TITLE:
6-DOF Aerobraking Trajectory Reconstruction By Use Of Inertial Measurements Unit (IMU) Data For The Improvement Of Aerobraking Navigation

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ABSTRACT

For any interplanetary mission, there are certain types of data that are used as a means of determining both the position and velocity of a spacecraft. The data types currently in use are Doppler, Range, Optical, and ΔVLBI. All of them are radiometric with the exception of the Optical data type. NASA's Deep Space Network (DSN) is employed for the purpose of transmitting and receiving data to and from the spacecraft, respectively. For this exchange of information to take place, both the DSN and spacecraft high gain antennae must be pointed towards each other.

To decrease propulsive expenses for a given mission, a spacecraft may be initially placed into a highly eccentric orbit, with periapse located within a planet's atmospheric influence. Outside this atmospheric influence, this highly eccentric orbit would theoretically (neglecting gravitational resonance effects) remain unchanged in size due to the spacecraft's presence in a conservative field (gravitational). However, because of the viscous effects that the spacecraft experiences within the atmosphere, the presence of a non-conservative force is encountered, commonly known as "drag". During each "pass" through the atmosphere (drag pass), the spacecraft's orbital semi-major axis will decrease in size and with it, its period. This decrease is allowed to take place until such time at which operations deems apoapse to have reached its desired altitude. Then, the spacecraft performs a periapse-raising maneuver and the orbit is essentially circularized or is placed in its final configuration. This method of orbit size reduction is commonly known as "aerobraking". Aerobraking can be viewed as a means to achieve a change in velocity provided *gratis* by the atmosphere, which would otherwise have to be provided by the spacecraft thrusters. The following figure illustrates this process.

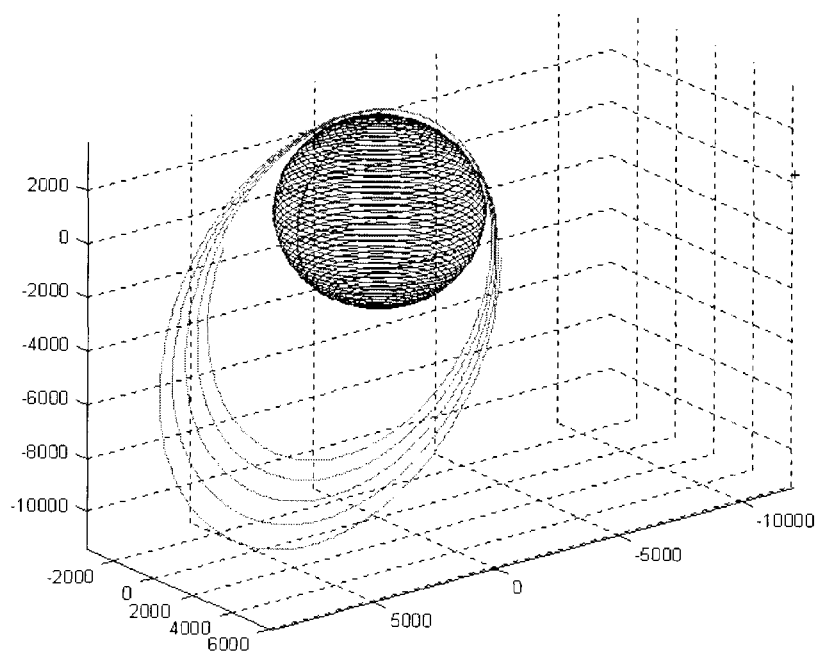

Figure 1. Example of Several Aerobraking Orbits

Aerobraking, a tried-and-true mission propellant-saving technique for planetary orbiters, has operational costs and risks:

1. The spacecraft must slew into the aerobraking orientation prior to each drag pass. There is a loss of radiometric tracking precisely when the spacecraft "flies" through the most dynamically changing and unknown portion of its trajectory. This leads to a significant increase in the spacecraft's post-pass state (position and velocity) uncertainty.

2. When reconstructing the drag pass, it is assumed that the spacecraft's total change in velocity due to the atmospheric effects is purely due to drag. In practice, the aerobraking orbits do not tend to fit the radiometric data unless residual noise is modeled as artificial dynamic acceleration events; it is likely that the residual noise is due to the lack of modeling of aerodynamic lift and side-force.

