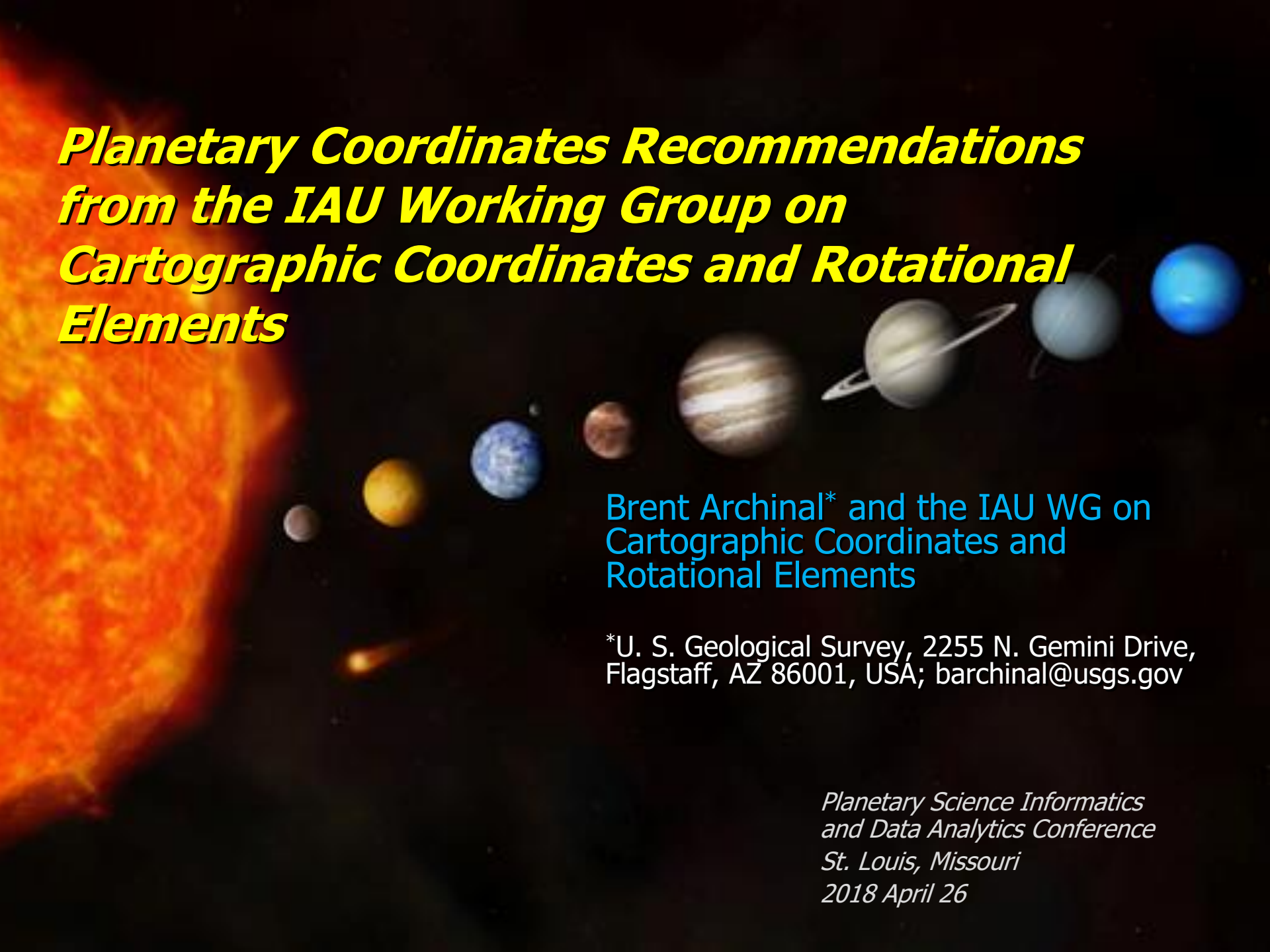
Planetary Coordinates Recommendations from the IAU Working Group on Cartographic Coordinates and Rotational Elements



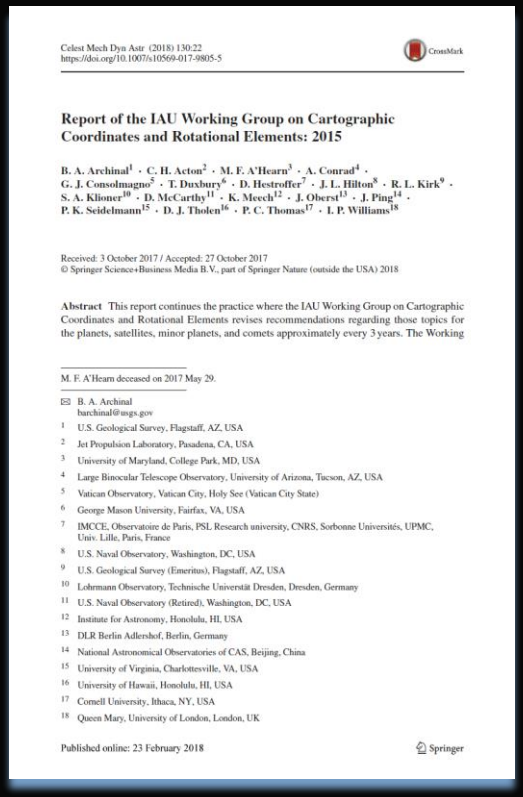
Brent Archinal* and the IAU WG on Cartographic Coordinates and Rotational Elements

*U. S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA; barchinal@usgs.gov

Planetary Science Informatics and Data Analytics Conference
St. Louis, Missouri
2018 April 26

