MARS GEODESY/CARTOGRAPHY WORKING GROUP RECOMMENDATIONS ON MARS CARTOGRAPHIC CONSTANTS AND COORDINATE SYSTEMS.

T. C. Duxbury[1], R. L. Kirk[2], B. A. Archinal[2], and G. A. Neumann[3], [1]Jet Propulsion Laboratory, Pasadena, CA (Thomas.C.Duxbury@jpl.nasa.gov), [2]U.S. Geological Survey, Flagstaff, AZ (rkirk@usgs.gov), [3]NASA Goddard Space Flight Center, Green Belt, MD (neumann@tharsis.gsfc.nasa.gov).

Introduction: NASA's Mars Geodesy/Cartography Working Group (MGCWG), established in 1998 and chaired since 2000 by one of us (TCD), consists of leading researchers in planetary geodesy and cartography at such diverse institutions as JPL, NASA Ames and Goddard Centers, Purdue and Ohio State Universities, MSSS, DLR, and the USGS, as well as representatives of the current and future Mars mission teams that are the customers for Mars maps. The purpose of the group is to coordinate the activities of the many agencies active in Mars geodesy and cartography in order to minimize redundant effort and ensure that the products needed by mission customers are generated. A specific objective has been to avoid repeating the experience of the 1970s–80s, when competing researchers produced geodetic control solutions and maps of Mars that were mutually inconsistent. To this end, the MGCWG has recently assembled a set of preferred values for Mars cartographic constants, based on the best available data. These values have been transmitted to the International Astronomical Union and will appear in the forthcoming report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites [1] as the officially recommended constants for Mars. The MGCWG has also recommended to NASA that the USGS adopt the IAU-approved coordinate system of planetocentric latitude and east longitude for future maps of Mars, in place of the (also IAU-approved) planetographic system with west longitude positive. In this paper we present the preferred values for Mars cartographic constants with discussion of the process by which they were derived, then discuss the rationale and implications of the use of east/planetocentric coordinates in future USGS Mars maps.

Cartographic Constants: The parameters that must be defined in order to carry out mapping of a planet such as Mars with spacecraft data are the orientation of the spin axis (including precession), rotation rate, rotational orientation at a specified time, and size and shape of an ellipsoidal reference surface. In addition to these parameters and their uncertainties, the IAU/IAG Working Group reports, where available, statistics on the deviation of the planetary surface from an ellipsoidal model.

Spin Axis and Rotation Period. Parameters describing Mars' rotation rate and direction of its polar axis in space have been adopted from those values determined by Folkner et al., 1997[2], based on tracking of Mars Pathfinder and the Viking 1 and 2 landers. The right ascension α and declination δ in degrees at a given time t are given by the expressions:

$$\alpha = 317.68143° - 0.1061°/\text{century} * T$$
$$\delta = 52.88650° - 0.0609°/\text{century} * T$$

where T is the number of Julian centuries of t from the standard epoch of J2000.0. The uncertainties in these values estimated by Folkner et al. are 0.00001° in offset and 0.0007°/century in rate for α, and 0.00003° in offset and 0.0004°/century in rate for δ.

The rotation rate of Mars is assumed to be W_dot = 350.89198226°/day, for which Folkner et al. cite an uncertainty of 0.00000008°/day.

Orientation at Epoch. The orientation of the prime meridian of Mars in space at a given epoch t is specified by the angle W, which is measured along the equator to the east between the 0° (or prime) meridian and the equator's intersection with the celestial equator. It is given (in degrees) by the expression:

$$W = W_0 + W\_dot * d$$

where W_dot is defined as above and d is the number of days from t to the standard epoch J2000.0. W_0 is the value of W at the standard epoch J2000.0.

