EU-ESA WORKSHOP

Size Determination of Potentially Hazardous Near-Earth Objects

November, 2024

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ESOC, Darmstadt, Germany

The EU-ESA Workshop on Size Determination of Potentially Hazardous Near-Earth Objects was organized as part of a task entrusted by the EU to ESA under the Space Programme (2021), aiming to promote networking of Member State facilities and research centres involved in NEO-related activities.

Within this task a mechanism will be developed for promoting networking activities among MS facilities and research centres in the field of NEO-related activities. This task can be realized at varying budget levels. The main mechanism is the organization of a yearly conference on NEOs. One conference per year will be organized until Q4/2027.

This specific workshop brought together experts in asteroid observations, planetary defence, and space instrumentation to assess current techniques for size estimation, identify key uncertainties, and establish pathways to improve the physical characterization of potentially hazardous NEOs.

All information about the workshop, including the list of participants, the presentations provided, and the recordings, is available on the official website: https://indico.esa.int/event/530/

This report is solely endorsed by its authors. While its content draws on presentations and conversations held during the EU-ESA Workshop, the analyses and recommendations offered here reflect the authors' own interpretation of those exchanges. They should not be understood as expressing the official views or consensus of all workshop participants.

The workshop was co-organized by the European Space Agency (ESA) and the European Commission, with participation from academic institutions, observatories, and planetary defence stakeholders.

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1 Executive summary

Planetary defence is critical for safeguarding Earth from potential impacts by near-Earth objects (NEOs). It is an interdisciplinary endeavour devoted to protect Earth from the threat of asteroid impacts. Its activities extend beyond astronomical observation and analysis as it also embraces international coordination, mitigation planning, and disaster-management policies (Rathnasree & Barucci, 2020, National Science & Technology Council, 2018).

From the observational perspective, its core tasks are the discovery of near-Earth objects (Gregori et al., 2023, Tonry et al., 2018), systematic follow-up to refine their orbits (Vaduvescu et al., 2017), rigorous orbital computations (Fenucci et al., 2024), and, whenever an object shows a non-zero chance of collision, a decisive emphasis on accurately determining its physical size, the parameter that ultimately drives risk assessment and response strategies.

Size determination is of primary importance as it guides the actions required when an asteroid is found to have a potential impact trajectory with Earth. For instance, the Space Mission Planning Advisory Group (SMPAG) sets its activation threshold at objects larger than 50 m in diameter while the International Asteroid Warning Network (IAWN) has set its threshold to 10 m to send a warning notification (Space Mission Planning Advisory Group, 2017).

Accurate size determination is therefore essential not only for assessing the level of impact threat an asteroid poses, but also for selecting the most appropriate mitigation response. Reliable sizes are estimated from various observational and analytical techniques. Each of which is coming with its own strengths and limitations that are considered and examined in detail in this report.

This document provides a comprehensive review and synthesis of the key results and discussions from the EU-ESA Workshop on Size Determination of Near-Earth Asteroids (NEAs) held at ESA ESOC in Darmstadt (Germany) between 11-13 November 2024. The primary objective of this workshop was to bring together experts from the planetary science and planetary defence communities to explore how the size determination of potentially hazardous Near-Earth Objects can be obtained and how the estimation obtained using these method can be improved.

We present an overview of the main techniques currently employed for size determination. We discuss how they are applied and when they are the most effective. Furthermore, we discuss and outline the current limitation and challenges. Finally, we highlight key recommendations and potential collaborative actions that have been identified by the workshop participants and should reflect the view and opinion of the scientific community.

However, the views and recommendations provided in this report are solely endorsed by its authors. While its content draws on presentations and conversations held during the EU-ESA Workshop, the analyses and recommendations offered here reflect the authors' own interpretation of those exchanges. They should not be understood as expressing the official views or consensus of all workshop participants.

2 Introduction

The EU-ESA Workshop on Size Determination of Near-Earth Asteroids was held between 11 and 13 of November 2024 at the European Space Agency's ESOC site in Darmstadt, Germany. Readers can find more information on the workshop website https://indico.esa.int/event/530/ where all the presentations and recordings are available.

The workshop was divided into four main sessions.

- Photometric observations
- Thermal infrared observations
- Polarimetric observations
- Miscellaneous and other observations techniques

The first session focused on photometric observations. It opened with and introduction to the scattering properties of asteroids for both photometric and polarimetric observations (Muinonen et al., 2022). Various models used to fit asteroid phase curves were reviewed (Bowell et al., 1989, Muinonen et al., 2009, 2010, Penttilä et al., 2016), followed by a discussion on how photometric data acquired in different filters can be transformed into a common system, typically the V band. A new de-biasing scheme was also presented (Hoffmann et al., 2025). Recent developments in phase curve modelling, particularly those incorporating shape information, have demonstrated improvements in determining the H magnitude (Carry et al., 2024). In a lot of cases, not including shape or aspect information leads to a fail of the fit as the model cannot reproduce the observed photometric variations. Recent works have shown that phase curve can directly inform on both the asteroid taxonomic class and its size. In particular, a strong correlation has been established between the photometric slope parameters G (expressed as G_1G_2 or its single-parameter variant G^*_{12}) and the geometric albedo. Combining this albedo estimate with the absolute magnitude H provides a diameter determination (Penttilä et al., 2016, Mahlke et al., 2021). The session concluded with updates from the principal orbit determination centres—MPC, NEOCC and CNEOS—each of which outlined its current strategy for phase curve modelling.

