Europa Clipper Preparatory Photometry to Constrain Surface Properties

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Abstract

We infer the surface reflectance properties of Europa using multispectral data sets available from previous missions. We use 21 full-disk images of Europa from Voyager’s Imaging Science System, Galileo’s Solid State Imaging, and New Horizons’ Long Range Reconnaissance Imager at differing observation geometries (10°–128° phase angle) to compute disk-integrated surface-scattering properties over various geologic units. The derived photometric models will serve the practical goals of data acquisition, aid in the calculation of instrument integration times, and facilitate quick-look data products for images acquired by Europa Clipper and other future missions to Europa. We use the Minnaert and Lommel–Seeliger plus Lambert reflectance models to constrain the photometric parameters of Europa’s surface. We find that the surface albedo parameter, B0, in the Minnaert function gradually decreases with increasing phase angles. We also note that the photometric properties of Europa (geometric albedo at 0.47 μm is 0.72 on the leading side and 0.62 on the trailing side) require a significant “Lambert” term (A < 1) in the Lommel–Seeliger plus Lambert reflectance model. We also observe that the photometric parameters are not highly dependent on the geologic terrain type despite their visibly different albedos.

Unified Astronomy Thesaurus concepts: Europa (2189); Planetary surfaces (2113); Photometry (1234)

1. Introduction

The Jovian moon Europa, with its fractured appearance (Lucchitta et al. 1982; Helfenstein & Parmentier 1983), salty subsurface ocean (Carr et al. 1998), and evidence of water plumes ejected ~160 km away from its surface (Sotin et al. 2002; Roth et al. 2014; Sparks et al. 2016) is a dynamic environment to be explored by Europa Clipper. Europa is also important from an astrobiological perspective due to the presence of subsurface water (Greenberg et al. 2000; Chyba 2001; Chyba & Phillips 2002). The tidal heating due to the resonant orbits (4:2:1) of the three Jovian moons Io, Europa, and Ganymede could also lead to volcanic or hydrothermal activity on the seafloor that might act as an energy source for the possibility of life (Collins et al. 2000; Thomson & Delaney 2001; Goodman et al. 2004). Much can be learned about the characteristics and dynamics of Europa through surface analysis.

An established method for surface science on these Jovian moons and other solar system bodies is photometry, which is the quantitative measurement of radiation from an object. In planetary sciences, the uses of photometry can be divided into two categories: practical and physical. The practical uses of photometry are centered on understanding how the specific intensity of a planetary surface varies as a function of viewing geometry (solar phase angle, incident, and emission angle; see Figure 1). A quantitative description of these changes is required to undertake a number of scientific investigations associated with the acquisition and analysis of data from spacecraft, including the determination of instrumental integration times, the creation of seamless mosaics in physical units (normal reflectance, for example), robust determination of surface composition, the separation of the effects of viewing geometry on spectral bands, and the characterization of a target’s shape. The physical uses of photometry focus on the derivation of surface properties from radiative transfer models, including macroscopic roughness, the compaction state of the upper regolith, and the particle size and shape, all of which can be related to the current physical state and geologic evolution of a planetary surface. In this paper we focus on the derivation of an empirical photometric model for the surface of Europa to serve the practical goals of the Europa Clipper mission and future missions to Europa. Further analysis of existing spacecraft data using current techniques is essential for improving the science and understanding of Europa for future missions.

Most of the variation in reflective intensity as recorded on spacecraft images is not intrinsic but rather due to changing geometry. Modeling these variations is a fundamental task of photometry, which underpins the scientific analysis of these images and of planning future spacecraft observations. The results of this modeling also allows scientists to generate seamless maps of planetary surfaces, such as those carried out by Robidel et al. (2020) for the surface of Enceladus. The scientific return of missions can be substantially enhanced by choosing integration times based on the accurate knowledge of intrinsic surface reflectance and how that changes with viewing geometry. Simple photometric models have been developed to describe the directional scattering processes of planetary surfaces since images have been returned from spacecraft (Buratti & Veverka 1983, 1984; Squyres et al. 1984), or, in the case of the Moon, ever since its reflective properties were quantitatively described (Minnaert 1941, 1961). The purpose of having a simple photometric function is twofold: to accurately predict the intensity reflected from a planetary surface, and to produce immediate data products that are corrected for the effects of viewing geometry.

