Assessing the Challenges to a Geosynchronous Space Tug System

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ABSTRACT

A space tug vehicle is designed to rendezvous and dock with a space object; make an assessment of its current position, orientation, and operational status; and then either stabilize the object in its current orbit or move the object to a new location with subsequent release. A subset of on-orbit servicing, space tug missions in the geosynchronous belt include stationkeeping of satellites which have lost attitude control and repositioning of satellites. Repositioning of spacecraft may be desirable as a means to rescue satellites launched into incorrect orbits, for the retirement of satellites into "graveyard" orbits, and for on-demand maneuvers that support flexible mission requirements. This paper aims to unify the political, legal, operational, and financial aspects of the space tug concept and highlight the challenges that stand in the way of an operational space tug vehicle. U.S. Space Transportation Policy is reviewed, and a space tug operation is recognized as an enabler of emerging national space transportation requirements. Customary international and United States laws are explored as potential constraining forces on future tug missions. A concept of operations in geosynchronous orbit, including parking orbit selection and approach strategies, is analyzed with emphasis placed on safety and reliability. Potential financing models and the issue of insurance for space tugs are discussed and identified as the principal challenges facing implementation of a space tug system. This paper offers a positive forecast for the future of on-orbit servicing and endorses continued government support for proof-of-concept missions.

Keywords: Space tug, on-orbit servicing, space policy, space law, automated rendezvous and docking

1. INTRODUCTION

"On-orbit servicing" can refer to a variety of functions, including refueling, hardware replacement or repair, and changing the orbit of a target spacecraft. At present, there are two Defense Advanced Research Projects Agency (DARPA) programs that deal with on-orbit servicing. One, known as Orbital Express, is developing a standard interface for refueling and avionics upgrades. The motivation is that future spacecraft will be able to incorporate a standard interface to enable servicing by a DARPA/Air Force-designed spacecraft. Orbital Express will culminate with a flight test in orbit, currently scheduled for October 2006. This work is aimed toward a separate program called Spacecraft for Universal Modification of Orbits (SUMO) which is oriented towards "space tugs," or servicing vehicles, designed to change or maintain the orbits of target spacecraft (Figure 1). Potential space tug missions would perform stationkeeping maneuvers to maintain the orbit of target satellites and reposition spacecraft, including the rescue of satellites launched into incorrect orbits, the retirement of satellites into "graveyard" orbits, and on-demand maneuvers to meet changing mission requirements.

The goal of this work is to unify the political, legal, operational, and financial aspects of the space tug concept in order to highlight the challenges that stand in the way of an operational space tug. One of the most likely tug mission scenarios is one that operates in the geostationary belt due to the large number of potential targets and favorable orbital dynamics in that orbit. A geosynchronous (GEO) space tug concept guides the discussion in this paper. The concept contains two assumptions. First, the tug will execute multiple missions over its design lifetime. That is, from a parking orbit near the geostationary belt, it will rendezvous and dock with a target satellite, carry out the required maneuvers, and return to its parking orbit until it is needed again. Second, it is assumed that the tug will have the capability to dock with an arbitrary target spacecraft. Although a universal docking capability currently does not exist, the SUMO program is addressing this in depth. Thus, this paper will not address SUMO's ongoing development in detail.

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The idea of on-orbit servicing has been around since the early years of human space flight. Waltz (1993) discusses several manned servicing missions, including the Skylab space station, the Solar Maximum Mission (SMM) spacecraft, and the Hubble Space Telescope.[1] NASA's first experience with on-orbit servicing came in 1973 on the Skylab space station. Severe technical problems during Skylab's launch—the meteoroid shield accidentally deployed and subsequently tore off due to atmospheric drag—precipitated the need for various unplanned repair activities by future crews. In 1984, the Space Shuttle Challenger intercepted the failing SMM spacecraft and extended its lifetime by replacing the attitude control module and repairing the main electronics box. NASA's Hubble Space Telescope was launched in 1990 as the first observatory designed for routine servicing activities and has undergone four manned servicing missions. Following the Columbia tragedy, NASA considered a robotic servicing mission to Hubble to extend its life beyond the estimated two to three years of remaining operational life.

