Planned Geological Investigations of the Europa Clipper Mission – Supplemental Material

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Supplemental Material: Geology-relevant Level 1 and Level 2 requirements of the Europa Clipper mission and their rationales

Level 1 - Global Photomosaic

RQ106.320

Produce a controlled photomosaic map of ≥80% of the surface at ≤100-m spatial scale.

Rationale:

The purpose of this requirement is to produce a coordinate-controlled map of Europa from images that have a pixel scale better than 100 m, a resolution sufficient to map the global distribution and relationships of larger and smaller geologic landforms, across at least 80% of Europa's surface, to understand global distributions of landforms and to serve as a coordinate-controlled basemap for other datasets.

Level 2 child (1):

Distribution of landforms

RQ104.918

EIS

The global-scale panchromatic and stereo DTM imaging datasets shall, in combination, consist of observations that characterize visible reflectance, morphology, and albedo of ≥80% of the surface at ≤100-m pixel scale, with associated topographic coverage to support radar sounding clutter characterization at ≤300-m horizontal scale and a vertical precision ≤50 m, in order to characterize endogenic structures, surface units, and the potential for shallow subsurface water, and to constrain formation processes, 3D structures, and history of geologic landforms.

Rationale:

Galileo images demonstrate that 100 m/pixel data are excellent for geologic studies of Europa, yet less than 10% of the planet was imaged at better than 250 m/pixel (Greeley et al., 2009). Global imaging at these scales will enable the characterization of the population of impact craters >1 km in diameter and reveal the locations and types of significant geologic features on Europa. 80% surface coverage will ensure that no major region of the planet is missed. Topographic representation of a smaller portion of the surface will be made through stereo imaging that achieves the required vertical precision (50 m) over 30% of the surface with possibly some portion of the topographic coverage achieved through photoclinometry techniques that would also satisfy REASON requirements. Stereo imaging coverage is achieved by a combination of pushbroom 3-line stereo and framing images obtained on different flybys.

Level 1 - Landform Geology

RQ106.319

Characterize the surface at ≤25-m spatial scale across ≥5% of the surface with global distribution, including measurements of topography at ≤15-m vertical precision across ≥1% of Europa's surface.

Rationale:

The purpose of this requirement is to understand the formation and evolution and surface features and their potential relationship to liquid water, by obtaining images of the surface at better than 25 m pixel scale, sufficient to resolve smaller landforms, across at least 5% of Europa's surface with wide-spread distribution across the surface, to sample Europa’s known landform types. This should include associated topography via stereo imaging, sufficient to resolve 15-m height differences within at least one third of that area, to understand small-scale topographic variations, with additional supporting data as available, including local-scale compositional maps.

Level 2 children (2):

Regional-scale topography of landforms

RQ104.919

EIS

The regional-scale panchromatic, color, and stereo DTM imaging datasets shall, in combination, consist of observations that characterize visible reflectance, morphology, albedo, and color of ≥5% of the surface with global distribution at ≤25-m pixel scale, with associated topographic coverage at ≤100-m horizontal scale and a vertical precision ≤15 m across ≥1% of the surface, in order to characterize endogenic structures, surface units, and the potential for shallow subsurface water, and to constrain formation processes, 3D structures, and history of geologic landforms.

Rationale:

The smallest and most recent known fractures on Europa can be observed at 25-m pixel scale, and this data will also improve age relationships determined by crater counting. 5% of the surface provides a minimum representative sample of terrain types and geologic features from a variety of locations around the globe. The topographic data will enable the analysis of topography and slopes of geologic features identified in the global-scale imaging data set (100-m pixel scale) and provide an intermediate scale between the global and local stereo vertical precisions enabling a better understanding of the scales at which surface features occur over an area sufficient to characterize typical topography.

Local-scale composition characterization

RQ104.922

MISE

The local-scale infrared imaging spectroscopy dataset shall sample compositionally diagnostic properties of ≥14 globally distributed sites at ≤50-m pixel scale, in order to determine composition of individual landforms, to investigate how composition influences the formation and evolution of landforms.

