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Mapping the Galilean Satellites of Jupiter with Voyager Data

Photomosaics and airbrush maps, both uncontrolled (preliminary) and controlled, were produced.

Introduction

On 5 and 6 March 1979, the Voyager 1 spacecraft flew past the planet Jupiter and its satellites, returning closeup images of three of its four largest satellites: Io, Ganymede, and Callisto*. On 7, 8, and 9 July Voyager 2 performed a similar feat, imaging Europa as well as hemispheres of Callisto and Ganymede not seen by Voyager 1. Both spacecraft are now en route to a 1981 encounter with Saturn, but during the few days they spent in the Jovian system they returned several thousand pictures of patterns in Jupiter's atmosphere and more than 2,500 pictures of the surface of the four Galilean satellites. These pictures contain sufficient information to make relatively detailed maps of 184 million square kilometres of land, more than the combined land area of the Earth and Moon.

This paper deals with the utilization of the pictures to make planimetric maps of Io, Europa, Ganymede, and Callisto. The maps will serve as base materials for the geologic study of the satellites and as planning charts for the Galileo mission, scheduled to orbit Jupiter in 1986. Maps are not being made of Jupiter because only the upper atmosphere is visible in Voyager pictures and its appearance changes hourly. There are no present plans to map the tiny (about 265 km by 140 km) satellite Amalthea because Voyager image resolution is too low.

Abstract: *The four Galilean satellites of Jupiter are being mapped using image data from the Voyager 1 and 2 spacecraft. The maps are published at several scales and in several versions. Preliminary maps at 1:25,000,000—required for mission planning and preliminary science reports—were compiled within three weeks of data acquisition and have been published. Later maps incorporate Rand Corporation photogrammetric triangulations. One of these, a color version of Io, has been completed at 1:25,000,000. The black-and-white versions are being produced at scales of 1:15,000,000, 1:5,000,000, and 1:2,000,000. The largest scale is applied only where the resolution justifies it. Although stereoscopic measurements were not possible, some relief information can be obtained from measurements of limb profiles and shadows.*

The Voyager Mission

Voyager 1 and Voyager 2 are identical spacecraft, each carrying two cameras as parts of its instrument package. The cameras are mounted on a scan platform that permits them to be aimed by programmed commands on the spacecraft com-

* These three satellites, together with the fourth (Europa), are called the Galilean satellites, in honor of Galileo, who observed them in 1610 with his first telescope.

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puter. Figure 1 is a sketch of the Voyager spacecraft.

The closest approaches of Voyager 1 to the bodies of the Jovian system occurred in the following order: Jupiter, Amalthea, Io, Ganymede, and Callisto (Figure 2). Voyager 2's closest approaches were to Callisto first, then Ganymede, Europa, Jupiter, Amalthea, and Io (Figure 3).

The two Voyager cameras are digital television cameras with nominal focal lengths of 200 and 1500 mm and fields-of-view of 3.2° and 0.4°, respectively. The image raster size is 800 lines by 800 samples. The narrow-angle camera has a filter wheel containing six color filters, including a clear filter. The wide-angle camera contains eight filters, including a clear filter. Brightness values are encoded in eight bits, resulting in 256 gray shades. Detailed descriptions of the Voyager missions and instrumentation can be found in Kohlhase and Penzo (1977), Smith *et al.* (1977), and Smith *et al.* (1979a, 1979b).

Signals were received from the spacecraft at Deep Space Net (DSN) receiving stations in Goldstone, California, Madrid, Spain, and Canberra, Australia. Digital tapes from the overseas stations were sent to the Mission Test and Imaging System (MTIS) at the Jet Propulsion Laboratory (JPL), California Institute of Technology, in Pasadena, California. The Goldstone tracking station transmitted the data directly to JPL and MTIS. Images were reconstituted, filtered to accent high-frequency detail, and contrast enhanced by computer at these facilities.

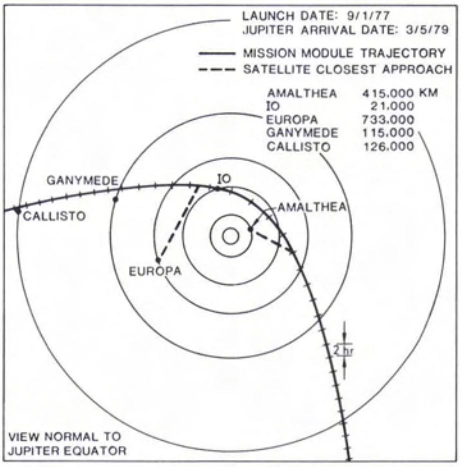

Fig. 2. The trajectory of Voyager 1 through the Jovian system (from Kohlhase and Penzo, 1977)

Table 1 summarizes the data acquired from the two spacecraft. Figure 4 shows the available coverage from both spacecraft of each of the Galilean satellites. Resolution is expressed in terms of the size of a picutre element (pixel) on the surface, but true resolution varies as a function of image smear (significant in several frames) and surface contrast.

