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An Investigation of the Orbital Status of Viking-1

David C. Jefferson*, Stuart W. Demcak†, Pasquale B. Esposito‡, and Gerhard L. Kruizinga§
Jet Propulsion Laboratory, Pasadena, CA, 91109

The dual orbiter-lander spacecraft of the Viking mission to Mars were launched in 1975 with an objective of analyzing the planet's surface and atmospheric characteristics. The Viking-1 orbiter's mission ended in 1980, after four years in orbit and a depleted supply of attitude control fuel, with the stipulation to the Viking navigation team that the spacecraft would not impact (i.e., contaminate) the planet before the year 2019. To date, it is presumed that no such impact has occurred. However, some preliminary analyses conducted in recent years at the Jet Propulsion Laboratory (JPL) suggest that the Viking-1 orbit could have undergone significant changes that might have led to a Mars impact as early as two decades before the original requirement. These implications prompted further investigation of the spacecraft's orbital evolution to determine the conditions under which an impact might be possible. Trajectory propagations using varied spacecraft states and models (planetary ephemeris, gravity field, solar radiation pressure, attitude, etc.) are examined. Findings point to the solar pressure force direction having a large influence on the spacecraft's periapsis altitude; then, depending on the altitude, atmospheric drag forces may be such that a rapid descent to the planet's surface (in effect, an "impact") is achieved in these simulations. An attempt to infer the current status of the Viking-1 orbiter is made, but is difficult in the absence of accurate and critical end-of-mission spacecraft data.

Nomenclature

a	=	orbital semi-major axis
e	=	orbital eccentricity
Fsp	=	off-sun component of the solar radiation pressure force in *Xsp*-*Ysp* plane
h_p	=	orbital altitude at periapsis passage
S/C	=	spacecraft
SRP	=	Solar Radiation Pressure
T	=	orbital period
Xsp, Ysp	=	*X*- and *Y*-axes of the SRP coordinate system in the plane perpendicular to *Zsp,* in various orientations as defined in the text
Zsp	=	*Z*-axis of the SRP coordinate system, defined along Sun-S/C line

I. Introduction

THE Viking-1 combination spacecraft was launched on August 20, 1975. Arrival at Mars was in June 1976, with the Viking-1 lander touching down on the martian surface one month later. While the Viking mission was planned for only 90 days after the landers reached the surface, the Viking-1 orbiter continued its operations in full (and subsequently lessened) capacity for four years, providing additional images, measurements of Mars' atmosphere, and other scientific data. When the on-board supply of attitude control fuel was fully consumed, the orbit of Viking-1 was modified such that its apoapsis was raised from approximately 34,000 to 56,000 km. The intention of this orbital change, made in July 1980, was to avoid a surface impact and possible pollution of the martian environment at any time before the year 2019.**

* Navigator; Guidance, Navigation and Control Section; MS 264-820; Non-Member
† Navigator; Guidance, Navigation and Control Section; MS 264-820; Non-Member
‡ Navigator; Guidance, Navigation and Control Section; MS 264-820; Non-Member
§ Navigator; Guidance, Navigation and Control Section; MS 301-276; Non-Member
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So far, there is no concrete evidence that an impact as described above has taken place. Two initially propagated trajectories used in this study (Table 1, ID's 01 and 02) were performed subsequent to a 2004 event in which Mars Exploration Rover (MER) Spirit observed a streak across the martian sky that was conjectured to be, among other possibilities, one of the Viking orbiters.†† Later, a published report identified this streak as a meteor[1]. Supplemental engineering data recovered from the Viking mission archives were used to derive spacecraft states (positions and velocities) in B1950 cartesian coordinates (Earth mean equator and vernal equinox of Besselian year 1950.0) from December, 1978 to July, 1980[2]. The most recent of these states was rotated to the J2000 coordinate frame (Earth mean equator and vernal equinox of Julian year 2000.0) and chosen as the set of initial conditions for the first long trajectory propagations of this research.

II. Long-term Trajectory Propagation – Initial Results

Two long-term orbiter trajectories, one for Viking-1 and the other for Viking-2, were integrated during the summer of 2006. The starting epochs were two years apart (July, 1980 for Viking-1; July, 1978 for Viking-2), but both were initialized to propagate to 2006 (August and July respectively).‡‡ The resulting Viking-1 orbiter trajectory propagation (ID-02) is what seeded the interest in the study reported here, in that it contained two large decreases in orbital period (and correspondingly semi-major axis) in February, 1998 and again five years later in February, 2003, ending the propagation early and resulting in a surface impact on or about 12-February-2003 (Fig. 1).