IAU Working Group on Cartographic Coordinates and Rotational Elements

- Issue reports with recommendations about coordinate systems and related parameters for making cartographic products of Solar System bodies
- Starting in 1979 (Davies et al., 1980), reports every ~three years
  - Associated with IAU General Assemblies
- Current "2015" report just published (Archinal et al. 2018)
- *Goal is to make recommendations, open to further modification when needed, to avoid confusion and facilitate the use and comparison of multiple datasets!*
- Web site:
  - http://astrogeology.usgs.gov/groups/IAU-WGCCRE



Celest Mech Dyn Astr (2018) 130:22
https://doi.org/10.1007/s10569-017-9805-5

CrossMark

Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015

B. A. Archinal[1] · C. H. Acton[2] · M. F. A'Hearn[3] · A. Conrad[4] · G. J. Consolmagno[5] · T. Duxbury[6] · D. Hestroffer[7] · J. L. Hilton[8] · R. L. Kirk[9] · S. A. Klioner[10] · D. McCarthy[11] · K. Meech[12] · J. Oberst[13] · J. Ping[14] · P. K. Seidelmann[15] · D. J. Tholen[16] · P. C. Thomas[17] · I. P. Williams[18]

Received: 3 October 2017 / Accepted: 27 October 2017

Abstract This report continues the practice where the IAU Working Group on Cartographic Coordinates and Rotational Elements revises recommendations regarding those topics for the planets, satellites, minor planets, and comets approximately every 3 years. The Working

M. F. A'Hearn deceased on 2017 May 29.

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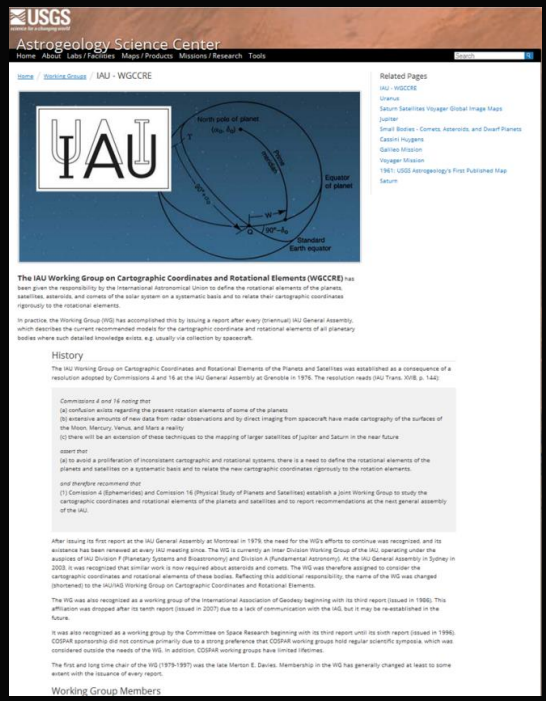
Published online: 23 February 2018

Springer

Current WGCCRE "2015" Report, published 2018



WGCCRE web site

Relevance to Planetary Science Informatics and Data Analytics

- This effort supports the many fields covered by this conference
  - Interoperability
  - Data modeling
  - Data comparison
  - Data visualization and interpretation
  - Planetary data processing generally
- A foundation for all planetary geospatial datasets
- The WG encourages input and is available to assist users, instrument teams, and missions

Working Group Operation

- Membership by invitation or volunteering
- Currently 17 members from 6 countries
- Newly a "Functional" (long term) WG of IAU
- Considers new published coordinate system related determinations
- Recommends standards based on consensus
- No independent resources of its own
- Does not "bless" or "enforce" recommendations – value is only from reflection of general consensus and use
- Recommendations primarily for mapping – other uses (e.g. dynamical) are possible
- Does not deal with formats, "lower level" mapping standards
  - There is a need for missions and space agencies to develop and maintain such standards
  - E.g. International Planetary Data Alliance, Planetary Data System, Mars Geodesy and Cartography WG , Lunar Geodesy and Cartography WG, Cassini Icy Satellites Cartography WG, and now MAPSIT
- Seeking new members who wish to help with our work
  - See me for info!

Current WGCCRE Membership

B.A. ARCHINAL (Chair)
U.S. Geological Survey, Flagstaff, AZ, U.S.A.

C.H. ACTON
Jet Propulsion Laboratory, Pasadena, CA, U.S.A.

A. CONRAD (Acting Vice Chair)
Max Planck Institute for Astronomy, Heidelberg, Germany

G.J. CONSOLMAGNO
Vatican Observatory, Vatican City State

T. DUXBURY
George Mason University, Fairfax, VA, U.S.A.

D. HESTROFFER
IMCCE, Observatoire de Paris, CNRS, Paris, France

J.L. HILTON
U.S. Naval Observatory, Washington D.C., U.S.A.

L. JORDA
Laboratoire d'Astrophysique de Marseille, Marseille, France

R. Kirk
U.S. Geological Survey, Flagstaff, AZ, U.S.A.

S.A. KLIONER
Technische Universität Dresden, Lohrmann Observatory, Dresden, Germany