The first section of this paper will consult the new U.S Space Transportation Policy, which endorses research and development activities in the area of on-orbit servicing. Next, the legal constraints imposed by customary international law and national law are discussed. Then, a concept of operations in geosynchronous Earth orbit is presented as a framework for the identification of areas where further technical development is needed. Finally, financing and insurance for a space tug is explored. This paper will not argue the business case for a space tug as business analyses exist in the literature.[2,3,4] Instead, it will survey the various finance models that might apply to a space tug system and will discuss the issue of insuring space tug operations. Despite the focus of the space tug system in the geosynchronous belt, much of the discussion in this paper is relevant to on-orbit servicing scenarios in any Earth orbit.

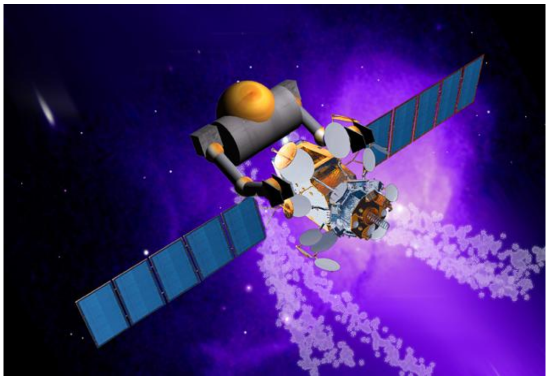


Figure 1 - Artistic representation of a space tug

2. POLICY RATIONALE

As the foundation for future government capabilities in space, it is necessary to consult national space policy to justify government on-orbit servicing operations. In the post-Cold War, development of a space tug capability was consistent with national space policy directives but not explicitly addressed. In a victory for proponents of on-orbit servicing, the recently released U.S. Space Transportation Policy outlines a next-generation technology development program and specifically endorses development of on-orbit servicing capabilities. In addition to discussing the evolution of U.S. space policy, this section will also address other important stakeholders of space tug operations and the challenges these stakeholders might impose on implementation of a space tug system.

2.1 Post-Cold War National Space Policy

Until recently, the only published post-Cold War statement of U.S. space policy was the 1996 Presidential Decision Directive (PDD) guidelines for national space security.[5] Developed by the National Science and Technology Council (NSTC), PDD/NSTC 8 provides a direction for U.S. space activities that is consistent with the development of an on-orbit servicing capability. Although space tug operations are not mentioned specifically in PDD/NSTC 8, a space tug system might constitute a means of accomplishing many of the guidelines outlined in the directive. For example, in the guidelines for civil space activities, NASA is instructed to develop "new and innovative space technologies…to improve the performance and lower the cost of future space missions." The potential space tug capabilities of relocation and refueling of satellites—which otherwise will fail to perform their mission—are certainly "new and innovative space technologies" that come at a lower cost than the replacement option. Indeed, NASA's Hubble Telescope provides not only a dramatic precedent for future servicing missions but also an excellent example of a space system remaining state-of-the-art through a series of servicing missions—at a fraction of the cost of launching new systems. By automating a process currently only performed by astronauts and Shuttle, space tugs offer the potential to expand the benefits of servicing enjoyed by Hubble to many government and commercial satellites.

2.2 New National Space Policy

The new U.S. Space Transportation Policy, authorized by President Bush in December 2004 and released by the White House Office of Science and Technology on January 6, 2005, extends and clarifies the 1996 Presidential Decision Directive in the area of on-orbit servicing by explicitly endorsing space tug technology development.[6] The new policy emphasizes a technology development program "that dramatically improves the reliability, responsiveness, and cost of access to, transport through, and return from space." This transformation of the U.S. space transportation infrastructure is found essential both to augment "space-based capabilities in a timely manner in the event of increased operational needs," and minimize "disruptions due to on-orbit satellite failures, launch failures, or deliberate actions against U.S. space assets." As a means to these improvements, U.S. Space Transportation Policy directs a sustained research and development effort that includes "automated rendezvous docking, and the ability to deploy, service, and retrieve payloads or spacecraft in Earth orbit."

2.3 Policy Challenges

Although space tug technology will likely be developed in accordance with U.S. Space Transportation Policy, the actual deployment of such a system is uncertain due to the nature of its potential customers. The primary policy challenge facing implementation of a tug system is gaining the trust of satellite operators to fund lifetime extension or orbital transfer missions. This challenge is particularly great in the Air Force, where program managers of national space assets are traditionally risk-adverse and might hold a short-term outlook of satellite operations given that the tenure of many program managers is less than two years.[7] To overcome this barrier, it might be necessary to review the incentive structure of Air Force program managers. Lengthening tours-of-duty of program managers or providing career incentives to program managers who extend mission life of space assets are possible improvements. Another alternative is to make mission life extension a requirement for high-value space assets.

