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The Io GIS Database 1.0: A Proto-Io Planetary Spatial Data Infrastructure

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Abstract

We collected a set of published, higher-order data products of Jupiter's volcanic moon Io and assembled them in an ArcGIS™ database we are calling the Io GIS Database, version 1.0. The purpose of this database is to collect image, topographic, geologic, and thermal emission data of Io in one geospatially registered location to form the data component of an Io planetary spatial data infrastructure (PSDI). The goals of an Io PSDI are (1) to make higher-order data products more accessible and usable to the broader planetary science community, particularly to new scientists that were not associated with the projects that obtained the data; (2) to enable new scientific studies with the data; and (3) to create a tool to support observation planning for future Io-focused planetary missions. In this paper we describe the motivation behind our project, discuss the data sets acquired for this first version of the database, and demonstrate how they can be used. We conclude with a discussion of how our database relates to other PSDIs, our plans for future updates, and a request for additional Io data sets.

Unified Astronomy Thesaurus concepts: Io (2190); Planetary science (1255)

1. Introduction

Over the last decade there has been great interest within the United States' National Aeronautics and Space Administration's (NASA's) Planetary Science Division regarding the long-term accessibility and usability of planetary data, particularly geospatial image data of planetary surfaces, and particularly the higher-order data products (e.g., regional to global image mosaics, digital terrain models (DTMs), geologic maps, etc.) derived from NASA's robotic planetary missions (see https://www.lpi.usra.edu/mapsit/about/ and https://science.nasa.gov/science-pink/s3fs-public/atoms/files/PDE%20IRB%20Final%20Report.pdf (NASA Planetary Data Ecosystem Independent Review Board Final Report)). NASA's desire to maximize its investment in its planetary missions and their accumulated data is motivated by the need to enable future generations of planetary scientists to utilize the data for research projects, long after the creators of those data are gone, and where many spacecraft data sets are not described well enough to enable ease of use. Likewise, NASA is looking to ensure that data from past missions is usable in tools that will support the planning of future missions. This is particularly desirable for geologically active worlds, such as Jupiter's volcanic moon Io, where multiple, ongoing volcanic eruptions produce thermal anomalies related to its interior processes, and where active eruptions emplace effusive and explosive volcanic materials and gases that regularly modify its surface at weeks to months timescales (see, e.g., Lopes & Williams 2005; Lopes & Spencer 2007).

In 2019 we were funded through a 1 yr grant from NASA's Planetary Data Archiving, Restoration, and Tools (PDART) program to collect a discrete selection of mostly image-based, higher-order data products of Io produced from NASA's Voyager, Galileo, and New Horizons missions, as well as thermal emission observations from the last two decades from spacecraft and Earth-based telescopes utilizing adaptive optics (AO), and assemble them in a geospatially referenced format. This database would become the initial data component of an Io Planetary Spatial Data Infrastructure (PSDI), which would serve as a tool for future research and future mission planning. In this paper we discuss the results of our work, which we call the Io Geographic Information Systems (GIS) Database version 1.0, and include further details on the driving motivation of this project, the formats used, examples of the data sets that were included, the availability of our database after NASA Planetary Data System (PDS) review, and how it would enable future work.

2. Background: Data Accessibility, Usability, and PSDIs

Over the last decade NASA and members of the US planetary science community have expressed concern about the long-term usability and accessibility of NASA-acquired planetary data, particularly those higher-order data products derived from past planetary missions that are usually not archived in NASA's PDS. The Mapping and Planetary Spatial Infrastructure Team (MAPSIT), the NASA assessment group tasked with cartography and spatial data issues across the Planetary Science Division (see MAPSIT Roadmap: https://www.lpi.usra.edu/mapsit/roadmap/), has focused on developing the concept of PSDIs (Laura et al. 2017) for all objects in our solar system with solid surfaces, which have been visited (or will soon be visited) by planetary spacecraft. A PSDI is derived from a similar concept in terrestrial geoscience called a spatial data infrastructure (SDI; Rajabifard et al. 2002). A PSDI is an enabling collection of planetary spatial data for a specific planetary object (planet, moon, asteroid, or comet), which also includes data access mechanisms, data interoperability agreements, data policies, and standards, as well as the spatial data users themselves (Figure 1). The goal of a PSDI is to collect data in a form that "just works" (i.e., is usable for science analysis without extensive calibration and processing from the original raw data), so that planetary scientists do not have to go back to the PDS and regenerate desired higher-order data products from scratch, a task that may be impossible for many