J.-L. MARGOT
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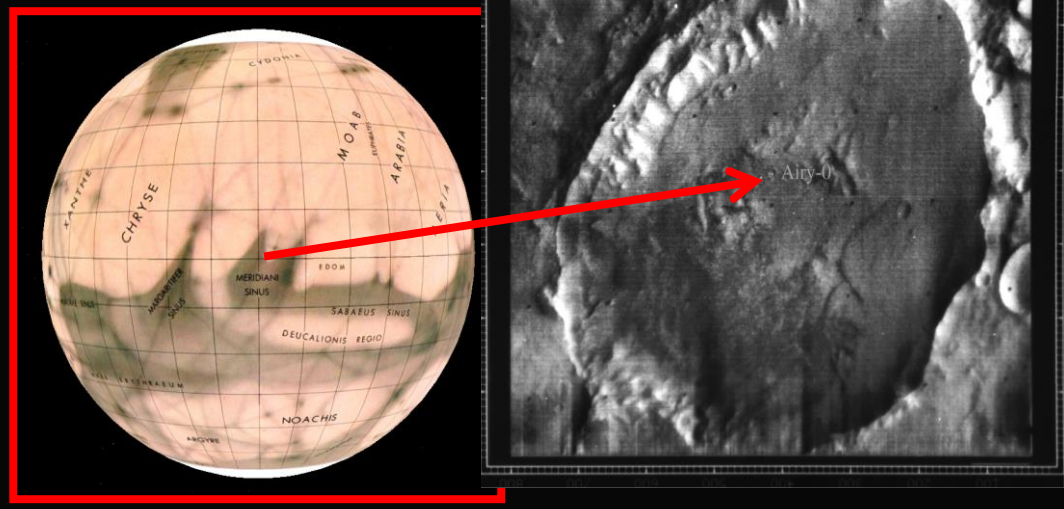
D.J. THOLEN
University of Hawaii, Honolulu, HI, U.S.A.

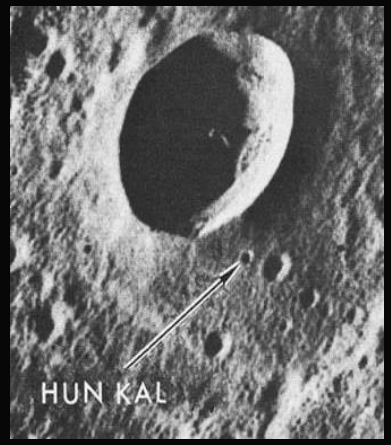
I.P. WILLIAMS
Queen Mary, University of London, London, U.K.

Definition of Longitude

- Must be done by convention
- WG has reiterated 1979 (Davies et al., 1980) recommendation: Once an observable reference feature at a defined longitude is chosen, the longitude definition origin should not change except under unusual circumstances; however *refinement* possible and expected
- Questions in recent years relative to Moon, Mercury, satellites of Jupiter and Saturn, Vesta, Lutetia, Ceres
- No clear advantage seen in creating multiple prime meridians and cartographic systems – alternate systems (e.g. dynamic) considered more useful
- Examples at right: Airy-0 on Mars (de Vaucouleurs et al., 1973; Hun Kal on Mercury
- With current report, *Mars longitude definition further refined* (see below); but Airy-0 still at 0° longitude



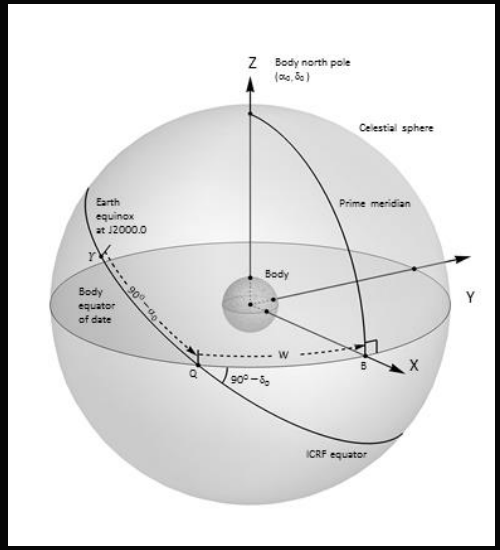
Refinement of Mars 0° longitude from Meridiani Sinus (left) to Airy-0 (right) in 1973. Left: USAF 1962 Mars map (ESA/DLR/FU Berlin (G. Neukum / Google Earth); Right: Mariner 9 image of Airy and Airy-0, no. 533B03



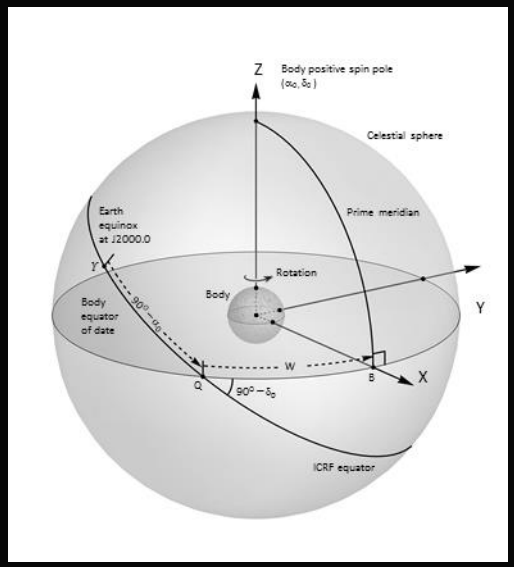
Left: Longitude origin for Mercury was refined in 1979 from dynamical one (long principal axis at 0°) to surface feature, crater Hun Kal ("twenty" in Mayan) at 20° west longitude.