Rationale:

The aim of this dataset is to acquire observations of at least 14 globally-distributed secondary landforms with three sites that are within 50 deg of the equator and sample the sub-/anti-jovian hemispheres for understanding exogenic influences. As specified within a lower-level requirement, each site will have minimally an along track length of 1.5 km and cross track width of 7 km (when acquired from a flight system altitude of 100 km; in size, a cube footprint will scale smaller when acquired from lower altitude). The resolution requirement is designed to determine composition of individual landforms; Galileo SSI images (resolution generally >100m/px but as good as < 10m/pixel) show albedo variations and processes down to the highest resolution data obtained including small-scale mass-wasting and small-scale or isolated outcrops of material (such as lag deposits at the bottom of bands) where key constituents may be concentrated. This dataset is "enhancing" towards achieving the L1 and would be paired with overlapping higher-resolution (i.e., <25 m/px) visible images. Information about what is included under "compositionally diagnostic properties" and the specific spectral measurement capabilities needed to achieve this requirement (e.g., band depth resolution needed for organics or salt detection) are defined within the next level of requirements (Measurement Requirements MIS.001-007, MIS.024-026, MIS.-028).

Level 1 - Local-Scale Properties

RQ106.311

Characterize the surface at ~1-m spatial scale to determine surface properties, for ≥18 globally distributed sites.

Rationale:

The purpose of this requirement is to determine the characteristics including roughness of Europa's surface at a scale of about 1 m, sufficient to resolve local-scale surface features and their variation, to understand local-scale surface processes and to inform potential future landed missions. Sampling should include at least 18 representative areas to understand the variety across Europa, with wide-spread distribution across the surface to provide information on variations in latitude, longitude, and landform type.

Level 2 children (4):

Local surface characterization

RQ104.923

EIS

The local-scale panchromatic and stereo DTM imaging datasets shall, in combination, consist of observations that characterize the visible reflectance, morphology, and albedo of ≥18 globally distributed sites ≥2 km by ≥4 km in area at ~1-m pixel scale, with associated topographic coverage at ≤4-m horizontal scale and a vertical precision ≤0.5 m, in order to determine regolith cohesiveness, thickness, and subsurface layering; surface roughness and slopes; and the distribution of blocks.

Rationale:

Three sites each within three latitude bins on both the sub- and anti-jovian hemisphere (18 total) will capture areas that are representative of those across the surface. The site size is a level 1 requirement. A ~1 m pixel scale will enable the characterization of meter-scale surface roughness, regolith cohesion, landforms associated with mass movements, and landing hazards. A stereo DTM with a horizontal scale of 4 m is needed to characterize slopes and topography at scales applicable to typical landers. A vertical precision of 0.5 m provides a complementary scale to the regional and global-scale vertical precision values. As negotiated with NASA Headquarters, local surface characterization is not required at Level-1 as part of the threshold mission and thus does not have a threshold requirement.

Small-scale surface characterization

RQ104.920

EIS

The small-scale panchromatic and color imaging datasets shall, in combination, consist of observations that characterize visible reflectance, morphology, albedo, and color of globally distributed sites ≥10 km by ≥10 km in area at ≤10-m pixel scale, in order to characterize resurfacing and degradation by processes such as weathering and erosion as context for interpreting the local-scale imaging dataset.

Rationale:

Small-scale imaging of areas ≥10 km by ≥10 km will provide contextual information for the 1 meter/pixel local-scale visible imaging, so is necessary support for that dataset. A 10-m pixel scale provides an intermediate scale between the regional- and local-scale datasets. This scale helps to understand possible ocean-surface exchange processes. In addition, a 10-m pixel scale provides a similar scale for comparisons to MISE cubes.

Surface thermophysical properties

RQ104.924

E-THEMIS

The regional thermal imaging dataset shall be sufficient to map daytime or nighttime temperatures of ≥40 geologically distinct sites at a ≤250-m pixel scale and with ≤2 K accuracy and precision, in order to characterize the thermophysical properties indicative of erosion and deposition processes at the sub-pixel spatial scale.