Preliminary Cartographic Products

Preliminary photomosaics (for example, Figure 5) were made within a few hours after the pictures were taken. Although basic enhancements were

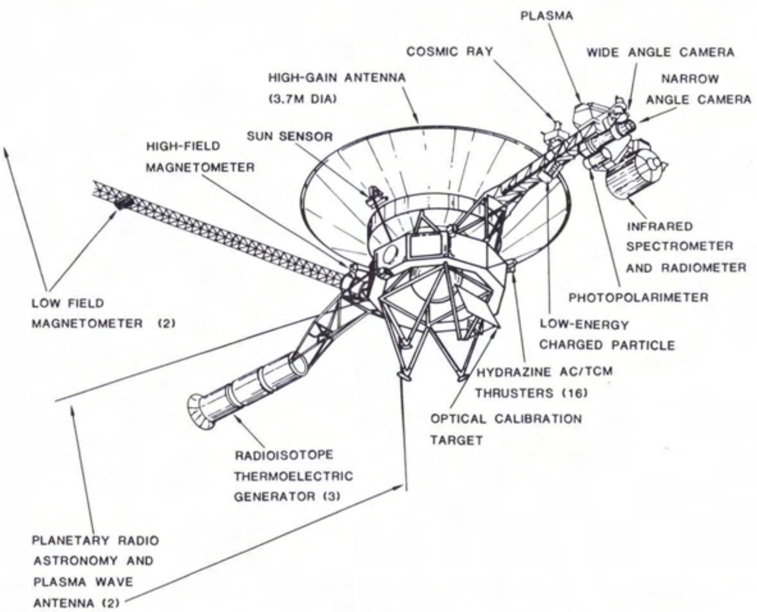

Fig. 1. Sketch of the Voyager 1 and 2 spacecraft. Total spacecraft mass is approximately 825 kg; total power available is approximately 400 W. (from Kohlhase and Penzo, 1977)

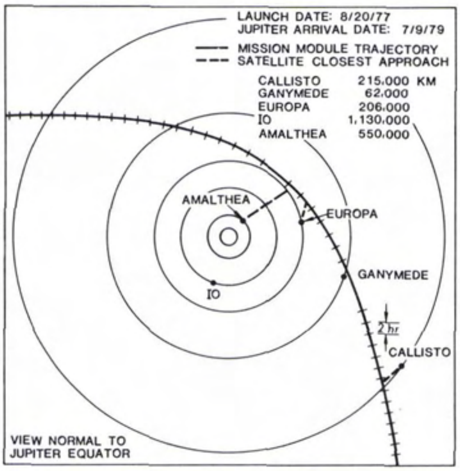

FIG. 3. The trajectory of Voyager 2 through the Jovian system (from Kohlhase and Penzo, 1977)

applied to each picture by the MTIS, they were not treated geometrically. Electronic camera distortions remained in the images, and, since the pictures were taken from a spacecraft that was traveling tens of thousands of miles per hour with respect to its target, no two pictures contain the same perspective or have the same scale. Thus, images between frames could not be matched precisely. The limbs of the satellites are, therefore, spirals rather than closed circles on many of these very early mosaics.

Because the mosaics are discontinuous, some form of map representation of all photocoverage of each satellite was required. Therefore, preliminary airbrush maps were made within three weeks after each encounter to support early scientific investigations (Smith *et al.*, 1979a, 1979b). These maps have been published and are available from USGS map distribution centers.

Two kinds of geometric data were used to control these maps. Ephemerides of the satellites are reasonably accurate and, when used in conjunction with spacecraft tracking data, provide the scale and latitude and longitude of the subspacecraft point for each picture. The longitude of the terminator is also accurately known from ephemeris data. If the terminator is assumed to be a meridian, the orientation of each picture can be determined. Telemetered information on the position of the scan platform is accurate to 0.15°, however, and the narrow-angle camera field of view is only 0.4°. Thus, the location of the picture on the satellite was not known accurately enough for even preliminary mapping.