Five spacecraft—Voyager 1 and 2, Galileo, Cassini, and New Horizons—have returned data that are ideal for our proposed photometric investigation, but the observations have been studied only cursorily for this purpose in the past (except for the Voyagers, Buratti & Veverka 1983; Domingue et al. 1984).
To prepare for a mission like Europa Clipper, it is essential to analyze the currently available data to hand. A systematic analysis of Europa’s photometric data will provide a practical formalism for describing Europa’s reflectance at any solar phase angle. The Europa Clipper (Phillips & Pappalardo 2014), JUpiter ICy moons Explorer (Grasset et al. 2013), and the proposed Europa Lander mission (Pappalardo et al. 2013) will benefit from this photometric study of Europa’s surface.

Europa has been photometrically studied previously with both Hapke-type and simpler models (Buratti & Veverka 1983, 1985; Buratti 1985, 1995; Domingue et al. 1991; Domingue & Verbiscer 1997). The simple lunar-like scattering law does not apply to Europa owing to its high albedo and multiple scattering (Buratti & Veverka 1983). The solar phase curve that describes the brightness of a reflecting body as a function of its phase angle at visible wavelength (0.55 μm) is less steep for Europa as compared to the Galilean satellites Ganymede and Callisto, as also determined by ground-based observers (Buratti & Veverka 1983). Europa’s spectrum indicates the particle size to be of the order 20–100 μm (Hansen et al. 2005). The photometric model fit to Europa implies that its surface is less rough than the Moon and the Saturnian satellite Mimas despite Mimas’s albedo being similar to Europa’s (Hapke 1968; Buratti 1985; Hansen et al. 2005). Helfenstein et al. (1998) performed a detailed analysis of the opposition surge from Galileo data, offering views of the compaction state of the surface, which in turn yields clues to possible active areas or regions of recent frost deposition, and regions for safe landing. Unfortunately, the Galileo data set was small due to a retracted antenna resulting in a limited number of regions studied.

More sophisticated radiative transfer models that describe the bidirectional reflectance of a planetary surface in terms of physical parameters have been published (Goguen 1981; Hapke 1981, 1984, 1986, 1990, 2008; Buratti 1985; Buratti & Veverka 1985). These models derive physical parameters such as macroscopic roughness, the compaction state of the surface, the single-particle phase function, and the single-scattering albedo. These parameters have been derived for the surface of Europa but the model is unnecessarily complicated for planning spacecraft observations and quick-look data analysis because the fits are not unique (see Helfenstein et al. 1998) and often cumbersome to use. In addition, all of these models were only fit to Voyager data. Recently Belgacem et al. (2020) used a Bayesian approach adaptable to Voyager and New Horizons data sets to infer that Europa’s surface is bright and backscattering, in agreement with the results of Buratti (1985). They also inferred that certain regions are forward scattering indicating fresh deposits.

In this manuscript we use two simple models to describe the observed bidirectional reflectance of Europa, the target for NASA’s next outer-planet flagship-class mission (Europa Clipper). For the first time, imaging data gathered from the Voyager, Galileo, and New Horizons cameras have been used in an analysis to fit two models, the Minnaert function and the Lommel–Seeliger plus Lambert function, to the available data and to produce a practical, easily used function to describe the reflectance of Europa’s surface. The advantage of this study over others in the past is the broadest coverage of observation geometry from phase angles of 10°–128° and the utilization of all the previously available data for Europa in the visible region.

Section 2 in this manuscript discusses the data and the calibration process used in the analysis. In Section 3 we describe the photometric models and the parameters derived from them. In Section 4 we identify the geologic regions and then derive the photometric model parameters for each region. We describe the results in Section 5 followed by the discussion and conclusions in Section 6.
The Data Used in Our Analysis