Because the location of the prime meridian is defined by the center of the crater Airy-0 [1, 3], it is necessary to estimate W_0 based on the expected position of Airy-0 at J2000.0. The determination of this angle is critical, as any change in this value will result in a change in longitude of any point on the planet whose position has been determined in inertial space. It is therefore desirable to determine a value for this that is as accurate as possible, and yet also a value that is unlikely to be improved on (thus changing longitudes again) in the near future. In the past this has been done as part of photogrammetric bundle block adjustment solutions of Viking Orbiter and Mariner 9 images [4, 5, 6, 7, 8, 9]; however, the advent of Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) and Mars Orbiter Camera (MOC) data has provided an alternative and more accurate method of determining the value of W_0. The MOLA observations allow for surface coordinates to be estimated with fairly high accuracy (order 100 m in horizontal position) in the same inertial coordinate system in which the spacecraft position is determined. Matching the MOLA ground track observations to images of the surface will therefore allow the position of surface features shown on the images to be determined at a similar level of accuracy in inertial space. Using this method, we have taken the center position of Airy-0 (measured by M.

Caplinger of Malin Space Science Systems to be sample 281, line 5498 in MOC narrow angle image M23-00923; see http://www.msss.com/mars_images/moc/01_31_01_releases/airy0/index.htm) and then determined the position of this pixel relative to MOLA data obtained at the same time in the area of this image. This comparison made use of the USGS calibration of the relative alignment of the MOC and MOLA instruments to an estimated precision of ~100 m on the ground [10]. From this analysis a value of $W_0 = 176.634°$ was derived. Similarly, we have compared mosaics of high-resolution Viking Orbiter images in the vicinity of Airy-0 with a MOLA derived digital image model (DIM), and determined a value $W_0 = 176.627°$. Additional work was also done to verify that these determinations of W_0 were consistent with the positions of the Mars Pathfinder and Viking 1 lander, as determined in inertial space and on global image mosaics. A final value of $W_0 = 176.630°$ was then chosen as the simple average of these two determinations, and in general agreement with photogrammetric solutions and other checks by others and other working group members (e.g. by M. Davies, T. Colvin, Kirk, W. Zeitler, J. Oberst, and M. Wählisch). Given these comparisons we expect the uncertainty of this value of W_0 (which derives mostly from the difficulty of relating the images to the MOLA ground track or DIM) to be ±0.003° to 0.004°, or about 250 m on the Martian surface. We believe it unlikely that this value can be improved upon until a radio transmitter (lander) can be placed in the vicinity of Airy-0, presumably at some point in the distant future.

Reference Surface: In order to derive best-fitting reference surfaces for Mars, a number of least squares fits of MOLA data (as of 2001 Spring) were performed. These solutions were done for spherical, rotational ellipsoid, and triaxial ellipsoid reference surfaces. Possible assumptions for these solutions included: a) using either a sinusoidal projection with 0.5 or 1.0° data spacing, or a cylindrical projection with 0.4° or 0.8° data spacing; b) using data up to ±90°, ±85°, and ±80° latitude; and c) solving for Cartesian offsets of the chosen spheroid from the center of mass or not solving for them. The cylindrical projection solutions were done in order to see the effect of over sampling data near the poles, in comparison to the sinusoidal solutions. The solutions with different latitude limits were done to look at the effect of data (e.g. elevation changes reflecting the permanent polar caps) near the poles. The solutions with and without offsets were done mostly to determine what the difference is in the north and south polar radii, assuming an ellipsoid whose center is offset from the center of mass of Mars. The MOLA data used were points from a grid including from 40726 to 230400 points, depending on the solution assumptions (spacing, projection, and latitude limits). These solutions were done mainly to check what type of variation occurred in the solutions

given the different assumptions used and to make sure the basic rotational ellipsoid solution was reasonable in comparison to the others. The solutions of primary interest were ones using all the data (i.e. to ±90°), using the sinusoidal projection (so data near the poles would not be over sampled), and with the densest grid spacing (of 0.5°). Accuracy estimates were made based entirely on the variation between the different solutions. These estimates come to order 100-200 meters, although the formal uncertainties of the individual solutions were at the few meter level. At this estimated accuracy level, fits to a triaxial ellipsoid showed no improvement over those to a rotational ellipsoid.

