

IN-SITU OBSERVATIONS IN THERMAL INFRARED ON (99942) APOPHIS. M. Hamm^{1,2}, M. Grott¹, J. Knollenberg¹, J. Biele³, T. Okada⁴, H. Senshu⁵, B. Gundlach⁶, M. Delbo⁷, A. Hagermann⁸ and H. Rauer^{1,2}, ¹(maximilian.hamm@dlr.de)German Aerospace Center (DLR), Institute of Planetary Research, Berlin, Germany, ²Freie Universität Berlin, Berlin, Germany, ³German Aerospace Center (DLR), MUSC, Cologne, Germany, ⁴Institute of Space and Aeronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan, ⁵Planetary Exploration Research Center, Chiba Institute of Technology, Narashino, Japan, ⁶Institut für Planetologie, University of Münster, Münster, Germany, ⁷Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France, ⁸Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Kiruna, Sweden

Introduction: Matter constantly emits electromagnetic radiation depending on its temperature according to Planck's Law. The maximum of this radiation lies for most planetary surfaces in the inner solar system within the mid-infrared region of the electromagnetic spectrum (5-25 μ m), also called thermal infrared. Observations in thermal infrared thus provide measurement of surface temperatures and the thermophysical properties of the planetary surfaces.

The thermal infrared spectrum also contains information about mineralogy. In particular, the Christiansen Feature is located around 9-10 μ m and indicative of different types of silicate [1]. The spectrum is sensitive to the presence of dust particles if their size comes close to the scale of the wavelength. Spectral features change in size and position and new features appear [2]. Furthermore, the surface roughness influences the observable infrared flux, depending on illumination and observation angles [3].

In-situ, i.e. on-surface, measurements of thermal properties were carried out on small bodies by radiometers MUPUS (comet 67P) [4] and MARA (162173 Ryugu) [5]. Soon miniRAD will perform on Phobos [6]. The radiometer MARA was a payload on MASCOT which landed on the surface of C-type asteroid (162173) Ryugu as part of the JAXA sample return mission Hayabusa2 [7,8]. MARA observed a single boulder on Ryugu through 2 broadband filters and 4 narrow band filters from 5 -15 μ m for a full diurnal cycle revealing its thermophysical properties [9]. The in-situ observations of MARA were complementary to the Thermal InfraRed imager (TIR) [10] on the Hayabusa2 spacecraft and offered a unique opportunity of multi-scale science.

Here we highlight the relevance of in-situ thermal infrared observations for a potential mission to asteroid (99942) Apophis, e.g., RAMSES.

Deriving Thermal Properties: The thermophysical properties, most significant the thermal conductivity, determines the amplitude of the diurnal temperature variation as well as its phase lag with respect to maximum insolation. A common approach is to combine thermal conductivity, specific heat capacity, and density into a single parameter, the thermal inertia.

MARA observed the diurnal temperature variation and thermophysical properties of the surface material could be estimated by fitting a thermal model to the data [11, 12] (Figure 1 top). The thermal conductivity further depends on mechanical properties such as porosity which could be derived using empirical models[9]. Depending on the applied model, the thermal inertia of the boulder observed by MARA was found to be between $256^{+4}_{-3} \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ (tiu) and 298 ± 4 tiu. Corresponding to a porosity of 47 - 42% [13,14,15].

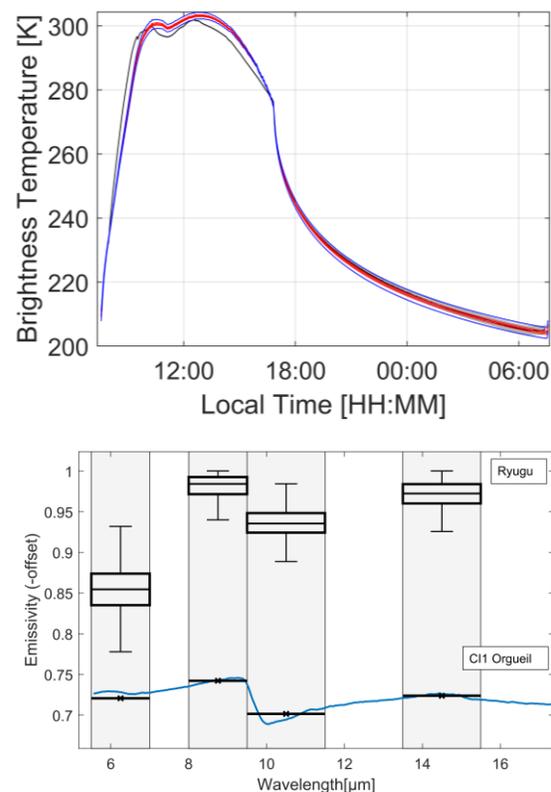


Figure 1: Top: MARA Observations (black) with uncertainty (grey) and best fitting model range (red and blue). Bottom: Emissivity estimated from narrowband filters compared to spectrum of CII Orgueil, offset for clarity.

The infrared emission of a rough surface differs from that of an ideal, Lambertian Emitter. For Ryugu, an adequate roughness model could attribute to that effect and by fitting daytime observations the degree of

roughness was quantified [15, 16]. By comparing the relative flux through the four narrow-band filters to each other, a rough emissivity spectrum around the Christiansen Feature was estimated, showing the similarity of Ryugu's boulders to hydrated carbonaceous chondrites [15] (Figure 1 bottom). The thermal signature is highly sensitive to the presence of dust deposits [17] and further analysis of MARA data in comparison to spectra of Ryugu sample C0137 showed that only very thin, discontinuous layers of dust can be consistent with MARA observations [18].