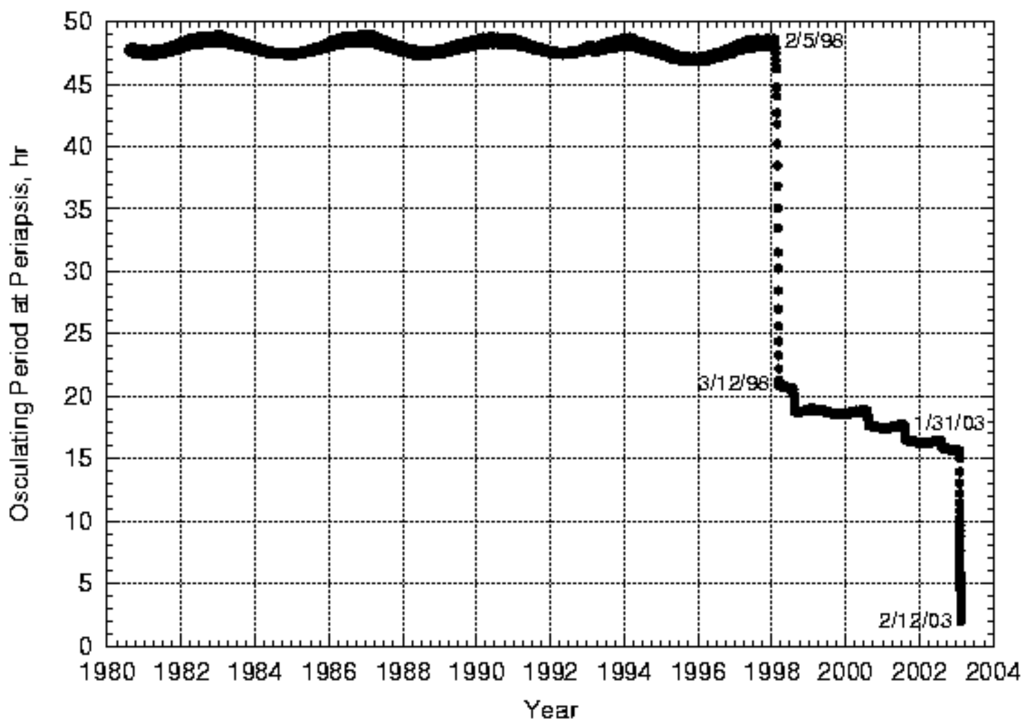

Figure 1. Initial result for Viking-1 Orbital Period (Table 1, ID-02)

This first analysis was completed using the Mars gravity field identified as MGS95J[3] (degree and order 95 but truncated to an 85x85 field), and then repeated using an alternate gravity field model identified as MGS85G. The sharp decreases in these orbital elements were realized in the second propagation as well; however, this time in February, 1998 and August, 2001. The MGS85G trajectory had not strictly impacted by the end of the propagation (August, 2006), but impact was expected within months thereafter, or sooner, based on periapsis altitudes towards the end of the trajectory and reasons presented later in this text. These two extensive gravity field models and related Mars information were derived from analysis of tracking data (Doppler and range) from the 2001 Mars Odyssey,

†† MER March 7, 2004 image, http://photojournal.jpl.nasa.gov/catalog/PIA05557

‡‡ Long-term Viking-1 and Viking-2 trajectories produced by Alex Konopliv, JPL, August 2006

Mars Global Surveyor, Mars Pathfinder, and Viking missions. A summary of the parameters and models used in these two propagations is:

Propagation Category I: "Simplified Viking-1 Model" (Table 1, IDs 01-02)

- Epoch 30-July-1980
- Spacecraft (S/C) mass = 943.7 kg
- Planet Ephemeris DE414[4], Satellite Ephemeris MAR033.7[5]
- Mars gravity field: MGS85G / MGS95J (both 85x85)
- Phobos and Deimos gravitational perturbations modeled
- Atmospheric model: Mars-GRAM[6] v3.5, daily 10.7 cm solar flux data
- Solar Radiation Pressure (SRP) model:
    - 1 symmetric component (bus), total area = 75.0 m^2
    - Orientation (see Fig. 6*a*):
        - reference direction = Earth
        - 0° rotation about Sun-S/C (Zsp) axis

The features and similarities of the MGS85G and MGS95J trajectories led to the initial interpretation that the Viking-1 orbiter may have impacted the surface of Mars at some time in the late 1990's or in the following decade. Independent analyses were needed to investigate the possible cause of the drastic orbital changes seen in Figure 1, as well as to test the repeatability of the results.

III. Additional Trajectory Propagations with Model Variations

Following the initial analyses, a series of trajectory propagations were performed; each one varied different parameters to evaluate their effect on the resulting trajectory. A "quick-look" set of two short propagations was completed to start, based on a nominal flight operations model set used for the Mars Global Surveyor (MGS) spacecraft, with the exception of using the full 85x85 MGS85F2 gravity field instead of truncating it to degree and order 65. This first trajectory spanned 3 months from December, 1997 to March, 1998 (Table 1, ID-03) and used trajectory initial conditions derived from ID-02. This analysis produced a result similar to that from the MGS85G/95J propagations (Fig. 2); the spacecraft's altitude decreases to just above 100 km in 1998, indicating a possible sooner-than-expected impact.