Rationale:

Erosional/depositional processes at the geological scale (km resolution, resolved with 250-m or better resolution) are associated with distinct regolith thermophysical properties, and therefore translate in different thermal behaviors. To distinguish surficial properties (including at subpixel and sub-meter scales), thermal inertia shall be determined +/- 20%, requiring 2 K accuracy and precision. Experience shows that 40 sites will provide meaningful diversity.

Near-surface properties

RQ104.925

REASON

The near-surface property dataset shall consist of near-surface reflectometry and altimetry measurements, in combination, to determine regolith cohesiveness, thickness, and subsurface layering; surface roughness and slopes; and the distribution of blocks.

Rationale:

The reflectometry and altimetry measurements (Grima et al., 2014; Grima et al., 2016) directly support the L1 by: (a) quantifying the character of reflections from near-surface features to discern frozen brine or ephemeral brine-soaked ice, (b) deriving scattering and reflection properties permitting inference of surface roughness and density over 2-km horizontal scales, and (c) constraining the average porosity (e.g., detect snow deposits) over depths within 150 m of the surface. Altimetry provides topographic context for reflectometry measurements.

Level 1 - Current Activity

RQ106.314

Search for and characterize any current activity, notably plumes or thermal anomalies, in regions that are globally distributed.

Rationale:

The purpose of this requirement is to search remotely and systematically for evidence of current activity at Europa, especially active or recent plumes or hot spots in regions that are well-distributed across the entire surface, and characterize any discovered active regions in as much detail as the instrument suite and mission plan reasonably permit.

Level 2 children (6):

Imaging plume search

RQ104.926

EIS

The plume search imaging dataset shall consist of limb and terminator images obtained at high phase angle at a ≤10-km pixel scale across a range of longitudes and true anomalies in order to search for active plumes via forward scattering by entrained particles.

Rationale:

Small particles expected to be in the plumes are highly forward scattering of incident light and thus observations of the limb at phase angles of 130-170 degrees are most likely to observe them. Observations of the terminator taken at phase angles of 90-120 degrees will be most likely to observe them when they are lit up against the dark side of Europa. Typical plumes on Europa, if they exist, are not expected to extend more than 26 km above the surface (e.g., Quick et al., 2013). A 10-km pixel scale is more than sufficient to image a 200-km-high plume like the putative vapor plumes inferred from Hubble observations (Roth et al., 2014). Plumes on Europa may vary in intensity throughout the Europa's orbital cycle (Hedman et al., 2013) and may not be localized to particular locations on its surface. In order to maximize the probability of observing a plume, high phase limb and terminator images need to sample the full range of longitudes with separation less than 10 degrees and sample the full range of true anomalies with separation of less than 30 degrees.

Ultraviolet plume search

RQ104.927

Europa-UVS

The ultraviolet plume dataset shall be sufficient to search for and characterize the vapor composition of any plumes ≥30 km in height on timescales of a Eurosol to at least two years, as related to the chemistry of subsurface water and variability of geophysical activity.

Rationale:

As the spacecraft will fly within 30 km of the Europan surface, the spacecraft may directly fly through plumes of this height or larger. Observations in the ultraviolet will constrain column density, spatial distribution and temporal variations of atmospheric constituents (e.g., O, H, H2, H2O, CO2, O2, etc.), and provide information complimentary to that obtained by in situ investigations. Coverage timescales spanning a Eurosol to two years account for the ~1 day lifetime of atmosphere escape/loss processes and span longer scales of potential geophysical activity variability.

Thermal anomalies

RQ104.929

E-THEMIS

The global thermal imaging dataset shall be sufficient to map daytime and nighttime temperatures over ≥80% of the surface at a resolution of ≤25 km and with ≤2 K accuracy and precision, in order to characterize the thermal state of the ice shell and identify heat flow anomalies, regolith depth, and block abundance.