| Image ID       | Mission            | Acquisition Date | Phase Angle | Exp. Time (ms) | SC Point    | SS Point    |
|----------------|--------------------|------------------|-------------|----------------|-------------|-------------|
| C2065013       | Voyager 2          | 1979-07-08       | 10°         | 120            | 64°W 3°N    | 73°W 0°N    |
| lor_0034735439 | New Horizons       | 2007-02-25       | 20°         | 4              | 168°W 8°S   | 173°E 3°S   |
| lor_0034823099 | New Horizons       | 2007-02-26       | 22°         | 4              | 91°E 8°S    | 70°E 3°S    |
| lor_0034866662 | New Horizons       | 2007-02-27       | 35°         | 10             | 53°E 7°S    | 19°E 0°S    |
| C0383694600R   | Galileo           | 1997-02-20       | 37°         | 6              | 144°E 1°S   | 179°W 0°S   |
| C0349875100R   | Galileo           | 1996-06-28       | 37°         | 4              | 142°E 24°N  | 114°E 1°S   |
| C0349875113R   | Galileo           | 1996-06-28       | 37°         | 4              | 142°E 24°N  | 114°E 1°S   |
| C0349875126R   | Galileo           | 1996-06-28       | 38°         | 4              | 142°E 24°N  | 114°E 1°S   |
| C0374649026R   | Galileo           | 1996-12-19       | 55°         | 12             | 78°E 0°S    | 134°E 1°S   |
| C0374649000R   | Galileo           | 1996-12-19       | 56°         | 12             | 78°E 0°S    | 134°E 1°S   |
| C0374649013R   | Galileo           | 1996-12-19       | 56°         | 6              | 78°E 0°S    | 134°E 1°S   |
| C0368639400R   | Galileo           | 1996-11-06       | 65°         | 12             | 153°E 1°N   | 88°E 1°S    |
| lor_0034930319 | New Horizons      | 2007-02-28       | 69°         | 6              | 14°E 6°S    | 56°W 3°S    |
| lor_0034931999 | New Horizons      | 2007-02-28       | 71°         | 4              | 13°E 6°S    | 58°W 3°S    |
| C2065022       | Voyager 2         | 1979-07-09       | 94°         | 120            | 132°W 22°S  | 134°E 0°N   |
| lor_0034975919 | New Horizons      | 2007-02-28       | 100°        | 6              | 9°W 5°S     | 109°W 3°S   |
| C2065211       | Voyager 2         | 1979-07-09       | 107°        | 120            | 124°W 26°S  | 128°E 0°N   |
| C2065213       | Voyager 2         | 1979-07-09       | 107°        | 22             | 124°W 26°S  | 128°E 0°N   |
| C2065219       | Voyager 2         | 1979-07-09       | 108°        | 120            | 123°W 26°S  | 127°E 0°N   |
| C2065221       | Voyager 2         | 1979-07-09       | 108°        | 22             | 123°W 26°S  | 127°E 0°N   |
| lor_0035025959 | New Horizons      | 2007-03-01       | 128°        | 6              | 40°W 3°S    | 168°W 3°S   |

Note: SC and SS are the subspacecraft and subsolar points.

2. Data and Methodology

We selected images using the SETI OPUS3 (Outer Planets Unified Search) tool (https://opus.pds-rings.seti.org/opus). We used the Planetary Data System (PDS) ring node to download the images and the USGS-ISIS3 (Integrated Software for Imagers and Spectrometers) software (Edmundson et al. 2012; Sides et al. 2017) to radiometrically calibrate the images and incorporate the observation geometry information. In the following sections we briefly explain the steps we used to process data; however, the detailed directions to calibrate images using ISIS3 can be found at the USGS website.

Our goal with this study was to achieve a photometric study and model for the most complete observation geometry possible for Europa. To accomplish this goal, we used data from the instruments and missions to achieve broad phase angle coverage (Table 1). We only use the clear filter images for the Voyager 2 Imaging Science Subsystem (ISS; Smith et al. 1982) and Galileo Solid State Imaging (SSI; Spencer & Schneider 1996) data as the data sets are most extensive in this filter and were obtained at the closest wavelength possible. The filter’s bandwidths for Voyager 2 are 0.28–0.64 μm, for Galileo are 0.36–1.05 μm, and for New Horizons are 0.35–0.85 μm.