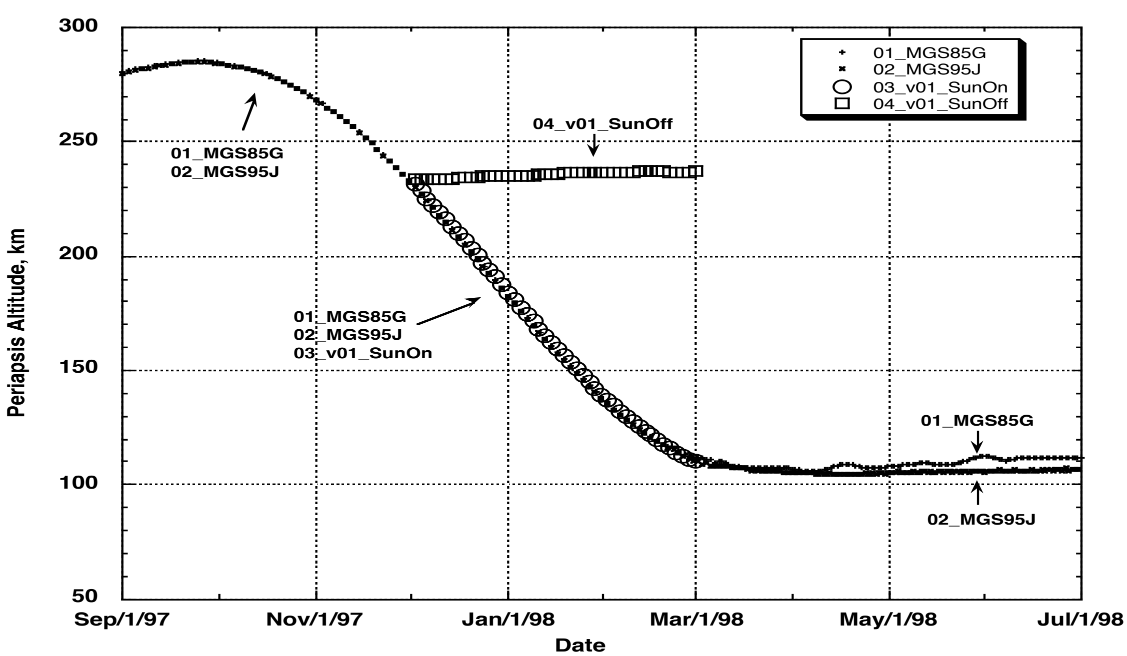

Figure 2: Effect of the Sun's gravity on Viking-1 Periapsis Altitude (Table 1, IDs-03 and -04)

To begin searching for the cause of this behavior, it was decided to first investigate one of the largest orbit influences, the gravitational perturbation from the Sun. The analysis described in the preceding paragraph was repeated, with the only difference being the exclusion of the Sun's gravity. In contrast, the periapsis altitude from this "Sun off" trajectory stayed at a plateau of about 235 km from epoch to end (Fig. 2). This early result revealed the extreme effect of this particular variation; however, since MGS-specific models were being used in this case, it was necessary to use models more consistent with the Viking-1 spacecraft itself in succeeding trajectory propagations. The models used in these two analyses can be summarized as follows:

Propagation Category II: "MGS Model" (Table 1, IDs 03-04)

- Epoch 01-December-1997
- S/C mass = 706.19 kg
- Planet ephemeris DE405[7], satellite ephemeris MAR063[8]
- Mars gravity field: MGS85F2 (85x85)
- Phobos and Deimos gravitational perturbations modeled
- Atmospheric model: none
- SRP model:
    - 6 components [5 flat plates + 1 high gain antenna (HGA)], total area = 28.5 m^2
    - Orientation based on components:
        - Bus: nadir-pointed
        - Solar arrays: Sun-pointed
        - HGA: Earth-pointed
    - Degradation: 70% (solar arrays) and 50% (all other components) as of 15-April-2001

A series of additional trajectory propagations were analyzed, varying models such as planetary ephemerides, Mars gravity fields, gravity perturbations from other bodies, spacecraft attitude, solar radiation pressure, and initial state. For all of these propagations, the atmospheric model chosen was the Mars Global Reference Atmosphere Model (Mars-GRAM)[6] version 3.5, and the drag coefficient used was 2.40; these were the same as in the initial MGS85G/95J trajectories. To start, the spacecraft's configuration, and therefore the solar radiation pressure, was left as the nominal 6-component model used by MGS. Solar flux values were applied on a monthly basis rather than daily as in the MGS85G/95J analyses; this contributed another level of independence, but also allowed longer durations of trajectory integration to be completed (10 years vs. 6 months due to a software limitation with respect to maximum array sizing). Because the tested models change from analysis to analysis, a general summary reflective of the "nominal" models used in the initial variations is shown below:

Propagation Category III: "Viking-1/MGS Adapted Model" (remaining propagations, with variations)

- Epoch 30-July-1980
- S/C mass = 943.7 kg
- Planet ephemeris DE405[7], satellite ephemeris MAR063[8]
- Mars gravity field: MGS85F2 (65x65) / MGS95J (95x95)
- Phobos and Deimos gravitational perturbations modeled
- Atmospheric model: Mars-GRAM v3.5, monthly 10.7 cm solar flux data
- SRP model:
    - 6 components (5 flat plates + 1 HGA), total area = 54.8 m^2
    - Orientation based on components:
        - Bus: nadir-pointed
        - Solar arrays: Sun-pointed
        - HGA: Earth-pointed
    - Degradation: 70% (solar arrays) and 50% (all other components) as of 1-January-1980

An abridged, basically chronological synopsis of some of the different analyses and their results is shown in Table 1; an "impact" here is the inference from trajectories that exhibited large decreases in orbital period, semi-major axis, and/or altitude, as occurred in the original MGS85G/95J propagations. A more comprehensive table containing all of the analyses, model variations, and outcomes can be found in Ref. 9. In the table, analysis IDs-05 and -07 are considered benchmarks: ID-05 because it was the first full, 30-year trajectory completed in the study to verify propagation IDs 01 and 02 with the introduction of Viking-1-like models; and ID-07 because (along with the other models from ID-05), it used the MGS95J gravity field, which is consistent with that used in ID-02 and an accurate representation of the Mars gravity field[3]. Both of these propagations are also important because, unlike analysis ID-02, neither one resulted in an impact, fostering the need for further investigation of this discrepancy.

Table 1: Summary of Viking-1 Orbiter Analyses - Models and Results

Orbital element symbols in "Results" (at periapsis): T = period, a = semi-major axis, e = eccentricity, h_p = altitude

