Time Model of Reduced Microaccelerations and Propellant Usage for an ISS Serviced Free-Flying Experiment Platform

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Abstract
The space shuttle provides for up to sixteen days in orbit to allow researchers to conduct microgravity research. Although conditions are less desirable during its construction, the International Space Station (ISS) promises to provide at least a thirty-day window of low microaccelerations after its completion. For both the shuttle and the ISS, activities such as orbital maneuvering, reboost, docking and undocking, and crew movement can impact the results of microgravity experimentation. These unwanted accelerations are often measured and reported to investigators to help the account for any unexpected results, but experimental platforms designed to minimize these disturbances are of interest. Research presented in this paper seeks to provide simple models to investigate the amount of microgravity experimentation time that would be available for an ISS serviced free-flying platform with the constraint of available ΔV for such platform. The timeline investigated includes the platform berthed at the ISS, separation of the platform from the station to various relative position, degradation of both the station and platform, and rendezvous of platform at the station.
Keywords: International Space Station (ISS), Space Shuttle, Microgravity, Perturbations.

1. INTRODUCTION

The space shuttle provides for up to around sixteen days of experimentation time on orbit for microgravity research. Although, microgravity research occurs during most space shuttle missions, the extended sixteen days is afforded by missions specifically designed for microgravity and life sciences research. During these missions, shuttle operations are specifically designed and scheduled to minimize the accelerations caused by activities such as maneuvering and docking. The reliance of the International Space Station construction on the space shuttle fleet has made these extended research periods even more difficult to come by.

The addition of the International Space Station (ISS) promises to be a great improvement to the microgravity researcher's lab resources. The space station is expected to provide desirable microgravity conditions 180 days out of each year in increments of at least 30 days [1].

Although, one of the primary reasons for the construction of the space station is to support the microgravity environment for research, the windows of acceptable conditions are limited by the nominal operations required for station upkeep. These activities include regular construction visits from the space shuttle before station completion, crew arrival and departure, supply vehicle docking and undocking. After completion, station orbit raising maneuvers are also anticipated every three months. In addition to these major disturbances to the microgravity environment, undesirable microaccelerations can also be induced by crew movement within the station. The limitations to the suitability of the International Space Station for long duration microgravity research raises interest in free-flying microgravity experiment platforms.

There have been several free-flying experiment platforms designed for use within the space shuttle program. Since the mid-eighties the Spartan Retrievable satellites have provided short duration opportunities for scientific research payloads to operate independent of the shuttle environment [2]. Other freeflyers include the EURECA [3] and the SPAS [4]. These free-flyers all had something in common: the expectation of a rendezvous and retrieval by the space shuttle. A space station serviced free-flying platform would have to take on the burden of performing the rendezvous. In response to such a challenge, the European Space Agency (ESA) had been making plans for the development of the Columbus Man-Tended Free-Flyer (MTFF) as one of its hardware contributions to the space station Freedom.

This research presented in this paper sought to develop a simple model of the interaction between the International Space Station Alpha and a station service free-flying experiment platform to roughly determine the ΔV budget requirements for the platform considering various periods of separation.

2. METHODOLOGY

2.1 Investigation Scenario

The intention of this investigation is to determine how long a typical free-flying experiment platform could perform operations while drifting away from the ISS before its propellant limitations would require its return. The investigation scenario begins with the experiment platform, in this case the modified Space Flyer Unit (SFU), berthed at the ISS. The platform then separates from the station with its initial relative velocity being provided by springs on the docking mechanism. The assumption here is that no SFU propellant would be needed to initiate the separation maneuver.

The separation continues for a preset time period before SFU thrusters bring its velocity relative to the ISS to zero for station keeping at a safe separation distance. For this investigation the initial separation velocities are arbitrarily set to 0.1 meters/second in the x, y, and z directions and the separation time is 30 minutes. The model allows other values to be used here which would affect the SFU propellant usage, but the ΔV used for this maneuver is small compared to others perform during the simulation. The important thing is that the separation of the platform be to a safe relative position from the station before its microgravity experimentation period begins.