Orthographic projection graticules were drawn and centered on the subspacecraft point, for each small-scale picture used in the mapping. Similar graticules were made for groups of pictures within mosaics, on the basis of average scales and subspacecraft points. The graticules were positioned by aligning them with the limb of the satellite and by aligning the terminator with the meridians on the graticule. Once a convincing alignment was achieved with small-scale pictures and mosaics, graticules were fitted to larger scale mosaics by matching meridians and parallels to features identifiable on the smaller scale materials. Many of the identifications used for fitting the graticules were made on images viewed from such different perspectives and resolutions that the correlations were tenuous at best. At high resolution, Voyager 1 viewed opposite faces of both Ganymede and Callisto. Correlation of images between these two data sets was particularly questionable. We estimate that many errors in graticule placement are on the order of 10° latitude or an equivalent distance in longitude. Errors of at least twice this magnitude may have occurred in the particularly difficult areas.

After the graticules were adjusted to all of the mosaics and individual frames used in the mapping, an airbrush drawing was made on Mercator or polar stereographic projections, by transferring image data from the mosaic grid to the map grid, cell by cell. All available pictures were carefully examined to exclude artifacts and to include all useful landform information. Details were generalized in many areas because of the requirement that the maps be produced quickly. On Callisto, particularly, portrayal of all visible craters could not possibly have been completed within the time allotted.

The Mercator projections were made at a scale of 1:25,000,000 at the equator. Polar stereographic sections were made at 1:13,980,000 at 56° latitude

TABLE 1. TOTAL NUMBERS OF VOYAGER PICTURES AS A FUNCTION OF IMAGE RESOLUTION. COLUMN HEADINGS ARE IN KILOMETRES PER PIXEL.

	Voyager 1					Voyager 2				
	<0.5	0.5-2	2-5	5-20	>20	<0.5	0.5-2	2-5	5-20	>20
Amalthea			26	9	28				10	23
Io	33	96	75	61	278				200	54
Europa				15	148		19	30	28	130
Ganymede		83	48	46	173		134	69	35	43
Callisto		138	59	122	220		35	49	73	29

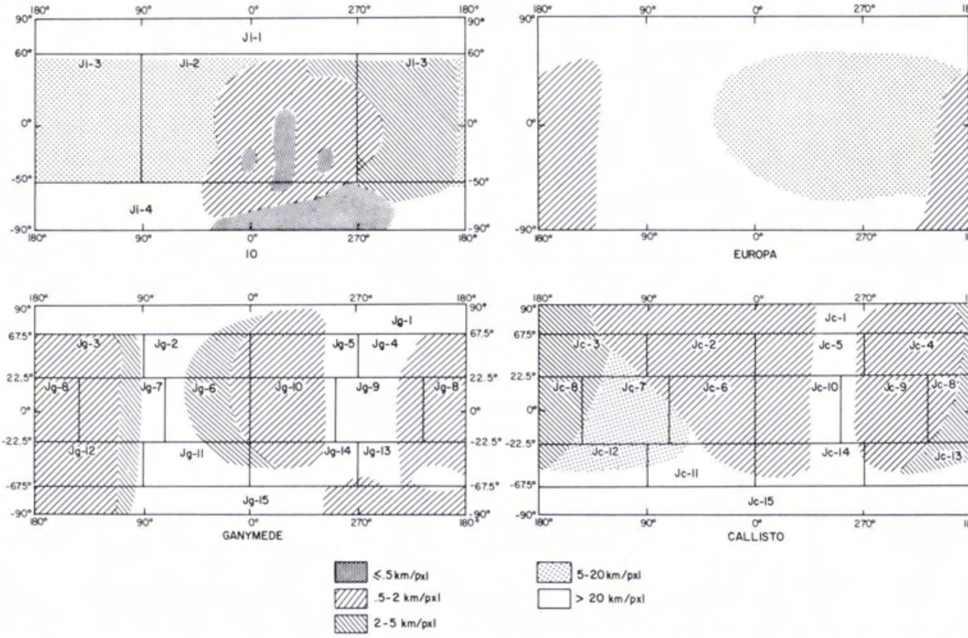

FIG. 4. Available photographic coverage of the Galilean satellites. Letter and number designations (Jc 1, Jc 2, etc.) of individual sheets are explained in text under Nomenclature.

to match the scale of the Mercator projections at that latitude.

A preliminary airbrush map of Io was also made in color (Plate 1). Io is the most brightly colored planetary body yet seen in our solar system. Colors include red, orange, yellow, ochre, black, and white. These colors are thought to delineate various forms and compounds of sulfur and, as such, are highly significant geologically.