All space-faring nations are stakeholders in the development of a space tug system. Foreign nations might welcome the development of a geosynchronous space tug system as an enabling tool for flexible mission profiles or might fear the new capability on safety or strategic grounds. The potential for negative international reaction to a U.S. orbital correction capability is one the key challenges facing space tug implementation. What if space tugs are perceived as a space weapon and the U.S. government faces stiff international resistance? In the eyes of U.S. policymakers, will the political capital required to gain international acceptance of this capability outweigh the extended lifetimes of national space assets? During the Cold War, the Soviet Union viewed the Space Shuttle as a weapon in Low Earth Orbit, capable of docking and manipulating a variety of sensitive on-orbit assets. In light of these concerns, one strategy to improve international acceptance of on-orbit servicing is to describe in detail what the functions of a tug system are (orbital transfer and lifetime extension) and what they are not (militarization of space). Another mechanism to increase international acceptance of a space tug system is to offer a notification protocol whereby mission profiles of tugs are shared with other space-faring nations. The issue of bringing transparency to space tug operations is discussed further in section 3.1.2, entitled "On-Orbit Liability and Registration."

3. LEGAL CONSTRAINTS

Legal constraints for space tug operations can be divided into two categories: customary international law and national law. Since its establishment in 1959, the United Nations Committee on Peaceful Uses of Outer Space (COUPOS) has launched five major international legal instruments that form the bulk of laws governing space. Other customary international space laws are derived from bilateral arms control treaties between the U.S. and U.S.S.R. National legal principles relevant to space tug operations include U.S. criminal law pertaining to interference with the operation of a satellite.

3.1 International Legal Principles

Three COUPOS treaties—the 1967 Outer Space Treaty, the 1972 Convention on International Liability for Damage Caused by Space Objects, and the 1975 Convention on Registration—contain provisions which may set forth legal constraints for space tug operations. In addition to the COUPOS treaties, the 1973 International Telecommunication Convention also has implications for space tug parking orbits and phasing maneuvers.

3.1.1 Jurisdiction and Control of Space Objects

According to Article VIII of the Outer Space Treaty, a country retains jurisdiction and control over its registered space objects. Additionally, Article VI provides that states bear international responsibility for government and private space activities and must supervise and regulate national activities in space whether conducted by government agencies or non-governmental entities.

A space tug capability in GEO would enable a variety of missions including the relocation of functioning space objects and the retrieval or salvage of nonfunctioning space objects. However, customary international law strictly limits missions of this variety to national space assets. Peacetime retrieval, alteration of orbit, or any other form of interference with foreign space objects would be unlawful without prior consent.

The retrieval or removal of nonfunctioning foreign space objects is also banned by customary international law. Article VIII of the Outer Space Treaty clearly holds that state property remains state property unless relinquished. The case of non-functioning satellites on-orbit is analogous to the case of sunken ships. The United States and most other countries have consistently upheld the principle that sunken ships remain the property of the flag state unless rights are transferred or explicitly abandoned (where abandonment cannot be implied from the absence of acts demonstrating interest in such property, even over long periods of time). Therefore, although a space tug capability near the geostationary belt would make possible a variety of relocation, retrieval, and salvage missions, customary international law would limit such operations to strictly national space objects.

3.1.2 On-Orbit Liability and Registration

The issue of liability in space has drawn attention since the dawn of the space age. Orbital transfer vehicles designed to dock with multiple space objects such as space tugs are likely to attract further attention to this area of international concern. Although the Outer Space Treaty provides that states bear international responsibility for all national space activities, it does not provide any mechanism for resolving liability disputes that may arise.

The 1972 Convention on International Liability for Damage Caused by Space Objects fills the void left by the Outer Space Treaty by clearly defining customary international legal principles in the areas of fault and liability and by establishing a dispute settlement mechanism for damage caused by collisions in space. Article II of the Liability Convention provides that a launching state is absolutely liable for damage caused by its space objects in space, and Article III provides that this liability is determined by fault. In cases where diplomatic negotiations fail, the Liability Convention enables signatories to request the formation of a Claims Commission to rule on the issue of fault and to determine the amount of compensation due. However, in the history of the Liability Convention, a Claims Convention has never been established due to the low frequency of incidents of damage in space from collisions between spacecraft or with space debris. The most serious collision in space—the 1996 collision of a French Cerise military satellite with an Ariane upper stage—involved two French space objects, so the question of international liability never arose.[8]