After a completion of the separation maneuver, the investigation scenario includes an experimentation period for the platform. During this period, the ISS and SFU platform drift away from each other due to the varying spaceflight dynamics characteristics of each vehicle. The minimum experimentation period of interest is thirty days. This is because, as discussed previously, that is the minimum continuous microgravity experimentation period to be provided on the International Space Station. The maximum experimentation period is constrained only by the ability of the platform to rendezvous with the space station within its propellant budget and length of useful experimentation time. A range of experimentation periods was studied during this investigation.

The last maneuver performed during this investigation scenario is the experiment platforms return to the International Space Station for servicing. The ability of the SFU to rendezvous with the ISS depends the relative positions of the two vehicles at the end of the experimentation period and the propellant available to the SFU. This investigation assumes a single targeting sequence after the completion of the experimentation period to complete the rendezvous. Because of this, there are times where the relative positions of the two vehicles do not allow a transfer orbit which avoids hitting the Earth. Intermediate targeting burns during the period when the platform is away from the station and considered, but discarded as they would be disruptive to the microgravity research.

2.5 Equations and Algorithms

2.2.1 Experiment Platform Separation

The experiment platform separation sequence was modeled using Hill's equations in an algorithm presented by Vallado [6] as follows:

Given: Initial position and velocity of the platform $\left\{x_0, y_0, z_0, V_{x_0}, V_{y_0}, V_{z_0}\right\}$

$$\omega = \sqrt{\frac{\mu}{r^3}} \tag{1}$$

$$x(t) = \left(\frac{V_{x_0}}{\omega}\right)\sin(\omega t) - \left(3x_0 + 2\frac{V_{y_0}}{\omega}\right)\cos(\omega t) + \left(4x_0 + 2\frac{V_{y_0}}{\omega}\right) \tag{2}$$

$$y(t) = \left(6x_0 + 4\frac{V_{y_0}}{\omega}\right)\sin(\omega t) + 2\left(\frac{V_{x_0}}{\omega}\right)\cos(\omega t) - \left(6\omega x_0 + 3V_{y_0}\right)t + \left(y_0 - 2\frac{V_{x_0}}{\omega}\right) \tag{3}$$

$$z(t) = z_0\cos(\omega t) + \left(\frac{V_{z_0}}{\omega}\right)\sin(\omega t) \tag{4}$$

$$V_x(t) = V_{x_0}\cos(\omega t) - \left(3\omega x_0 + 2V_{y_0}\right)\sin(\omega t) \tag{5}$$

$$V_y(t) = \left(6\omega x_0 + 4V_{y_0}\right)\cos(\omega t) - 2V_{x_0}\sin(\omega t) - \left(6\omega x_0 + 3V_{y_0}\right) \tag{6}$$

$$V_z(t) = -z_0\omega\sin(\omega t) + V_{z_0}\cos(\omega t) \tag{7}$$

For this investigation, the initial position is assumed to be berthed with the station at {0,0,0} and the initial velocity imparted by the separation springs is assumed to be 0.1 m/s along each axis. After a separation time of t, the platform produced the required ΔV to halt the separation.

2.2.2 Orbit Propagation considering Two-Body Motion and Perturbations

The orbit propagation for the model used a Fourth Order Runge-Kutta numerical integration scheme. For this model, the two-body motion and the drag and gravitation perturbations were considered. For the gravitational perturbation, the J_2 geopotential coefficient is used to account for the non-homogeneous Earth. The atmospheric drag, considered the principle non-gravitational force, is also modeled [7].