The second session was dedicated to thermophysical observations. It featured two review talks on thermal infrared observations. These included discussions of widely used models such as the NEATM (Harris, 1998), which enables derivation of size and temperature while more advanced thermophysical models (TPMs) (Delbo et al., 2015) provide more information on the asteroid thermal properties (Müller, 2002) such as the thermal inertia (e.g. MacLennan & Emery, 2021, Alí-Lagoa et al., 2014, Delbo' & Tanga, 2009), surface roughness, regolith grain size (e.g. Gundlach & Blum, 2013, MacLennan & Emery, 2022), and surface temperature distributions (Spencer, 1990). Subsequently, the upcoming space missions NEO Surveyor (Mainzer et al., 2023) and NEOMIR (Conversi et al., 2024) were presented. Examples of ground-based observations of NEOs were reviewed, with emphasis on the cases of Icarus (MacLennan et al., 2022) and Ivar (Selmi et al., 2025). The use of current ground-based telescopes and instruments like IRTF SpeX (Rayner et al., 1998) and MIRSI (Hora et al., 2024) were shown. Finally the session concluded with a discussion on the prospects for future ground-based thermal infrared facilities, notably the 6.5 m TAO telescope (Miyata et al., 2010).

The third session addressed polarimetric observations. It started with a review representing the basic capabilities of polarimetric observations of NEOs (Belskaya et al.,

2015). It was followed by the presentation of polarimetric instrumentations and major surveys such as the current Calern Asteroid Polarimetric Survey (CAPS) (Devogèle et al., 2017, Bendjoya et al., 2022) and the upcoming Rapid-Defender instrument (Fernandez-Valenzuela et al., 2024). Results demonstrating how single polarimetric measurements can constrain an object's albedo were highlighted (Devogele et al., 2022). The session concluded by the presentation of the specific case of NEO (1627) Ivar for which an albedo and size have been determined by combining photometric, thermal, and polarimetric measurements (Selmi et al., 2025).

Finally, the last session introduced NEOs physical characterization surveys such as the one conducted with the TRAPPIST telescopes (Jehin et al., 2011, Miftah et al., 2023) or at the Instituto Astrofísico de Canarias (IAC) (de León et al., 2010, Vaduvescu et al., 2017). It also showcased other observational techniques that enable reliable size determination, such as stellar occultation (Tanga & Delbo, 2007, Souami et al., 2025).

During each session a large amount of time was devoted to discussion among participants to explore the various topics and issues addressed in the workshop. The event concluded with a plenary group discussion, during which the outcomes from the session-level discussions were summarized, and potential recommendations or actions for the communities were considered.

3 Photometric session

The main method to estimate the size of an asteroid is the relation between the absolute magnitude H, geometric albedo p_{V} and size of an object. This relation has been known and used for many years and can be formulated as follow (Bowell et al., 1989, Harris, 1997):

$$D = \frac{1329 \times 10^{-0.2 H_{\mathrm{V}}}}{\sqrt{p_{\mathrm{V}}}} \tag{1}$$

where D is the equivalent diameter of the object in kilometre, H_{V} is the absolute magnitude and p_{V} the geometric albedo of the object in the V band. The absolute magnitude H_{V} corresponds to the magnitude that an object would display if observed at a distance of one astronomical unit (au) from both the Sun and the observer and at a phase angle of 0° (see Fig. 1 for a sketch of the geometric definition of the phase angle). The subscript corresponds to the band (here V) in which that absolute magnitude was calibrated to. Usually references to H without subscript means that it is calibrated in the V band. The geometric albedo is the fraction of light that is reflected by the surface of the object at a specific wavelength (i.e. here at 0.55 μm). A geometric albedo of 1 would correspond to a fully reflective surface while a value of 0 would correspond to a surface completely dark and absorbing all the incoming light (at that specific wavelength).

