MERCURY'S REFERENCE FRAMES AFTER THE MESSENGER MISSION

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Mercury's Prime Meridian & Hun Kal crater

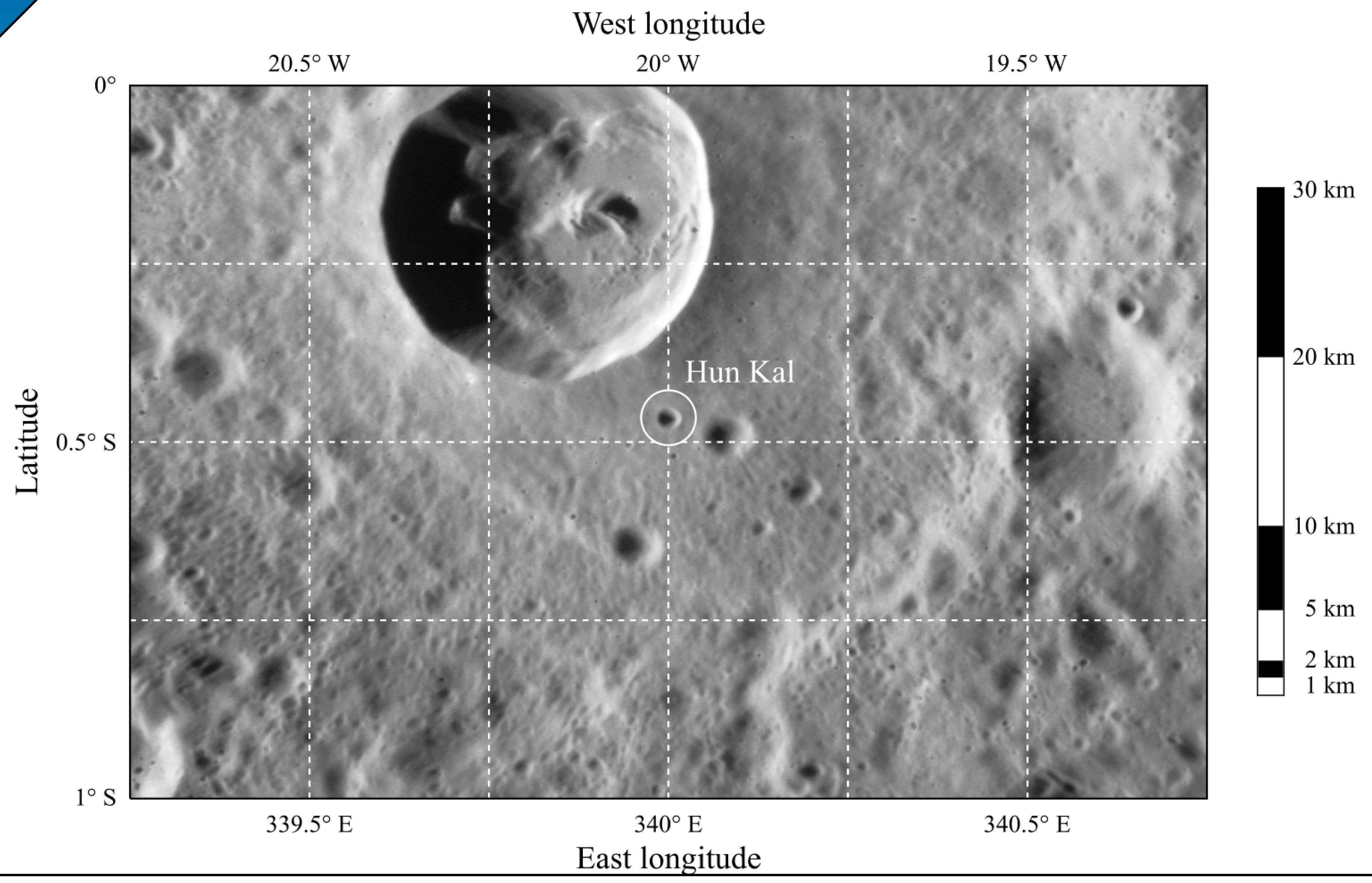

Image	Diameter in longitude [km]	Diameter in latitude [km]	Latitude [degree]	East longitude [degree]	Image resolution [km]	Viewing quality scale (5 = good, 1 = bad)
EN1005053163M	1.28	1.32	-0.4669	339.9919	0.047	4
EN1002521325M	1.49	1.41	-0.4602	339.9868	0.054	5
EN1015451668M	1.58	1.32	-0.4759	340.0008	0.059	5
EN1007130467M	1.43	1.30	-0.4636	340.0047	0.073	5
EN0251340756M	1.59	1.37	-0.4459	340.0054	0.082	4
EN0251369558M	1.60	1.35	-0.4492	340.0046	0.084	4
EN0131770954M	1.46	1.18	-0.4601	339.9574	0.126	2
EN1004678315M	1.24	1.28	-0.4625	340.0182	0.134	2
EN1004678277M	1.54	1.37	-0.4574	340.0180	0.134	1
EN1067842322M	1.38	1.36	-0.4970	339.9522	0.139	3
EN0251369585M	1.62	1.25	-0.4466	339.9745	0.168	3
EW0228112559G	1.39	1.34	-0.4726	339.9812	0.237	4
EW0228155763G	1.42	1.41	-0.4736	339.9848	0.238	4
EN1067841884M	1.32	1.24	-0.4979	339.9942	0.245	2
EW0228199096G	1.39	1.47	-0.4727	339.9828	0.274	4
EW0228112703G	1.39	1.43	-0.4725	339.9821	0.275	3
EN0131772248M	1.25	1.09	-0.4600	339.9347	0.291	1
Weighted average	1.463 ± 0.120	1.341 ± 0.061	-0.4646 ± 0.0124	339.9930 ± 0.0153	-	-

MDIS NAC and WAC images are used for measurement of the diameter and crater center coordinates of Hun Kal. Averaged values are obtained by weighting the measurements by viewing quality scale and image resolution. We obtain a mean diameter of **1.402 ± 0.112 km**. By computing the length of the shadow in images with low Sun elevation we roughly estimate the **crater depth to about 340 