**Martian Length of Day Measurements from Rovers**
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**Introduction:** Changes in the Length of Day (LOD) of the Earth and Mars are expected to be driven by many of the same processes, such as by exchanges of angular momentum between the atmosphere, hydrosphere, lithosphere, and fluid core. Terrestrial LOD measurements provide information on a wide array of geophysical processes, including tidal deformations, climate changes, and fluid motions in the liquid core [1]. The Martian LOD was first measured using radiometric tracking data from the *Viking* Landers. Although *Viking* range data has a typical accuracy of only about 6 meters [2], data were available from 1976-82 and were sufficient to estimate the mean LOD and its seasonal variation [3]; the seasonal variation agreeing reasonably well with that expected from meteorological data and the solar tide[4]. It is commonly assumed that there is little scientific purpose in geodetic observations conducted with or from active rovers on the surface Mars, as their frequent motions would overwhelm any signals from Mars rotation or other geodynamic sources. We examine this in the light of both expected geophysical variations and typical scheduling of the Mars Exploration Rovers (MER) and those planned for the Mars Science Laboratory (MSL). A combination, in a Kalman filter, of regular (but not necessarily frequent) range and Doppler measurements from Earth and rover dead reckoning should suffice to determine both the absolute geodetic path of a rover and provide geophysically useful estimates of variation in the Martian LOD over the course of a mission.

**Martian Length of Day:** Martian rotational dynamics are superficially similar to those of the Earth, with a similar rotational period (differing by 3%) and obliquity (differing by 8%). Both bodies of course possess a dynamical atmosphere and fluid core, and thus for both there should be variations in the LOD. We will use the conventional units of seconds, milliseconds (msec) and microsecond (μsec) of UT1 and LOD, with the reference seconds being TAI. (As Mars moves in its orbit there will be relativistic variations in its rotation rate when compared to clocks on the Earth; these can be calculated using General Relativity and will be otherwise ignored in this paper.)

The LOD is determined by the change in the UT1 over time, one msec of LOD representing a UT1 rate of 1 msec / (Martian) sol. At the equator of Mars, one msec of UT1 represents 0.247 meters of longitude change. Either range or Doppler measurements, repeated during a single day, should be able to determine the Martian UT1 offset for that day to within 1 meter. Two such UT1 measurements separated by N sols thus yields

$$\sigma_{\mathrm{LOD}} \sim \frac{\sqrt{2}\sigma_{\mathrm{UT1}}}{\#\,Sols} \sim \frac{5700\,\mu\mathrm{sec}}{\#\,Sols} \qquad (1)$$

This accuracy is assumed to be obtainable for the remainder of this paper. The experience of Mars rovers is that they frequently remain stationary for periods ranging from weeks (for examination of rock outcrops or for Superior Conjunction) to months during the local winter (for the Solar Powered MERs). Such stationary periods at a given rover "station" thus represent an opportunity to determine the Martian LOD with an accuracy between 500 and 50 μsec, independently of any longitude ties between these intervals.

**Decadal LOD Fluctuations on Mars:** Decadal-scale variations in the Earth's LOD can be as large as a several msec of LOD over a decade. These variations are large enough that they must, by a process of exclusion, be due to fluid motions in the liquid outer core[1]. Yoder et al. [6] concluded that the Martian core was at least partially liquid, based on satellite observations of solar tidal deformations, with a radius between 1520 and 1840 km. The Martian core is generally assumed to be quiescent, due to the lack of a strong magnetic dipole. However, fluid core magnetohydrodynamics is poorly understood, even for the Earth, and there is no reason not to expect decadal fluctuations from Mars's fluid core. (The lack of a dipole field is clearly not proof that there are no fluid motions, as the Earth's core spends a significant fraction of its time without a dipole field while undergoing geomagnetic reversals, and there are certainly fluid motions during those periods.) Such fluctuations, being entirely in the "motion" excitation term, cannot be observed with satellite gravity data. Detection of decadal fluctuations in the Mars LOD would thus confirm the existence of a fluid core, and, if present, provide a means of observing Mars dynamics that is currently not possible by any other means [7].