Report Contents

- General recommendations
  - Latitude, longitude, planetographic vs. planetocentric, cardinal directions
  - Creating / refining planetary coordinate systems
  - For historical reasons, separate handling of planets and satellites vs. other ("small") bodies
- Models and parameters for body orientation
  - Longitude definition, spin, pole
- Models and parameters for body shape
  - Mean radius, ellipsoidal parameters, some global DTMs
- As much as possible, based on peer-reviewed results of others



Coordinates for planets and their satellites; planetographic or planetocentric



Coordinates for other bodies (right handed)

Changes in just published report – General/Recommendations

- Added procedures for WG to consider informal and formal requests
- Body shapes defined (where necessary) for reference shape, topography, and map scale (e.g. Venus, Moon, Mars, Titan)
- Modifying terminology for poles of small bodies and cardinal directions

Significant general recommendations

- *The construction of controlled cartographic products should be emphasized*
- *For planets and satellites planetographic systems have generally been historically preferred over planetocentric systems; In cases when planetographic has been widely used in the past, there is no obvious advantage to switching to planetocentric*
- *Planetographic is not defined for use with small bodies, but planetocentric and planetodetic latitude could be used*

- See report for additional recommendations and details

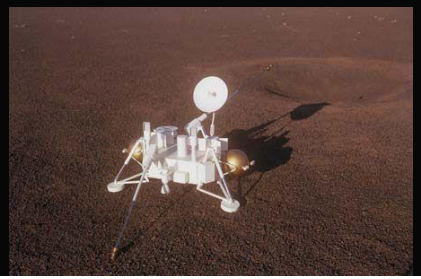
Changes in just published report – Major Bodies

- Sun, radius updated
- Mercury, MESSENGER results, orientation and radius
- Earth orientation, referred to IERS
- Moon, continuing to use DE421 ME system
- Mars, using Kuchynka et al. (2014)
  - Longitude definition refined with Viking 1 longitude fixed
- Neptune orientation, using Karkoschka (2011)

Changes in just published report – Other

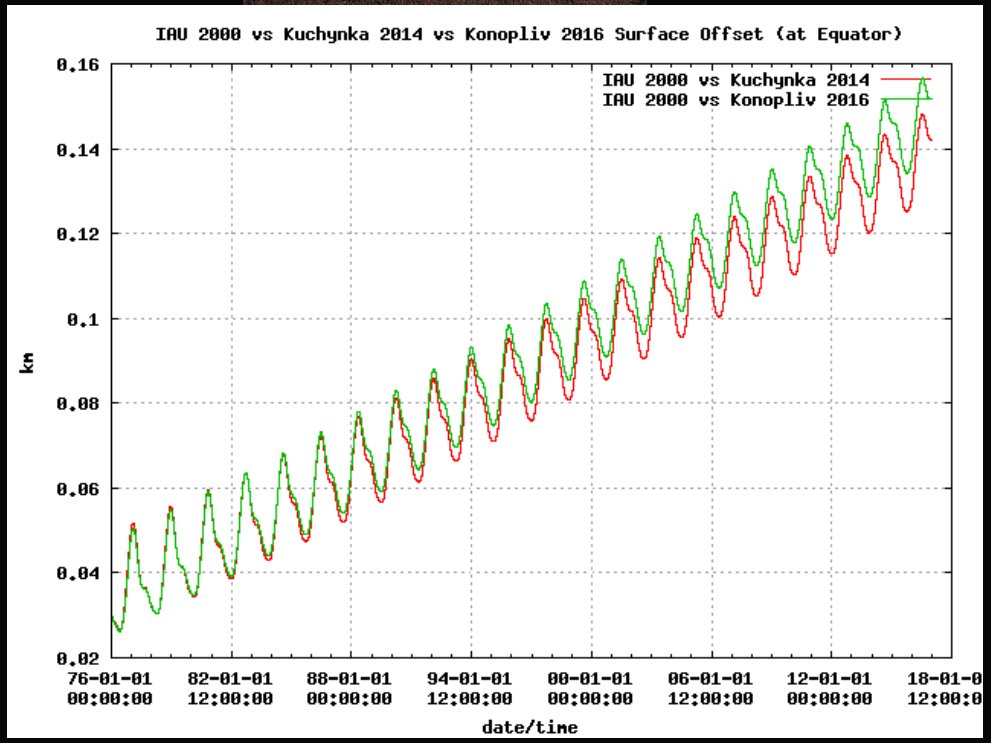
- Phobos and Deimos, improved orientation
- Titan and 14 other Saturnian satellites, size
- Pluto and Charon, radii from New Horizons results
- Ceres, size, orientation from Dawn results
- Vesta, orientation from Dawn results (Claudia”/IAU 2013)
- (52) Europa, Šteins updated
- Itokawa, axes’ lengths corrected
- Comet issues addressed (Tempel 1, Borrelly, Churyumov-Gerasimenko, Hartley 2)
- Psyche and (52) Europa, size

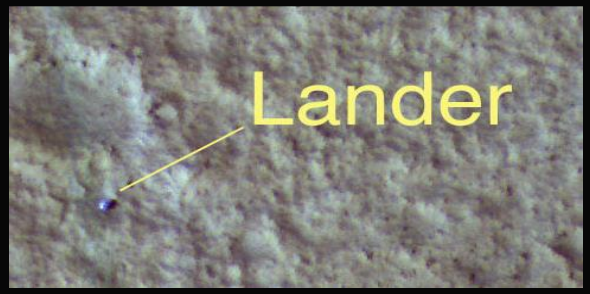
Example – Updating the Orientation Model for Mars



Viking 1

- Recommending use of Kuchynka et al. (2014) model
- Further improved model by Konopliv et al. (2016), but only just now in usable form from Jacobson et al. (2018)
- Substantial improvement over IAU (WG) "2000" model. (See figure)
- Longitude definition refined: Viking 1 lander – defined with 312.04863° east longitude => keeping Airy-0 at 0° longitude.
  - Viking 1, much smaller feature than Airy-0
  - Has radiometric tracking used in all Mars solutions
- Needs to be implemented carefully – will affect results on active missions (MRO: HiRISE, CTX; MO: THEMIS VIS; Mars Express: HRSC, SRC)
- Recommended by NASA MGCWG
  - Contact T. Duxbury, GMU, for details (tduxbury@gmu.edu)





View of Viking 1 from orbit. Detail of HiRISE Image PSP_001521_2025.