The color map of Io was controlled by a preliminary photogrammetic triangulation (Davies et al., 1979) and is, therefore, probably correct within about 2°. In general, color pictures have lower resolution than do the black and white. Furthermore, because of Io's intense coloration, contrast reversals occur in images taken through different color filters. The black-and-white pictures were taken through the "clear" filter, the transmission of which is centered in the blue region of the spectrum (about 0.507 μm). The appearance of the surface of Io at high resolution in blue light is rather different from its appearance at low resolution viewed through the red, green, and violet filters used to make the color pictures. The patterns of color maps therefore differ significantly from those of black-and-white ones.

The Mapping Plan

We have begun compilation of detailed maps showing all available Voyager data. These maps will include airbrush portrayals and photomosaics, in both black and white and color, at a variety of scales as appropriate to data availability and user requirements. They will be published in a map series designed, in general, according to guidelines outlined by Batson *et al.* (1979).

First, we assumed that five to eight picture elements are required to define a feature of geologic interest, and that such features should not have dimensions smaller than about 1 mm at map scale. Map scales were selected by these criteria and according to the resolution of photographic coverage shown in Figure 4.

Second, we agreed that map formats should be similar to those used for the planets already mapped. Thus, any 1:5,000,000 mapping of Io (Figure 6) and Europa should be done in the same format as 1:5,000,000 mapping of the Moon, because all three bodies are approximately the same size. Similarly, any 1:5,000,000 maps of Callisto (Figure 7) and Ganymede should be done in a format similar to that used for the planet Mercury, because those three bodies are approximately the same size. Table 2 gives the diameters of the satellites, along with those of Mercury and the Moon for comparison. In general, in order to provide a set of charts for planning future missions, a 1:5,000,000 quadrangle will be prepared if it contains any significant detail, even though large areas may have rather sparse coverage. Details of the map projections are given in Table 3.

Third, we have reduced the amount of overlap along latitudinal boundaries between sheets. The wide overlaps of previous maps added to compilation costs and have not proved to be especially helpful to users.

