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Impacts of tug and debris sizes on electrostatic tractor charging performance

Erik A. Hogan *, Hanspeter Schaub

University of Colorado at Boulder, Boulder, CO 80309, United States

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Abstract

Active debris removal techniques enable relocating noncooperative geosynchronous (GEO) debris objects into graveyard orbits. One proposed method is the electrostatic tractor concept. Here a tug vehicle approaches a target debris object and emits an electron beam onto the debris. The charging that results yields an attractive electrostatic force that is used to tow the debris object into a new orbit. In this study, the impacts of relative sizing between tug and debris on the efficacy of this charge transfer process are considered. By applying a charging model and incorporating nominal, quiet GEO space weather conditions, limitations on the size ratio that preclude charge transfer are identified for different levels of beam energy. The resulting electrostatic forces and impacts on reorbiting performance are studied. The results indicate that a larger tug vehicle will enable the tugging of a broader range of debris sizes, and that the tug size should be roughly as large as the expected debris size.

Keywords: Electrostatic tractor; Spacecraft charging; Active charge transfer; Active debris removal

1. Introduction

For GEO satellites, international guidelines for end-of-life operations call for removal of the spacecraft from the GEO region. With a goal of preventing reentry into GEO within 25 years, a minimum increase in altitude of 200–300 km is typically expected, though certain spacecraft may be raised higher (IADC, 2007; NASA, 1995). For the case of defunct satellites and other debris objects, a method is needed for achieving this transition into a graveyard orbit. To that end, the use of an electrostatic tractor, illustrated in Fig. 1, has been proposed (Schaub and Moorer, 2012). A tug vehicle approaches a target object and emits an electron beam onto the debris, charging it negatively. With the beam emission resulting in a positive charge on the tug, an attractive electrostatic force between the tug and debris results, which is then used in conjunction with low thrust to tow the debris object into a disposal orbit (Hogan and Schaub, 2013). The charging that results is dependent on several current sources, and is impacted by the variations in the space weather environment at GEO (Denton et al., 2005; Schaub and Sternovský, 2013; Hogan and Schaub, 2014).

Due to the potential impacts of spacecraft charging on operations and spacecraft lifetime, much work has been performed in this area (Garrett, 1981; DeForest, 1972; Mullen et al., 1986; Katz et al., 1998; Cho et al., 2012; Anderson, 2012). Typically, these studies focus on a single satellite in orbit and investigate natural charging events that occur as a result of the space weather environment. A serious concern for spacecraft that experience differential charging across their outer surface is electrostatic discharge (ESD) events, where arcing occurs between different substructures possessing a significant surface potential

* Corresponding author.
E-mail addresses: erik.hogan@colorado.edu (E.A. Hogan), hanspeter.schaub@colorado.edu (H. Schaub).

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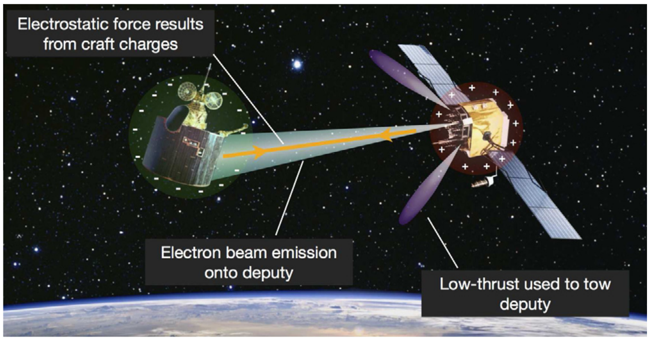

Fig. 1. Electrostatic tractor concept.

difference (Katz et al., 1998). These ESD events can be destructive to electronic hardware. Recent studies indicate that large satellites in GEO may experience many thousands of discharges over their lifetimes (Cho et al., 2012). With the electrostatic tug concept, the electron beam is used to raise the absolute potential of the vehicle, and thus avoids the differential charging issues. Current GEO spacecraft construction practice ensures that all outer surfaces are interconnected, thus minimizing differential charging issues. For electrostatic tugging, potential levels on the order of tens of kiloVolts are required (Schaub and Jasper, 2013). While certainly the near proximity of highly charged spacecraft raises a concern of potential arcing between tug and debris, in GEO arcing occurs over distances of a few centimeters for kiloVolt levels of potential difference (Cho et al., 2003). This is many times smaller than the separation distances considered, so arcing between tug and debris is not a concern.

Due to the recent nature of the electrostatic tractor concept, limited work has been performed in modeling the charge transfer process. In Schaub and Sternovský (2013), a charging model is developed to predict the potentials on tug and debris as a function of electron beam emission, spacecraft properties, and the space environment. A similarly sized tug and debris object are considered, and the charges are computed for a single space weather condition. Hogan and Schaub (2014) investigates the charge transfer process further, considering the impacts that fluctuations in the GEO plasma conditions over a typical day have on tractor performance. Modifying the beam current to counter varying conditions is contrasted with simply maintaining a constant current, and a simulation is used to illustrate a reorbiting maneuver. Once again, a single size is chosen for the debris object and tug, with the debris object roughly half the size of the tug. Thus far, the question of whether or not a tug could successfully tow a much larger object has not been investigated.

In this study, the impacts of relative size between the tug vehicle and debris object are considered. Because several of the currents impacting charging are dependent on spacecraft surface area, it is possible that sufficient charging may not occur if there is a significant size difference between tug vehicle and debris object. In order to charge a debris object to the kiloVolt levels considered for tugging, a large enough portion of the electron beam current must reach it in order to overcome the various currents it is subjected to. If the tug vehicle emitting the electron beam is small enough relative to the debris object, it will charge completely (referred to here as supercharging) and prevent sufficient beam current from reaching the debris. The amount of current that can be emitted by the tug is limited by the beam energy. Once the tug potential reaches the level of the beam energy, any additional beam current will be recollected by the tug (Lai, 2012). The impacts of size differences on the resulting charging are studied, with hopes of identifying a threshold for the onset of charging. The electrostatic forces and reorbiting performance for different sizing configurations are also considered.

The paper is structured as follows. First, an overview of the charging process and the model used to compute the potentials on tug and debris objects is presented. This is followed by a brief explanation of the method used to compute the electrostatic forces between tug and debris. Next, a threshold for the onset of charge transfer is defined, and the impacts of relative sizing on meeting this threshold are investigated. Then, the electrostatic forces acting between tug and debris are studied for a range of sizes and charging conditions. Lastly, the impacts of relative sizing on the debris reorbiting performance are considered for a range of tugging configurations, and power requirements are determined.

2. Background

In this paper, it is assumed that the tug vehicle is equipped with an electron gun that is used to remotely charge a neighboring deputy (or debris) object up to 10s of meters away. The charge transfer, in combination with the near proximity of tug and deputy, results in an attractive electrostatic force used for tugging, as illustrated in Fig. 1. Here, the problem of reorbiting a GEO debris object into a graveyard orbit is considered. A semi-major axis change is required and the tug and deputy maintain a constant leader–follower position throughout the duration of the maneuver (Hogan and Schaub, 2013; Schaub and Jasper, 2013). The study utilizes a charging model that accounts for the numerous current sources experienced by a satellite in the space environment. It is assumed that both the tug and deputy are conductive, with spherical geometries. While typical spacecraft do not necessarily satisfy these assumptions, the following analysis is used to provide first-order insight into the limitations of relative sizing between tug and deputy, and identify trends that would extend to more general spacecraft models.

2.1. Spacecraft charging model

The electrostatic tugging force used for towing is a function of the charging that results from the charge transfer between tug and deputy. Several factors influence this