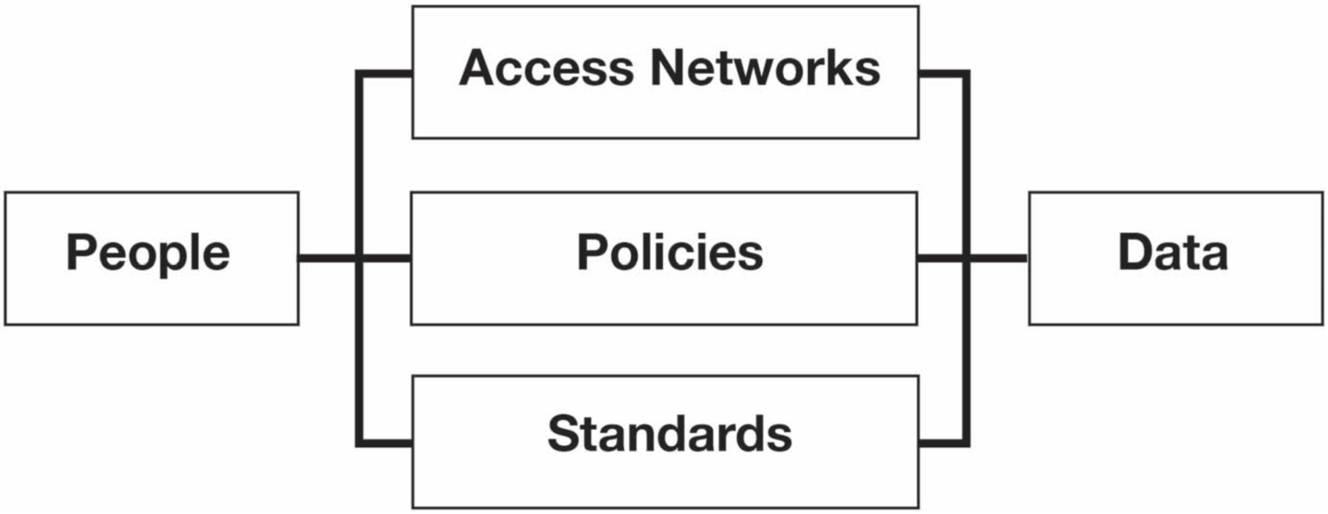


Figure 1. Concept diagram for a planetary spatial data infrastructure (PSDI). Modified from Laura et al. (2017).

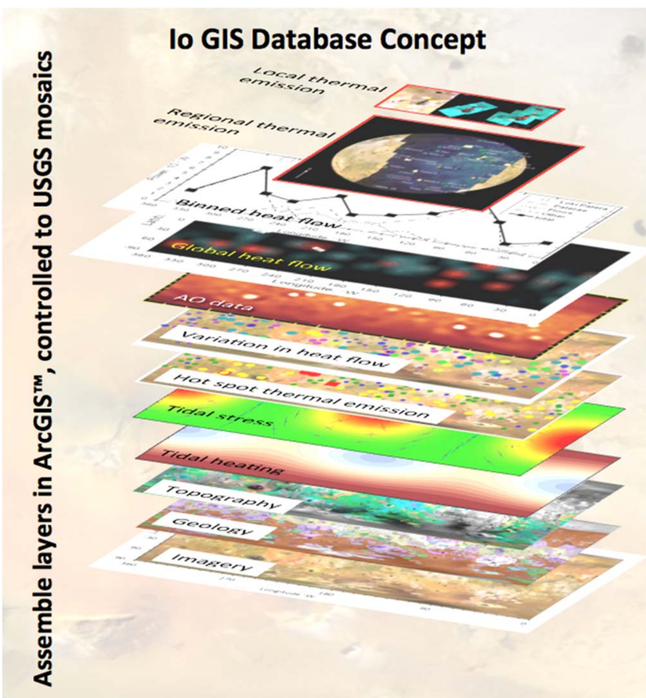


Figure 2. Conceptual diagram for our Io GIS Database, created by A.G. Davies (NASA JPL). Building on the ArcGIS™ project created for the Williams et al. (2011) global geologic map, we have added all new data sets as new layers to this project, registered to the geodetically controlled (Archinal et al. 2001), combined Galileo–Voyager global mosaics of Io (Becker & Geissler 2005). Using the layering capability of ArcGIS™ enables data sets of interests to be compared while ignoring others. References for the data in conceptual diagram, from bottom to top: imagery—Io Galileo–Voyager mosaic (Becker & Geissler 2005); geologic map—Williams et al. (2011); topography—White et al. (2014); tidal heating (shown here—deep mantle heating)—Ross et al. (1990), Hamilton et al. (2013); tidal stresses—credit: D. Alex Patthoff; hot spot thermal emission—Veeder et al. (2009, 2011, 2012, 2015); variation in heat flow—credit: Ashley Davies; AO data—Marchis et al. (2005); global volcanic heat flow—Davies et al. (2015; not yet included in the database); binned heat flow—Veeder et al. (2012, 2015); regional thermal emission—Veeder et al. (2012); local thermal emission—Davies et al. (2012a, 2012b).

planetary researchers decades after the data were acquired. PSDIs would thus more easily enable future research on the planetary object of interest and/or would support observation planning of that object for any future missions (Laura et al. 2017).

PSDIs are especially important for planetary objects that have been visited by past missions that are probable targets of future missions. For example, the Moon and Mars are probable targets for human missions in upcoming decades, whereas Venus, Mercury, Jupiter's icy moons Europa and Ganymede, and Saturn's moon Titan are definite targets of new robotic missions within this decade or the next. Europa especially has been considered an ideal target to develop one of the first PSDIs (Laura et al. 2018), given (1) the limited existing image data, and (2) that the NASA Europa Clipper Flagship mission is in development for launch later this decade.

Jupiter's innermost large moon Io is the most volcanically active object in the solar system (see, e.g., Lopes & Williams 2005, and references therein). Io was visited by NASA's Voyager (Smith et al. 1979a, 1979b), Galileo (McEwen et al. 1998), Cassini (Porco et al. 2003), and New Horizons (Spencer et al. 2007) spacecraft; has been observed by the NASA Hubble Space Telescope; and is the target of ongoing observations by several Earth-based telescopes applying AO techniques to compensate for the distortion caused by the Earth's atmosphere and to improve the spatial resolution of thermal emission from active volcanoes. Because of Io's ongoing geologic activity, with eruptions producing thermal anomalies indicative of different eruption styles (Carr 1986; Davies 1996; Davies et al. 2001, 2010, 2018), it has been the target of multiple mission proposals over the last decade (e.g., McEwen et al. 2014, 2019; Suer et al. 2017) to better understand its tidally induced volcanism. Thus, given Io's wide interest and limited available data (relative to the Moon or Mars), Io is also a prime candidate to develop one of the first PSDIs.