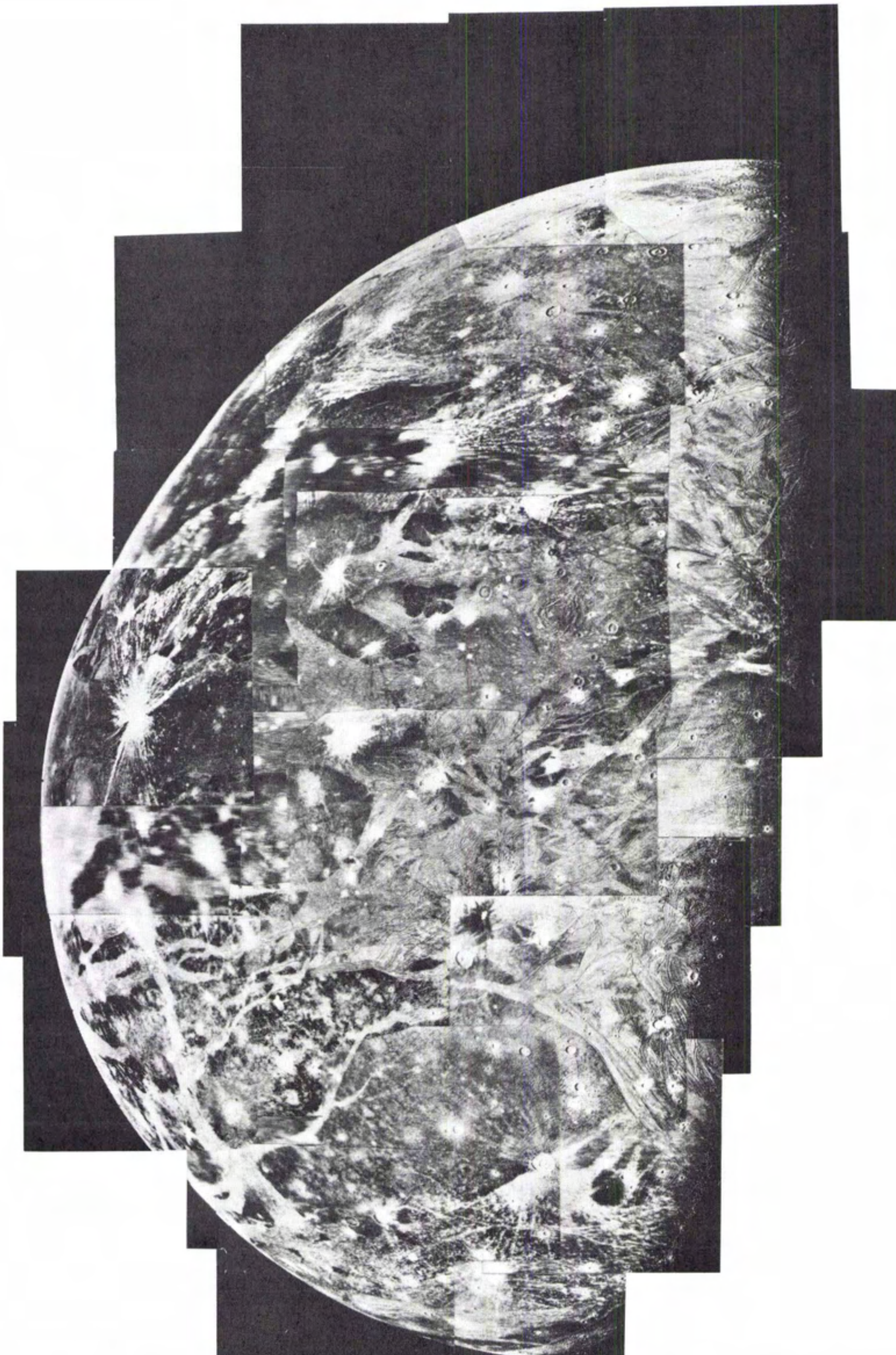

FIG. 5. Preliminary Voyager 1 mosaic of Ganymede. This satellite is the largest of the group. Resolution of the individual images is approximately 1 km per pixel. The latitude of the center of the disk was approximately 15° N when these pictures were taken and the longitude was approximately 315°.

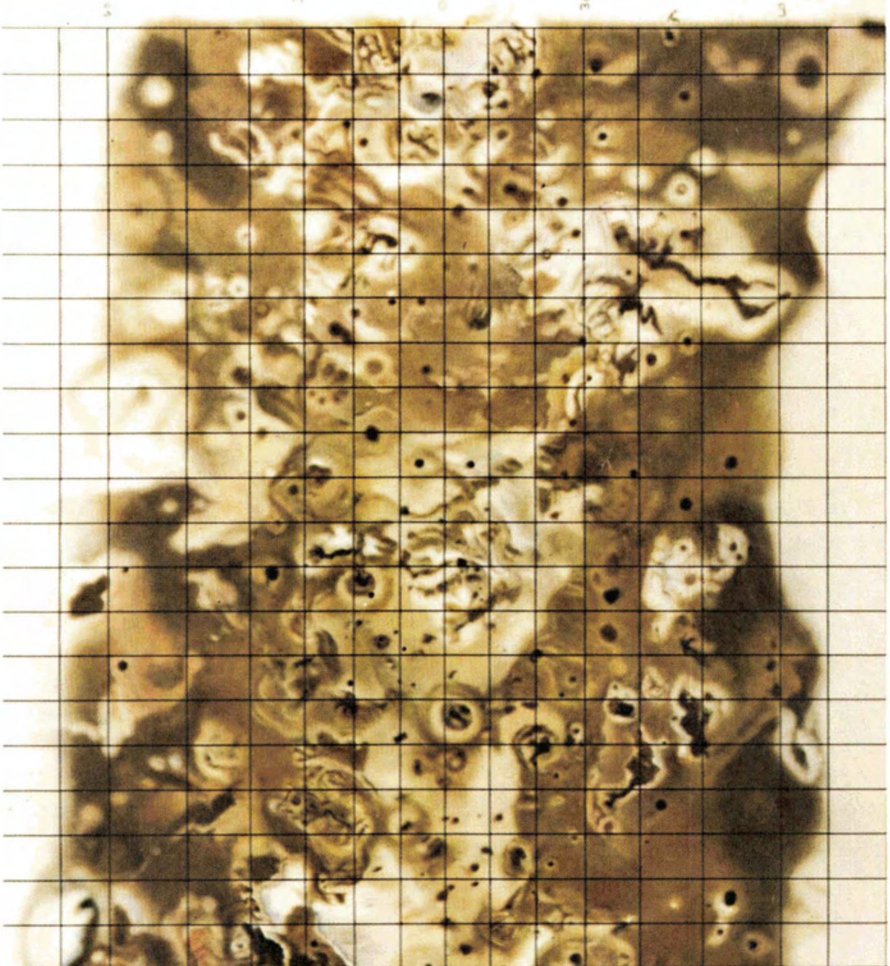

Plate 1. Natural color map of Io, made with the airbrush. Scale of the published map is 1:25,000,000.