IDs 01 and 02 used Mars radius 3394.2 km; all others used 3393.4 km

ID	LABEL and EPOCH S/C Event Time, Ephemeris Time (SCET, ET)	GRAVITY FIELD and SIZE	MODEL VARIATION and COMMENT	RESULT and COMMENT (times are SCET, ET)
CATEGORY I (Simplified Viking-1)				
01	V01_85g 30-JUL-1980 22:14:57.000	MGS85G 85x85	Initials results, Category I models, alternate gravity field	Impact; trajectory ends 01-AUG-2006 02:00:00; min. h_p=94 km at 31-JUL-2006 20:11:16
02	V01_95j 30-JUL-1980 22:14:57.000	MGS95J 85x85	Initial results, Category I models	Impact; trajectory ends 13-FEB-2003 01:09:44; min. h_p=82 km at 14-JAN-2003 12:43:01
CATEGORY II (MGS flight operations)				
03	v01_nominal (Sun gravity on) 01-DEC-1997 00:00:00.000	MGS85F2 85x85	Advance epoch just before large decrease in hp(01); Category II models; only 3 month max propagation	Possible impact; no T or a decrease as in (01), (02), but e increase => hp decrease; trajectory ends 01-MAR-1998 01:00:00; min. h_p=110 km at 28-FEB-1998 19:18:41
04	v01_no_10 (Sun gravity off) 01-DEC-1997 00:00:00.000	MGS85F2 85x85	Same as (03) but disable Sun gravitational perturbation; only 3 month max propagation	No impact; only slight decreases in T, a, e; hp increases with time; sun has significant effect on orbital evolution; future orbital evolution sensitive to small orbital parameter changes; trajectory ends 01-MAR-1998 01:00:00; min. h_p=234 km at EPOCH
CATEGORY III (Viking-1/MGS adapted)				
05	30yr_nom 30-JUL-1980 22:14:56.893	MGS85F2 65x65	Use Category III models to become consistent with Viking-1 configuration; use MGS flight operations truncated gravity field	No impact; basically a comparison of 3 different gravity fields (01), (02), (03); trajectory ends 30-JUL-2010 22:14:57; min. h_p=215 km on 22-FEB-1981
06	30yr_85f2_85x85 30-JUL-1980 22:14:56.893	MGS85F2 85x85	Like (05) but use full 85x85 gravity field	No impact; higher order gravity terms do not significantly influence orbit; trajectory ends 30-JUL-2010 22:14:57; min. h_p=215 km on 22-FEB-1981
07	30yr_95j_95x95 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (05) but use current best estimate of Mars gravity field	No impact; a comparison of 4 different gravity fields (01), (02), (06), (07); trajectory ends 30-JUL-2010 22:14:57; min. h_p=215 km, on 22-FEB-1981
09	6mth_ask980101_95j_95x95 01-JAN-1998 00:00:00.000	MGS95J 95x95	Like (07) but use state at advanced epoch directly from initial results (02); only 6 month max propagation	Impact; large decrease in T, a, e and hp; trajectory ends 22-APR-1998 23:18:20 (by software integration control); min. h_p=88 km at last periapsis
31	30yr_95j_askSRP 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (07) but use simpler 1-component SRP model as in original propagations (01)/(02) but different orientation	No impact; T, a, increase; no change in e; trajectory ends 30-JUL-2010 22:14:57; min. h_p=210 km on 22-FEB-1981
34	30yr_95j_askSRPfix 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but use s/c SRP coordinate definitions from (01)/(02)	Impact; trajectory ends 19-MAR-1998 03:42:57; min. h_p=95 km on 03-MAR-1998
37	askSRPfix_MGalex (state from ID-34) 01-DEC-1992 00:00:00.000	MGS95J 95x95	Like (34) but uses atmospheric temperature models from (01)/(02) which affect density, which affects T, a	Impact expected; trajectory ends 21-MAR-1998 09:42:15; min. h_p=98 km on 21-MAR-1998
40	dj_95j95_mar063_AlexSRPa-45, ECL 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (34) but rotate bus X, Y coordinates -45 deg. w.r.t. +Z axis (off-Sun SRP component in solar system ecliptic)	Impact; trajectory ends 19-MAR-1993 03:29:26; min. h_p=89 km on 19-MAR-1993
41	dj_95j95_mar063_AlexSRPa+45, Pole 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (34) but rotate bus X, Y coordinates +45 deg. w.r.t. +Z axis (off-Sun SRP component along solar system ecliptic s. pole)	No impact; trajectory ends 31-JUL-1990 23:14:57; min. h_p=89 km on 22-FEB-1981

42	30yr_95j_askSRPc+135, ECL 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (34) but rotate bus X, Y coordinates +135 deg. w.r.t. +Z axis axis (off-Sun SRP component in solar system ecliptic, opposite direction of (40)	No impact; trajectory ends 30-JUL-2010 22:14:57; min. h_p=231 km on 20-FEB-1981
43	30yr_95j_askSRPc-90, ECL+45 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (34) but rotate bus X, Y coordinates -90 deg. w.r.t. +Z axis axis (off-Sun SRP component 45 deg above –ecliptic (40)	Impact; trajectory ends 17-JUL-1998 15:32:08; min. h_p=103 km on 17-JUL-1998
44	SWD_30yr_95j_askSRP+45, ECL 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but rotate bus X, Y coordinates +45 deg. w.r.t. +Z axis (off-Sun SRP component in solar system ecliptic)	No impact; trajectory ends 30-JUL-2010 22:14:57; min. h_p=210 km on 06-MAR-1981
45	SWD_30yr_95j_askSRP+135, S. Pole 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but rotate bus X, Y coordinates +135 deg. w.r.t. +Z axis (off-Sun SRP component along solar system ecliptic south pole)	Impact; trajectory ends 17-AUG-1996 06:03:56; min. h_p=99 km on 17-AUG-1996
46	SWD_30yr_95j_askSRP+225, ECL 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but rotate bus X, Y coordinates +225 deg. w.r.t. +Z axis axis (off-Sun SRP component in solar system ecliptic, opposite direction of (44)	No impact; trajectory ends 30-JUL-2010 22:14:57; min. h_p=231 km on 20-FEB-1981
47	SWD_30yr_95j_askSRP+315, N. Pole 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but rotate bus X, Y coordinates +315 deg. w.r.t. +Z axis axis (off-Sun SRP component along solar system ecliptic north pole	No impact; trajectory ends 30-JUL-2010 22:14:57; min. h_p=216 km on 22-FEB-1981
48	SWD_30yr_95j_askSRP+90 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but rotate bus X, Y coordinates +90 deg. w.r.t. +Z axis axis (off-Sun SRP component 45 deg below -ecliptic (44)	No impact; trajectory ends 30-JUL-2010 22:14:57: min. h_p=231 km on 20-FEB-1981
49	SWD_30yr_95j_askSRP+180 30-JUL-1980 22:14:56.893	MGS95J 95x95	Like (31) but rotate bus X, Y coordinates +180 deg. w.r.t. +Z axis axis (off-Sun SRP component 45 deg below +ecliptic (46)	No impact; trajectory ends 30-JUL-2010 22:14:57: min. h_p=216 km on 22-FEB-1981