The determination of the H magnitude is not an easy task. To obtain it directly from observations, one would have to observe the object at exactly opposition (*i.e.* at a phase angle of 0°) and when the object is located at 1 au from the Sun and the observer. Such observation geometry is impossible as it would require the observer to be located on the Sun. However, correcting for the distances from the Sun and the observer to the asteroid is trivial and can be performed using the following relation:

$$M = m - 5 \log (r \Delta) \tag{2}$$

where M is the magnitude corrected for distance, m is the observed magnitude, Δ is the

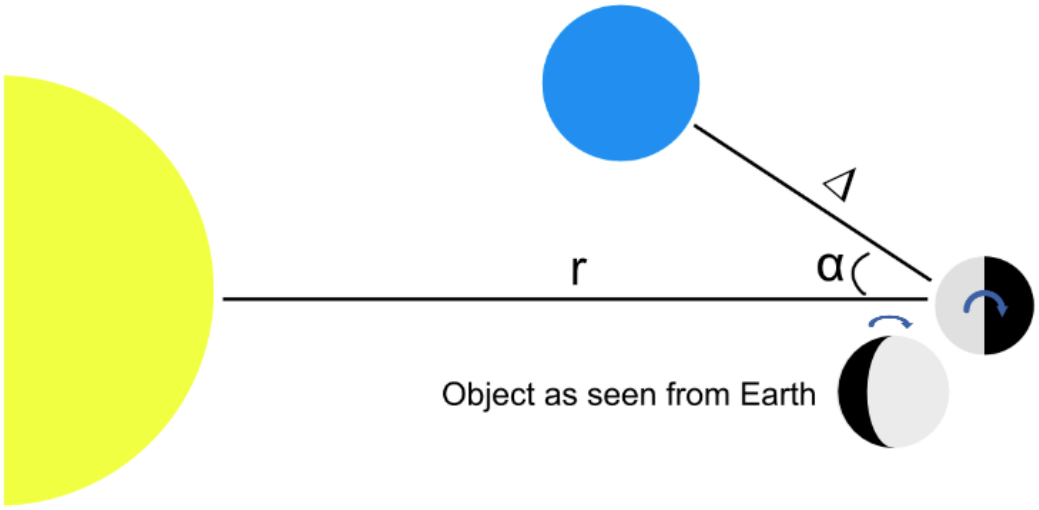

Figure 1: The phase angle corresponds to the angle between the illuminating body (the Sun), the target (the asteroid) and the observer. As seen from the observer, the target will not be fully illuminated, but the illumination will be inversely proportional to the phase angle. At 0° of phase angle the target is fully illuminated while at 180° only the unilluminated part will be seen.

distance (in astronomical unit) of the object from the observer and r the distance (in astronomical unit) of the object from the Sun (see Fig.1).

However, one would still need to observe the object at perfect opposition. Such observations are possible, but are not easily reachable for most asteroids. Indeed, the range of phase angles observable for an asteroid depends on the configuration of the orbit of the Earth (*i.e.* the observer) and the orbit of the object. This results in that most asteroid observations are performed at a non-zero phase angle. To determine the H magnitude through observations obtained at a non-zero phase angle, one has to model the brightness variation of that object as a function of the phase angle (phase curve). This allows to extrapolate observations obtained at non-zero phase angle to opposition and obtain the absolute magnitude H.

The main used approach to model the brightness variation of an asteroid as a function of phase angle is the HG model. This model was adopted by the International Astronomical Union (IAU) in 1985 (Marsden, 1985) and is discussed in detail in (Bowell et al., 1989). This model is using only two parameters, the absolute H magnitude that allows to shift up and down the phase curve in magnitude and the G parameter that will define the shape of the curve as a function of the phase angle. The G parameter is basically a weighting factor between two functions describing the slope of the phase function going from around 0 for a steep phase curve (low albedo) to 1 for a shallow phase curve (high albedo). Although $G < 0$ and $G > 1$ are not mathematically impossible, they are often assumed to be non-physical and the range of G values is usually (but not always) restricted to values between 0 and 1.

This phase function is still used today even if a new, more sophisticated, phase function has been now recognized as the standard by the IAU in 2012. This usage is driven by its simplistic two uncorrelated parameters form. Effectively, all the main centres performing orbit computations and H magnitude determination are assuming $G = 0.15$ as default to fit the photometric observations even if newer single parameter phase function models

have been developed.

As the number of asteroid photometric observations increased, a new model to fit the phase curve was introduced by (Muinonen et al., 2010) and adopted by the IAU as the standard for phase function modelling in 2012. This model adds an extra parameter and is called the HG_1G_2 model. The addition of the extra G parameter (*i.e.* a parameter controlling the shape of the phase curve), allows to better represent the opposition effect and the slope of the phase curve. On the other hand, for most asteroids, for which we cannot constrain the G parameters (*i.e.* for which we do not have enough observations covering a wide range of phase angles and especially observations at low phase angles), we now have to fix two parameters. Moreover, leaving these parameters to vary freely when not having enough data to have a constraint on them can lead to worse estimation of the H magnitude. One should thus carefully choose what model to use and most specifically how to use these models.