Multi-Scale Opportunities: The Hayabusa2 TIR instrument observed the dayside surface temperatures of Ryugu [19], deriving the thermophysical properties of Ryugu's boulders on a global scale [20]. TIR filters are identical to one of the MARA broadband filters (8-12 μm). This presented a unique setting for multiscale science. The low thermal inertia estimated with MARA was found to be most common on Ryugu [21]. TIR measurements alone could not exclude the presence of finer particle deposits that would average out with a hypothetical higher thermal inertia of boulders. Only the analysis of the full diurnal temperature curve with MARA showed that the low thermal inertia is indeed an intrinsic property of the boulders. Similarly, without the results from TIR it would be unclear if the boulder observed by MARA was an exception or not. It was the complementary measurements that substantiated each other significantly.

Current and Future Designs: Based on MARA two new instruments were developed: miniRAD for the JAXA MMX mission [6] (Figure 2) and LRAD for the Intuitive Machine mission IM-2 (NASA CLPS PRIME-1) [22]. Both instruments use six thermopile sensors, which can be equipped with individual IR-filters to fulfill specific scientific measurement goals. The sensor head weighs approximately 90 g, while the avionics including the enclosure will add approximately 400 g to the mass. The thermopile sensors consist of 72 Bismuth-Antimony ($\text{Bi}_{0.87}\text{Sb}_{0.13}/\text{Sb}$) thermocouple junctions. At the hot junction interference absorbers are used. The power consumption during science operation lies typically around 1.5 W and peak consumption of up to 3 W depending on the constraints and design of the mission. At DLR we are currently developing electrically tunable Fabry-Perot filters that could be integrated into the radiometer sensor head to measure spectra from 5-11 μm with a spectral resolution of about 50-80. That approach offers a big improvement in constraining surface mineralogy compared to current narrow-band filters, while keeping the small form factor and low engineering budgets of the current radiometer designs.

RAMSES Lander Radiometer: We propose the addition of a radiometer for a lander as part of the proposed RAMSES mission by ESA that could study Apophis during its close encounter with Earth 2029. Thermal infrared measurements taken in-situ on the surface of Apophis can constrain thermophysical properties and mineralogy of Apophis surface materials. Together with a potential TIR-like camera on the RAMSES orbiter we could benefit from a similar multi-scale opportunity as TIR and MARA at Ryugu. It will be an extraordinary opportunity to compare the results from C-type asteroids Ryugu and Bennu to those of S-type Apophis, particularly relevant for understanding regolith formation and processes [23,24]. Besides their high scientific relevance of understanding composition and structure of the asteroid materials, the mechanical properties derived from thermal infrared observation are also highly relevant for designing spacecraft interaction and planetary defense.

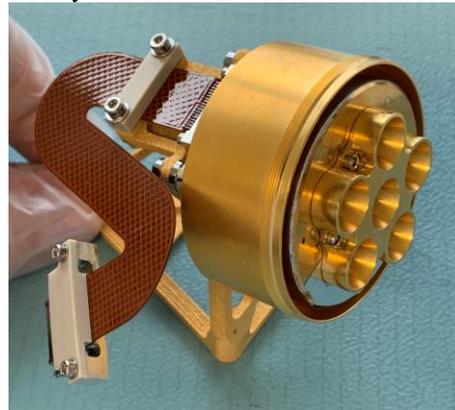


Figure 2: Flight model of the miniRAD radiometer.

References: [1] Salisbury, J. et al. *Infrared (2.1-25 μm) spectra of minerals*. (1991). [2] Aronson, J. R. & Emslie, A. G. *Appl. Opt.*, **AO 12**, 2573–2584 (1973) [4] Spohn, T. et al. *Science* **349**, aab0464 (2015). [5] Grott, M. et al. *Space Sci Rev* **208**, 413–431 (2017). [6] Grott, M. et al., LPSC53, #1199, 2022 [7] Ho, T.-M. et al. *Planetary and Space Science* **200**, 105200 (2021) [8] Watanabe, S. et al. *Science* eaav8032 (2019) [9] Grott, M. et al. *Nat Astron* **3**, 971–976 (2019). [10] Okada, T. et al., *Space Sci. Rev.* **208**, 255–286 (2017) [11] Hamm, M., et al., *Planet. Space Sci.* **159**, 1–10 (2018). [12] Hamm, M., et al. *Monthly Notices of the Royal Astronomical Society* **496**, 2776–2785 (2020). [13] Grott, M. et al. *Nat Astron* **3**, 971–976 (2019). [14] Grott, M. et al. *J Geophys Res: Planets* **125**:6519 (2020) [15] Hamm, M., et al. *Nat. Comm.*, **13**, 364, (2022), [16] Senshu, H., et al., *Int. J. Thermophys.* **43**:102 (2022) [17] Biele, J. et al. *Prog Earth Planet Sci* **6**, 48 (2019). [18] Hamm, M., et al., *GRL*, **50**, e2023GL104795. (2023) [19] Okada, T. et al. *Nature* **579**, 518–522 (2020). [20] Shimaki, Y. et al. *Icarus* **348**, 113835 (2020). [21] Sakatani, N. et al. *Nat Astron*, **5**, 766-774 (2021). [22] Hamm, M., et al., THERMOPS IV (2023) [23] Cambioni, S., et al., *Nature* **598**, 49–52 (2021) [24] Walsh, K. et al., *Sci. Adv.* **8**, eabm6229(2022)