If the Martian core is relatively as active Earth's then the LOD change since *Viking* should be detectable without requiring longitude ties between the *Viking* landers and the rover, or between different rover stations. At any time when a rover is stationary for 10 days or more (or when its movements are below ~1 meter for a period), the LOD should be measured, ideally through one or more tracking sessions at both the beginning and the end of the stationary period.

**LOD Changes from Changes in the Martian Atmospheric Angular Momentum:** By conservation of angular momentum, variations in the Atmospheric Angular Momentum (AAM) cause corresponding changes in the LOD, and the LOD can thus be used as a proxy for AAM and this for global atmospheric dynamics. For Mars, there is currently only information about seasonal changes in the LOD, with these changes being mostly due to the exchange of mass between the atmosphere and the $CO_2$ polar caps [8].

*Decadal Fluctuations of Atmospheric Origin.* It is known that Mars has undergone recent climate changes [9], as reflected in the polar layered terrain and elsewhere, and there is no reason to expect that these are not continuing at present. Haberle et al. [10] found long term erosion of the North polar cap, with the volume of material being as much as 2.5% of the atmospheric mass per Mars decade [Haberle et al. 2009]. This latter loss rate corresponds to an LOD decrease of 1.3 μsec per (Earth) year. If this loss rate has been continuous during the decades since the *Viking* Lander period, and if the mass lost from the polar cap is retained in the atmosphere, the total LOD change would be ~ 43 μsec, which would be marginally detectable at best from a simple combination of *Viking* and recent LOD data. However, the change in the Martian UT1 from an linear rate in the LOD of that magnitude would be ~ 270 msec, equivalent to 66 meters at the equator. This would be easily detectable in the geodetic data if the *Viking* Lander and MSL landing site longitudes could be linked at the meter level by satellite imagery or radar. These changes would of course be combined with the decadal fluctuations of the core, and it might be hard to distinguish these two effects with the existing data. Going forward, climate changes and core driven fluctuations during the MSL mission could potentially be confirmed and separated by a comparison of satellite imaging estimates of polar cap volume, satellite gravimetry, and MSL LOD data.

*Seasonal Fluctuations in the Martian LOD.* The seasonal Martian AAM variations are dominated by $CO_2$ exchanges between the polar caps and the atmosphere, being ~ 500 and 250 μsec for the annual and semiannual variations, respectively. The agreement with geophysical modeling is not as good as for the Earth, particularly for the semi-annual term, with discrepancies at the 100 μsec level or larger. On Earth, seasonal (primarily annual and semi-annual) LOD variations are dominated by changes in atmospheric wind velocity (the "wind" AAM term), with an excellent agreement between geodetic and meteorological observations,. On Mars, by contrast, the seasonal pressure variations are larger, being driven by the sublimation of Carbon Dioxide during the Martian spring and summer, its redistribution throughout the atmosphere, and then its redeposition during the following winter [4]. The total mass exchange is as much as one third of the total atmospheric mass. LOD measurements thus provide a direct insight into this global atmospheric process.

There is no reason to expect seasonal processes to repeat exactly from year to year, or not to drift as the climate changes. Van den Acker et al.[8] used a General Circulation Model to estimate the effect of global dust storms on the LOD, and concluded that these could modify the seasonal variations by ~10%, or as much as 50 μsec of LOD. Determining the LOD from rover data will be marginal at best without some means of linking the longitude of successive rover stations.

**A Kalman Filter For Martian LOD**: A Kalman filter has been used for over 2 decades to smooth and predict Earth orientation changes for spacecraft navigation [11]. In this case, spacecraft tracking can obtain estimates of the change in the sum of the Martian UT1 and the rover longitude, potentially for more than one rover. A similar Kalman filter could be used to combine these observations plus rover odometer and heading information to determine both the LOD change and the absolute rover longitude in an optimal fashion. With this infrastructure, and with repeated (although not necessarily frequent) rover tracking data, it should be possible to determine the seasonal LOD to 10% or better, and thus provide a scientifically useful determination of changes in the seasonal LOD since the Viking period, as well as possibly observe higher frequency variations in the Martian LOD. A unified Kalman filter for Martian UT1/LOD variations and transporter movements will also have considerable utility in the case of multiple rover sample return missions (which would require the coordination of two or more rovers on the Martian surface) and future human exploration (which might have a variety of astrometric measurements to a number of different stationary or mobile surface components).

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