NEW INSIGHTS INTO SURFACE PROPERTIES OF GANYMEDE AND CALLISTO USING GROUND-BASED MEASUREMENTS FROM SINFONI/VLT.

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Context: Icy bodies hold a privileged place in the Solar System as they can help to better understand the emergence of life on Earth due to their respective subglacial oceans [**1**]. The three icy Galilean satellites, Europa, Ganymede and Callisto, are among the most exciting of them. Their diversity and their strong exobiological interest enticed NASA to conduct the ambitious Galileo mission in the late 90s. Significant science advances have been made thanks to this mission, but many question remain unanswered. Hence, ESA and NASA have decided that the Galilean moons, and especially the icy ones, will be visited once again during the next decade with two major dedicated space missions: JUICE (ESA) and Europa Clipper (NASA). In preparation of these missions, and more specifically of the infrared imaging spectrometer MAJIS of the JUICE mission [**2**], ground-based campaigns have been performed using SINFONI (SINgle Faint Object Near-infrared Investigation), one of the instrument mounted on the VLT. A first paper about Europa using SINFONI measurements has recently been published [**3**]. Here are presented new, unpublished, results concerning physical and chemical properties of the surface of the two outermost Galilean satellites: Ganymede and Callisto.

The dataset: The SINFONI instrument combines an adaptive optics module and an imaging spectrometer using four different filters (J, H, K and H+K) in the near-infrared. Observations were carried out in the H+K band and near opposition to optimize the angular resolution.

The spatial sampling of SINFONI (12.5 x 12.5 milliarcsec^2) allows to obtain a pixel corresponding approximately to an area of 40 x 40 km^2 (the effective spatial resolution is about 150 x 150 km^2) projected on the surface, hence easily resolving large-scale geomorphological units and some smaller ones like craters [**4**,**5**]. The spectral resolution of SINFONI in the H+K band reaches ~1500. This high spectral resolution is required to accurately locate eventual absorption features and so to trace back to chemical species engendering them.

To fully cover the moon's disk, each measurement is composed by a mosaic of 10 overlapping frames. Finally, in order to perform a global scale study similar to the one already published on Europa [**3**], Ganymede and Callisto were both observed at different dates; 5 and 4 observations have been acquired for Ganymede and Callisto (**Table 1**), respectively. In both cases, overlapping areas exist between observations to obtain information on the influence of back scattering on the reflectance level, but also to allow the normalization of their reflectance level in order to produce global maps.

GANYMEDE			
Acquisition date	*Distance to Earth*	*Strehl ratio*	*STP [1] lat./long.*
2012/10/30	4.221 A.U.	~ 14.7	3° N / 124° W
2012/11/23	4.077 A.U.	~ 37.3	3° N / 253° W
2015/02/17	4.358 A.U.	~ 22.0	0° N / 205° W
2015/03/06	4.471 A.U.	~ 23.5	0° N / 338° W
2015/03/08	4.484 A.U.	~ 21.4	0° N / 77° W

CALLISTO			
Acquisition date	*Distance to Earth*	*Strehl ratio*	*STP [1] lat./long.*
2015/01/23	4.366 A.U.	~ 18.8	0° N / 155° W
2015/02/16	4.370 A.U.	~ 27.1	0° N / 314° W
2015/03/08	4.493 A.U.	~ 26.1	0° N / 26° W
2016/03/19	4.441 A.U.	~ 28.8	-2° N / 208° W

Table 1. Main characteristics of each observation of Ganymede and Callisto. [1] STP: Sub-Terrestrial Point.

Data reduction: Following the H+K band acquisition, a series of processing steps need to be done to get a 3D-cube for each piece of a mosaic and then to reconstruct a single a 3D cube for each night of acquisition. This procedure is presented in [**3**]. Once 3D cubes are reconstructed, some geomorphological units such as craters and darker terrains are identifiable both on Ganymede and Callisto (**Figure 1a,b**), already suggesting important spectral variation and then chemical composition. The next step of the reduction consists in getting geometrically corrected reflectance spectra by performing photometric corrections. Unlike Europa's H+K data in [**3**], the Lambertian model is not relevant at all because it clearly overcorrects pixels having angle values ≥ 30° with the sub-solar point (**Figure 1c**). Hence, another photometric model has been implemented, namely the qualitative model of Oren-Nayar, generalizing the Lambert's law for rough surfaces by using the roughness as parameter [**6**]. Applying this model empirically yielded the best photometric correction (up to angle values ≈ 70°), insofar that few high inclination residuals are found while surface structure is recovered (**Figure 1d**).

Results & interpretations: The roughness parameters (θ) fitted in the Oren-Nayar qualitative model have the following values: from θ = 14° to θ = 21° for Ganymede and from θ = 16° to θ = 19° for Callisto (**Table 2**).