The results are, for a best fitting sphere with no offsets from the center of mass, a radius of R = 3389.50 ±0.2 km. The best fitting rotational ellipsoid, again with no offsets included, results in a semi-major (equatorial) axis A = 3396.19 ±0.1 km and a semi-major (polar) radius of B = 3376.20 ±0.1 km. If an identical fit is done, but with the polar axis allowed to have an offset from the center of mass, this offset amounts to 3.01 ±0.1 km and the fitted minor axis is unchanged, resulting in a north polar radius of such an offset ellipsoid of 3376.20 - 3.01 = 3373.19 ±0.1 km and a south polar radius of such an offset ellipsoid of 3376.20 + 3.01 = 3379.21 ±0.1 km. For the best fitting rotational ellipsoid, with no offset, the RMS deviation from spheroid is 3.0 km, the maximum elevation is 22.64 ±0.1 km (Olympus Mons), and the maximum depression is 7.55 ±0.1 km (Hellas). It is unlikely that these values can *ever* be improved upon, given that the uncertainties are now almost entirely due to the fact that Mars' topographic surface simply does not match these geometric reference surfaces at accuracy levels of 0.1 km and better. This issue is also discussed by Smith [11] in a companion abstract for this meeting.

The rotational ellipsoid with best-fit dimensions A = 3396.19 km, B = 3376.20 km is being adopted by the USGS as the reference surface for map projections for a variety of Mars image mosaics and maps currently in production and will be used in products generated in the forseeable future. These mosaics include a final version of the global 1/256° monochrome digital mosaic of Viking Orbiter images (MDIM 2.1) and global 1/256° color and stereo mosaic of MOC wide angle images (MDIM 3.0) [12, 13, 14]. A revised global 1/64° color mosaic based on Viking Orbiter data is also under consideration. It is important to note that the ellipsoid will be used only as the reference surface for defining map projections. Other surfaces can be adopted for other purposes, with no inconsistency. In particular, the detailed MOLA topographic model will be used for accurate projection of images and other remote-sensing data onto the planet, and a spherical-harmonic representation of an equipotential surface will be used as the reference for elevations.

The MOLA team also plans to use the reference surface and other parameters given here in the final archived version of the MOLA dataset. Adoption of a common set of parameters for the altimetry and image-mosaic archives is necessary but not sufficient to ensure direct compatibility of the dataproducts. A common coordinate system must also be adopted.

Coordinate System: The International Astronomical Union, meeting in 1970 [15], formalized the use of two types of coordinate systems for planets. The first, sometimes called "planetocentric coordinates," consists of longitude measured positive eastward and planetocentric latitude, defined as the angle between the equatorial plane and a line from the center of the body to a given point. This system is right-handed and identical to spherical polar coordinates as commonly defined; it is used almost universally in cartographic calculations and is generally preferred by geophysicists for display of their data. The other system measures longitude positive in the direction opposite the planetary rotation, so the sub-Earth longitude increases with time. Planetographic latitude is defined as the angle between the equatorial plane and the normal to a spheroidal reference surface at the given point. (If the point of interest is above or below the reference surface, the planetographic latitude is determined for a point on the ellipsoid whose normal passes through the given point.) This coordinate system conforms to earlier astronomical usage for Mars and was extended by the IAU to the other planets and satellites. It has been used for all USGS (and many other) planetary maps to date, including digital and paper maps of Mars [16]. The second IAU-approved system is sometimes called "planetographic coordinates" but we prefer to explicitly include the direction of positive longitude (e.g., "west/planetographic" or just "west/'ographic" for Mars and other bodies rotating prograde) because some software packages use a non-IAU-approved combination of planetographic latitude and east longitude. Similarly, we refer to the other IAU coordinate system as "east/'ocentric".