To alleviate the need to constrain two parameters instead of one, other models (based on the HG_1G_2) have also been introduced. The HG_{12} was introduced at the same time as the HG_1G_2 by (Muinonen et al., 2010). The HG_{12} results from the fact that the two parameters G_1 and G_2 are strongly correlated and at first order we can estimate G_1 based on the value of G_2 or vice-versa. This choice simplifies the fit and improves the reliability of the phase curve modelling, preventing combinations of G_1 and G_2 that are mathematically admissible yet physically meaningless—pathological solutions that usually appear when the data are too sparse or contaminated by shape- or aspect-dependent variability, leaving insufficient information to disentangle the separate contributions of the two parameters.

Later, (Penttilä et al., 2016) noticed that not only the G_1 and G_2 parameters are correlated, but they also correlate with the albedo of the analysed object. Using new available data, they improved on the HG_{12} model and introduced the HG^*_{12} model and proposed relationships between G_1 and G_2 and albedo.

Yet, despite the greater flexibility of the HG_1G_2 formulation, a substantial fraction of phase curves extracted from large sky-survey datasets still cannot be fitted reliably, often returning non-physical estimates of G_1 and G_2. This is due to the well known fact that the absolute magnitude of an asteroid is actually not a constant. Indeed, the H magnitude is proportional to the projected area of the asteroid on the plane of the sky. However, this area varies as the asteroid rotates, but also as the aspect (*i.e.*, orientation of the spin axis with respect to the observer) varies. This results in the asteroid, observed at different moments in time, displaying different H magnitudes. As the H magnitude varies over time, this can lead to failure in the fitting of the phase curve and thus the determination of the H, and G parameters. To fix this issue, a new model, sHG_1G_2, has been introduced by (Carry et al., 2024). This model includes three new parameters that help model the variation of the H magnitude over time. First, it is assumed that the object is an ellipsoid with its axis $a = b > c$ instead of a sphere as in the previous model. This means that the object projected area does not change with rotation, but changes as a function of its aspect angle. To take into account this aspect angle, the model also contains the spin axis orientation of the asteroid as two parameters (i.e. its ecliptic longitude α, and latitude β). These three new parameters are fully shape and rotation related and uncorrelated with the previous H, and G parameters. They can either be fitted directly using the phase curve information over a long period of time or be determined independently. (Carry et al., 2024) showed that this new model allows to improve the determination of the H parameter and allows to satisfactory fit more phase curves at the expense of adding three new parameters. The next step would be to assume an ellipsoid with $a > b > c$ and take

into account the rotation period (P) as a new parameter in the model.

3.1 What model should we use?

Even if newer and better models exist, the community is still using the HG model with a fixed $G = 0.15$ as a default value. It has however been discussed during the workshop that using such model produces biases in the H magnitude toward overly bright object (*i.e.* under-estimation of H and thus implying too large objects). This is due to the fact that the HG model tends to overestimate the opposition effect. Using the new HG_1G_2 model would have the potential to fix that issue, but we now have to fit the values of G_1 and G_2.

It has also been shown that the HG model is incompatible with the HG_{12} and HG^*_{12} systems. While the G_{12} and G^*_{12} are correlated with albedo and the object's taxonomy, the G is not. By varying G, G_{12}, and G^*_{12}, we observe that the slope of the phase curve at a phase angle of 20° exhibits directions of variation that are approximately orthogonal between the HG and HG_1G_2 systems—and consequently also between HG and the G_{12} and G^*_{12} models. Since the latest models have been calibrated with much more extensive data than the HG model, we can conclude that the HG model fails to correctly represent the phase function of asteroids and produces an overly too strong opposition effect.

3.2 Photometric band

When photometric observations of an asteroid are obtained, they need to be calibrated in a photometric system. Asteroids are not grey and their brightness varies as a function of the wavelength used to observe them. Moreover, all asteroids have different spectra meaning that their colours differ. This means that the H magnitude should be defined in a specific photometric band and it will be slightly different from band to band. Currently the default photometric band is the V band. The V band stands for "visible" band and corresponds to the range of wavelengths were the Sun is the brightest.

The use of the V band has a great advantage as it corresponds to the peak brightness of the Sun and facilitates thermophysical modelling. However, in the recent years most of the photometric observations have been obtained using the R band or the Sloan r band or derivatives. This means that to model the phase curve in the V band and determine the H_V absolute magnitude, one needs to apply a correction. This correction is a priori unknown as all asteroids will display different V-R or V-r colours. However, a default value corresponding to the average colour of the whole population of asteroid can be applied to correct to the V band, but this results in an unknown systematic error in the H_V magnitude determination.

This problem is not valid only for the R or r band, but for any other band in which asteroids are observed in and are subsequently corrected to the V band for phase curve fitting.

The H_V magnitude determined by the main centres (MPC, NEOCC, and CNEOS) are using conversion tables to go from a specific band on which an asteroid has been observed to the V band. However, these conversion tables could be affected by biases and could bias the H_V computation depending on the distribution of observations in the different bands. To alleviate these issues, (Hoffmann et al., 2025) recently completed a detailed analysis of the biases that can affect the band corrections and published a set of new conversion between the different bands to minimize such biases.