Table 1 – Relevant international and national legal instruments

1967 Outer Space Treaty	Article VIII: Provides a state jurisdiction and control over its registered space objects
1972 Liability Convention	Article II: Holds a state liable for damage caused by its launched space objects
	Article III: Determines liability by fault
	Article IV: Holds states jointly liable if a collision of their space objects causes third party damage
1973 Telecommunication Convention	Bans harmful interference to the communications of other states
1975 Registration Convention	Requires states to maintain a registry of objects launched into space
US Criminal Law Title 18, Section 1367	Makes interference with satellite communications a federal offense

Space tug operations would require new interpretations of the Liability Convention and could serve as the impetus for innovative contractual relationships between space tug operators and operators of target satellites. A worst-case scenario illuminates why the assignment of fault in the course of space tug operations may not be a clear decision. Suppose a tug fails to safely rendezvous with a target satellite and instead crashes into the satellite. Then, suppose debris from the fractured satellite damages a third-party satellite. Which party is at fault for the third-party damage, the tug operator or the operator of the fractured satellite that physically caused the damage?

The Liability Convention holds the launching state responsible for damage caused by its space objects and offers insight into the case of third-party damage. According to Article IV, in the event of damage being caused in space to a space object of one launching state by a space object of another launching state, and of damage thereby being caused to a third state, the first two states are jointly liable. Furthermore, in cases of joint liability, the burden of compensation for the damage is divided between the first two states in accordance with the extent to which they were at fault. Finally, if the extent of the fault of each of these states cannot be established, the burden of compensation shall be divided equally between them.

The uncertainty associated with liability claims would need to be addressed contractually between space tug service providers and satellite operator customers prior to space tug operations. The Liability Convention is not sufficient in itself to resolve liability. The Convention has already become outmoded in other areas, such as commercial launch, where fault is assigned to launching states despite the frequent practice of packaging a payload from one state inside a launch vehicle of another. Just as liability for multi-party commercial launches are resolved contractually, so, too, might liability issues be resolved for space tug operations.

The 1975 Convention on Registration of Space Objects requires a state to maintain a registry of objects it launches into space. Information on each registered object—including date and location of launch, basic orbital parameters, and the general function of the space object—is to be provided in timely manner to the United Nations register for full and open access to the international community.

Current customary international law pertaining to registration and liability does not assign direct legal constraints to space tugs but may be amended in the future as satellite servicing operations mature. A significant exemption to the Registration Convention is the lack of a requirement for states to provide updated orbital properties if space objects move from original orbits as functioning space tugs certainly would. Although national security space assets currently move to unreported orbits without issue, the high frequency of phasing maneuvers inherent to space tugs may prompt calls for eliminating this gap in the Registration Convention. Liability concerns could drive calls for strict notification requirements of changing space tug orbital properties. For example, in the case of a space tug operating in undisclosed orbit and accidentally colliding with another state's space object, the injured party would want accurately to attribute fault for a liability claim to the offending tug, not be led to believe that orbital debris is the cause of damage.

3.1.3 Noninterference with Communications

The 1973 International Telecommunication Convention holds that all space objects must be operated so as not to cause harmful interference to the radio services or communications of others. Traditionally, this interference is linked to issues of limited bandwidth and frequency. For space tug operations in the highly-populated GEO belt, it is also necessary to avoid physical blockage of communication beams. Appropriate parking orbits and rendezvous maneuvers for avoiding communication beams of GEO spacecraft during space tug operations are discussed in the next section.