The geometric albedo in the bandpass of each filter (Voyager 2 ISS narrow-angle and wide-angle cameras (NAC and WAC), Galileo SSI, and New Horizons LOnG Range Reconnaissance Imager (LORRI)) varies between 0.53 and 0.61, representing a relative difference of up to 7.6% from the mean albedo across all filters, as seen in Figure 2. Europa’s spectral signature is shown in Figure 2 and seems relatively unvarying beyond 0.50 μm. Thus, we use the clear filter from each instrument even if their actual bandpasses are not the same (Spencer 1987). The effective wavelengths of all the instruments’ filters do not make a huge difference as also seen in the trends of the photometric function (see Section 5).

2.1. Voyager

Voyagers 1 and 2 contained cameras with filter wheels—the ISS (Danielson et al. 1981)—that consist of two-camera systems (narrow angle/wide angle) to provide imagery of Jupiter, Saturn, their moons, and serendipitous objects. We downloaded the Voyager ISS images in the IMQ format from the PDS website and radiometrically calibrated them using ISIS3 software. First, we imported the Voyager ISS images from IMQ to cub format using voy2isis. Then we added the camera-pointing information from the SPICE kernels using the command spiceinit on the data cubes in cub format. The next step incorporated the radiometric calibration that also removed the dark current using the command voycal. The last step before we used the image files for our analysis was to import the geometry information from the backplanes using the phocube command. The phocube command creates backplane bands that contain photometric, geometric, and spacecraft instrument information for an image file. We did not use any images from Voyager 1 as Voyager 2 images are better resolved. Also, Voyager 1 images did not offer any additional range in solar phase angle.

2.2. Galileo

The Galileo SSI (Belton et al. 1996) data set’s resolution (∼10 m) far exceeds the one from Voyager (∼100 m). The Galileo clear filter is a broadband filter that covers the peak of solar radiation (0.36–1.05 μm). Due to the unavailability of full-disc images of Europa in the clear filter, we used a few high-resolution images of Europa’s surface for our analysis in this filter at varying phase angles. For the Galileo SSI calibration the steps are similar to the Voyager ISS images. We imported the images using the command gllss12isis that converts the images from lbl to cub. Then we added the camera-pointing information from the SPICE kernels using the command spiceinit over the data cubes before radiometrically calibrating them using the command gllsscal.
The last step before we used the image files for our analysis was to import the geometry information from the backplanes using the phocube command.

The pointing geometry in some Galileo and a few images from Voyager did not always overlap (Figure 3). The error in the pointing information reported in the SPICE kernels led to a translation of the geographic and illumination values calculated by ISIS3 (Belgacem et al. 2020). This problem was corrected by a realignment of the backplanes with the position of the edge of the limb (where possible) in the sample and line axis. No rotation error is considered. The alignment can be done automatically in most full-disk images with a precision of 1 pixel. When only a fraction of the disk is visible, we did not correct for camera pointing. The potential pointing error in the high-resolution data could be a probable source of error. An example of an automatic alignment is presented in Figure 3. In this case the offset is −99 pixels in the sample direction and −30 pixels in the line direction. In order to perform an accurate photometric analysis, it is crucial to correct this offset of pointing in all the images.

2.3. New Horizons

The New Horizons LORRI (Grundy et al. 2007; Cheng et al. 2008) is a monochromatic camera with a pivot wavelength of 0.607 μm. LORRI images are in .fits format on the PDS and before using them, we did the conversion of count rate to radiance value (Cheng et al. 2008). Peterson et al. (2014) give the most recent formula to be used for scaling the count rates to $I/F$. Here, we use $R_{\text{SOLAR}} = 2.664 \times 10^{5}$ DN s$^{-1}$ pixel$^{-1}$/erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. This value is very close (with the Å to nm and erg s$^{-1}$ to W (watt) conversion) to the one used by Belgacem et al. (2020), which were not available when this study was conducted. The relative difference is about 1%. These calculations made the $I/F$ values of New Horizons images equivalent to the ones already calibrated for Voyager and Galileo.