We also observe that the photometric phase curve is colour dependent. This means that if we model the phase curve of an asteroid in a different photometric band, we will not only obtain a different H magnitude, but the value of the G parameters will be different. This is due to the fact that the spectrum of an asteroid will not be identical at all phase angles and that bluing or reddening of spectra are observed when the phase angle is varying. Thus, using the single fit while applying a simple colour correction identical at all phase angles might result in a failed fit.

Recommendation: To minimize the uncertainties and biases related to band correction, we encourage observers to obtain observations in the V band. If observations are obtained in another band, it is recommended to use the new (Hoffmann et al., 2025) photometric correction.

However, if possible, it is recommended *not* to combine measurements taken in different photometric bands, as the asteroid phase function is wavelength–dependent: phase curves recorded in different filters can have systematically different slopes, and merging them will introduce a band–dependent bias into the fit.

When fitting a phase curve obtained in a band other than V, please report the H magnitude in that same band with a subscript indicating the filter used (*e.g.* H_{R}).

3.3 Definition of the H magnitude

Currently the H magnitude is defined as the magnitude that would be displayed by an object if observed at a phase angle of 0° and at a distance of 1 au from both the observer and the Sun. However, this definition is incomplete. If an object were to be observed in such condition its magnitude will vary as the object rotates. This definition also does not take into account the fact that the H magnitude of an object can vary from opposition to opposition due the variation of aspect angle.

As we are compiling more and more data, the limitation of such definition is starting to be apparent. It is thus needed to agree on a more precise definition.

Recommendation: Let's use the definition of the H magnitude proposed by (Carry et al., 2024). In this definition, the H magnitude is the magnitude that would be displayed by an asteroid if observed at 0° and at a distance of 1 au from both the observer and the Sun and observed at an aspect angle of 90° (i.e. equator on).

3.4 Need for observations at low phase angles

To constrain the H magnitude, observations at low phase angles are critical. The design of many surveys (ground and space based) do not observe at opposition or perform few observations at opposition. It would be highly valuable if the surveys could specifically target the opposition location on the sky around local midnight. This would allow to observe asteroid when being at, or close to, opposition and thus constrain their H magnitude.

Recommendation: Surveys should consider performing dedicated observations at or around opposition to observe asteroids close to 0° of phase angle.

3.5 How to submit and make use of photometric observations?

Thousands of astrometric observations are submitted daily to the Minor Planet Center. The rules for submitting these observations and for them to be accepted and used in orbit computations are strict. These submissions are often accompanied by an assessment of the brightness of the measured object. However, the rules on how to report and on the quality of the photometric measurements are not the same as for the astrometric measurements. The MPC treats the photometric determination as a by-product of the astrometric measurements and not as essential information requiring careful attention and review. This treatment of the photometric observation is legitimate from the MPC standpoint, as their mandate is to determine the orbit of observed objects and provide an estimation of the brightness of the object in their ephemerides computation.

However, this is not sufficient for the precise computation of the H magnitude. Moreover, the number of observations and their cadences are different depending on whether one wants to determine a rotation period or a phase curve.

Recommendation: There is a need for a photometric database mirroring what the Minor Planet Center is performing for astrometric observations in the case of photometric observations. A standard should be defined on how to submit photometric observations and the parameters to be reported (e.g. better definition of the filter that was used for the observation and the band used for calibration). That Centre responsible for collecting the observations and maintaining the database should then provide a precise computation of the H magnitude in the different bands in which the observations were submitted.
Action: A proposal was submitted to the IAU to set up a Working Group to explore the needs for an IAU-approved global archive for small body photometric data to complement the astrometric archive kept at the MPC. The proposal was approved by Division F and will report their findings before the next IAU General Assembly.

3.6 How to perform photometric observations?

As already stated in the previous section, most of the photometric measurements come as a by-product of astrometric measurements. As a consequence, most of these measurements come from low SNR observations and are often stacked. The stars or the object could be trailed. In case of heavily trailed stars, it is extremely complicated to obtain a reliable photometric calibration of the field, hence the photometry measurement of the target will be heavily biased. In case of a trailed target, extreme care should be taken to get a reliable measurement of the absolute flux of the target, as its flux will be diluted over many more pixels than those of the stars. Moreover, most of the observers are also using stacks of images to increase the SNR of the object, as it is often not seen in individual images. Performing photometric measurements on stacked images requires extreme care to properly photometrically calibrate the stacked images.

Many astrometric observers are reporting calibrated fluxes and magnitudes using commercial software like Astrometrica and Tycho Tracker. These software packages have not been properly vetted for photometric measurements and are often reporting low-accuracy photometric measurements without a proper estimation of the uncertainties associated with them.