3.2 U.S. National Law

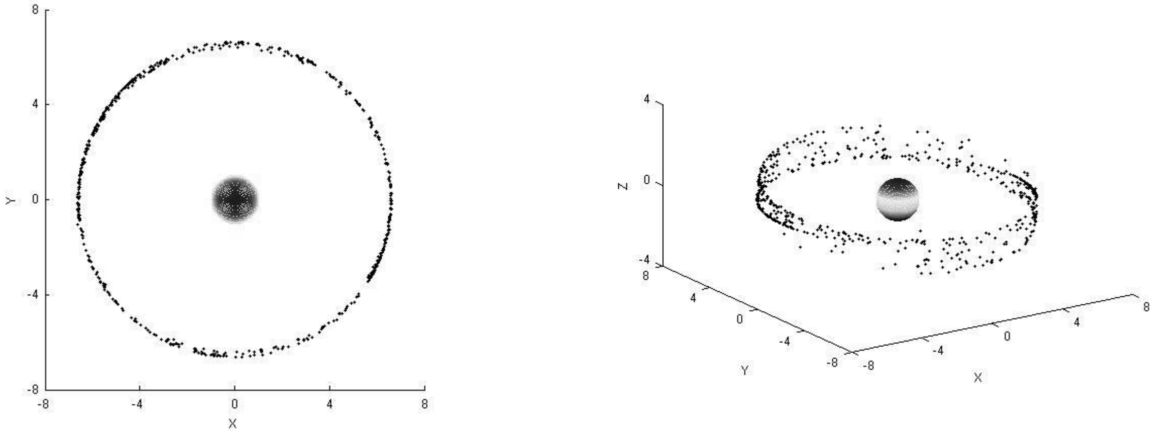
U.S. criminal law Title 18, Section 1367, pertains to interference with the operation of a satellite. This statute makes it a federal criminal offense for anyone who, "without the authority of the satellite operator, intentionally or maliciously interferes with the authorized operation of a communications or weather satellite or obstructs or hinders any satellite transmission." Title 18, Section 1367, specifically exempts U.S. government agencies involved in lawfully authorized investigative, protective, and intelligence activities. For space tug operations in the GEO belt, this statute serves to reinforce the international requirement of noninterference with communications.

4. SPACE TUG OPERATIONS

This section addresses issues associated with the operation of a geosynchronous space tug with a focus on parking orbit selection and target spacecraft rendezvous strategies. The impact of assumptions implicit in the geosynchronous space tug concept are briefly discussed as well. The most important considerations throughout all phases of space tug operation–or any on-orbit servicing operation–are safety and reliability. It is imperative that tug operations not damage or otherwise interfere with the function of the target spacecraft or any other nearby spacecraft. This follows, for one, from the issue of liability discussed in the previous section. Additionally, program managers for major military space programs have identified reliability as the primary operational concern for space tugs. Other considerations in space tug operations include fuel efficiency and timeliness. These are secondary to safety and reliability. Typically, timeliness will be a low priority, so fuel efficiency will be the primary driver of tug operations after safety. It is conceivable, however, that an urgent mission might utilize a faster rendezvous strategy, albeit with a higher fuel consumption than would otherwise be necessary.

4.1 Parking Orbit

Figure 2 shows all unclassified space objects in geosynchronous or near-geosynchronous orbits as of January 10, 2005, according to element sets available from Air Force Space Command.



(a)

(b)

Figure 2 – Geosynchronous space objects, 10 January 2005. The view in (a) is from above the north pole. The positive y-axis points toward 0° longitude and the positive z-axis in points toward the north pole. The axes have units of Earth radii.

Parking a space tug in a geostationary slot seems out of the question given the high commercial and military value of these slots. However, as Figure 2 indicates, unused regions of the geostationary belt do exist where a space tug "parking space" could be located. A slightly inclined geosynchronous orbit can be ruled out as a parking orbit by the expensive maneuvers that would be required to reach target spacecraft in the geostationary belt. A better option for space tug parking orbits might be equatorial orbits near geosynchronous altitude.

The altitude bounds on potential equatorial parking orbits are shown in Figure 3 and are established by the United States Government Orbital Debris Mitigation Standard Practices. The upper limit on disposal orbit apogee between medium Earth orbit (MEO) and GEO is an altitude of 35,300 km, and the lower limit on disposal orbit perigee above GEO is 36,100 km. Furthermore, it may be prudent to exclude orbital altitudes between approximately 50 km below and 50 km above the geostationary altitude because the probability of collision, while still low, is significantly higher at these altitudes due to variance in the actual orbital altitudes of geosynchronous satellites (see Figure 3). Estimates of collision probabilities according to altitude were calculated using the Poisson distribution and principles of the kinetic theory of gases based on research conducted by the Federal Aviation Administration's Office of Commercial Space Transportation Licensing and Safety Division.[9] A ten year tug lifetime was assumed.