Comparison in longitude (km) of previous IAU (2000) model to new IAU recommended model of Kuchynka et al. 2014 (red); and also to Konopliv et al. 2016/Jacobson et al. 2018 (green) orientation model. E.g. offset from 1976 to present is > 100 meters!

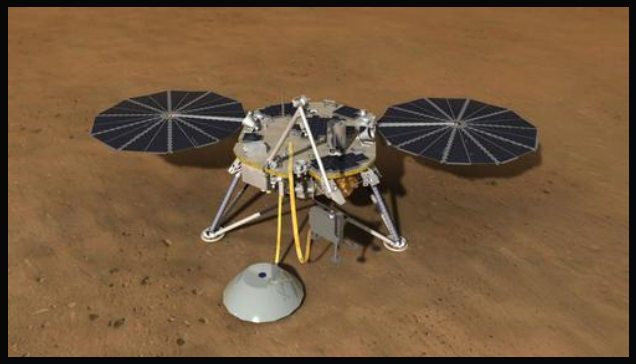
Image Credit: Boris Semenov (NAIF).

Availability

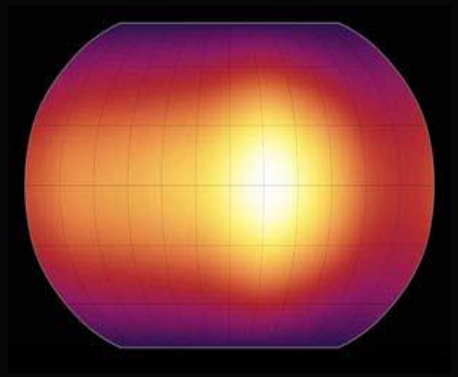
- Published report
  - Archinal et al (2018). "Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015," Celestial Mechanics and Dynamical Astronomy, 130:22, DOI: 10.1007/s10569-017-9805-5
  - On line soon at WGCCRE site
- Models via PDS/NAIF
  - Ref: Marc Costa presentation from Tuesday
  - Default PCK file to be updated soon by NAIF
  - Will include mean radii for first time, and new routine coming soon for access
- Older versions in other software
  - E.g. WMS, ESRI ArcGIS, other software, shape info only; updates?

Outlook for Later Reports and Activities

- Mars: Recommend Konopliv et al. 2016 rotation model. Eventually use *Insight* lander or lander network to define longitude?
- Moon: Improved orientation model?
- Community consensus models for orientation of Jupiter and Saturn?
- Updates from missions: Mercury, Saturnian satellites, Pluto and moons, Vesta, Ceres, Comet Churyumov–Gerasimenko
- Updates from terrestrial observations of asteroids
- Consultation needed within IAU about exoplanets
- Continuing to provide assistance on coordinate system and mapping issues
- WG meeting at August IAU GA; next report planned for 2019 publication



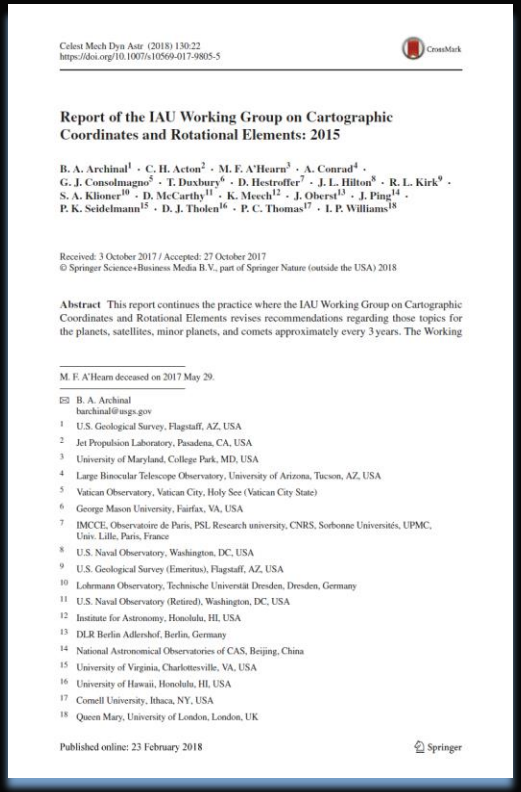
InSight – Mars Lander and Geophysical station



Temperature map of "hot Jupiter" exoplanet HD 189733b (Knutson et al. 2007)

Summary

- New ("2015") report just published
  - *Celestial Mechanics and Dynamical Astronomy*
- Major changes:
  - Clarifies how to refine longitude definition when new data arrive
  - Differentiates between best fitting body size and shape vs. reference values
  - Mars orientation model improvement
  - Many orientation and shape updates for small bodies
  - Updated general recommendations
- Supports the many fields covered by this conference



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Published online: 23 February 2018

Springer

Questions?

Discussion?

Input?

Interest in membership?