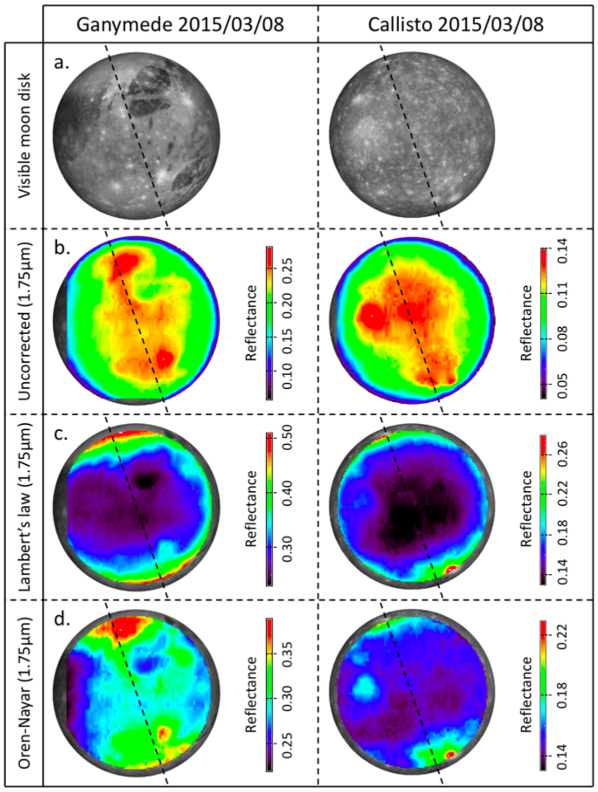

*Figure 1. One observation of Ganymede and Callisto (acquired the same night, the 8th March 2015) in the visible at the time of acquisition (**a**), uncorrected reflectance at 1.75 µm (**b**), and corrected reflectance using the Lambertian model (**c**) or the Oren-Nayar qualitative one (**d**). Dashed lines represent moons' rotational axis.*

FITTED ROUGHNESS PARAMETERS FOR GANYMEDE'S OBSERVATIONS				
2012/10/30	2012/11/23	2015/02/17	2015/03/06	2015/03/08
θ = 21°	θ = 16°	θ = 14°	θ = 15°	θ = 18°

FITTED ROUGHNESS PARAMETERS FOR CALLISTO'S OBSERVATIONS			
2015/01/23	2015/02/16	2015/03/08	2016/03/19
θ = 17°	θ = 19°	θ = 16°	θ = 18°

Table 2. Fitted roughness parameters of each observation of Ganymede and Callisto.

These values are quantitatively different than those obtained by a previous study using Hapke's photometric function to analyze ground-based measurements in the visible wavelength range [**7**]. However, the variation of the values according to the phase observed follows the same trend than in [**7**]: while the roughness seems to be more or less constant whatever Callisto's phases, Ganymede's phases exhibit non negligible variations where the highest values (2012/10/30 and 2015/03/08) are all located on the leading orbital hemisphere (0° – 180°W of longitude) and the lowest ones correspond to the trailing hemisphere (180° – 360°W longitude). However, these results have to be taken with caution as further analysis on the validity of the model on the whole wavelength range has to be done, and error bars determined.

At 1.75 µm, every Oren-Nayar corrected reflectance cubes of Ganymede and Callisto show common, well-known, units: polar caps. In terms of spectral characteristics, spectra in general exhibit absorption features at 1.50 µm, 1.57 µm, 1.65 µm and 2.02 µm (**Figure 2**); it corresponds to the H_2O-ice, and more particularly of its crystalline form because of the 1.65 µm absorption. An early analysis seems to show that, globally, the depth of this latter absorption is much more pronounced for Ganymede than Callisto, suggesting a higher abundance of crystalline ice for the former satellite. This result is opposed to the one of a previous study based on NIMS/Galileo data [**8**], but a thorough investigation will be performed to confirm this. Finally, the chemical distribution of both satellites seems to be first driven by an hemispherical dichotomy that could be due to the implantation of the Io's plasma torus. Nevertheless, spatial correlations with geomorphological units do exist (**Figure 1**), especially for Ganymede. Global mapping is required to go further in the analysis and spectral modeling using cryogenic end-members is envisioned before the meeting to better constrain the surface composition.

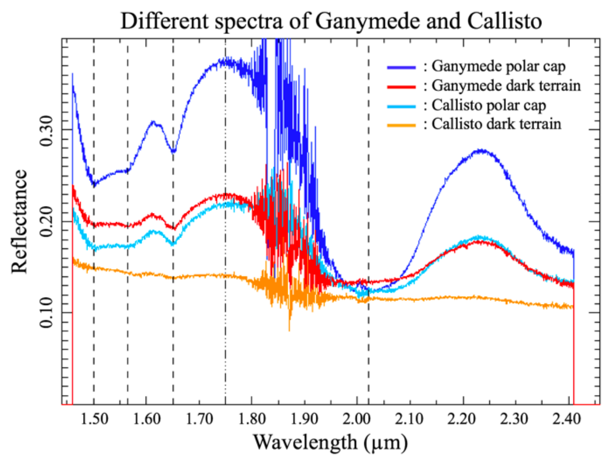

*Figure 2. Different spectra of Ganymede (dark blue and red) and Callisto (light blue and orange). The principal spectral features (highlighted with dashed lines) are all characteristics of H_2O-ice, probably mostly crystalline. The dashed dotted line corresponds to the wavelength (1.75 µm) used in **Figure 1**.*

References: [**1**] Sotin et al. (2004), Comptes Rendus Physique 5, 769. [**2**] Langevin et al. 2014, LPSC XLV, Abstract #2493. [**3**] Ligier et al. 2016, AJ, 151, 6. [**4**] Patterson et al. 2011, Icarus, 207, 845 – 867. [**5**] Schenk 1995, JGR, 100, 19023 – 19040. [**6**] Oren & Nayar 1994, SIGGRAPH 94, ACM Press, 239 – 246. [**7**] Domingue & Verbiscer 1997, Icarus, 128, 49 – 74. [**8**] Hansen & McCord 2004, JGR, 109, E01012.