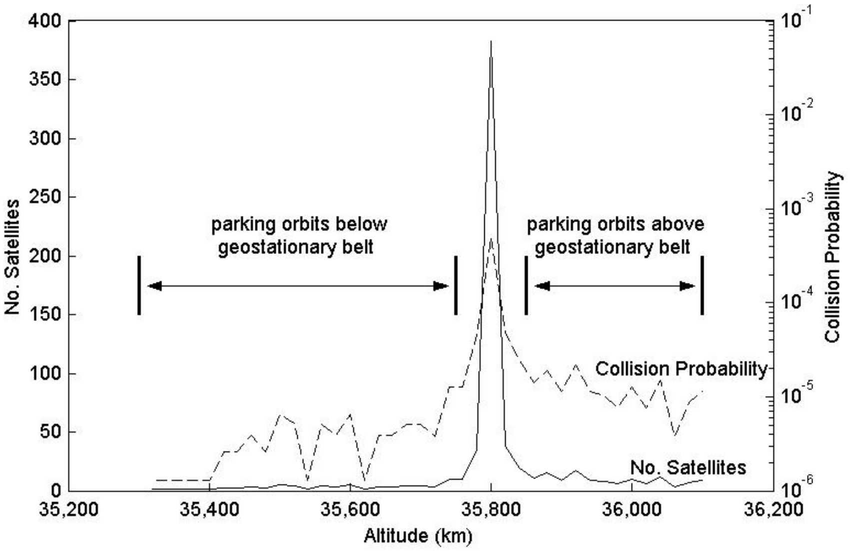


Figure 3 – Possible geosynchronous space tug parking orbit altitudes

Velocity change (ΔV) requirements for stationkeeping are approximately constant over the range of parking orbit altitudes shown in Figure 3. However, the ΔV and time requirements to reach geosynchronous altitude do vary over this range. The ΔV requirement varies between 1.8 m/s and 16.6 m/s depending on the altitude change necessary. Propulsion choice (*i.e.*, chemical vs. electric) affects the time requirements for transfer from parking to geosynchronous orbit, although the ΔV's between chemical and electric propulsion are nearly equal since the kinetic inefficiency of a continuous thrust transfer is low for small changes in altitude near geosynchronous orbits. The time required for transfer via electric propulsion can range to as high as 180 days, depending on the acceleration produced by the engine, while the transfer time via chemical propulsion is approximately 12 hours over the range of possible parking orbit altitudes.

The advantage of low thrust electric propulsion systems with specific impulses exceeding 1,000 seconds is a combination of reduced tug mass and increased ΔV capability. On the other hand, because of the slow, spiraling trajectory followed when changing altitude, the tug would orbit repeatedly at altitudes where the probability of collision is heightened slightly. In addition, the power requirement for electric propulsion systems, ranging from 0.5 kW up to 4.5 kW, is much higher than for chemical propulsion.[10] It should be noted that even if a space tug were equipped with electric propulsion for all or part of the transfer between its parking orbit and the target orbit, chemical thrusters would still be required for maneuvers in close proximity to the target spacecraft. The use of electric propulsion to reach the vicinity of the target spacecraft would also restrict the responsiveness of a space tug. Although rendezvous times in geosynchronous orbit are on the order of days, not hours, it may be desirable to assure a shorter response time than is achievable using electric propulsion.

A final issue relevant to the tug parking orbit is the potential for interference with other geosynchronous spacecraft. Two types of interference could result from space tug operations. The first is communications interference. The Federal Communications Commission and International Telecommunication Union licensing processes are intended to mitigate communications interference between communications satellites in geostationary orbits, but it is unclear how these processes would apply to a spacecraft constantly moving near the geostationary belt. However, given the number communications satellites already operating in the geostationary belt and the relatively low communications requirements of a space tug, it is unlikely that communications interference would be a major issue. The second type of interference is electromagnetic interference (EMI). The potential for electromagnetic incompatibility between a tug and target has not been fully explored.

4.2 Approaching the Target Spacecraft

The position of a satellite at geosynchronous altitude can be determined from the ground to within 24 km in the along-track direction, 17 km in the cross-track direction, and 2.6 km in range.[11] Therefore, a tug could conceivably navigate to within a few kilometers of the target satellite on its own. Realistically, this distance will be larger, for example due to the propagation of small thrusting errors. Performing the transfer from parking orbit to target orbit under ground supervision should help reduce such errors and assure that the tug can be brought reliably to within radar range of its targets as well as ease autonomous navigation requirements. Once the target is acquired by an on-board radar or other long-range sensor, rendezvous maneuvers can commence.

Space rendezvous is a complex but well understood procedure. Fehse (2003) provides one introduction to automated rendezvous in space and discusses the major drivers of approach strategy.[12] It is impossible to devise a detailed rendezvous sequence here since target- and time-specific information would be required. Given the necessary emphasis on the safety of the target spacecraft, passive trajectory safety should heavily influence planning. A longer-term look at trajectory safety must take into account disturbance forces. The most prominent trajectory disturbances at geosynchronous altitude are due to solar radiation pressure and, at close range, thruster plume impingement. Thruster plume impingement is also a concern in terms of direct damage to the target spacecraft. Solar radiation pressure is relatively easy to model. To analyze fully the effects of thruster plume impingement, much more detailed modeling reflecting the geometry of both the tug and target as well as the nature of thruster plumes is needed. This is beyond the scope of the present paper.