Rationale:

Excluding the polar and high latitude regions (i.e., over 80% of Europa's surface), heat flow anomalies and surficial regolith structure (including subpixel block abundance) will be adequately characterized using nighttime and daytime observations. With 2 K accuracy, mapping will be performed for block abundance at 15% accuracy, and heat flow anomalies 2 K above background values will be detected.

In-situ plume particle composition

RQ104.931

SUDA

The plume particle dataset shall be sufficient to identify and characterize potential recent activity, and/or ongoing activity in any encountered plumes, for flybys ≤110 km altitude and determine the composition, including any organic compounds if present, number density, and size distribution of any plume particles to identify and constrain the plume's source mechanism and the salinity of the source.

Rationale:

This requirement will allow identification of recent activity deposits on Europa's surface, similar to the proven scenario on Enceladus (Kempf, et al., 2010). When flying through an active plume, whether intentionally planned or serendipitous, SUDA will detect the plume particle composition, including potential organic compounds such as amino acids and fatty acids, if present; salts, mineral hydrates such as olivine, if present; providing critical compositional information necessary to assess Europa's Habitability. Because plume particle number density decreases with increasing altitude, the Europa Clipper spacecraft will need to fly through a plume at low spacecraft altitudes (i.e. at or below 80% of the plume scale height) to collect plume particles. Plume particles fall back rapidly than plume gases, with larger-mass grains falling more rapidly. For this reason, it is necessary to fly at least at 80% of the plume-particle scale height. The Europa plume model for ice particle ejecta, assuming similar plume volume conditions as seen on Enceladus (Southworth et al., 2015). It is clearly demonstrated in this paper that in order to detect sufficient ice grains, it is required to fly at 100 km or below. Placing some margin on this altitude makes it less than or equal to 110 km. The models show that below 130 km the particle density precipitously drops, failing to collect necessary particles to assess their compositional commonalities and variations within the plume. The instrument measurement capability will produce a dataset that will determine the chemical composition of plume particles (including indicators of salinity).

In-situ plume composition

RQ104.932

MASPEX

The atmospheric plume and ice-ocean volatile datasets shall, in combination, be sufficient to measure the composition of volatiles at ≤110 km spatial scale to characterize any active geological features and determine the relative fluxes of endogenous particles and gases in any encountered plume material, in order to constrain ocean geochemical properties relevant to habitability.

Rationale:

Spatial resolution in the MASPEX data during flybys must be sufficient to determine potential occurrence of plumes from the background exosphere. This spatial scale is sufficient to locate the geographical region where activity may be occurring, e.g., plumes, chaos, or fracturing. The scale is conservative relative to what the investigation can achieve, but is based on current analysis, supported by modeling of Europa's sputtered atmosphere (Teolis et al. 2017a, 2017b). Plumes are anticipated to manifest themselves via enhanced density of volatiles, presence of ice grains, and different composition from the background sputtered exosphere (Teolis et al. 2017b). Ice grains would likely accompany plumes, as observed on Enceladus (Teolis et al. 2010). The composition of plume volatiles would provide a new window into the geochemistry of Europa's internal ocean to constrain its properties, like the analysis of Cassini INMS data enabled at Enceladus (Glein et al. 2015, Waite et al. 2017, McKay et al. 2018, Glein & Waite 2020). The value of <100 km is derived from the modeling of Teolis et al. (2017b), which showed that less volatile complex organics possibly originating from the ocean should not travel far from their point of deposition across the surface due to the small and infrequent (due to volatility) hops these molecules may make before they are radiolytically destroyed.

In the event of any performance relaxation to MASPEX, such would reduce the number of species measurable, in particular trace and low-abundance isotopic species, making it more difficult to reliably assess their sources. If such a reduction in performance were to take place in the future, this requirement might become overambitious, as a much lower number of species would be available to determine source processes, and to constrain ocean geochemistry. Furthermore, the impact of the relaxation of the flight system contamination control requirement to an uncertain outgassing composition would further complicate the interpretation of the results, strengthening the need for the planned in-flight MASPEX Contamination Characterization Activities.