Subsequent trajectory propagation variations completed early on also resulted in no impact of the orbiter. An important test was analysis ID-09, in which we attempted to repeat the original outcome by just using a state from the initial propagation (ID-02) near the time of the first large decline in orbital period (Fig. 1), but with the same set of models from ID-07. This analysis was enlightening because, although it was only a 6-month trajectory, it was the first one in Category III to exhibit an impacting orbit result, showing more evidence in agreement with the existence of a fundamental difference between the initial trajectory ID-02 and propagations ID-05/07. The epoch for propagation ID-07 is on July 30, 1980 and the state was derived from the original archived data set. The epoch for ID-09 is on January 1, 1998 and the state comes from propagated MGS95J trajectory ID-02. Each of their orbital periods is shown for the 4-month span from January to April 1998 in Figure 3.

As the study continued, more focus was placed on the spacecraft's attitude, and by implication, the solar pressure model being used. It was previously noted that the initial solar pressure model used in the variational analyses (Category III) was the 6-component model taken from MGS (Category II), but with dimensions more consistent with Viking-1 specifications. Later, this was changed to the simpler 1-component bus model which was similar to that from the Category I MGS85G/95J propagations (ID's 01, 02). This change alone did not result in a surface impact, but other solar pressure model parameters such as component degradation factors, solar pressure scaling coefficient, and spacecraft solar pressure orientation definitions were examined in later analyses. The most influential of these turned out to be related to the latter, namely the component of solar pressure force perpendicular to the Sun-S/C direction.

IV. The Influence of Spacecraft Attitude and Solar Radiation Pressure

It appears that the spacecraft would have only impacted the Martian surface if the following conditions were met:

- There was a large component of the SRP force acting perpendicular to the Sun-S/C line-of-sight.
- This off-Sun component acted consistently in a limited region of the plane perpendicular to the Sun-S/C vector.

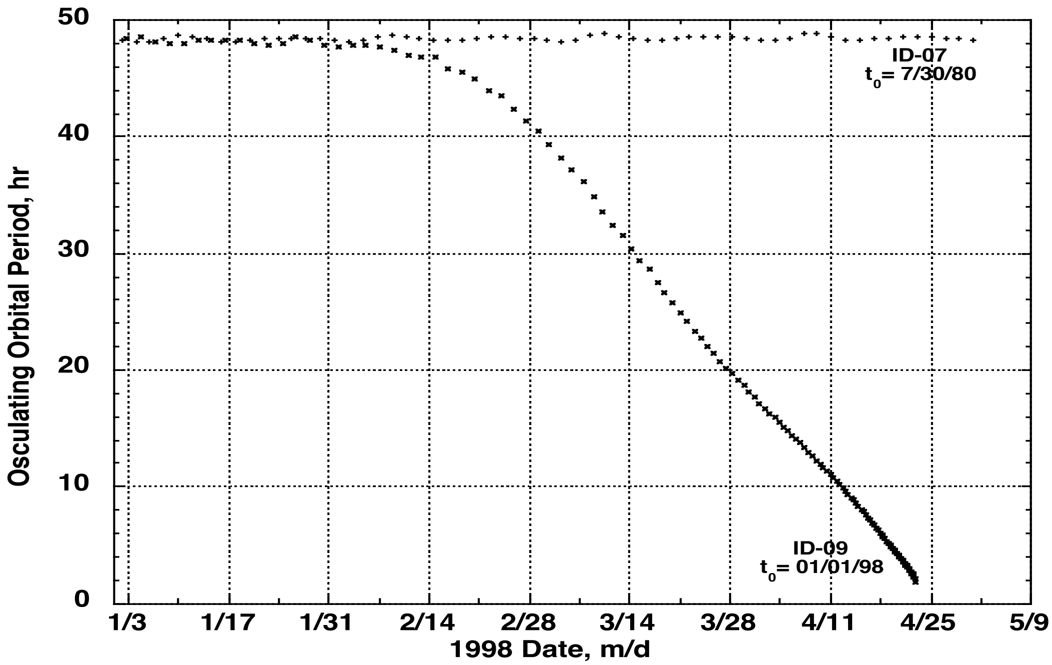

Figure 3: Viking-1 orbital periods based on the original 1980 state in ID-07 and propagated 1998 state in ID-09. *All trajectory models are the same between the two propagations.*

With these results, we have identified an SRP force component and the corresponding S/C attitude that ultimately results in an impact. However, we have not determined the possibility of the Viking-1 orbiter being in this limited orientation region.

The modeling of the SRP force is the initial factor in whether the orbiter impacts. However, much of the uncertainty in the SRP and atmosphere models is due to the uncertainty in the orientation of the spacecraft and its components. While the SRP effect perturbs the orbit, which can generate small periapsis altitudes, the direct cause for Viking-1 impacting Mars is the atmospheric drag perturbation. At periapsis altitudes around 150 km or lower the atmospheric drag will be large enough to cause significant reductions in the apoapsis altitude. If the apoapsis altitude is reduced to a few hundred kilometers, resulting in a more circular trajectory, the drag will act on the spacecraft throughout most of the orbit and cause the spacecraft to quickly spiral into the planet surface. Any realistic Mars atmosphere model, for almost any spacecraft orientation, will cause Viking-1 to impact under these conditions, provided that the spacecraft stays at these low periapsis altitudes for a reasonable period of time. The atmosphere model will only affect how long it will take for Viking-1 to impact.