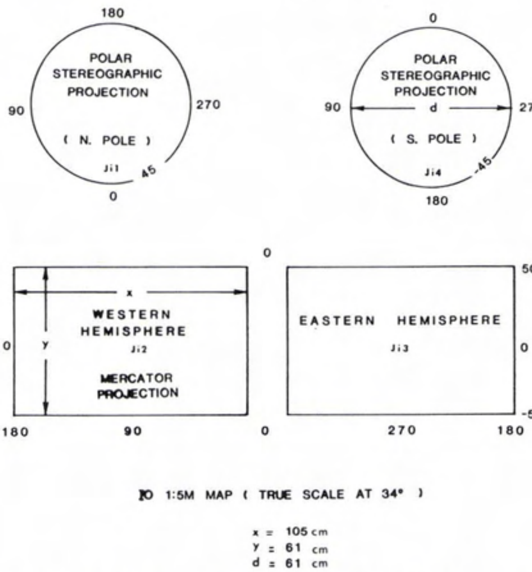

FIG. 6. 1:5,000,000 map format for Io. The format for Europa is identical except for smaller dimensions.

Fourth, we determined that map scales larger than 1:5,000,000 are justified by some of the Io pictures. The maps will be on transverse Mercator projections centered on the areas of interest. A scale of 1:2,000,000 will probably be used. Maps at

TABLE 2. DIAMETERS OF THE GALILEAN SATELLITES (km) (FROM DAVIES ET AL., 1979). DIAMETERS OF THE EARTH, MOON, AND MERCURY ARE GIVEN FOR COMPARISON.

Io	3632 ± 10
Europa	3126 ± 20
Ganymede	5276 ± 20
Callisto	4820 ± 20
Earth	12756 (Equatorial)
Moon	3476
Mercury	4878

scales larger than 1:5,000,000 are not planned for the other satellites. Table 4 shows the current mapping plan.

The maps in Table 4 are being compiled as follows:

- The 1:25M preliminary maps show surface markings, relief, and feature nomenclature.
- The 1:25M color maps show surface markings and relief in color. They are drawn with the airbrush, on the basis of examination of all available color pictures. Feature nomenclature is omitted to avoid obscuring surface detail.
- The 1:15M planetwide maps, 1:5M quadrangles, and special maps will show surface markings, relief, and feature nomenclature. Second versions of these are planned on which nomenclature will be omitted. Where possible, a third version will be compiled showing relief only.

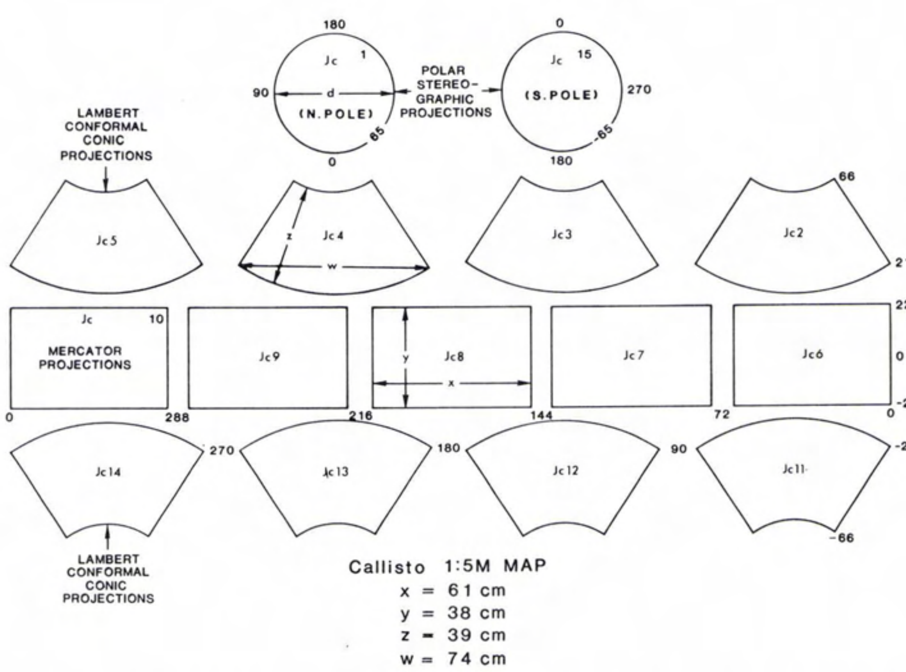

FIG. 7. 1:5,000,000 map format for Callisto. The format for Ganymede is identical, except for slightly larger dimensions. One degree of overlap is provided along boundaries between projections. Letter and number designations (Jc 1, Jc 2, etc.) of individual sheets are explained in text under Nomenclature.