The foundation for propagation equations used, is the two-body equation, $\vec{a} = -\frac{m}{r^2}\frac{\vec{r}}{r}$. This equation produces the following six first order equations:

$$\frac{dr_x}{dt} = v_x \quad (8)$$

$$\frac{dr_y}{dt} = v_y \quad (9)$$

$$\frac{dr_z}{dt} = v_z \quad (10)$$

$$\frac{dv_x}{dt} = -\frac{m}{r^3} r_x \quad (11)$$

$$\frac{dv_y}{dt} = -\frac{m}{r^3} r_y \quad (12)$$

$$\frac{dv_z}{dt} = -\frac{m}{r^3} r_z \quad (13)$$

To account for the perturbations due to gravitation, Vallado [6] offers the following simplified accelerations that can be added to the $\frac{dv}{dt}$ equations:

$$a_x = -\left(\frac{3J_2 m R_{Earth}^2 r_x}{2r^5}\right)\left(1 - \frac{5r_k^2}{r^2}\right) \quad (14)$$

$$a_y = -\left(\frac{3J_2 m R_{Earth}^2 r_y}{2r^5}\right)\left(1 - \frac{5r_k^2}{r^2}\right) \quad (15)$$

$$a_z = -\left(\frac{3J_2 m R_{Earth}^2 r_z}{2r^5}\right)\left(1 - \frac{5r_k^2}{r^2}\right) \quad (16)$$

Vallado [6] also offers the following simplified accelerations for atmospheric drag assuming an exponential atmosphere, no winds, and that V_{rel} equals the satellite velocity:

$$a_x = -\left(\frac{1}{2m}\right) r C_D A v v_x \quad (17)$$

$$a_y = -\left(\frac{1}{2m}\right) rC_D Avv_y \tag{18}$$

$$a_z = -\left(\frac{1}{2m}\right) rC_D Avv_z \tag{19}$$

2.2.3 Platform Rendezvous

This investigation was looked into using several techniques presented by Vallado [6] to perform the final rendezvous sequence. The Lambert-Universal Variable and the Lambert-Gaussian Solution were used with some success, but the Battin Method discussed by Vallado [6] for solving Lambert's problem proved to be most stable for all of ISS and SFU relative positions, it was called to account for during the many simulations run.

2.3 Simulation

A C program has been prepared for the experiment platform simulation, that drives through the simulation scenario. 30 minutes initial separation time and the initial separation velocities $(\dot{x}, \dot{y}, \dot{z})$ were chosen arbitrarily to provide a safe distance between the ISS and SFU prior the start of the platform experimentation time. The experiment time variable is used to indicate the number of days the SFU remains separated from the ISS while performing its microgravity experiments.

The spacecraft characteristics include the drag coefficient (C_d), mass, and area values for the two spacecraft. The simulation parameters include options to enable/disable the drag and gravitational perturbations and the timestep for the numerical simulation. The initial ISS/SFU conditions were pulled from a current NASA data. The simulation starts with the SFU berthed with the ISS. The separation is modeled using the Hill's equations. The ISS orbit is propagated during the separation time and the SFU relative position is converted to inertial frame and applied to determine its position after the separation. Both the ISS and SFU position and velocity vectors are converted into orbital elements for output purposes.

The orbital decay portion of the simulation has two loops. The first loop propagates the simulation forward for the specified number of days while the second iterates through 24 hours per day. For each hour of the microgravity experimentation time, the simulation propagates the orbits of each spacecraft forward for one hour considering the two-body motion and the gravitation and drag perturbations and outputs the new state of the spacecrafts. Before moving forward another hour, the simulation then calculates the ΔV required for the rendezvous of the SFU platform with the station at that time.

As mentioned previously, the rendezvous calculation is performed using the Battin method. This Lambert function is imbedded in the targeting algorithm presented by Vallado [6]. The algorithm involves propagating the position and velocity of the ISS forward the time of the rendezvous maneuver (Δt), calculating the initial and final transfer velocities using the Lambert function, calculating the initial and final velocity changes, and checking to see if the calculated orbit will hit the Earth. This targeting process is repeating using Δt values from 20 to 130 minutes in 10-minute intervals in order to find the rendezvous acceptable path with the minimum ΔV used by the platform upon its return to the station. After finding the optimum transfer path, the simulation moves on through an additional hour platform expiration time until the specified number of days is reached.