Figure 4 shows that the periapsis altitude is periodic. The time spent at low periapsis altitude in a given cycle usually lasts for a few months. Models with higher atmospheric drag could cause Viking-1 to impact in just a few weeks, as in the case of ID-34. Models with lower atmospheric drag could cause the Viking-1 apoapsis altitude to decrease, but no impact will take place until a later periapsis altitude cycle occurs. This is what occurred for ID-02. The atmosphere model configuration used in ID-02 (Category I trajectories) gives approximately 30% lower densities than the one used in ID-34 (Category III trajectories), causing the relative delay in impacting; ID-02 does not impact Mars until the next drop in periapsis altitude to around 100 km in 2003.

Thus in determining if the spacecraft will impact, the important aspect is not so much how the atmosphere model is implemented, but what effect is driving the periapsis altitude changes and whether it is lowering the periapsis altitude enough to be largely affected by atmospheric drag. The SRP model is the only force model whose uncertainty is large enough to vary the periapsis altitude greatly between trajectory propagations. Note that Viking-1 is in a large, eccentric orbit. Small perturbations in the orbit, especially near apoapsis where the Mars gravity effects are smallest and where the spacecraft spends most of its time, can result in large perturbations in the periapsis altitude. This is best seen by looking at a plot of the eccentricity (e) of the orbit (Fig. 5). Since e is close to 1, and the periapsis distance is given by $a*(1-e)$ (where a is the semi-major axis), a small variation in e can result in a large variation in periapsis altitude. In fact, for the Viking-1 orbit, a small change in e of 0.002 results in a large change in periapsis altitude of about 50-70 km.

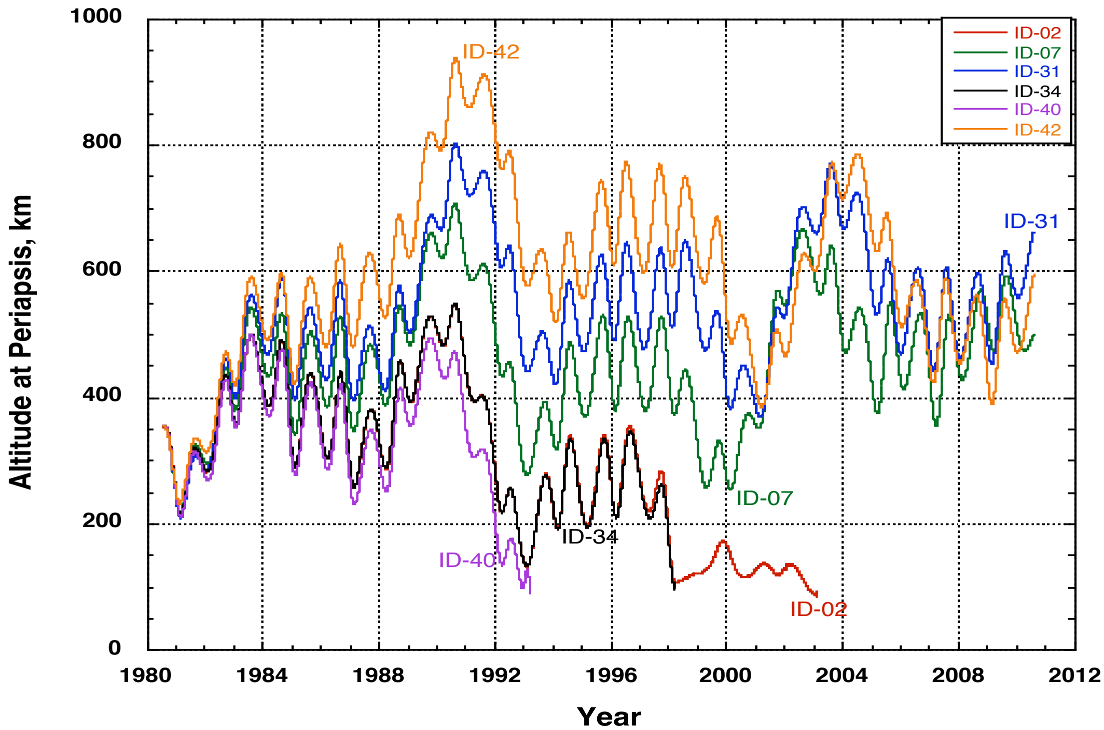

Figure 4: Comparison of spacecraft orientation and SRP force effect on periapsis altitudes for several trajectory propagations.

Figure 4 shows how several trajectories varied due to the SRP and atmosphere variations discussed above. Trajectories ID-02 and ID-34 used the same SRP model. This SRP model causes the orbit eccentricity to increase by 0.004 and larger as compared to the benchmark ID-07 trajectory. This results in their periapsis altitudes being typically 150 km (or more) lower than those of ID-07. Thus the ID-07 minimum periapsis altitudes of 250-300 km manifest as altitudes of 100-150 km in trajectory IDs 02 and 34. Just a few brief dips to these lower altitudes is enough to cause the spacecraft to impact Mars.

The trajectories in Figure 4 for IDs 31, 34, 40 and 42 show the effect of different directions of the off-Sun solar pressure force. Both ID-40 (impact) and ID-42 (no impact) have the off-Sun SRP force acting along the ecliptic, but in opposite directions (Figure 6, illustration c). During most of 1992, the eccentricity difference between these two propagations is 0.013-0.019, which corresponds to a difference of approximately 500 km or more in periapsis altitude. Thus a periapsis altitude near 600 km in ID-42 becomes 100 km in ID-40, leading to the impact for this case in 1993.