3. Data and Methods

Our concept was to collect a subset of the accessible and usable, higher-order image-based data products of Io that have been peer-reviewed and published over the last two decades, and assemble them in a geospatially controlled and registered format to enable future work (Figure 2). The primary software we chose to use is ArcGIS™ (ESRI 2020). We chose ArcGIS™ for two reasons. First, we have prior experience with that software, which was used by D.A.W. to produce the first complete global geological map of

Table 1
Directory Structure and Data Sets Listing for the ASU Io GIS Database, Version 1.0

Item Name	Description	References
Surface Heat Flux Based on Interior Models		
	Extracted from Figure 2.	Hamilton et al. (2013), *Earth and Planetary Science Letters*: https://doi.org/10.1016/j.epsl.2012.10.032
Earth-based Adaptive Optics (AO) Telescopic Observations	Track spectral radiances and variability in Io's hot spots over time.	
2013–2018	Data Table 5	de Kleer et al. (2019), *Astronomical Journal*: https://doi.org/10.3847/1538-3881/ab2380
2001–2016	Data Tables 3, 4, A1, Figure 1	Cantrall et al. (2018), *Icarus*: https://doi.org/10.1016/j.icarus.2018.04.007
2010	Data Figure 3	de Pater et al. (2014), *Icarus*: https://doi.org/10.1016/j.icarus.2014.06.019
2001	Data Figure 3	Marchis et al. (2005), *Icarus*: https://doi.org/10.1016/j.icarus.2004.12.014
Additional Data on Io's Hot Spots:		
NIMS NITED Database, Part I	Table S1. 250 Hot spot locations, temperatures, and estimates of thermal emission from Galileo Near Infrared Mapping Spectrometer (NIMS) observations	Veeder et al. (2015), *Icarus*: https://doi.org/10.1016/j.icarus.2014.07.028; also SOM in Davies et al. (2015), *Icarus*: https://doi.org/10.1016/j.icarus.2015.08.003
Map of hot spot locations, 1979–2007	170 locations of active hot spots detected by spacecraft (Hubble, Voyager, Galileo through New Horizons 2007 flyby)	Appendix A.2, Lopes and Spencer et al. (2007), Io After Galileo, and references therein: https://link.springer.com/book/10.1007/978-3-540-48841-5. See also Hot Spot Locations layer in Williams et al. (2011) SIM 3168 geologic map.
Geologic Maps		
Regional maps (2002–2010)	Chaac-Camaxtli map	Williams et al. (2002), *JGR-Planets*: https://doi.org/10.1029/2001JE001821
	Culann-Tohil map	Williams et al. (2004), *Icarus*: https://doi.org/10.1016/j.icarus.2003.08.024
	Zamama-Thor map	Williams et al. (2005), *Icarus*: https://doi.org/10.1016/j.icarus.2005.03.005
	Amirani-Gish Bar map	Williams et al. (2007), *Icarus*: https://doi.org/10.1016/j.icarus.2006.08.023
	Zal region map	Bunte et al. (2008), *Icarus*: https://doi.org/10.1016/j.icarus.2008.04.013
	Prometheus map	Leone et al. (2009), *J. Volcanology Geothermal Res.*: https://doi.org/10.1016/j.jvolgeores.2009.07.019
	Hi'iaka–Shamshu maps	Bunte et al. (2010), *Icarus*: https://doi.org/10.1016/j.icarus.2009.12.006
Global map: USGS I-2209 Voyager	1:15M, covers sub-Jovian hemisphere	Crown et al. (1992), USGS map: https://pubs.er.usgs.gov/publication/i2209
Global map: USGS SIM 3168 Galileo–Voyager	1:15M, covers the whole moon	Williams et al. (2011), USGS map: http://pubs.usgs.gov/sim/3168/
Mission Image Data		
New Horizons 2007 Flyby, LORRI grayscale mosaic	Extracted from Figure 1(a)	Spencer et al. (2007), *Science*: https://doi.org/10.1126/science.1147621
LEISA hot spot images and data	Table 2, Figure 10	Tsang et al. (2014), *JGR-Planets*: https://doi.org/10.1002/2014JE004670

Table 1
(Continued)