m**. The averaged location of the crater center is 0.4646° ± 0.0124° S and 339.9930° ± 0.0153° E. The prime meridian of Mercury is defined by assigning the longitude 340° E (20° W) to the center of Hun Kal. The observed offset of 0.007° (300 m) from the 340° E longitude is not significant given the uncertainty of the measurements.

Overview of Mercury Rotation Models

The table below provides an overview on derived rotational parameters. Thereby the orientation of the rotation axis is parameterized by the declination $\delta(t) = \delta_0 + \delta_1 t/\mathrm{cy}$ and right ascension $\alpha(t) = \alpha_0 + \alpha_1 t/\mathrm{cy}$. The temporal evolution of the right ascension and declination angles is described by a linear function, where the first term gives the orientation of the rotation axis at the J2000 epoch (with respect to ICRF) and the second term denotes the long-term precession of the rotation axis ('cy' refers to Julian century, i.e. 36525 days). The rotation about that axis is defined by the prime meridian angle $W(t) = W_0 + W_1 t/\mathrm{d} + W_{\mathrm{lib}}(t)$, which is composed of the prime meridian constant W_0, the mean rotation rate W_1 and the forced libration in longitude $W_{\mathrm{lib}}(t)$. The amplitude of the latter is denoted by $A_{\mathrm{lib}} = \max_t W_{\mathrm{lib}}(t)$. Values in rows below the dashed line are based on MESSENGER observations. Rotational parameters **adopted for MESSENGER cartographic products are highlighted in bold face**. Computed values refer to the orientation and precession of the orbit plane normal and to the rotation rate obtained by the assumption of a 3:2 spin-orbit resonance.