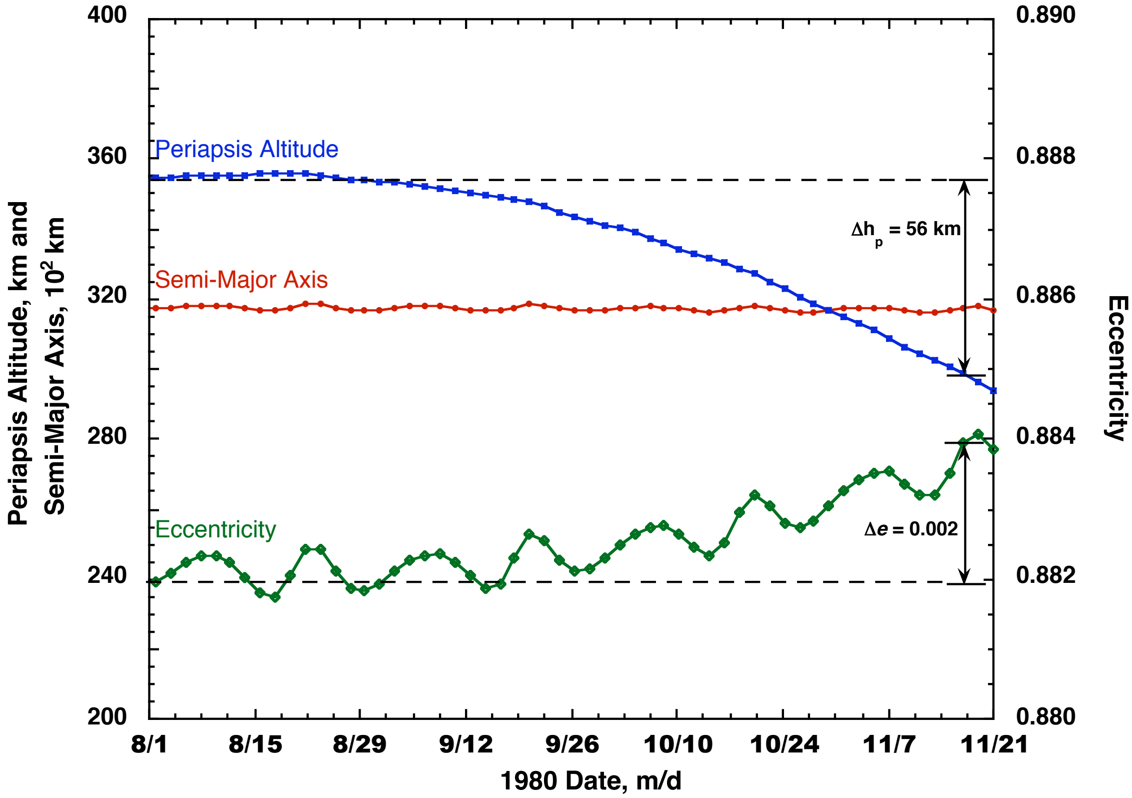

Figure 5: Effect of eccentricity increase on periapsis altitude for propagation ID-02, Aug 1 – Nov 16, 1980.

In IDs 31, 34, 40, 41 and 42, the SRP force components are equally specified along three axes of a coordinate frame (Xsp, Ysp, Zsp). Zsp is in the Sun-S/C direction. The off-Sun component of the SRP model (Fsp) is defined by the orientation of a set of Xsp and Ysp coordinate axes, which themselves are defined by a reference direction. IDs 34, 40, 41, and 42 all have an Earth-pointed solar pressure model reference direction ("REFB" in Fig. 6); this direction defines the orientation of the Xsp and Ysp axes in the plane perpendicular to the Sun-S/C line, Zsp. However, since Mars takes almost twice as long to orbit the Sun as Earth, the Xsp-axis, Ysp-axis and off-Sun SRP force component will shift 180 degrees every year about the Sun-S/C line because of the changing relative motion of Earth and Mars. One set of orientations before a shift occurs is shown in Figure 6, illustration *c*, which is a two-dimensional "snapshot" of Fsp vectors for the latter four propagations mentioned above.

To observe the effect of keeping the off-Sun SRP force component "fixed" with respect to the ecliptic plane (fixed in direction relative to the Mars orbit velocity vector) over the span of the trajectory, an inertially fixed reference direction is needed. ID-31 used such a reference direction, namely the ecliptic south pole, to define its SRP force (Figure 6, illustration *b*). Four additional propagations were generated using this inertial reference direction. These trajectories, found in Table 1, had the off-Sun SRP component in the following four directions:

- Along the ecliptic, in the direction of Mars orbit velocity (ID-46)
- Along the ecliptic, in the opposite direction from the Mars orbit velocity (ID-44)
- Along the ecliptic north pole (ID-47)
- Along the ecliptic south pole (ID-45)

The only one of these trajectories to impact Mars was ID-45, which had Fsp pointed along the ecliptic south pole. Examining the above trajectories leads to the inference that the S/C impacts Mars if either of the following conditions is met when a large off-Sun component of SRP exists (Figure 6, illustrations *c* and *d*):

• Fsp is pointed near the ecliptic (approximately ±45 degrees), away from Earth

OR

• Fsp is pointed continually near the ecliptic south pole (approximately ±45 degrees)

