical and thermal control surfaces.

Changes in the Optical Properties Induced by Surface Erosion

In order to evaluate the effect of ion sputtering on the performance of solar cells and optical solar reflectors (OSRs), material properties, such as transmissivity and absorptance, were measured as a function of sputter depth and ion incident angle [3]. Specimens for these measurements were prepared by sputtering a number of samples of selected materials for a specified period of time at a prescribed incident angle. Among the various materials tested were cerium doped borosilicate glass, used as solar cell cover glass with a MgF_2 antireflective (AR) coating and an indium tin oxide (ITO) charge control coating. The analysis was mainly focused on solar array samples, as these surfaces were considered to be most susceptible to erosion damage. Additional measurements of absorptance and emittance were made on a number of OSR and germanium coated black kapton specimens.

The effects of erosion on the optical properties of cover glass were evaluated both as a function of wavelength and erosion depth. Specifically, a 3% drop in transmission was observed in the case where the entire AR coating was removed by erosion, a result consistent with expectations. Transmission loss due to sputtering of the cover glass surface at various beam incident angles was determined using a probe that directly measured the intensity of the transmitted light. A large reduction in transmission was observed for samples that were exposed to the ion beam at near-grazing incident angles. This change was attributed to the development of highly refractive surface structures causing diffuse scattering of light. The existence of these surface structures was confirmed by examining images obtained by the Atomic Force Microscope. No such surface features were observed for samples exposed to ion beams at near-normal incident angles. Additional information on the execution and the results of these tests can be found in Ref. [3].

A simplified model was developed to gain better understanding of the aggregate effects of surface features on the optical properties of cover glass. The analysis was based on the empirical nominal values of the transmittance and absorptance combined with an idealized model of the observed surface features. The reflection and transmission coefficients were calculated using geometrical optics for a prescribed angle of incidence of the incoming radiation. After proper averaging, these values were used to estimate the reduction of transmission and the increase in the optical path length that directly affects optical absorptance. The model will be validated via a series of controlled experiments that will take place at the beginning of 2002.

Spacecraft Charging

In order to avoid differential charging in orbit and to reduce the risk of electrostatic discharges (ESD), dielectric surfaces on spacecraft are often coated with thin layers of an optically transparent conductive material (usually ITO). When applied to all dielectric surfaces, including sunlit surfaces of solar arrays, these coatings allow electrons, collected from the ambient plasma elsewhere on the spacecraft, to be transferred to the sunlit surfaces and removed by the process of photoelectric emission. This prevents local accumulation of charge anywhere on the spacecraft, thus reducing differential potentials, and eliminating static discharges.

The longevity and the long-term effectiveness of these charge control layers may be compromised due to the possibility of partial removal of such coatings over time. The impacts of surface erosion on differential spacecraft charging and the available options for mitigating risk associated with ESD are currently being evaluated.

Plume Transmission of Communication Signals

The Lockheed Martin team is developing a set of analytical tools for assessing Hall thruster plume interference with communication signals to or from spacecraft antennas. The tools are designed to predict the plume's influence on the antenna's far field patterns. Hall thrusters produce plume regions with high electron densities that can significantly modify microwave communication transmissions. Transmission through the center of the plume is unlikely but passing signal beams through the wings of the plume appears unavoidable. The analysis of the impact of the plume on the transmitted signal entails building detailed analytical tools that can handle the complex 3D relationships between the variable plasma field and the signal beam. Development and use of these tools is described in detail in [5]-[7]. The last of these is a companion paper in this conference.

In general, non-influence over the communication antenna far-field pattern is the ultimate test of whether or not there is any effect from the Hall thruster plume. Any differences in the pattern due to the plume have to be acceptably small. Communication satellites have stringent beam-pointing requirements, which must be met despite the general tendency of the plasma refraction to bend the signal beam away from the plume. Even slight changes of the order of a few hundredths of a degree would have significant edge-of-coverage implications for an antenna pattern on the earth. In addition, the HCT plume is known to be temporally non-steady, with oscillations typically in the 10-30 kHz range. Such oscillations will be phase modulated into sidebands of the microwave signal. These may be strong enough to interfere directly with adjacent channels, or act to increase sidelobes of the main antenna pattern. In addition to beam deflection and modulation, other areas of concern are polarization purity, beam distortion, sidelobe levels, and polarization isolation.

A geometrical optics vector ray tracing analysis code is being used to evaluate communication signal effects. Bundles of independent rays are passed through the plume and have their trajectories modified depending on the refractive index field they individually encounter. After leaving the plume, the ray's position, amplitude, and phase are collected at an exit-plane position. The far-field antenna pattern is computed from this exit-plane information using the radiation integral. Fourier transforms of time varying plume "snapshot" patterns yield modulated sideband antenna patterns. The steady-state antenna pattern analysis tool that is being developed is called BeamServer. It incorporates a companion plasma modulation pattern model. The tool allows a user to model the impact of HCT plumes on far field antenna patterns for user-specified plume electron distributions (in space and time), spacecraft feed-reflector-HCT geometries, and the signal characteristics of the payload.

Flight Controls and Orbit Transfer Optimization

Lockheed Martin is also engaged in a multi-year effort to develop flight control methodology for the use of Hall Current Thrusters. Trade studies have been performed to determine the desired thruster locations and configuration to gain the maximum benefit from HCT technology. Strategies for orbit transfer and on-orbit operation of the HCTs have been devised, and software tools for analyzing and optimizing mission design are in development. In addition, attitude control and ephemeris logic to utilize the gimballed thruster configuration are included in the HTPS effort.

In many areas, the flight controls effort builds on existing GN&C logic in use on Lockheed Martin's A2100 spacecraft. The on-orbit mission elements draw heavily on the baseline stationkeeping capabilities of the A2100 arcjet thruster system, which has comparable thrust levels. The control scheme for gimballed thrusters was developed for an A2100 spacecraft equipped with gimballed arcjets, and will undergo minor modifications for implementation with Hall thrusters. The same basic gimballed thruster controls will also be used during the orbit transfer portion of the mission with refinements to address attitude control tasks specific to low thrust orbit transfer.

Beyond refining existing capabilities, the Lockheed Martin flight controls effort is developing several new capabilities in mission optimization. A software tool has been developed to determine minimum time orbit transfers from an arbitrary initial orbit to a desired final orbit for a continuous thrust trajectory. This tool is currently being extended to optimize thruster usage (on/off times) to achieve higher effective mission propellant efficiency. A method of implementing the resulting thrust profiles in spacecraft flight software will be developed in the coming year.

Future efforts in flight controls include refining the gimballed thruster control logic for contingency operations, and development of a complete ascent mission optimization tool. The ascent tool will determine the ideal combination of bipropellant and electric propulsion transfer orbit operation given specific constraints on launcher performance, propellant capacity, and transfer orbit duration. While this can currently be done manually, the tool envisioned will provide automated and mathematically rigorous optimization solutions in a shorter period of time to facilitate trade studies and address customer needs.

Conclusions

Lockheed Martin is pursuing a comprehensive development program to implement Hall Current Thrusters on GEO satellites. In addition to hardware development and tests, activities in the areas of plume and surface effects, signal propagation effects, spacecraft charging, and flight controls are addressing all aspects of integration of this propulsion technology. These efforts have already produced significant results and are expected to yield a fully integrated and qualified Hall Thruster Propulsion System.

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