3. RESULTS

The primary focus of this research is the development of the model of the space station and experiment platform system. Once the simulation code is completed and tested, several scenarios are run to test the original premise that a free-flying experiment platform can spend extended periods "drifting" away from its berth at the space station and safely return for servicing.

Figure 1 and figure 2 shows the effects of orbit propagation over time for ISS and SFU, respectively. As expected, the trend is for both the orbits to decay over time with the ISS losing more altitude because of its more detrimental drag characteristics. Although the ISS plans call for a re-boost to occur every three months to maintain a safe altitude after completion of construction, notice that the drag characteristics used for this investigation would not require such a maneuver despite the altitude loss [1].

The results of all of the simulation calculations are summarized in Figure 3. It shows the total ΔV required to complete the simulation scenario for one hour through 365 days of experimentation time for the platform away from the station. Included in the total ΔV values are relatively small and constant ΔV to complete the separation maneuver at the beginning of the scenario and the two burns required for the SFU rendezvous with the ISS to complete the scenario.

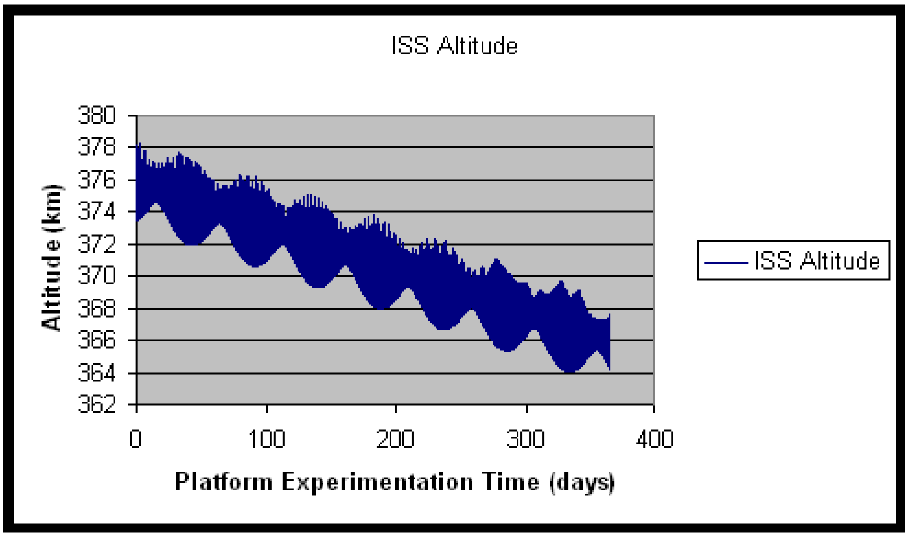

Figure 1 ISS altitude for one-year simulation

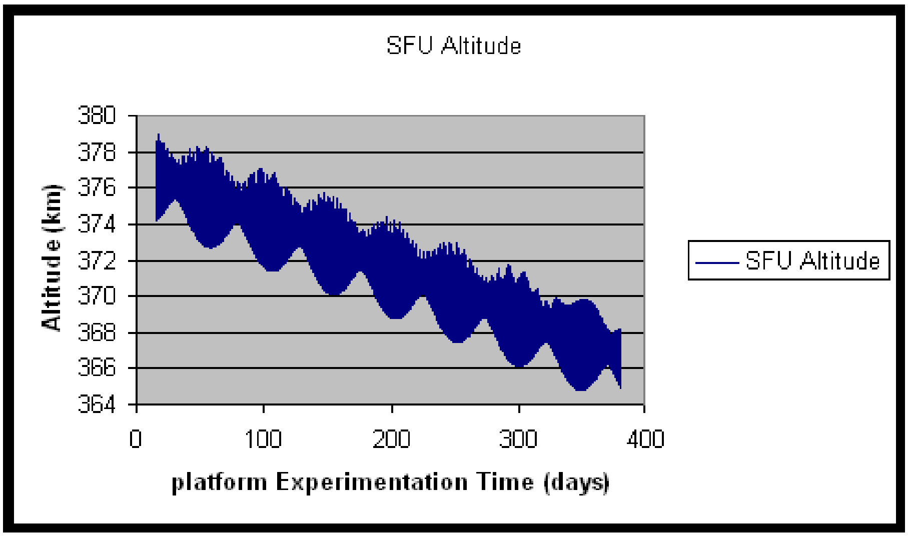

Figure 2 SFU altitude for one-year simulation

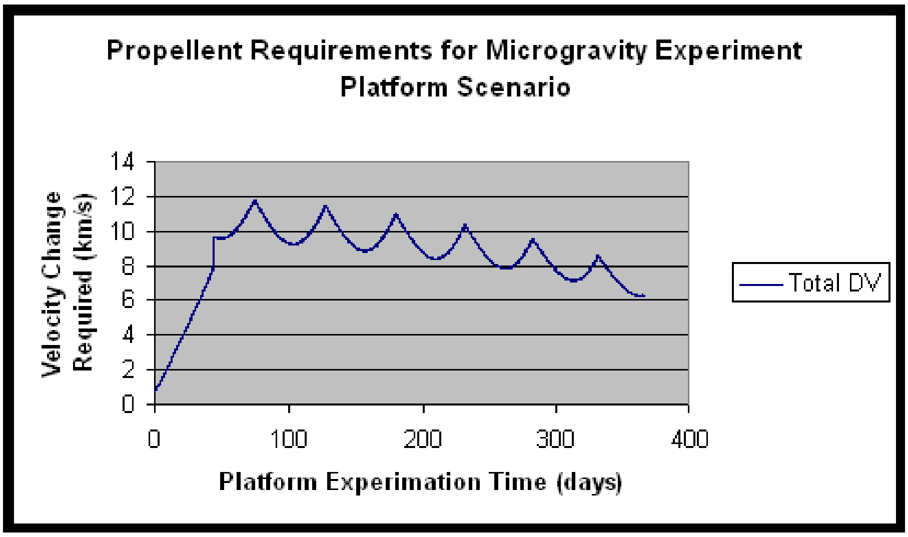