Author	α_0 [°]	α_1 [°/cy]	δ_0 [°]	δ_1 [°/cy]	W_0 [°]	W_1 [°/day]	A_{lib} ["]
Pettengill and Dyce (1965) (radar)						6.1±0.5	
Colombo (1965) (computation)						6.138505138	
McGovern et al. (1965) (visual)						6.16±0.04	
Dyce et al. (1967) (radar)						6.1±0.3	
Camichel and Dollfus (1968) (visual)						6.136 ± 0.003	
Smith and Reese (1968) (visual)						6.1367 ± 0.0021	
IAU 1970 (computation, Davies and Batson (1975))	280.980		61.447		329.714	6.138505138	
Murray et al. (1972) (visual)						6.1387 ± 0.0009	
Klaasen (1975) (Mariner 10)						6.1369 ± 0.0018	
Klaasen (1976) (Mariner 10)	281±10		63±5			6.13852 ± 0.00052	
Davies et al. (1980); Davies et al. (1983) (computation, W_0 from Mariner 10 images)	281.01	-0.0033	61.45	-0.005	329.71	6.1385025	
Davies et al. (1996) (Mariner 10)					329.68		
Robinson et al. (1999) (Mariner 10)					329.548 ± 0.470		
Margot et al. (2007) (Earth-based radar)	281.0097		61.4143				35.8 ± 2
Margot (2009) (computation)	280.9880	**-0.00328**	61.4478	**-0.0049**	329.75		
Margot et al. (2012) (Earth based-radar)	**281.0103**		**61.4155**				**38.5 ± 1.6**
Mazarico et al. (2014) (MESSENGER radio science)	281.00480 ± 0.0054		61.41436 ± 0.0021			**6.13851079 ± 0.00000120**	
Stark et al. (2015a) (computation)	280.987971 ± 0.000099	-0.032808 ± 0.000020	61.447803 ± 0.000036	-0.0048464 ± 0.0000073	329.7564 ± 0.0051	6.138506839 ± 0.000000028	
Stark et al. (2015b) (MESSENGER laser altimeter and images)	281.00980 ± 0.00088		61.4156 ± 0.0016			6.13851804 ± 0.00000094	38.9 ± 1.3
Stark (2016) (MESSENGER images)					**329.5988 ± 0.0037**		
Verma and Margot (2016) (MESSENGER radio science)	281.00975 ± 0.0048		61.41828 ± 0.0028				
Baland et al. (2017) (based on Stark et al. (2015b))	281.00981 ± 0.00083	-0.032907	61.41565 ± 0.00150	-0.0048590			

Mercury's Reference Frames

MESSENGER reference frame: This cartographic frame is currently used for all data products from the MESSENGER mission. The rotation parameters are based on Earth-based radar and MESSENGER radio science measurements (see table on the left). Since the analysis of MESSENGER data revealed Mercury's rotation rate to be significantly different from the previously assumed rotation rate, the prime meridian constant W_0 was revised. The previous rotation rate, based on the assumption of a 3:2 spin-orbit resonance, leads to a longitudinal offset of 0.0519° (2.2 km) in Hun Kal's position in MESSENGER images.

Dynamical frame: Mercury's rotation state is tied to its orbital motion through a 3:2 spin-orbit resonance. This property allows to define a dynamical reference system, which can be realized by accurate analysis of Mercury's ephemeris. Within the dynamical frame the prime meridian is defined as the mean location of the sub-Solar point at every second pericenter passage of Mercury. Interestingly, the cartographic frame defined by the crater Hun Kal and the dynamical frame do not coincide. The difference amounts to 0.12° (5.12 km) in longitude at the midterm of the orbital phase of the MESSENGER mission.

Principal-axes frame: The principal-axes reference system is defined by the principal components of Mercury's moment of inertia. The low-degree gravity field coefficients reflect the mass distribution within the planet and can be used to derive the orientation of the principal axes. Considering Mercury's gravity field estimates based on MESSENGER radio science data we found that the principal-axes frame coincides with the dynamical frame within the measurement accuracy.

Ellipsoid frame: Due to the strong tidal force from the Sun Mercury's global shape can be characterized by a tri-axial ellipsoid and allows a definition of an ellipsoid reference system. The ellipsoid reference system is related to the center of figure. While there are hints at an offset between the center of mass and the center of figure in the order of 100 m, the orientation of the long axis of the ellipsoid frame is consistently offset from the axis of smallest inertia through all available data sets. The transformation from the MESSENGER frame to the ellipsoid frame is given by a translation of

$$d_r = (d_x, d_y, d_z) = (0.082 \pm 0.057, 0.147 \pm 0.045, -0.077 \pm 0.030)\ \mathrm{km}$$

and a subsequent rotation by

$$E = R_x(1.9° \pm 1.1°) \cdot R_y(-2.9° \pm 0.5°) \cdot R_z(16.7° \pm 1.7°).$$

Thus, the transformed vector r' is obtained from the initial vector r expressed in the MESSENGER frame by $r' = E(r + d_r)$.

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