See or e-mail me (barchinal@usgs.gov)

Backup

General Use, Availability of IAU Recommendations

A Reminder from 2012 IAU General Assembly

- The IAU provides many different types of recommendations and services
- Common goal is to facilitate international astronomical science
  - Common data formats, units, coordinate systems
  - Naming conventions
  - No need to "reinvent the wheel"
  - Facilitates data exchange, quicker understanding of data
- A few planetary examples
  - Planetary coordinates
  - Planetary nomenclature
  - Asteroid and comet names and designations
  - Astronomical constants
  - Planetary ephemerides
  - Time
  - Meteorite names
  - Meteor showers!
- Available to authors, journal editors, instrument teams, missions, and agencies
- Developed over decades of input by IAU members, national space agencies, and other institutions
- Care should be taken to follow such recommendations *or* to present well-reasoned arguments why they should be changed
- New data and results allowing for improvements of recommendations always welcome
  - E.g. for so-called "constants" that improve on existing coordinate systems
  - E.g. name suggestions following existing themes
  - E.g. improved astronomical constants and ephemerides
- The IAU and its Commissions & Working Groups stand ready to help authors, journal editors, missions, and space agencies understand and follow IAU recommendations

New Mars Orientation model

Based on Konopliv et al. 2016 and NAIF PCK file series expansion

Mars

$$a_0 = 315.34551871 - 0.1086497127 84T$$
$$+ 0.\sin MS1 + 2.33559631 \sin MS2 + 0.00004628 \sin MS3 - 0.00001031 \sin MS4 +$$
$$+ 0.00013117 \sin MS5 + 0.\sin MS6 + 0.00001882 + \sin MS7 + 0.00001116 \sin MS8$$
$$- 0.00001014 \sin MS9 - 0.00000041 \sin MS10 - 0.00008977 \sin MS11 - 0.00008600 \sin MS12$$
$$- 0.00011513 \sin MS13 - 0.00000051 \sin MS14 - 0.00000136 \sin MS15 - 0.00001764 \sin MS16$$
$$- 0.00004755 \sin MS17 - 0.00000059 \sin MS18 - 0.00000873 \sin MS19 + 0.00000035 MS20$$
$$- 0.00000134 \sin MS21$$

$$d_0 = 61.69239825 - 0.061587333591T$$
$$- 8.80604547 \cos MS1 + 0.\cos MS2 - 0.00080268 \cos MS3 + 0.00012392 \cos MS4$$
$$+ 0.\cos MS5 + 0.00079170 \cos MS6 - 0.00001272 \cos MS7 - 0.00000141 \cos MS8$$
$$+ 0.00000251 \cos MS9 + 0.00000082 \cos MS10 - 0.00005458 \cos MS11 + 0.00020651 \cos MS12$$
$$+ 0.00004026 \cos MS13 - 0.00000048 \cos MS14 + 0.00000772 \cos MS15 + 0.00001712 \cos MS16$$
$$+ 0.00001857 \cos MS17 + 0.00000097 \cos MS18 + 0.00000523 \cos MS19 + 0.\cos MS20$$
$$+ 0.00000083 \cos MS21$$

$$W = 173.30879242 + 350.891982519523d$$
$$- 0.75667792 \sin MS1 + 3.32310358 \sin MS2 - 0.00230232 \sin MS3 - 0.00025587 \sin MS4$$
$$- 0.00220746 \sin MS5 + 0.00006338 \sin MS6 - 0.00001442 \sin MS7 - 0.00000909 \sin MS8$$
$$- 0.00000076 \sin MS9 - 0.00002912 \sin MS10 + 0.00019723 \sin MS11 - 0.00009194 \sin MS12$$
$$+ 0.00018709 \sin MS13 + 0.00000142 \sin MS14 - 0.00003743 \sin MS15 + 0.00002073 \sin MS16$$
$$+ 0.00007035 \sin MS17 + 0.00000270 \sin MS18 + 0.00000419 \sin MS19 - 0.00000028 \sin MS20$$
$$+ 0.00000107 \sin MS21 \quad (d)$$

Where

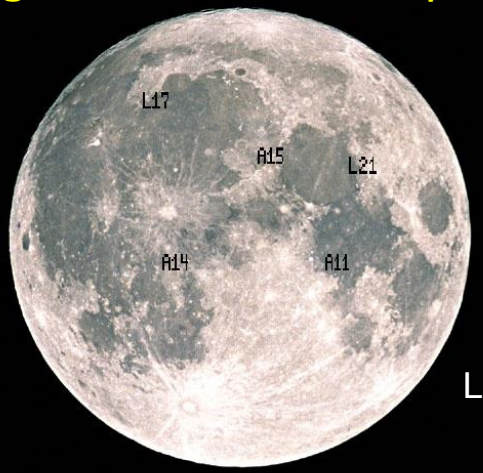
MS1 = 0° + 0° .21134279T
MS2 = 90° + 0° .21134279T
MS3 = 0° + 19139° .86461912T
MS4 = 90° + 19139° .81084919T
MS5 = 190° .02859433 + 19139° .85801553T
MS6 = 354° .26708690 + 19139° .85801553T
MS7 = 0° + 19140° .99045156T
MS8 = 90° + 19141° .16081386T
MS9 = 0° + 38279° .76346293T
MS10 = 90° + 38279° .64898292T
MS11 = 0° + 38280° .78360991T
MS12 = 41° .18790047 + 38280° .88273809T
MS13 = 90° + 38280° .96773580T
MS14 = 0° + 57413° .23685793T
MS15 = 90° + 57420° .61182408T
MS16 = 0° + 57420° .61254870T
MS17 = 90° + 57420° .76966903T
MS18 = 0° + 76560° .22756307T
MS19 = 90° + 76560° .60395345T
MS20 = 0° + 95700° .82351052T
MS21 = 90° + 95700° .45229604T (e)

(d) The longitude of the Viking 1 lander is defined to be 47° .95137 west (Kuchynka et al., 2014), maintaining the 0 ° meridian through the crater Airy-0.

(e) It is assumed in these expressions that the values of 0° and 90° are exact.