TABLE 3. PROJECTION SPECIFICATIONS FOR MAPS OF THE GALILEAN SATELLITES.

Satellite(s)		True Scale at:		Approx. Join Parallels		Overlap between Projections
Io, Europa, Ganymede,	1:25,000,000	equator	Mercator	±56°	1:13,980,000	2°
Callisto		—	Polar stereographic	±56°	1:13,980,000	2°
Io, Europa, Ganymede,	1:15,000,000	equator	Mercator	±56°	1:8,388,000	2°
Callisto		—	Polar stereographic	±56°	1:8,388,000	
Io, Europa	1:5,000,000	±34	Mercator	45	1:4,268,000	5°
		±90	Polar stereographic	±45	1:4,268,000	
Ganymede, Callisto	1:5,000,000	±13	Mercator	±21.3	1:4,780,000	1°
		±30	Lambert	±21.3	1:4,780,000	
		±58	conformal conic	±65.2	1:4,769,000	
		±90	Polar stereographic	±65.2	1:4,769,000	

The photomosaic base used to control each airbrush representation will also be published without feature nomenclature. In previous planetary mapping, separate versions were made showing relief only, to avoid ambiguity when colored geologic overlays are superimposed on the shaded relief maps. For Mars, this technique was especially necessary because the surface markings vary with the seasons. We do not yet know if this separate version can be made for the Galilean satellites: in general, neither stereoscopic pictures nor pictures taken under different illuminations are available to the airbrush cartographer as an aid in assessing the relief. After we have made the maps that combine relief and surface markings, we will decide whether to attempt maps showing relief only.

Each 1:25,000,000 color map is on a Mercator projection and covers the zone between the 70° parallels of latitude. (The polar regions in available color pictures are so foreshortened that conformal mapping is not useful.) A montage of the best color pictures and color mosaics in orthographic projections is to be included on the same sheet with the airbrush map. Graticules are shown on each of these map images, but nomenclature is omitted to avoid concealing surface details.

NOMENCLATURE

1:5,000,000 MAP SHEET DESIGNATIONS

Sheet names and designations follow the system outlined by Batson *et al.* (1979). The tradition of naming the quadrangles for distinctive features within their boundaries is retained. In addition, each quadrangle is given a number starting in the northernmost latitude zone and increasing with longitude. This number is prefixed by the capitalized initial of the primary body followed by the lower-case initial of the satellite. Thus, 1:5,000,000 maps of Io are designated Ji 1 through Ji 4, maps of Ganymede are designated Jg 1 through Jg 15, and maps of Callisto are designated Jc 1 through Jc 15 (Figures 4, 6, and 7). A file code for each map contains the satellite prefix (Ji, Jg, etc.); the abbreviated denominator of the map scale (25M, for 1:25,000,000, etc.); the latitude and longitude to the nearest degree, separated by a

TABLE 4. MAPPING PLAN FOR THE GALILEAN SATELLITES. NUMBERS REFER TO THE NUMBER OF SHEETS PLANNED FOR EACH FORMAT. (LACK OF PHOTOGRAPHIC COVERAGE PREVENTS THE MAPPING OF THE NORTH POLAR REGION OF IO AND THE SOUTH POLAR REGION OF CALLISTO.)

	Io	Europa	Ganymede	Callisto
1:25M preliminary maps	1	1	1	1
1:25M color maps	1	1	1	1
1:15M planetwide	1	1	1	1
1:5M quadrangles	3	2	11	9
"large"-scale special maps	5	0	0	0
TOTALS	11	5	14	12

slash, of the center of the map; and a code for the type of map. The codes for the various sheets in the Galilean satellite series are: CM, for controlled mosaic; CMK, for controlled color mosaic; A, for shaded relief and surface markings; AK, for color shaded relief and markings; and R, for versions showing relief only. The letter N is added to these codes for the sheets showing feature nomenclature. This designator uniquely identifies each sheet as to planet or satellite, scale, sheet location, and version. Finally, a serial number prefixed by the letter "I" is assigned by the U.S. Geological Survey at the time the map is published. The "I number" is used to order the map from USGS map distribution centers.