Recommendation: A proper standard defining the different photometric measurements should be established. Proper flags should be associated with each type of photometric measurements (*i.e.* stars trailed, target trailed, stacked, circular stars and target). Standard techniques on how to deal with each type of measurements should be established and proper estimation of the uncertainties associated with each measurement should be provided.
Recommendation: A comparison study on the performances of commercial software like Astrometric or Tycho Tracker should be conducted.

4 Thermal infrared of NEOs

Thermal infrared observations of NEOs are crucial for size determination. Observing in thermal IR has a lot of advantages compared to observations in the reflective parts of the spectrum. First, most of the Solar radiation received by a NEOs is re-emitted in the infra-red (Müller et al., 2025). Second, the risk of source confusion (at least when observed from space) is about two orders of magnitude smaller in the thermal infrared. Third, the observed lightcurve, especially for NEOs that are often observed at high phase angles, is less irregular in the thermal infrared. Indeed, in the reflected part, the lightcurve is produced by the fraction of illuminated area. At high phase angle, this fraction can vary quite erratically and strong shadowing can produce highly irregular lightcurves that are difficult to interpret. This effect is strongly reduced in the thermal infrared, as the lightcurve is dominated by the cross-section of the object on sky and not only by the illuminated fraction. Fourth, for small and fast rotating NEOs, the temperature distribution can approach an isothermal structure where the temperature varies across the latitudes (the poles being colder than the equator) but is almost isothermal in longitude (e.g. the Fast Rotating Model introduced by Lebofsky et al., 1978), meaning that the object will be much brighter and more easily detectable in the thermal infrared compared to visible light.

Using reflective light, we can obtain the absolute H magnitude. However, without any information on the albedo, the range of possible sizes can vary by a factor of 4 to 5. Once you obtain thermal emission, you can constrain the size much better as it is almost independent on the albedo of the object. If you can obtain both the H magnitude and the thermal emission, you can constrain both the size and the albedo of the object.

The current challenges for small NEOs are their highly different properties compared to larger objects. Small object can rotate much faster, have monolithic structure, more exotic shape, or even lack regolith compared to larger object. Hence, they need different modelling that leads to larger uncertainties on the resulting size determination. Another difficulty is that these objects are often observed at much higher phase angles than main-belt objects.

As for the phase curve modelling, there exist many different models to analyse the thermal infrared observations of NEOs. The main one is called the NEATM model (Harris, 1998). This model assumes a spherical object shape and only considers thermal emission from the dayside.

The temperature of the object is provided by the relation:

$$T = [S(1 - A)\cos(\Theta)/(\eta\epsilon\sigma)]^{1/4} \quad (3)$$

where A is the Bond albedo, ϵ is the bolometric emissivity (assumed to be 0.9), σ is the

Stefan-Boltzmann constant, S is the solar insolation at the distance of the object, Θ is the angle away from the sub-solar point, and η is the beaming parameter. The reflected sunlight (at zero phase angle) is determined by the visible geometric albedo p_V. It is connected to the Bond albedo A through the phase integral q, as $A = qp_V$. Parameter q can be calculated from the slope parameter G via (Bowell et al., 1989):

$$q = 0.290 + 0.684G \tag{4}$$

In the NEATM model, the critical element is the beaming parameter η. This parameter can be fitted based on the data, but can also be obtained from the literature. However, it is important to note that η is NOT a property of the object. It is a fit parameter that has many dependencies. It can change with temperature, wavelength, phase angle, distance from the Sun, etc.

More advanced models are denominated Thermo-Physical Models (TPMs). These models are called physical as they attempt to describe the distribution of temperature on the surface using the physical properties of the object. They can take the true shape and physical properties of the object into account and model the temperature and thermal behaviour of the object (Delbo et al., 2015, MacLennan & Emery, 2018, Hanuš et al., 2015). These properties include shadowing, self-heating, and heat conduction into the surface. For TPMs, even if we know perfectly the properties of the body and have perfect data, there is a need to add artificial roughness; otherwise the model fails completely.

TPMs provide a lot of information about the body. First, they can provide accurate size determination and temperature distribution on the surface, but they also provide the so-called thermal inertia:

$$\Gamma = \sqrt{\kappa\rho C} \tag{5}$$

The thermal inertia provides information on the presence or absence and the depth and thickness of the regolith. It also provides information on the presence of exposed rocks on the surface. For example, the Moon has low thermal inertia and is covered by a fined-grained and deep layer of regolith (Hayne et al., 2017), while when we move toward larger thermal inertia we see more rocks on the surface of the objects. It is important to note that the thermal inertia is temperature dependent. As the temperature goes down, the thermal inertia goes down. A correlation with size and thermal inertia has been noticed in the past (Delbo' & Tanga, 2009, MacLennan & Emery, 2021); however as we gather more and more data, this correlation seems to weaken for large objects. For the NEAs, on the contrary, they still predominantly show larger thermal inertia, indicating larger rock fraction and less regolith than larger bodies.