Orientation of the Moon

- An updated JPL ephemeris, DE430, *is* available
  - The underlying ephemeris is in the principle axis (PA) system, with rotation angles to the mean Earth/polar axis (ME) system (i.e. from DE421 ME frame) – tied to the LRRR locations – in use for cartographic products
  - However, the change relative to current DE421 ME is on the order of only 1 meter in XYZ!
  - So DE 421 ME still current WGCCRE (and LRO) recommended eph.
- Another update possible soon
  - Planning to *wait* to recommend changes based on new ephemeris
- Next report, may recommend
  - Use of INPOP ephemeris as alternate model – for principle axis orientation
    - French consortium: http://www.imcce.fr/inpop/
    - Only if rotation angles to the ME system become available
  - Direct definition of ME frame from LRRR coordinates



LRRR array sites

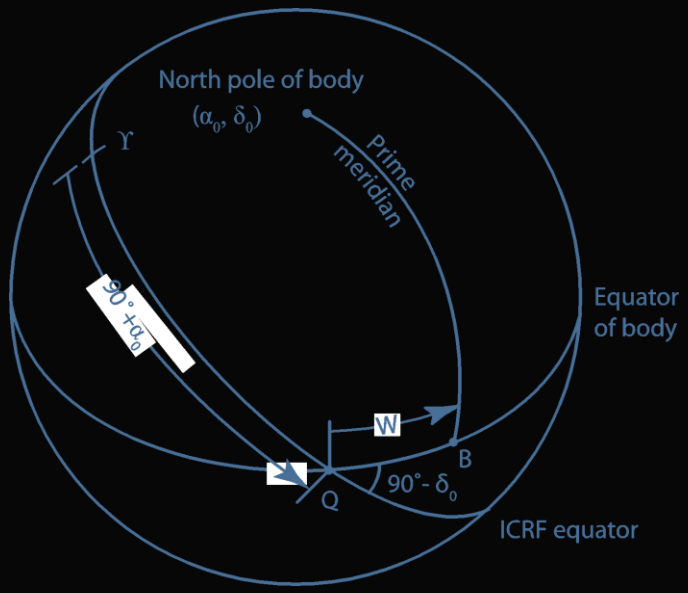
Two Recommended Systems: Planets & Satellites vs. "Small Bodies"

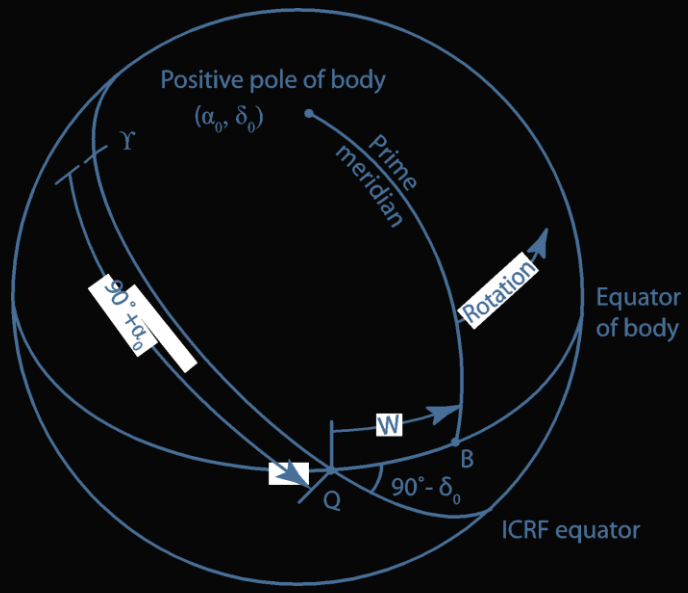
Planets and Planetary Satellites

- Planetographic
  - Longitude increases as viewed from Earth (west or east)
  - Latitude defined relative to ecliptic (north or south)
- Planetocentric
  - Longitude toward east
  - Latitude same as planetographic
- Classical system
- Kept for historical reasons

Dwarf planets, asteroids, comets

- Right handed system
  - Longitude is right handed (positive, negative)
  - Latitude is right handed (positive, negative)
  - No reliance on Earth or ecliptic
  - Adopted 2003





Small Bodies in Current Report

Rotational Elements (Orientation)
α_0, δ_0, and W_0 defined* for:

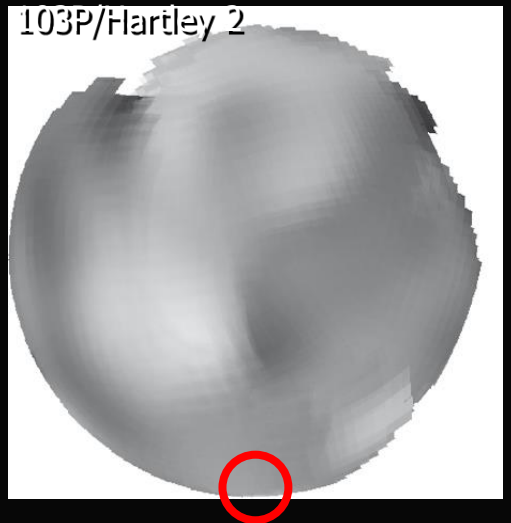
(1) Ceres
(2) Pallas
(4) Vesta
(21) Lutetia
(52) Europa
(243) Ida
(433) Eros
(511) Davida
(951) Gaspra
(2867) Šteins
(25143) Itokawa
(134340) Pluto
(134340) Pluto : I Charon
9P/Tempel 1
19P/Borrelly
67P/Churyumov-Gerasimenko
103P/Hartley 2

* Only "mapped" bodies – no photometric only definitions

Size and Shape
Radius, principal axes defined for:

(1) Ceres
(4) Vesta
(16) Psyche
(21) Lutetia
(52) Europa
(243) Ida
(253) Mathilde
(433) Eros
(511) Davida
(951) Gaspra
(2867) Šteins
(4179) Toutatis
(25143) Itokawa
(134340) Pluto
(134340) Pluto: I Charon
1P/Halley
9P/Tempel 1
19P/Borrelly
67P/Churyumov-Gerasimenko
81P/Wild 2
103P/Hartley 2