FEATURE NAMES

Shortly after the two Voyager spacecraft began their journey to Jupiter, the International Astronomical Union, the governing body for planetary nomenclature, convened a task group for Outer Planets Nomenclature. This group decided to continue the mythological theme for nomenclature of the Galilean satellites originated by the astronomer Marius, who named them for nymphs and mortals beloved by Jupiter. A list was compiled of the names in each myth associated with the personage for whom the satellite was named. Another very large list of names was also assembled from myths of ethnic groups throughout the world. Names from these lists were then grouped by terrestrial regions and continents into categories of personages, place names, and objects that played prominent roles in the myths. These subgroups were established because the committee planned, during the pre-encounter period, to name features on Io (the Galilean satellite nearest Jupiter) from myths of equatorial peoples; Europa was to be assigned names from European temperate-zone myths; Ganymede from non European; and Callisto, the outermost Galilean satellite, from Far-Northern myths.

Images returned by Voyager 1 revealed strange new "worlds" of fire and ice that appeared very different from any planetary bodies studied previously. Craters on Amalthea, Ganymede, and Callisto are the only features similar to those imaged by earlier space missions to terrestrial planets. Some features are so completely different that new terms such as "macula" (dark spot), "linea" (elongate markings), and "flexus" (low, curvilinear, scalloped ridges) were adopted; the term "regio" (large area of distinctive albedo marking) was revived from its use on Mars by early astronomers. In other cases, where some features of the satellites resemble named features on the Moon, Mars, or Mercury, previously adopted terms like "patera" (irregular depression) and "planum" (high plateau) are used. For Io, the original plan to use names from equatorial-zone myths was abandoned when eight volcanic eruptions were documented during the two encounter periods. Instead, the features from which the eruptions emanated, and similar features thought to be dormat eruptive centers, were assigned names of fire, sun, and smith gods, and gods associated with terrestrial volcanoes. The regional theme was followed for features on icy Callisto, where craters and large ringed basins were named for characters and places in Far-Northern myths. Crater names on Ganymede were chosen from the most ancient Near-Eastern civilizations. Names on Europa and Amalthea are all derived from the myths associated with these personages. Myth-related names are also assigned to nonvolcanic features on Io, some craters and a catena on Callisto, and the arrays of linear grooves and a few craters on Ganymede. Another category was devised to name the regions of very dark albedo on Ganymede; the astronomers who discovered satellites of Jupiter are commemorated by these regions.

Features on new, high-resolution maps, which are still being compiled, will be named from the established name banks, using schemes already adopted; for example, features on future editions of the Europa map will be named from temperate-zone European myths. It may also be necessary to invent new terms and to expand the name banks when the high-resolution pictures are studied in detail.

FINAL MAPPING TECHNIQUES

Planetary mapping programs involve preliminary and final products. Preliminary mapping, discussed above, utilizes early data products that have not been fully processed. Final mapping, on the other hand, involves more intensive control and more detailed airbrushing.

All Voyager pictures used in the final mapping are specially processed for cartography in the computer. This processing removes known shading artifacts that vary with location within the field-of-view, and with the camera, filter, and proximity to the Jovian magnetic field at the time the pictures were taken. These decalibrations include correction of camera shading, and removal of bit-errors and reseau marks. Dropped lines are filled by interpolation.

Second-level digital processing includes correction for known camera distortions and transformation to specified map projections. The latter depends on the orientation matrices computed by analytical photogrammetry by Davies *et al.* (1979) for each frame used in the mapping. These computations also result in a control net consisting of latitudes and longitudes of selected map features. The individual frames are placed in the photomosaic according to the plotted location of the control points. When feasible, this task is done in the computer, but when very large numbers of pictures at a wide variety of scales are involved, the mosaic may be made by hand. The techniques are essentially identical to those described by Davies and Batson (1975) for the mapping of Mercury.

Airbrush drawings are prepared by techniques described by Inge (1972), Inge and Bridges (1976), and Batson (1978). Feature placement is tied to the controlled mosaic. All enhancements of all available pictures are examined by the cartographer to augment and improve the portrayal. This data set includes pictures processed at the MTIS and at the IPL at JPL: different spatial filters have been applied to these pictures, resulting in the enhancement of surface details at different frequencies. Relief is drawn as if illuminated from the west, consistent with previous planetary maps. This convention leads to an ambiguity at the poles, but allows consistent portrayal at the latitudes where the polar sheets join those in the intermediate latitudes.

Summary and Applications

Several versions each of maps compiled at a variety of scales are being made available to scientists studying the satellites of Jupiter. These maps are also available to other interested persons through USGS map distribution centers and through the National Space Science Data Center at Goddard Space Center in Greenbelt, Maryland. The maps include photomosaics and airbrush representations that show all surface detail visible in the pictures returned by Voyagers 1 and 2. They serve as bases for geologic mapping and for topical studies of the Galilean satellites, and also for planning future exploration.

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