Item Name	Description	References
Digital Elevation Model	Stereo photoclinometry, Figure 5(a)	White et al. (2014), *JGR-Planets*: https://doi.org/10.1002/2013JE004591
Galileo regional mosaics		
SSI Orbit I25 observations	I25ISEMAKNG02, 146 m px^{-1} I25ISGIANTS01, 186 m px^{-1} I25ISCULANN01, 205 m px^{-1} I25ISTERM__01, 259 m px^{-1}	Keszthelyi et al. (2001), *JGR-Planets*: https://doi.org/10.1029/2000JE001383
SSI Orbit I27 observations	I27ISTOHIL_01, 200 m px^{-1} I27ISCAMAXT01, 230 m px^{-1} I27ISAMRANI01, 230 m px^{-1} I27ISTVASHT01, 450 m px^{-1} I27ISZALTRM01, 300 m px^{-1} I27ISSHM-SHU01, 340 m px^{-1} I27ISSOPOLE01, 520 m px^{-1}	Keszthelyi et al. (2001), *JGR-Planets*: https://doi.org/10.1029/2000JE001383
SSI Orbit I32 observations	I32ISLOKI_01, 1 km px^{-1} I32ISTVASHT01, 300 m px^{-1} I32GSHBAR01, 340 m px^{-1} I32ISTERMIN01, 370 m px^{-1} I32ISTERMIN02, 370 m px^{-1}	Turtle et al. (2004), *Icarus*: https://doi.org/10.1016/j.icarus.2003.10.014
USGS Galileo–Voyager Global Mosaics		
1a) Image mosaics	a) SSI-only monochrome, b) SSI-only color, c) SSI-VOY monochrome, d) merged SSI-VOY monochrome and SSI color	USGS Astropedia: https://astrogeology.usgs.gov/maps/io-voyager-galileo-global-mosaics See also: Becker & Geissler (2005), 36th LPSC: https://www.lpi.usra.edu/meetings/lpsc2005/pdf/1862.pdf, NASA Photojournal PIA 09257
1b) Ancillary data maps	Maps of emission angle, incidence angle, phase angle, and spatial resolution for component images making up mosaics a–c in 1a (above)	USGS Astropedia: https://astrogeology.usgs.gov/maps/io-voyager-galileo-global-mosaics See also: Becker & Geissler (2005), 36th LPSC: https://www.lpi.usra.edu/meetings/lpsc2005/pdf/1862.pdf

Note. (1) Compare to Figure 3. Note that there are additional thermal emission data for Io in the community, which we hope to add to future versions of this database. Please contact David Williams (David.Williams@asu.edu) to contribute new data sets to future versions of this database. (2) Galileo SSI I24 observations were damaged by radiation exposure to the camera electronics and were only partially recoverable. There were insufficient resources to include them in this project. (3) Co-I Milazzo thinks Io mosaics better than 200 m px^{-1} would require too much time to tie to this database, so they are not included in this first version of the database.

Io (Williams et al. 2011: http://pubs.usgs.gov/sim/3168/).[3] Second, the image basemaps on which the Williams et al. (2011) global geologic map of Io were produced are already available in ArcGIS™. These include a set of four combined Galileo–Voyager global mosaics (Becker & Geissler 2005), in which the mosaicked images were geodetically controlled using a triaxial ellipsoid shape model and the best available Galileo control point network (Archinal et al. 2001). Reported horizontal accuracy is nominally 1 pixel, translating to 1 km in low-latitude regions with good coverage. These mosaics were recommended to be used as foundational data products for Io (Laura & Beyer 2021) and thus are the best available prepared and controlled data set on which to build an Io PSDI.

Table 1 lists the published Io data sets we chose to include in this first version of the database, which were listed in our selected PDART proposal. In addition to the combined Galileo–Voyager mosaics, we wanted to include all other regional-scale Galileo Solid State Imager (SSI) mosaics (∼150–900 m pixel^{-1} spatial resolution; Keszthelyi et al. 2001; Turtle et al. 2004) as well as other SSI-derived products, including the digital elevation model (DEM) of Io made using stereo photoclinometry (White et al. 2014), global geologic maps from Voyager (Crown et al. 1992) and Galileo (Williams et al. 2011) data, derived geologic maps from the regional SSI mosaics (Williams et al. 2002, 2004, 2005, 2007; Bunte et al. 2008, 2010; Leone et al. 2009), as well as global mosaics from the New Horizons Long Range Reconnaissance Imager (LORRI) and the Linear Etalon Infrared Spectral Array (LEISA) instruments, obtained during the 2007 February flyby (Spencer et al. 2007; Tsang et al. 2014). Some thermal emission data of Io exists both in image format, and as tables of hot spot area, power, and temperature information. We included thermal emission data as derived from the Galileo Near Infrared Mapping Spectrometer (NIMS) Thermal Emission Database (NITED: Veeder et al. 2009, 2011, 2012, 2015; Davies et al. 2012a, 2012b, 2015), New Horizons' LEISA instrument (Tsang et al. 2014), and several Earth-based telescopes such as Keck and Gemini using AO, as reported in multiple papers (Marchis et al. 2005; de Pater et al. 2014; Cantrall et al. 2018; de Kleer et al. 2019). Finally, a study by Hamilton et al. (2013) used the location and clustering of subsets of hot spots that were then compared with underlying geology and were subsequently compared to models of heat flux assuming heat derived from different Ionian interior layers (i.e., asthenosphere, deep mantle, various combinations thereof (Ross et al. 1990). A reviewer of this paper noted that the Hamilton et al. (2013) cluster analyses were not weighted by individual hot spot thermal emission. Instead, there was a comparison of hot spot number and geology with predicted models of global heat flow, not measurements of heat flux.

[3] NASA now requires all planetary geologic maps to be produced using GIS software, and ArcGIS™ is favored by the US Geological Survey, who oversees NASA's Planetary Geologic Mapping Program.

Figure 3. ArcGIS™ table of contents for the Io GIS Database v. 1.0. Compare to Table 1.

Thus, we included those interior heat flux model maps in this database to enable future comparisons of additional thermal activity to heat flux source regions.