4.1 Signed phase angle

The phase angle is the angle between the Sun, the object, and the observer (see Fig. 1). In the case of reflected light, the observer will only received light from the illuminated surface. However, in the case of thermal infrared observations, the night side (the fraction that is not illuminated by the Sun) will still emit light. This is due to the fact that objects have a non-zero thermal inertia and will take some time to cool down and stop emitting observable radiation in the infrared. The effect of thermal inertia and rotation on the thermal emission is very crucial for small, fast-rotating objects.

As the surface of the asteroid is cooling down over time, the non illuminated part of the object will have a different temperature based on how long it has been in the night side. It means that regions close to the sun-set are warmer than regions close to the sun-rise.

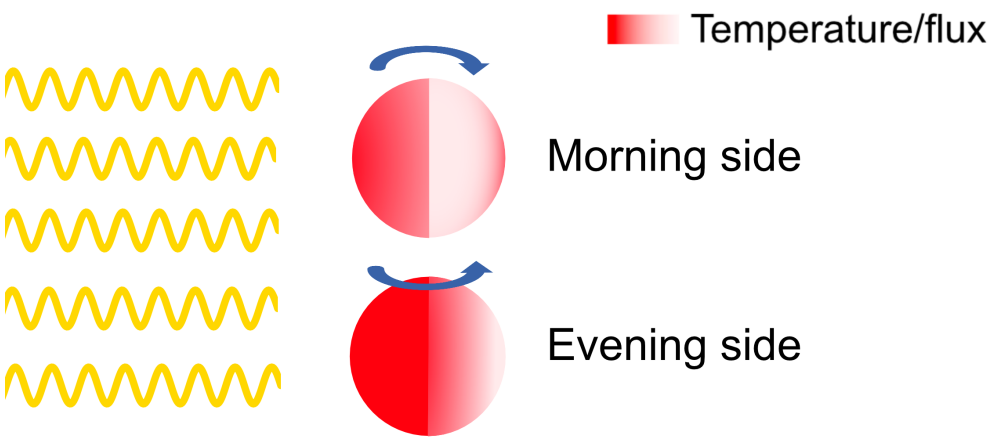

Figure 2: Example of an object observed at a phase angle of 90° as seen from Earth. The top example shows the case when the morning side is observed while the bottom example shows the case when the evening side is observed. The thermal infrared flux will be larger if we observe the evening terminator than if the morning terminator is observed.

From an observer perspective, based on the rotation of the object and its geometry with respect to the Sun, either the evening side of the morning side of an object can be seen. This will result in a different observed flux as we can have either a large contribution from the non-illuminated side or small or absent contribution from the non-illuminated side (see Fig. 2).

The phase angle can be defined as a signed value. The sign allows to distinguish if the asteroid is proceeding or receding the Sun. Combined with the knowledge of the orientation of the spin axis, the sign of the phase angle allows to know if we are observing the evening side or the morning side of an object. The sign of the phase angle is defined as the sign of the cross product of the vector going from the target to the Sun and the vector going from the target to the observer.

Recommendation: The ephemerides service providers (MPC, NEOCC, CNEOS, ASTORB) should provide an option to display the sign of the phase angle.

4.2 Observations at high phase angles

When observing objects at high phase angles, the reliability of existing thermophysical models (TPMs) remains uncertain, as very limited observational data are available in this regime. Near-Earth objects (NEOs) are known to display a wide range of thermal behaviours, making it difficult to predict their emission properties and to constrain the beaming parameter η. However, without more extensive observations it remains unclear which TPMs are most appropriate at high phase angles.

The community expresses the need for more NEO observations in thermal infrared at high phase angles. These observations would allow to constrain better the different TPMs and improve our modelling of NEOs in the thermal infrared.

4.3 Database for thermal observations

Most of the thermal observations available for asteroids are from space missions. All these missions have their own archive, but they are all using different services and methods to store and retrieve the data. Sometime, these databases are not properly developed to allow easy retrieval of measurements of Solar System moving objects.

Space based observations of asteroid are already grouped in a centralized database even is some missions are still missing (Szakáts et al., 2020). However, for ground based observations, there is most of the time no database and the measurements are either scattered in published paper or not available at all.

Recommendation: development of a central database for thermal infrared measurements. This database would collect all the available space and ground based measurements.

5 Polarimetry

Polarimetry is an invaluable tool for the physical characterization of small bodies of the Solar System and even more for Near-Earth Objects. When combined with spectroscopic and photometric observations, polarimetry provides constraints on surface texture, regolith properties, composition (Devogèle et al., 2018), and taxonomic classification (Belskaya et al., 2017). One of its main strengths is its ability to estimate the geometric albedo (Cellino et al., 2015), which, when combined with absolute magnitude, allows the determination of an object's effective size.