2.4. Methodology

In this work, we describe the variation of each geologic terrain’s specific intensity through two photometric models. We started by identifying, downloading, and calibrating the full-disk images in the clear filter, as stated in Section 2. We then reprojected the data to overlay with the geologic map of the Voyager 2 ISS-NAC filter. Then we fitted the reprojected data with the photometric models discussed in Section 3 for varying phase angles ($\alpha$). To examine the variation of fit parameters over phase angles, we extracted the fit parameters $B_0, k, A$, and $f(\alpha)$ (defined below) at a given phase angle ($\alpha$) for each geologic region—ridged plains, bands, high-albedo chaos, mottled chaos, low-albedo chaos, and crater material—available in the data file. We then plotted the variation of the fit parameters $B_0, k, A$, and $f(\alpha)$ in relation to the phase angle ($\alpha$) for a given geologic region. Finally, we fitted simple functions to the variation of the fit parameters (Table 2).

3. Photometric Models

We make use of two empirical models describing the bidirectional reflectance of a planetary surface, one given by Minnaert’s function (Minnaert 1941, 1961), and the other given by a combination Lommel–Seeliger plus Lambert function (Squyres & Veverka 1981; Buratti & Veverka 1983; Fairbairn 2005), as shown in Figure 4. Minnaert’s model is a Fourier representation of the intensity. It is a generalized form of Lambert’s law with an additional term that depends on the cosine of the emission angle (Minnaert 1941). The second photometric function is the combination of a solar-scattering law dominated by single scattering and a Lambert photometric function, characteristic of multiple scattering. This function represents the first-order terms of radiative transfer models that more completely describe the surface (Horak 1950; Goguen 1981; Hapke 1993).

Minnaert’s equation is given by:

$$I/F(\mu_0, \mu) = B_0 \cdot \mu_0^k \mu^{k-1}.$$

(1)

Here $I$ is the intensity of scattered sunlight at a point on the planetary disk, $\mu_0$ is the cosine of the incidence angle, $\mu$ is the cosine of the emission angle, $\pi F$ is the incident solar flux, and $B_0$ and $k$ are two photometric parameters that depend on the solar phase angle ($\alpha$). At $\alpha = 0^\circ$, $B_0$ is proportional to the

Figure 2. Average geometric albedo of Europa (and relative difference from the mean across all instruments considered) is 0.53 (7.6%) in the Voyager 2 ISS-NAC filter, 0.56 (3.1%) in the Voyager 2 ISS-WAC filter, 0.61 (6.0%) in the Galileo SSI filter, and 0.60 (4.8%) in the New Horizons LORRI filter.
albedo of the surface; for a lunar photometric function, it is the normal reflectance or geometric albedo of the surface. The parameter $k$ describes the functional form of how the intensity changes on the surface: for $\alpha = 0^\circ$, a low-albedo surface that exhibits a fully Lommel–Seeliger scattering law has a value equal to, or close to 0.5, while a Lambert surface has $k = 1$.

The Lommel–Seeliger plus Lambert photometric function has been widely used (Buratti & Veverka 1984; Squyres et al. 1984; McEwen 1986; Buratti et al. 1990, 2017; Buratti & Mosher 1991) for many icy satellites in the outer solar system, including that of Europa. It is given by:

$$ I/F(\mu_0, \mu, \alpha) = A \cdot f(\alpha) \cdot \frac{\mu_0}{\mu + \mu_0} + B \cdot \mu_0 $$

(2)

where $A$ and $B$ are parameters that depend on the amount of multiple scattering on the surface, and $f(\alpha)$ is the surface phase function that describes the physical properties of surface such as roughness, compaction state, and the characteristics of surface particles. $A$, $B$, and $f$ are all functions of $\alpha$. Buratti & Veverka (1985) and McEwen (1986) determined the

Table 2
Linear Fitted Photometric Parameters for All the Units Studied

| Units                  | $B_0$ | $k$ | $A$ | $f(\alpha)$ |
|------------------------|-------|-----|-----|--------------|
|                        | $a$   | $b$ | $a$ | $b$          |
| Ridged plains          | −0.002| 0.728| 0.004| 0.532       |
| Bands                  | −0.003| 0.739| 0.003| 0.563       |
| High-albedo chaos      | −0.011| 1.726| −0.001| 1.046      |
| Mottled chaos          | −0.001| 0.647| 0.004| 0.541       |
| Low-albedo chaos       | 0.002 | 0.487| 0.008| 0.358       |
| Crater material        | −0.008| 1.056| −0.007| 1.158      |
| Continuous crater ejecta| −0.005| 0.940| −0.006| 1.036     |