Note: There are many more data sets (e.g., Galileo Photo Polarimeter-Radiometer: Rathbun et al. 2004), particularly thermal emission data sets, of Io that were not included. This is not because we did not like them but because we chose the data sets we were most familiar with so as to keep this 1 yr PDART project manageable. If there are Io data sets that the reader thinks would enhance the value of this database, then please contact David Williams at David.Williams@asu.edu and they will be assessed for inclusion in the next version of the database.

4. Results: Database Version 1.0

We assembled version 1.0 of the Io GIS Database using ArcGIS™ version 10, which is readable by ArcGIS™ Pro™. In addition to the data sets described (Table 1, Figure 3), we included the latest file of named surface features from the USGS Planetary Nomenclature website, as well as a graticule displaying a 30° latitude–longitude grid (Figure 4). Data are presented using a simple cylindrical projection centered on the anti-Jovian point (0°, 180°W), as the Galileo mission obtained its best imaging data over the anti-Jovian hemisphere.[4] To enhance usage and availability of our database materials, we have reproduced them in Arizona State University's Java Mission-planning and Analysis for Remote Sensing platform (JMARS: Christensen et al. 2009), which is another GIS-based application with widespread usage in the planetary community for planetary mission data analysis.

Figures 5–6 demonstrate the functionality of the Io GIS Database. In Figures 5(a)–(c), we show the various regional and global geologic maps derived from the Voyager and Galileo images. Having geologic maps from the 1990s, 2000s, and 2010s in this database enables comparisons and can show the evolution in interpretation of Io's geologic features, particularly between the Voyager and Galileo eras.

Figures 6(a) and (b) show two examples of thermal imaging of Io, first by passing spacecraft (New Horizons, 2007) and second by Earth-based telescopes using AO (2001–2018). Importantly, the anomalous thermal emission hot spot data sets include attribute tables, which contain details on the recorded thermal activity at every location on Io, covering a time period between 1996 and 2018. By checking the power, area, and temperature variations at hot spots of interest, it is possible to investigate the waxing and waning of volcanic activity over this 20 yr time period. We note that the data from Veeder et al. (2015; see also their Figure 10), containing 250 discrete thermal sources, represent a more recent and complete thermal emission data set than the table from Lopes & Spencer (2007) that contained 170 hot spot sources and was originally included in the Williams et al. (2011) geologic map GIS. With the inclusion of heat flux maps (Figure 6(c)), it is possible to correlate the spatial location of volcanic activity with models of specific distribution of heat in Io's interior. An early attempt at this was done using spacecraft-only thermal data (Hamilton et al. 2013), but they did not include the telescopic observations. With these data now included in the Io Database, more robust studies could be done.

The primary advantage to collecting these Io data sets in one geospatial database, for both the ArcGIS™ and JMARS versions, is that it allows users to pick and choose which data sets to visualize, enabling comparison of geologic, thermal emission, topographic, and image data for any location on Io. Because of Io's active volcanism, and repeated observations by both spacecraft and telescopes, our database contains a history of Io's activity, enabling studies in both space and time. Our database thus provides a powerful tool both to enable further scientific research of Io and to identify imaging targets of repeated

[4] Like the Earth's Moon, Io is in synchronous rotation about Jupiter, such that from Jupiter's perspective only one hemisphere is visible. This is called the sub-Jovian hemisphere (centered at 0°, 0°), equivalent to the Moon's near side. The anti-Jovian hemisphere of Io is equivalent to the Moon's far side.