3. The aerobraking orbit reconstruction process is very time consuming (i.e. lasting several hours for each orbit) and workforce intensive (9 navigators for the Mars Odyssey aerobraking operations).

4. All of the spacecraft events occur on a ground-generated timeline (i.e. a sequence of commands). At times, up to 3 sequences must be generated and successfully uplinked to the spacecraft every 24 hours. The personnel required to perform this task constitutes an additional operational cost.

5. Spacecraft events take place at times relative to the predicted time of periapse. Any error in this prediction could lead to:

    a. aerobraking corridor control maneuver errors and thus inefficient propellant usage.
    b. aerobraking drag pass attitude configuration slewing at off-nominal times, capable of inducing inadvertent compensative thruster firings, and thus another source of inefficient propellant usage (inadvertent safe-mode entry triggering is another possible outcome).

These costs and risks can be mitigated with the navigation usage of Inertial Measurement Units (IMU), comprised of gyroscopes and accelerometers. The gyroscopes provide data pertaining to the spacecraft's attitude/rotation, while the accelerometers provide data pertaining to the spacecraft's translation. IMUs are especially sensitive to non-gravitational forces (i.e. precisely the environment not captured by current tracking techniques). The following figure (as an example) shows accelerometer data for MGS aerobraking orbit number 137:

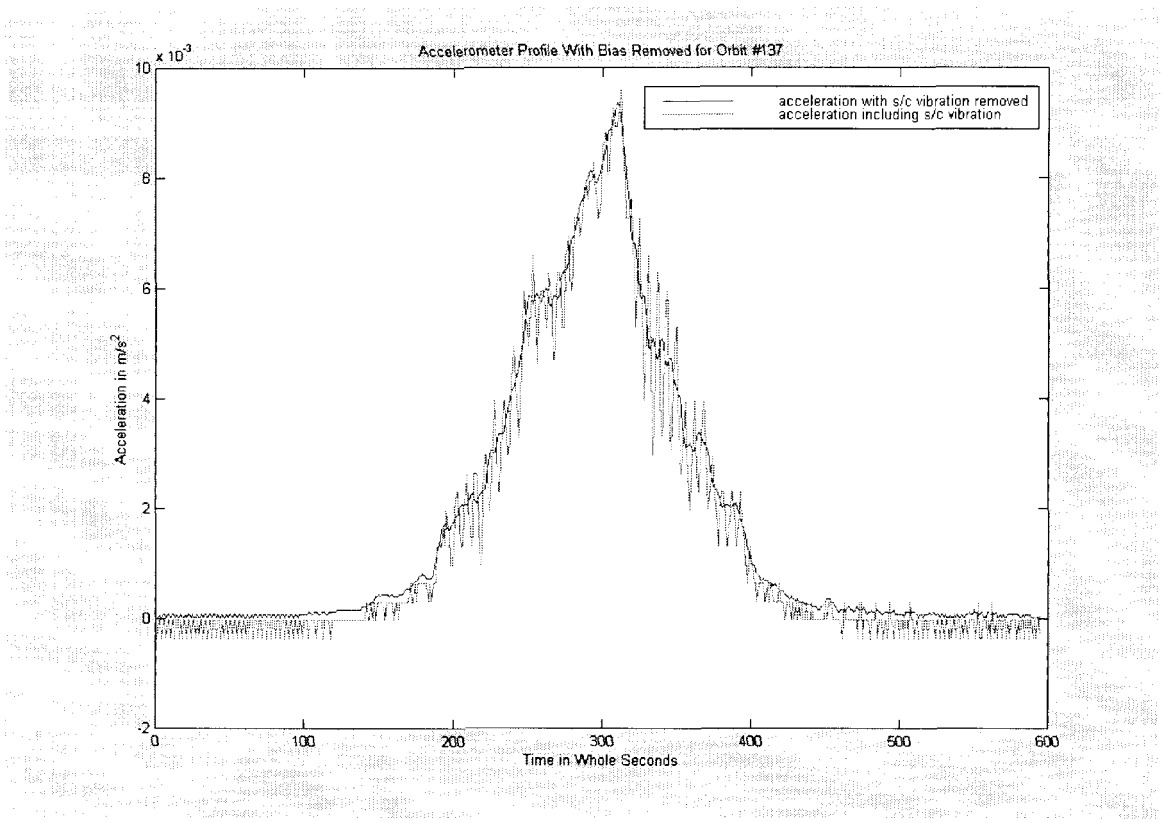

Figure 2. MGS Accelerometer Profile with s/c Vibration Removed

This research demonstrates how to exploit this sensitivity for navigation performance, and thus reduce costs and risks. Because the current uses of IMUs are deterministic, they do not statistically improve the knowledge of the spacecraft's state. Therefore, this research quantifies statistical and actual improvements in spacecraft trajectory estimation by adding IMU data to radiometric-based orbit estimates. To achieve this the following questions are answered: a) Can IMU data be used to reconstruct the 6-DOF time history of the spacecraft's trajectory and attitude profile during an aerobraking atmospheric pass? Will an improvement be made over the sole use of radiometric data processing (i.e. the way it is currently done)? b) Is the spacecraft state following an aerobraking pass improved by making use of the IMU data as an orbit determination observation type? c) Can periapse time, altitude, and location predictions be improved by making use of the IMU data?

In the past several years, there has been work in the area of EDL (but not aerobraking) seeking to incorporate IMU data as navigation measurements instead of the traditional use of the data directly into the computed dynamics. Bob Bishop & Olivier Dubois-Matra, at UT Austin, have been developing and testing different approaches for this. At the Jet Propulsion Laboratory (JPL), Mike Lisano & Geoff Wawryzniak have been developing and testing methods of doing this on the upcoming Mars Exploration Rover (MER) mission, to be launched in 2003. They have been developing a software package called IPANEMA (Interim Planetary Atmosphere Navigation for Estimation and Mission Analysis) for the 6-DOF reconstruction of the EDL trajectory of MER. This work takes advantage of IPANEMA's capabilities. Previous work by the author in the area of using IMU data for aerobraking, funded through an autonomous

aerobraking technology effort at JPL, revealed encouraging results. The current work builds upon those results. This paper is a continuation of AAS-01-386.

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References:

1. Wawrzyniak, G., Lisano, M., "*Using Inertial Measurements for the Reconstruction of 6-DOF Entry, Descent, and Landing Trajectory and Attitude Profiles*", AIAA/AAS Astrodynamics Specialist Conference, AAS 02-164, 2002.

2. Bishop, R., "*Precision Entry Navigation Dead-Reckoning Error Analysis – Theoretical Foundations*", collection of personal notes, 2001.

3. Bishop, R., Dubois-Matra, O., "*Development of a Planetary Entry Model Suitable for Processing Acceleration Measurements*", Interim Report #1 to Todd Ely (JPL), 2001.

4. Bishop, R., Dubois-Matra, O., "*Entry Navigation Extended Kalman Filter for IMU Processing*", Interim Report #2 to Todd Ely (JPL), 2001.

5. Jah, M.K., "*A Proposed Use of Accelerometer Data for Autonomous Aerobraking at Mars*", AIAA/AAS Astrodynamics Specialist Conference , AAS 01-386, 2001.

6. Lisano, M., *"Interim Planetary Atmosphere Navigation for Estimation and Mission Analysis (IPANEMA) Algorithm Design Document (ADD) Version 1.0"*, JPL document, 2002.

7. Mase, R., Antreasian, P., Bell, J., Martin-Mur, T., *"The Mars Odyssey Navigation Experience"*, AIAA/AAS Astrodynamics Specialist Conference, AIAA 2002-4530, 2002.

8. Esposito, P., Alwar, V., Demcak, S., Graat, E., Johnston, M., Mase, R.A., "*Mars Global Surveyor: Navigation and Aerobraking at Mars*", AIAA/AAS Astrodynamics Specialist Conference AAS 98-384, 1998.

CONDENSED ABSTRACT

For interplanetary missions, radiometric data is used as a means of determining both the position and velocity of a spacecraft. This requires the DSN and spacecraft to maintain communication lock, which is not continuous throughout aerobraking, specifically while the spacecraft is within the atmosphere. Some spacecraft are equipped with an Inertial Measurement Unit (IMU). The IMU provides information about the spacecraft's non-conservative acceleration and angular motion. Since the spacecraft loses lock during the drag pass, this research focuses upon the use of the IMU data (collected during the radiometric data gap) as a means of augmenting aerobraking navigation capabilities.