Surface changes

RQ104.933

EIS

The recent activity imaging dataset shall consist of observations that characterize albedo and color variations of globally distributed regions at ≤500-m pixel scale using images that overlap with Voyager, Galileo, or other EIS images, in order to search for recent activity by documenting any surface changes between repeat images and identifying signatures of fresh materials.

Rationale:

The comparison among EIS, Voyager, and Galileo data enables the assessment of surface changes over the intervening decades, and the comparison of repeat EIS surface coverage enables the assessment of surface changes over the duration of the mission. To identify recent activity, observations overlapping and comparable in pixel scale to those acquired by Voyager and Galileo are required. The required resolution was chosen because Galileo acquired 14.2% of the surface at 400-m pixel scale or better (Greeley et al., 2009; C. Phillips analysis for project). Color variations will be assessed using multiple EIS broadband color filters.

Guiding Level 2 - Correlation

RQ104.936

The following datasets shall permit cross-correlation including and among each of the following categories: (1) in-situ-mapping and remote sensing datasets; (2) fields and particles (excluding gravity), and plasma plus auroral datasets, and; (3) gravity and any tidal deformation datasets.

Rationale:

The strength of the suite of science investigations is that their combined analysis provides the greatest insight into different and correlated processes that act on Europa (e.g. the subsurface expression, composition, and geologic structure of landforms). As such, the ability to cross-correlate the various data sets is essential. In its implementation, the key aspects of ensuring that data sets can be correlated is based on requirements that boresights are co-aligned with corresponding in-flight alignment characterization, that the instruments use common time references and geographical coordinate systems, and that common pre-launch calibration sources are used. Adhering to these requirements will allow processed data to be co-registered when collaborative products are generated on the ground.

Geology Planning Guideline

PG109.981

When a groundtrack crosses a landform to fulfill a desire as identified in the Geology Working Group Landform Map, those in Category A should be crossed at an altitude greater than or equal to 35 km and less than or equal to 100 km, and those in Category B should be crossed at an altitude less than or equal to 400 km. Over the course of the mission, it is desired to have at least one crossing of a Category A landform per landform type. All Category A and B landform observations should have an incidence angle of 20-75 deg at the groundtrack crossing.

Rationale:

Ensuring that groundtracks cross over landforms at these altitudes will provide opportunities for all instruments to observe the landform simultaneously, which is a high science priority especially for the Geology Working Group. There are four landform types – Chaos, Bands, Craters, and Depressions – with a map for each landform type (see http://europapsg.jhuapl.edu///uploadedDocs/documents/1511-LandformsAndAltitudesv3.pptx). Each landform within a map is colored based on whether it is in Category A or B, which indicates the priority of the specific landform. Category A contains those that are highly desired to have a flyby of at least one of each landform type with all instruments taking data. Only a select number of landforms have been identified to be in this category. The requested altitude range is derived from a combination of the best observing conditions for REASON (altitude of flyby should be greater than 35 km (PG106.183)), in situ instruments including SUDA (altitude of flyby must be less than the radius of the feature; see RQ106.214 and RQ106.198 or SUD.017 and SUD.018), and imaging instruments for which the balance between the best pixel scale/resolution and field of view are a function of altitude (altitude of flyby must be less than 100 km or greater than 25 km). Note, that observing Category A landforms at the Category B altitude (<400 km) is acceptable, but does not count toward the "one observation of a Category A landform per landform type" unless it is within the Category A altitude range (35-100 km).

Category B contains landforms that the Geology Working Group generally would benefit from having as many flybys of these landforms as possible. The Geology Working Group will qualitatively evaluate tours for spatial distribution and distribution between type of these landforms. The requested altitude range is derived from REASON (see PG106.144), while still maintaining desired resolutions and field of views from other remote sensing instruments (e.g., EIS NAC better than 25 m/pixel below 2500 km; WAC ~90 m/pixel at ~400 km), and the in situ instruments as well.