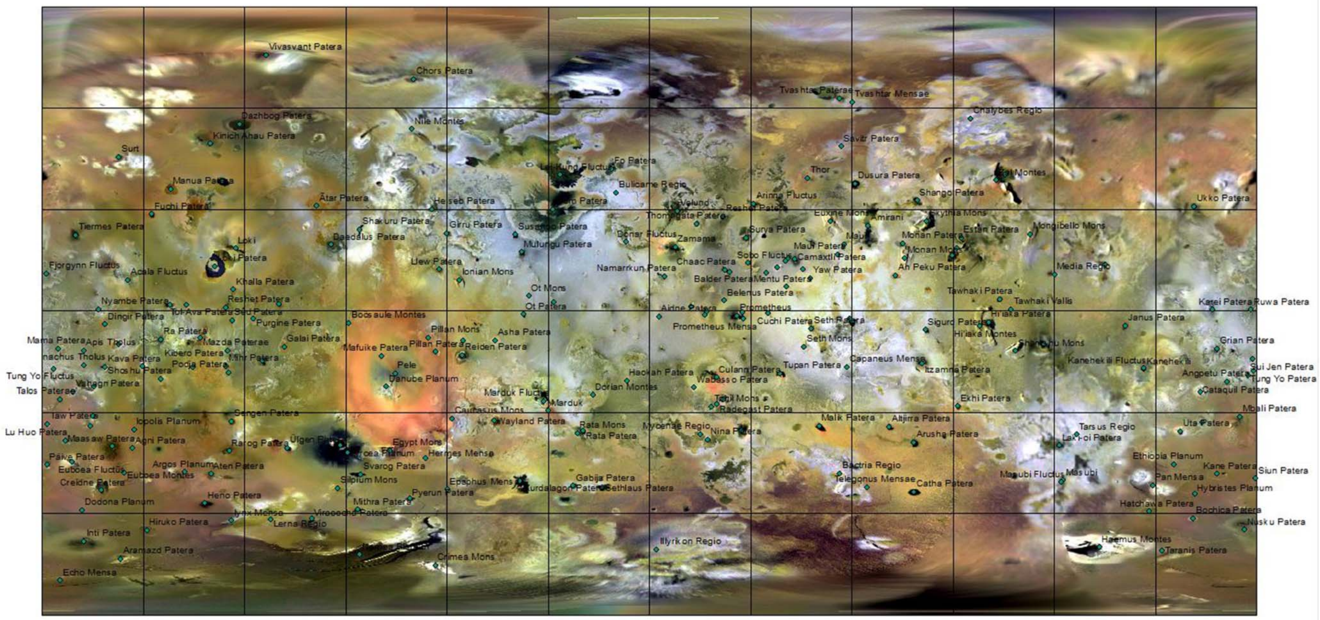
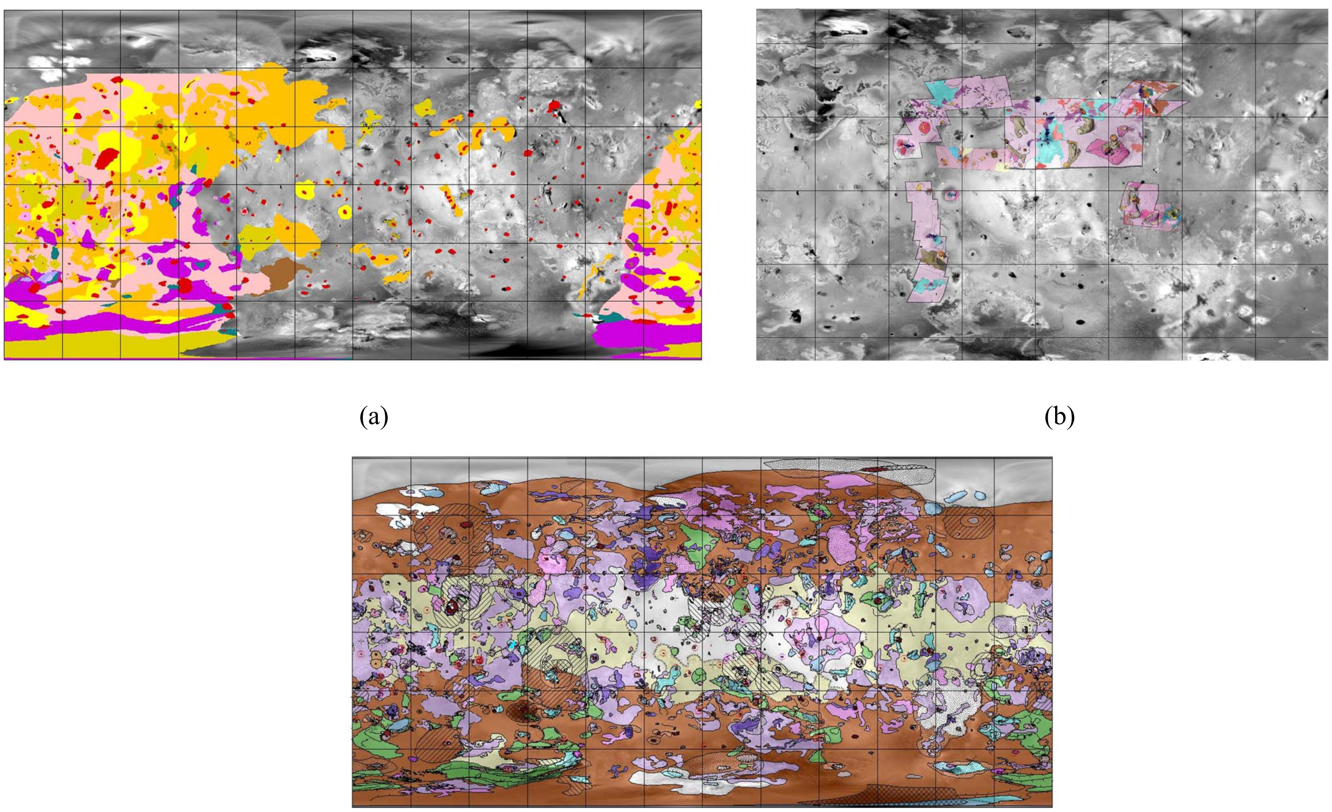