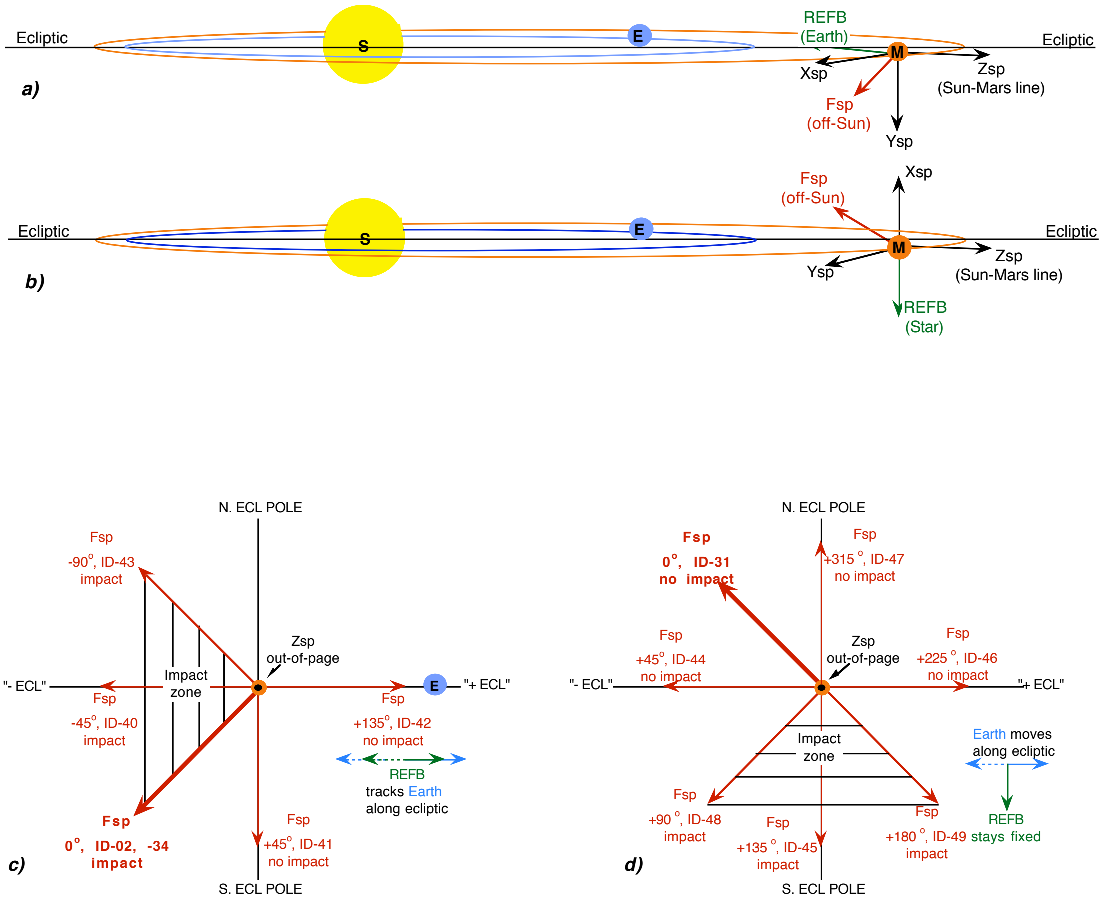

Figure 6: Solar Radiation Pressure Model Orientation (*category I and some propagations of category III). a) Table 1, ID-02 and -34; result: impact. b) Table 1, ID-31, result: no impact. c) REFB=Earth, "snapshot" at 30-Jul-1980, all vectors shift 180 deg. within 1 year (approx. 1/2 Mars year). Impact zone is along minus ecliptic direction. d) REFB=Star (towards S. Ecliptic), impact zone is along south ecliptic pole direction.*

V. Conclusion

Per end-of-mission requirements, the Viking-1 orbiter was not to impact the surface of Mars until 2019 at the earliest. The numerous analyses conducted in this study produce a dichotomy of results; some of them indicate that an impact has already occurred while the others do not. The sequence of events necessary for impact are as follows:

a) The SRP force will only reduce the periapsis altitude to low values if the spacecraft attitude results in the SRP force having a large component in a certain direction perpendicular to the Sun-S/C line. The two possible directions are: near the ecliptic south pole, or near the ecliptic and pointing away from Earth.

b) Viking-1 periapsis altitudes are typically above 150 km and can only be made lower via the solar radiation pressure force.

c) Atmospheric drag large enough to reduce orbit size will only occur at low periapsis altitudes (approximately ≤ 150 km).

d) At these low altitudes, atmospheric drag becomes the dominating force and is responsible for the impact.

Note that this sequence of events is applicable to this case, namely an initially highly eccentric orbit, and may not be true for more circular orbits. It has been demonstrated here that depending on the solar perturbation models chosen, an impact scenario similar to the initial trajectories (IDs 01 and 02) can be recreated. In these cases, the decrease in periapsis altitude caused by an increase in orbital eccentricity may be just enough to allow atmospheric density to significantly degrade the orbit and result in further altitude loss and ultimate impact.

Item (a) above indicates these models are highly dependent on spacecraft orientation. The spacecraft could be in a static orientation or it could be tumbling. Without knowledge of the actual pointing, or information regarding the likelihood of being in a particular attitude, it is difficult to declare with absolute certainty whether an impact has already occurred. While the implications of the propagation results generated in this study, along with the observed behavior of the solar radiation pressure models (i.e., limited range of influence resulting in large altitude decrease), provide more insight into the conditions which could lead to a possible early impact, we conclude that Viking-1 most likely remains in orbit around Mars.

One way of modifying a spacecraft's orbit is by aerobraking: propulsive maneuvers are executed to bring the spacecraft's periapsis altitude low enough to take advantage of atmospheric drag forces that circularize its trajectory. It is conceivable that the method of "tuning" the attitude of a spacecraft to achieve a desired altitude via the resultant solar pressure force, as presented here, could possibly be a fuel-saving alternative; no propellant is consumed in this technique. This is essentially the idea behind the operation of solar sails, a relatively newer application in space flight that is being continually researched.

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