A method of final approach that is advantageous in terms of safety and fuel consumption, based on Zero Closing Speed (ZCS) guidance, has been developed by Bell (2003). This type of approach consists of a series of small “hops” toward the target, either along V-bar (aligned with the velocity of the target spacecraft) or R-bar (aligned with the nadir from the target spacecraft). Simulations performed on hardware at the Naval Research Laboratory (NRL) Spacecraft Robotics Engineering and Controls Lab (SRECL) have validated this method of final approach.[13] The direction of final approach (*e.g.*, +/- V-bar, +/- R-bar) depends on the state of the target satellite. For an attitude-stable but non-operational target satellite, the direction of final approach can simply be chosen according to the location of the most convenient docking area on the target spacecraft. Operational targets could require that the tug dock from a specific direction to maintain a certain attitude. For instance, if the target were a communications satellite, it may require an approach from above in order to maintain a nadir-pointing orientation. In the case of uncooperative or tumbling targets, approach and docking could prove exceedingly difficult.

Automated rendezvous and docking has already been demonstrated in low Earth orbit (LEO) by the Japanese ETS-VII mission.[14] Other demonstrations are planned as of this writing, including NASA’s Demonstrator for Autonomous Rendezvous Technology (DART) to be launched after March 2, 2005, and DARPA’s Orbital Express. The state of the art in relative navigation lies in relative GPS and sensors such as the Advanced Video Guidance Sensor (AVGS).[15, 16] However, these technologies are not entirely suitable for use by a space tug as it is conceived in this paper. At geosynchronous altitude, the use of relative GPS is not possible. Additionally, the space tug cannot assume that the target satellite is cooperative. The advances in autonomous navigation technology that will enable a space tug to rendezvous and dock with an arbitrary target in geosynchronous orbit are under development but not yet flight-proven. A flight demonstration of the ability to reliably deal with uncooperative targets will be a critical milestone on the way to an operational space tug.

4.3 Assumptions

There are implicit assumptions in this section that a space tug system would consist of a single spacecraft and that its targets would be single spacecraft such as Intelsat or Milstar satellites. These assumptions permit this analysis to concentrate on issues associated with the tug parking orbit and rendezvous with the target spacecraft. Other potential space tug architectures, such as those involving multiple tugs or on-orbit fueling stations, are not considered. Looking forward, technological advances could radically alter the architecture of target spacecraft, which would in turn affect tug operations. For instance, future concepts for geostationary communications satellites include tethered or formation flying satellite clusters and even swarms of up to 100,000 pico-satellites.[17] In the case of tethered or formation flying spacecraft, the problem of tugging would be compounded by the dynamics of tethers and the need to move multiple modules. For clusters of very small satellites, orbit determination at geosynchronous altitudes could become a problem.

5. FINANCIAL CHALLENGES

A variety of civil and military programs are in development to verify technologies needed for space tug operations and on-orbiting servicing. It may seem that major technological breakthroughs are necessary before space tugs are launched. In reality, this is only one aspect of the problem. Perhaps the greatest challenge to implementation of space tug systems is financial. A number of papers have made a strong business case for space tugs.[2,3,4] However, little work has been done in the areas of financing and insuring space tug operations.

5.1 Existing Financing Models

Government-commercial cost sharing precedents exist for space assets and other shared resources. However, it is unclear what type of financing model space tug operations will assume or how the issue of proprietary development will impact financing. The Commercial Space Competitiveness Act of 1992 authorized NASA and other agencies to make their facilities available to private entities. This provides a number of options for ownership, operation, and use of a satellite servicing system. Three financing models are discussed below.

5.1.1 Government owned and operated with no commercial use

This most restrictive case would entail government development, ownership, and operation of a space tug operation with no cost-sharing or use by private industry. An example is the Milstar satellite communication system. Although the most simplistic financing model with near-term potential, an all-government system would limit the benefits of space tug operations to civil, military, and intelligence space systems.

5.1.2 Government owned and operated with commercial use

The United States has a history of developing systems for government purposes that end up being utilized as shared resources. For example, the national highway system was constructed to satisfy a defense policy of moving troops around the country more efficiently.