Figure 3 SFU ΔV required to complete scenarios up to a year away from station

4. CONCLUSION

A model was developed to address the scenario of ISS-serviced free-flying microgravity experiment platform separating from the space station, performing a variable period of experimentation, and returning to the station. The model considered the propagation of both the ISS and experiment platform orbits depending on user specified spacecraft characteristics. After initial simulation runs of the model, the results indicate that some existing free-flying experiment platforms designed for use and final retrieval by the space shuttle could support an ISS-based mission as described in this investigation. Future work associated with this investigation would be the addition of the periodic orbit raising of the space station and the refinement of the simulation parameters such as the spacecraft characteristics and the separation variables.

References

[1] NASA, “International Space Station Familiarization,” Mission Operations Directorate Space Flight Training Division, NASA, 1998.
[2] NASA, “Cassini,” Flight Project Data Book, NASA, 1995.
[3] Federation of American Scientists, “Eureca,” - https://fas.org.
[4] M. Grewing, I. Appenzeller, J. Barnstedt, S. Bowyer, M. Hurwitz, G. Kramer, N. Kappelmann, J. Krautter, H. Mandel, “ORFEUS,” Institut fur Astronomie u. Astrophysik, pp. 757-762,1998.
[5] Federation of American Scientists, “Columbus,” - https://fas.org.
[6] D. A. Vallado, “Fundamentals of Astrodynamics and Applications,” McGraw-Hill, 1997.
[7] J. R. Wertz, W. J. Larson, “Space Mission Analysis and Design,” Microcosm publishing, 3rd Edition, 1999.