Pallas example: positive *polar projection* K band map of shape model, with 0° (long axis) at bottom (from Keck II and VLT images; Carry, et al., 2010)



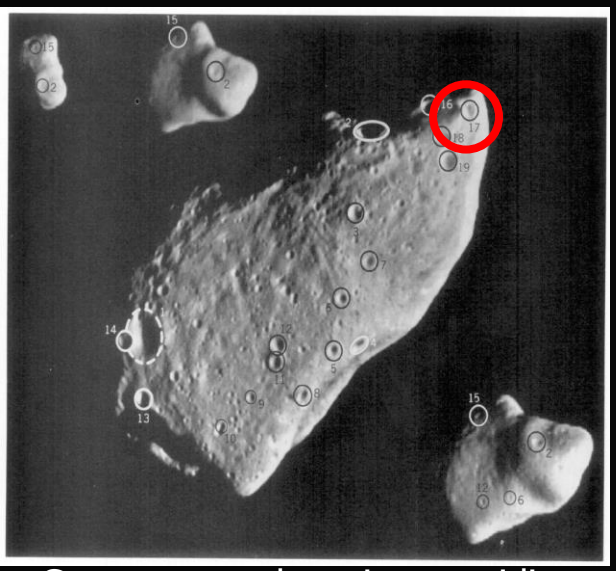
Definition of Longitude on Small Bodies

Guidelines:

- Initially, use arbitrary meridian, e.g. $W_0 = 0°$ at J2000.0 or observation epoch
- When surface first mapped chose "small" feature near equator, set longitude (e.g. 0°), calculate W_0
- Maintain definition into future, as new data obtained (pick new feature if necessary, modify W_0 within accuracy limits as necessary)
- Specify second feature for chaotic ("tumbling") rotation bodies (none yet)

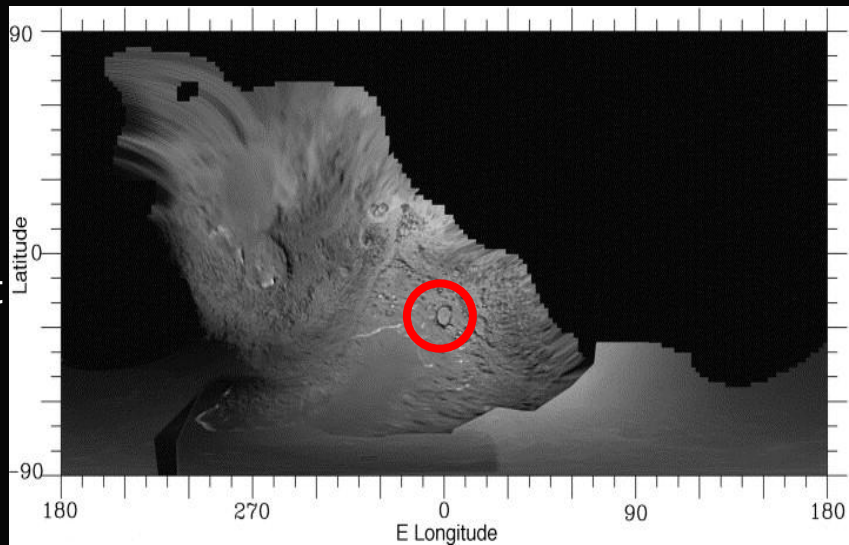
Cases so far:

- No feature chosen, $W_0 = 0°$
  - Itokawa, Borrelly
- No feature chosen, arbitrary W_0
  - Davida
- Arbitrary W_0, based on light curve
  - Lutetia (in WG report)
- Arbitrary (obvious) feature chosen at 0°
  - Ceres (unnamed bright spot)
  - Vesta ("Olbers Regio", informal name)
  - Eros (unnamed crater)
  - Gaspra (Charax crater, near long axis)
  - Šteins (Topaz crater)
  - Tempel 1 (unnamed crater near impact)
- Feature near long axis chosen at 0°
  - Ida (Afon crater)
  - Considered for Wild 2?
- Long axis of shape model chosen at 0°
  - Pallas
- Synchronous rotation defines W_0
  - Pluto and Charon



Gaspra example: prime meridian crater Charax (no. 17) (Galileo; Davies et al., 1994, Fig. 1)

Tempel 1 example: unnamed prime meridian crater (center) (Deep Impact; Thomas et al., 2007, Fig. 3)



Recommendations to and Requests for input from the Planetary Community in "2015" Report

(Paraphrased – see report for full recommendations)

1. Geodetically controlled cartographic products should be planned for and made as part of the normal mission operations and data analysis process
2. To ease community use, publications should use common notation to express orientation and size models
3. Further research and planetary community consensus is needed regarding Jupiter's and Saturn's rotation models. E.g. as was done in the past for Jupiter (Riddle and Warwick, 1976)

   Suggestions on how to develop such a consensus welcome

   E.g. for Jupiter: Between Hess et al. (2011); Higgins et al. (1997, 2011); Yu and Russell (2009); Use Juno mission observations?

   E.g. for Saturn: Use Cassini Grande Finale mission observations to break orbit vs. rotation correlation
4. Detailed summaries of coordinate system evolution (such as A. Zangari's (2015) for Pluto) are very useful
5. Important to recognize and use IAU recommendations or recommend updates to them
6. Once planetographic or planetocentric coordinates are predominantly in use for a given body, there is no obvious advantage and many disadvantages in switching to the other system
7. The WG seeks input on plans to evaluate community requests on coordinate systems
8. The WG seeks input on whether to extend recommendations to exoplanets