An example of government ownership and operation in space with commercial use is the Tracking and Data Relay Satellite System (TDRSS). TDRSS is owned by NASA and supports near-real time communications between low Earth orbit satellites and Earth. Under the Commercial Space Competitiveness Act of 1992, NASA allows the private firm SpaceData International (SDI) of the marine seismic industry to operate four underutilized TDRSS satellites on a time-share basis. SDI provides per-minute payments to NASA for use of the TDRSS satellites in frequency bands allocated to US government use.[18] Similarly, if the Air Force and the National Reconnaissance Office were to develop a space tug system, it may make sense to allow commercial use at marginal cost.

5.1.3 Commercially owned and operated for commercial and government users

Commercial ownership and operation of a space system for commercial and government users (*e.g.*, the Iridium Satellite System) is another financing option for space tugs. Currently, Orbital Recovery Corporation is developing an “orbital tugboat” concept, Spacecraft Life Extension System (SLES), to supply propulsion, navigation and guidance to maintain a satellite in its orbital slot for 10+ years. Exploratory commercial ventures such as SLES will gain credibility as the government invests in a sustained research and development program of autonomous rendezvous and docking technology.

The private sector in the United States is particularly adept at developing commercially-viable systems once the government has bridged the gap between fundamental research and deployable technology by funding high-risk research and development. For example, the origins of the internet can be traced to the “ARPANET” project of the Defense Advanced Research Projects Agency during the Cold War which aimed to create a distributed communications network that could survive a nuclear strike. Satellite servicing and space tug technology investment, such as continued funding of DARPA’s Orbital Express and SUMO programs, may have equivalent implications for the satellite industry.

5.2 Insuring Space Tugs

The TDRSS-SDI relationship is a good example of a government owned and operated space system with commercial use. However, the liability issue associated with the government-commercial sharing of TDRSS bandwidth is not of the same magnitude as the liability issues associated with a spacecraft approaching and docking with another spacecraft. Sharing excess bandwidth certainly does not entail the same level of risk as docking two spacecraft. In addition to the safe approach maneuvers discussed in the previous section, mitigation of the risk associated with space tug operations can also be accomplished through financial instruments such as on-orbit insurance.

Space insurance providers are typically large multinational conglomerates with large premium bases. The space insurance industry is characterized by volatile market conditions. Current premiums are closely tied to recent returns. In recent years, the space insurance market has “hardened” after the “soft” market of the late 1990’s that featured low premiums and coverage often extending from launch plus five years of mission life.[19]

Given that it is often difficult for satellite operators to secure reasonable premium for in-orbit insurance policies for normal operations, obtaining affordable insurance for space tug missions is a significant challenge. During the assessment process for space mission coverage, underwriters scrutinize the intended mission profile and conduct detailed reliability analyses of the launch vehicle and satellite. With an underwriting process that places great weight on past performance, obtaining reasonable insurance for space tug missions in the near-term may be impossible. As such, it is critical for the government to support standard-setting and proof-of-concept satellite servicing missions to provide commercial space tug operators access to insurance.

6. CONCLUSIONS

From a policy standpoint, the greatest difficulty in rolling out an operational space tug will be overcoming resistance from the international community. Despite the functional intentions of the tug operator, having a space tug capability on orbit is sure to generate some objections as the Space Shuttle did during its development. Avenues exist for mitigating this concern. The U.S. military is adept at summarizing its core functionalities in language that is readily understood in the international community. For instance, military tug operations could be framed in terms of “freedom of space.” A commercial tug might frame its operations in terms of reducing the liability of companies responsible for space junk.

On the operational side, the technical hurdles that remain in the way of a space tug are not insurmountable. In fact, as has been noted, the major remaining technology developments are under way. The most significant of these is an arbitrary docking capability. One area that needs to be studied in more detail is the potential for electromagnetic interference between the tug and the target spacecraft. In the authors’ estimation, this will not present any major problems yet warrants further study. A larger problem for an operational space tug will be maintaining its capability across changing satellite architectures, which could eventually be very different than what is in orbit presently.

Perhaps the greatest barrier to an operational space tug is the financial challenge. Although U.S. Space Transportation Policy endorses on-orbit servicing technology development, risk-adverse military space program managers are unlikely to pay for servicing capabilities individually, and the research and development costs combined with the risk appear to be too high for the commercial sector to undertake development on its own. While innovative financing arrangements between government and industry may be possible once an operational space tug exists, it is likely that the government will need to continue to bear the brunt of unmanned on-orbit servicing technology development through programs such as Orbital Express and Spacecraft for Universal Modification of Orbits (SUMO).

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