The east/'ocentric coordinate system has a number of technical advantages such as being right-handed, independent of the definition of reference ellipsoid (or of the height of a point above/below such an ellipsoid), and identical to the spherical coordinate system used in gravitational potential calculations, spacecraft navigation, etc. The primary justification of the west/'ographic system has always been the weight of historical usage. A second potential advantage of planetographic latitude is that it is referenced to the local normal, which is close to the local vertical. Thus, on Earth, a surveyor with a leveled theodolite can measure planetographic (geographic) latitude directly to a good

approximation. This supposed advantage is largely negated by the absence of surveyors on Mars and by the considerable deviations of the Martian solid surface and equipotential surface from an ellipsoid (so that the local vertical determined by a hypothetical surveyor would not correspond accurately to the ellipsoid normal that defines planetographic latitude). Nevertheless, the importance of consistency over mere technical advantages led to the use of west/'ographic coordinates in all Mars maps produced from 1970 through the late 1990s.

From a practical standpoint, the situation was radically changed by the decision of the MOLA team to use east/'ocentric coordinates for its products. As a result, the best global map of Mars (the MOLA gridded elevation data, with a final grid spacing of ~1 km and ~100 m horizontal accuracy [17]) is in east/'ocentric coordinates and there are no image maps that register to it. This is the "gold standard" of Mars geodetic control for the foreseeable future, hence the basis for all other maps. Another important result is that the existence of different maps in both IAU coordinate systems is forcing users to be careful about the direction of positive longitude and to convert coordinates between systems as needed. Unfortunately, whereas converting individual latitude values such as target coordinates between systems is straightforward and can be done with a pocket calculator, converting maps between systems requires specialized software. Until quite recently not even the leading planetary cartography software packages (ISIS and VICAR) were able to resample Mars image mosaics to the MOLA grid or vice versa.

The USGS is in the process of enhancing its ISIS software to work with datasets gridded uniformly in either planetographic or planetocentric latitude, as well as with data labeled in terms of either east or west longitude. In addition, future Survey data products will clearly distinguish the latitude-longitude system used and will provide information to assist use with data in the other system. For example, USGS I-maps will be printed with dual east/'ocentric and west/'ographic coordinate grids, distinguished by different colors. Digital products will include tables with boundary coordinates in both systems.

Furthermore, the USGS, with the support and partly at the instigation of the MGCWG, has formally proposed to NASA to make future digital and paper Mars maps in the east/planetographic coordinate system. Digital products currently in production that would be affected are the final Viking Orbiter global image mosaic (MDIM 2.1), global color and stereo mosaics of MOC wide-angle data (MDIM 3.0) [11, 12, 13], and possibly global Viking color mosaics. The

USGS proposal was motivated by two considerations. First, many potential users lack the time, interest, and knowledge (even if the necessary software is available) to resample data from one coordinate system to another, so it is desirable for the USGS to do this resampling work. Second, MOLA has been joined by the MGS TES team, the entire 2001 Mars Odyssey mission, and the Mars Exploration Rovers site selection process in adopting east/'ocentric coordinates. The Mars Reconnaissance Orbiter and the HRSC team of the ESA Mars Express mission are likely to follow suit. Producing USGS image mosaics in east/'ocentric coordinates will reinforce this trend of widespread use of the system and will require much less work than resampling and rearchiving the MOLA and numerous other datasets in the west/'ographic system.

It is important to note that although the projections for digital products will be different in the future (equally sampled in planetocentric rather than planetographic latitude), the projections of printed maps will not be affected by the adoption of east/ 'ocentic coordinates. Whereas digital products are made in "database" projections (Sinusoidal and Simple Cylindrical) defined by simple formulae in which either kind of latitude can be substituted, printed maps use conformal projections (Mercator, Polar Stereographic, etc.). Definition in terms of conformality (i.e., no distortion of angles) ensures that these projections are the same regardless of whether planetographic or planetocentric latitudes are adopted as the primary system. The only difference in future printed maps will be the location of quadrangle boundaries at "round" numbers of degrees planetocentric rather than planetographic.

Conclusion: The adoption of cartographic constants based on high-quality MGS data and therefore unlikely to be superseded for many years, as well as the proposed adoption of east/planetocentric coordinates by the USGS and the majority of mission teams, will ensure that the many Mars datasets produced over the coming decade will share a common cartographic reference frame. As a result of these advances (and of the availability of the MOLA data as a source of highly accurate control), it will be possible to compare disparate datasets with confidence that they are coregistered to order 100-m accuracy.

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