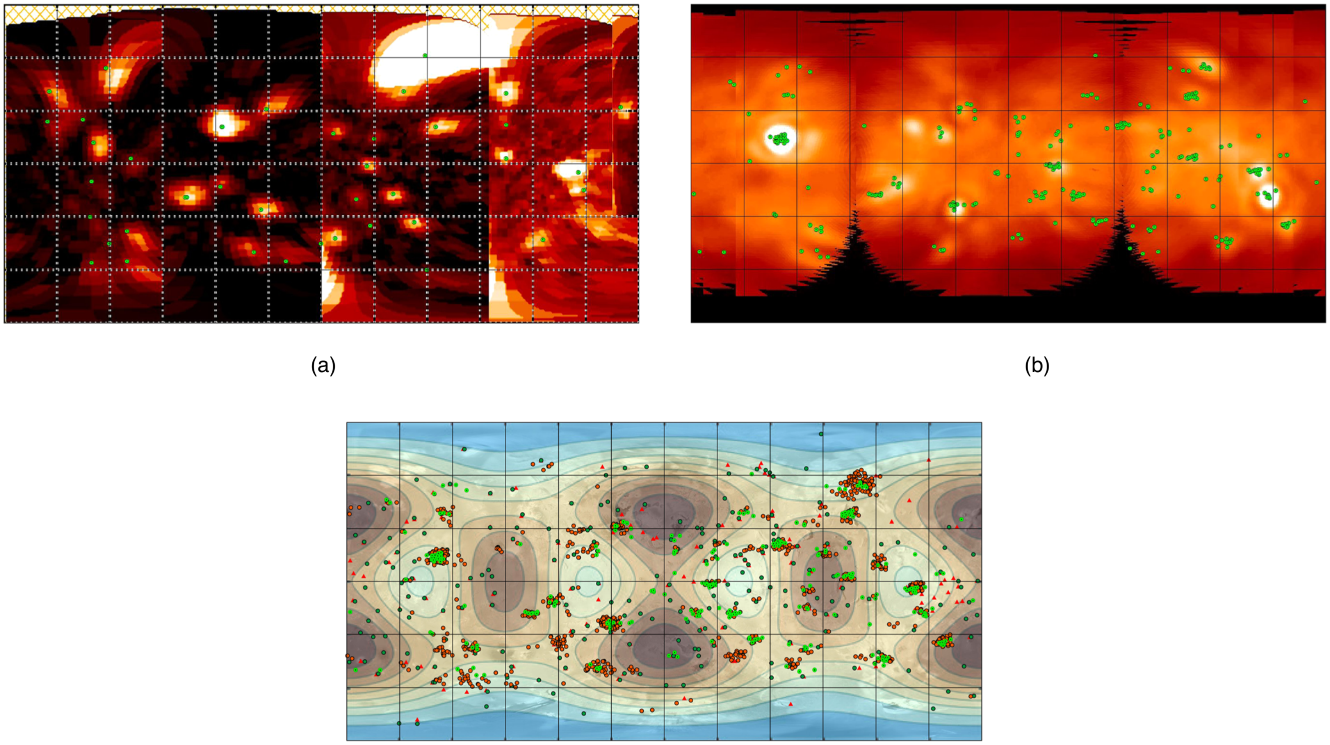
Figure 4. Output from the Io GIS Database v. 1.0, as viewed in ArcMap 10 (ArcGIS). This simple cylindrical projection (used in all subsequent database figures) shows the complete surface of Io centered on the anti-Jovian point (0°, 180°). The basemap includes the best grayscale Galileo coverage of the anti-Jovian hemisphere combined with the best grayscale Voyager coverage of the sub-Jovian hemisphere, then merged with the best Galileo color imaging of the whole globe (Becker & Geissler 2005). A 30° latitude–longitude grid and the USGS current list of named surface features are visible.



(a) (b)

(c)

Figure 5. (a) Output from the Io GIS Database v. 1.0, showing the Voyager-era global geologic map of Crown et al. (1992) rendered over the combined Galileo–Voyager monochrome global mosaic (Becker & Geissler 2005). Map unit names are included in the ArcMap Table of Contents for this layer. (b) Output from the Io GIS Database v. 1.0, showing the eight regional geologic maps made from regional Galileo SSI mosaics over Io's anti-Jovian hemisphere (Williams et al. 2002, 2004, 2005, 2007; Bunte et al. 2008, 2010; Leone et al. 2009). Rendered over the combined Galileo–Voyager monochrome global mosaic (Becker & Geissler 2005). (c) Output from the Io GIS Database v. 1.0, showing the Galileo-era global geologic map of Williams et al. (2011) rendered over the combined Galileo–Voyager monochrome global mosaic (Becker & Geissler 2005). Map unit names are included in the ArcMap Table of Contents, under the "Geologic Units" menu.



(a) (b) (c)

Figure 6. (a) Output from the Io GIS Database v. 1.0, showing the New Horizons LEISA hot spot map and data after Tsang et al. (2014). These hot spots (green dots) correlate with temperature and power data in a corresponding attribute table in ArcMap. By switching basemaps, users can compare hot spot measurements to imaged features and interpreted geology, and they can compare with data from other instruments to track thermal evolution at any given location on Io over the last 20 yr. (b) Output from the Io GIS Database v. 1.0, showing the hot spot data from Earth-based AO telescopes between 2001 and 2016 (Cantrall et al. 2018), rendered over a 2011 observation at 3.99 μm. These hot spots (green dots) correlate with temperature and power data in a corresponding attribute table in ArcMap. (c) Output from the Io GIS Database v. 1.0, showing thermal emission hot spot detections from Lopes & Spencer (2007, red triangles), Davies et al. (2015, dark green circles), Cantrall et al. (2018, light green circles with black dot), and De Kleer et al. (2019, red circles), rendered over the surface heat flux map in which Io's heat is modeled as one-third coming from the deep mantle and two-thirds coming from the asthenosphere (Hamilton et al. 2013). By adding thermal hot spot data from both spacecraft and Earth-based telescopes, better correlations of volcanic activity and heat flux from Io's interior can be done.

activity for future Io-dedicated missions. JMARS in particular was developed to aid observation planning by the NASA Mars Odyssey orbiter Thermal Emission Imaging System (THEMIS) camera (Christensen et al. 2009), and thus we hope that this database (in either ArcGIS or JMARS) could be equally helpful for planning observations for future Io missions.