Figure 3. Europa $I/F$ image C2060513 taken by Voyager 2 in 1979 with the clear filter. The original position of Europa in the field of view from the camera-pointing kernel (orange solid line) is offset by −99 pixels in the sample direction and −30 pixels in the line direction, compared to our limb-centering method (dashed orange circle). Both top and right histograms represent the integrated intensity on each axis that were used to fit the center of Europa by cross correlation (with a precision of 0.5 pixels).
parameters $A$, $B$, and $f(\alpha)$ for the moons of the giant planets over a wide range of solar phase angles. The equation can be further simplified by the normalization condition $B = (1 - A)$. The surface phase function can be computed by using equations derived in Buratti & Veverka (1983, 1984) based on integral solar phase curves, or it can be measured from an image or from a point on the surface. This function at $0^\circ$ can be derived by fitting a function to $f(\alpha)$ measured at larger solar phase angles, and it can also be used to derive the geometric albedo (Buratti et al. 2017).

4. Geologic Regions

To better understand the surface-scattering properties and the albedo differences between the terrain types, we determine the two photometric functions for the major geologic regions over varying observation geometry (Greeley et al. 2000). Buratti & Veverka (1983) determined the average normal reflectance for two main geological regions on Europa: plains and darker mottled terrain (Lucchitta et al. 1982). They used $3 \times 3$ pixel areas to analyze the photometric properties of the plains and mottled terrain. Here we used the recent, most updated, geologic map generated by Leonard et al. (2020). We superimposed the geologic map over the image data that includes $I/F$ values and geometric parameters (Figure 5). The advantage of utilizing the geologic map of Europa with the albedo information (as compared to previous analyses from Buratti & Veverka 1983) is to employ the albedo and geologic information from each pixel in the image data. We ensured that the phase angle did not change by more than a few degrees over an image. Thus, we better utilize the data and provide a thorough and complete analysis.

Previous geologic mapping of Europa established four primary global unit types: ridged plains, bands, chaos, and crater material (Lucchitta et al. 1982). In this analysis we broadly focus on these four units. However, we also add the various morphological types of chaos material (low-albedo chaos, high-albedo chaos, mottled chaos, knobby chaos), and impact crater units (continuous crater ejecta, discontinuous crater ejecta, and crater material; Figure 5).
Ridged plains (Figueredo & Greeley 2004; Shirley et al. 2010) are of a high albedo, compared to the surrounding terrain, and are smooth at a global resolution. They make up >50% of Europa’s surface area (Leonard et al. 2020). Band terrain (Head et al. 1999; Manga & Sinton 2004; Howell & Pappalardo 2018) is defined as linear to curvilinear belts that are greater than 15 km in width and can have a distinct, abrupt, relative brightness in contrast to the surrounding region. Chaos or disrupted terrain might have formed through melting of a floating ice shell from a subsurface ocean (Carr et al. 1998; Greeley et al. 2000), or by breakup from diapirs rising from the warm lower portion of the ice shell. Leonard et al. (2019) divides these terrains into four subunits. Impact crater units are also divided into crater material, continuous, and discontinuous crater ejecta units. Figure 6 shows the extent of five geographical units on the Voyager image C2060513. We separated the units for the image data in Table 1 and determined the fit photometric parameter value for each unit.

5. Results

The photometric models in this analysis can distinguish four photometric units: ridged plains, band terrain, high-albedo chaos, and crater material based on the varying fit photometric parameter values. The high-albedo chaos unit is brighter (higher $B_0$) than the mottled and low-albedo chaos and abuts the ridged plains and bands. We do not fit the knobly chaos or discontinuous crater ejecta units because the phase-angle range for these terrains was insufficient.

Figure 7 shows the four photometric function parameters $B_0$, $k$, $A$, and $f(\alpha)$ (panels (A)–(D)) for the two geographic units of ridged plains and bands. In any given image of Europa, it is possible to visually separate the bright ridged plains from the
darker band unit. However, we find that both regions have very similar fit photometric parameters. This result could be due to the narrow nature of bands: a trivial pointing error could result in sampling the data from neighboring regions. The photometric parameter values for the multiterrain types were fairly similar (see Table 2). A first-order polynomial line fit to the
distribution of the parameters at varying phase angles yields a nominal photometric function for the multiple terrain types as shown by the red line.