5. Policies and Standards

Every PSDI must address data policy issues and standards, as well as the community of data users, access, and the data themselves. Our approach for the Io GIS Database as a proto-Io PSDI is outlined in Figure 7. In terms of standards, we chose ArcGIS™ and JMARS because of the wide usage of these software in the planetary science community, and because of their demonstrated performance in handling planetary geospatial data. We chose to use the combined Galileo–Voyager global mosaics of Becker & Geissler (2005) as our foundational data products, as recommended by Laura & Beyer (2021), because they represent the best global image products produced for Io since the end of the Galileo mission and were produced using the best geodetic control (Archinal et al. 2001). All other data are registered to these products. Finally, all data included in version 1.0 of the Io GIS Database have already been previously peer-reviewed and published, and thus have passed the scrutiny of the planetary science community.

In terms of policy, our goal is to update the database about every two years, as new Io data sets are published and made available to us, up to the start of the next Io-dedicated planetary mission. A NASA Discovery mission proposal for an Io-focused mission, the Io Volcano Observer (IVO; McEwen et al. 2019), was under consideration by NASA along with three other missions in 2021 but was not selected for this Discovery round. We think eventually IVO or another Io-dedicated mission will be selected and return new high spatial resolution data of Io, after which the onus would fall on members of the Io community and/or the mission Science Team to continue to update the database with new data products or create a new Io PSDI.

6. Peer Review and Access

Io GIS Database version 1.0 will undergo peer-review for formatting and operability considerations by the NASA PDS Imaging and Cartography Node during fall 2021. Upon approval, it will be considered open access, and it will be made freely available for download both at the PDS and at our university website, and announcements will be made to the planetary science community through various listservers and newsletters. A pre-PDS review copy of the whole Zipped Arc project can be downloaded from https://rpif.asu.edu/downloads/PDART_Io_DB_GIS_data_1.0_v2.zip. Accessing the data in

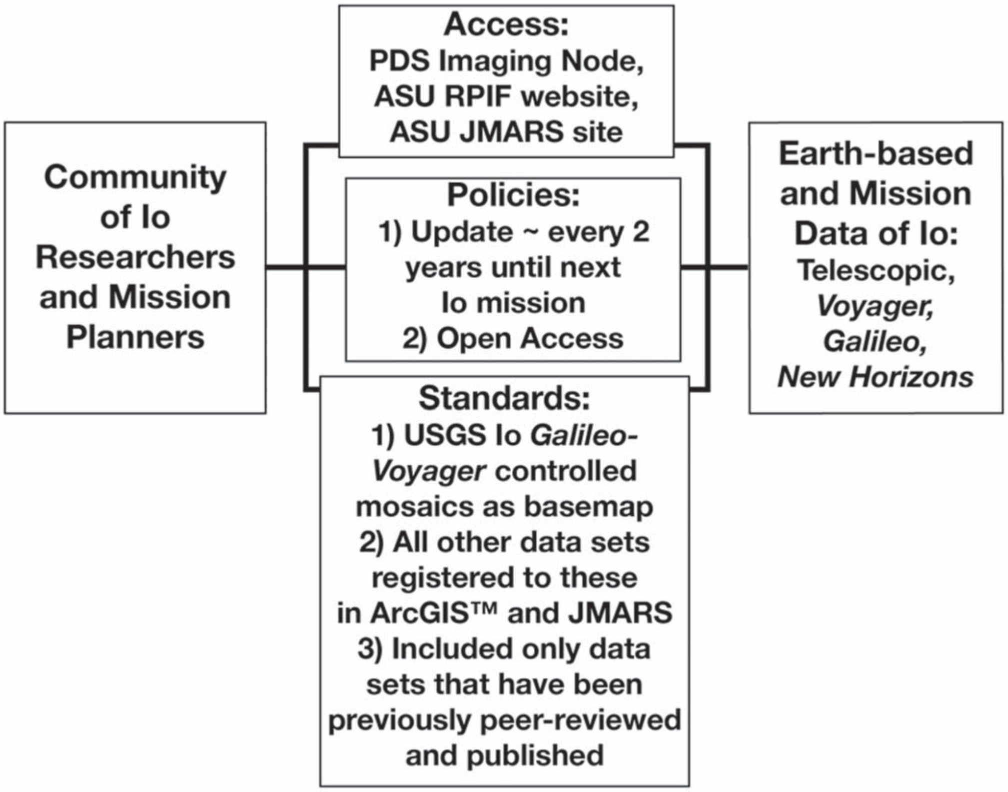


Figure 7. Proposed Io PSDI structure utilizing this database, derived from Figure 1. It includes statements on data standards, updates, and policies, etc.

JMARS via a web browser will require a free JMARS account. To sign up for an account, go to https://jmars.asu.edu/.

7. Conclusions and Future Directions

We constructed a GIS database containing a variety of higher-order data products of Jupiter's volcanic moon Io, derived from NASA's Voyager, Galileo, and New Horizons missions, and from Earth-based telescopic observations using AO. Contained in both ArcGIS™ and JMARS software, Io GIS Database version 1.0 is designed to serve as the initial data component of an Io PSDI. The goal of this database is to collect as many peer-reviewed and published, higher-order data products of Io as possible in a geospatial format to enable easy comparison of the data, as a tool to enhance future Io research and to enable observation planning for future Io missions. We previewed the content of the database, and we discussed the policies, standards, and accessibility of the database, which we hope will be useful to the community of Io scientists until new high-resolution spacecraft data are obtained. Until then, we are hoping to revise the database every few years, as we acquire new published Io data sets. We especially want to add new thermal emission data sets that track the variability of Io's volcanic activity, including from AO telescopes and the Juno mission. We hope this database serves as a benchmark for the planetary science community to develop PSDIs for other objects in our solar system.

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