Similarly, Figure 8 shows the variation of the fit parameters $B_0$, $k$, $A$, and $f(\alpha)$ (panels (A)–(D)) for the chaos region. As expected, the high-albedo chaos region has a higher albedo than the low-albedo chaos in panel (A) (fit parameter $B_0$) in a majority of the data points. The best-fit lines do not always pass through the data points in a way that would minimize the residuals. This could be due to some points having significantly smaller error bars than others and being weighted more for the fit. Figure 9 shows the variation of the parameters for the crater material unit and crater ejecta (continuous and discontinuous). The span of data points over phase angles in these plots are caused by the scarcity of craters on Europa’s surface. At all phases angles, the crater ejecta exhibit the brightest albedo ($B_0$) and the chaos the lowest albedo values. The other regions vary between these two boundary cases.

The scatter of the data points seen in Figures 7–9 is mainly due to the grouping and mixing of terrains from different parts of Europa. Despite isolating the $I/F$ of one terrain type, the photometric function varies due to the albedo variation of neighboring terrains. Observing an isolated terrain with varying emission angles will accurately determine the photometric function and minimize this scatter, but this situation is not possible with the available spacecraft data. However, our study does take advantage of the largest range of solar phase angles over varied terrains afforded by multiple spacecraft missions.

We make use of a first-order polynomial to describe the variation of our model parameters $B_0$, $k$, $A$, and $f(\alpha)$ with respect to the phase angle for each geological unit. For all the geological units the model parameters can be fit by a line as shown in Figures 7–9. Table 2 shows the linear fit parameters for all the units as a function of phase angle (e.g., $B_0(\alpha) = a \cdot \alpha + b$).

The linear fit (red line in Figures 7–9) provides an analytical function that can be used for the photometric models derived in this manuscript. The photometric correction will then depend explicitly on the observation geometry (incidence, emission, and phase). This linear fit provides an initial photometric function for Eurpan terrains but the parameters may have to be tweaked for specific observation geometries and regions. Some terrains are better described than others by this fit. The knobby chaos and discontinuous crater ejecta (not shown here) had high errors due to the limited phase angle and spatial coverage by those geographic regions in any image. Similarly, the crater material unit (Figure 9) can be seen to have higher error bars due to the scarcity of craters on Europa. The $f(\alpha)$ plot in Figure 9(D) has larger error bars; however, the average data points are not too scattered. The dispersion in the $I/F$ is high, which we suspect is due to the smaller targets (crater and crater ejecta), which causes the surrounding areas with lower albedo to be included in the fits.

6. Discussion and Conclusion

In this study we explored the photometric properties of Europa’s various geological regions using all the available spacecraft data to maximize the observation geometry coverage. This work enables the expansion of scientific returns from initial Europa Clipper data, and assists in the planning of efficient scientific observing sequences. We extracted the scans of $I/F$ with associated incident, emission, and solar phase angles from Voyager, Galileo, and New Horizons images of Europa for the major types of terrain mapped in previous studies (ridged plains, bands, high-albedo chaos, and crater).
We show the global variations of $I/F$ within terrains with varying viewing geometries. The completeness of viewing geometry, coupled with the finer sampling afforded by data from multiple missions, enables us to derive simple photometric functions for each major terrain.

Buratti & Veverka (1983) derived the average normal reflectance for the plains in the Voyager clear filter to be 0.71, while the mottled terrain’s value ranges from 0.48 to 0.60 based on whether it is located in the leading or the trailing hemisphere. However, the parameter values from their study are for only two observations at phase angles of 2.5° and 3.8°. Our analysis using images from Voyager, Galileo, and New Horizons finds the reflectance values for ridged plains to be 0.70, which agrees with the previous values. When compared to the darker mottled terrain values from Buratti & Veverka (1983), band and low-albedo chaos units vary between 0.50 and 0.69 respectively (Table 2), which is higher than the previous result. We attribute this discrepancy to the larger sample of solar phase angles used in this work. Another reason for this dissimilarity could be the differing regions studied previously in contrast to this work.

Photometric models depend largely on the range of phase angles or observation geometry being fit. Changing the range of phase angles or observation geometry alters the photometric fit. For smaller phase angles the photometric models adequately predict the light-scattering properties of a surface. Ground-based observations also help in constraining the surface properties at smaller phase angles. Buratti et al. (2017) provide an explicit equation (see Equation (2)) for normal reflectance using the phase function $f(\mu)$ and $A$ that can be derived using the Lommel–Seeliger plus Lambert function. However, if higher phase angles are not available, measurements of cognate objects with similar albedo and composition need to be included in the data set to derive a photometric function at those higher solar phase angles.

Squyres & Veverka (1981) applied a combination Lommel–Seeliger plus Lambert function to the surface of Ganymede with a visual geometric albedo of 0.45 and concluded that Ganymede’s surface can be described adequately by a lunar-like scattering model corresponding to $A = 1$. Buratti & Veverka (1983) applied the combination model on Voyager images using colored filters and suggest that the “Lambert” component becomes significant once the satellite’s normal reflectance exceeds about 0.6. The photometric properties of Europa (reflectance 0.7) thus require a significant “Lambert” term ($A < 1$). The values for the parameter $A$ in this study vary between 0.8 and 0.6 with increasing phase angles for ridged plains and bands. The dearth of data points for the crater material add to the large error bars and large variation of the parameter $A$ (Figure 9(C)) for this terrain.

Both simple photometric models—Minnaert’s function and the combination Lommel–Seeliger plus Lambert function—describe the reflectance properties of Europa using a linear statistical fit (Table 2). The high uncertainty in the fit parameters at high phase angles could be due to surface shadowing induced by regional topography. The shadowed regions contribute no signal to the data being fit (except for multiply scattered photons that partly illuminate shadows), which is already comprised of very-low-albedo (noisy) data. Thus, the results derived at these large solar phase angles have higher error bars.

Photometric functions that describe reflectance as a function of viewing geometry and specific terrain (Figures 7–9) enable efficient signal to noise calculations to determine instrument integration times that in turn lead to optimizing data return for missions to Europa. Wasteful “bracketing” of integration times, particularly at large solar phase angles, can largely be avoided by predicting the surface reflectance based on the photometric functions derived in this study.

The simplicity of Minnaert and Lommel–Seeliger plus Lambert photometric functions will aid in efficiently generating data products by correcting for the effects of viewing geometry on the surface intensity for Europa Clipper data or future missions to Europa. We encourage the users of these photometric corrections to also refer to Figure 12 of Buratti & Veverka (1983), which plots the variation of photometric parameter $A$ as a function of the surface albedo parameter $B_0$. Using this approach can provide the first approximation for the parameter $A$ if the normal reflectance is known for a particular terrain and/or wavelength. Of course, detector response and spatial sensitivity variations are present in raw data and must be taken into consideration before the data can be utilized for scientific purposes. After accounting for the detector response, along with radiometric calibration which converts the data to $I/F$, our simple photometric corrections will correct for any variations in $I/F$ due exclusively to viewing geometry.

Europa’s young surface has been weathered by exogenic processes such as magnetospheric charged-particle bombardment, ultraviolet photolysis, impacts, and perhaps plume depositions (McEwen 1986; Dalton et al. 2013; Roth et al. 2014; Sparks et al. 2016). These exogenic processes alter the composition and albedo of the surface to obliterate some of the character of the underlying terrain, a process that results in a more similar photometric function among Europa’s terrains. Since we can use either of our simple photometric functions irrespective of the terrain, this will be useful for an image with numerous terrains.

The camera system on board Clipper, the Europa Imaging System (Turtle et al. 2016; Centurelli et al. 2018), combines the NAC and WAC and operates in the visible spectrum (0.39–0.7 μm). This spectral range overlaps the bandpasses of the clear filter images we use in our analysis. The Europa Lander (Pappalardo et al. 2013; Hand et al. 2021) is a proposed astrobiology mission concept to land on the surface of Europa to collect samples from about 10 cm beneath the surface. The terrain for landing must be one with low topography variability so as to minimize the hazards of landing. The results from this study, along with additional physical photometric modeling such as that done to derive the roughness of the surface (Buratti & Veverka 1985), could greatly inform the mission’s landing site selection during a reconnaissance period (Ivanov et al. 2011).

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