The polarization state of light is described by the Stokes parameters (McMaster, 1954) (I, Q, U, V). They provide a complete description of the polarization state of a light beam:

- I – the total intensity of the light.
- Q – the difference in intensity between light polarized linearly at 0° and 90°.
- U – the difference in intensity between light polarized linearly at 45° and 135°.
- V – the difference in intensity between right-handed and left-handed circularly polarized light (typically negligible for asteroid polarimetry).

They are defined in terms of measured intensities as follows:

$$I = I_{0^\circ} + I_{90^\circ} = I_{45^\circ} + I_{135^\circ}, \tag{6}$$
$$Q = I_{0^\circ} - I_{90^\circ}, \tag{7}$$
$$U = I_{45^\circ} - I_{135^\circ}, \tag{8}$$
$$V = I_{\mathrm{RHC}} - I_{\mathrm{LHC}}, \tag{9}$$

where I_θ is the measured intensity of light through a linear polarizer oriented at angle θ, and I_{RHC}, I_{LHC} are the intensities of right- and left-handed circularly polarized light, respectively.

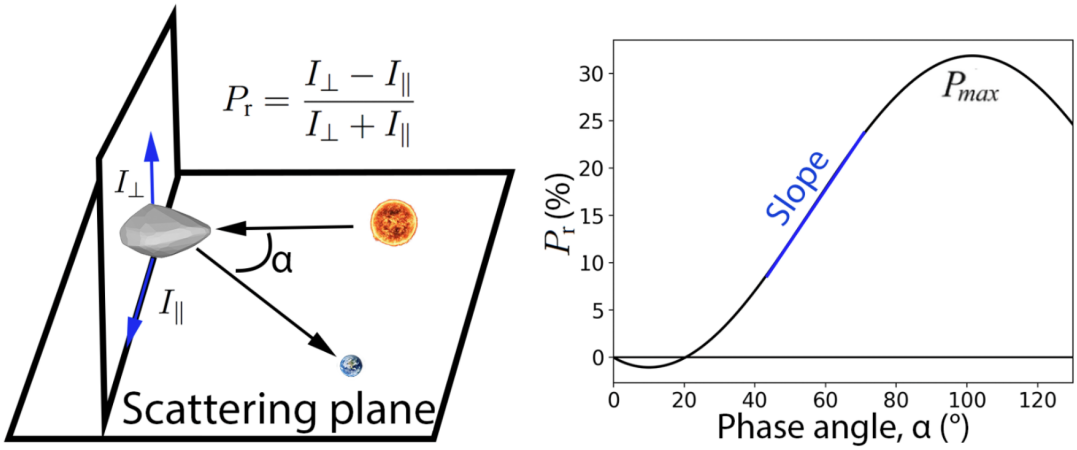

Figure 3: Left: Observation geometry with the sun-light scattered by the asteroid and then observed on Earth. The polarization is measured in the scattering plane and the plane perpendicular to the scattering plane. Right: typical variation of the polarization as a function α. $P_{\rm min}$ corresponds to the maximum value of polarization usually occurring between 80 to 120°

For asteroid polarimetry, circular polarization is generally negligible ($V \approx 0$), and the degree of linear polarization P and the polarization angle θ can be computed using the reduced Stokes parameters:

$$q = \frac{Q}{I}, \quad u = \frac{U}{I}, \tag{10}$$

$$P = \sqrt{q^2 + u^2}, \tag{11}$$

$$\theta = \frac{1}{2} \arctan\left(\frac{u}{q}\right). \tag{12}$$

For Solar System objects, it is customary to express the degree of linear polarization with respect to the scattering plane (the plane defined by the Sun, the target asteroid, and the observer). The polarization is then given by:

$$P_{\rm r} = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel}, \tag{13}$$

where $I_\perp$ and $I_\parallel$ are the intensities of light polarized perpendicular and parallel to the scattering plane, respectively.

Unlike P, which is always positive, the quantity $P_{\rm r}$ can be either positive or negative, depending on the orientation of the polarization vector. It is strongly dependent on the phase angle α, and for each object, a well-sampled phase–polarization curve is needed to derive key diagnostic parameters. Typically, such a curve includes a negative polarization branch at small phase angles, a minimum polarization value $P_{\rm min}$ at an angle $\alpha(P_{\rm min})$, and an inversion angle $\alpha_{\rm inv}$ where $P_{\rm r}$ changes sign (see Fig. 3).

A commonly adopted empirical representation of the phase–polarization curve is the exponential-linear model proposed by (Muinonen et al., 2009):

$$P_{\rm r}(\alpha) = A \cdot \left[\exp\left(-\frac{\alpha}{B}\right) - 1\right] + C \cdot \alpha, \tag{14}$$

where A, B, and C are fitting parameters. From this model, one can derive the inversion angle $\alpha_{\rm inv}$, the minimum polarization $P_{\rm min}$, and the angle at which it occurs.

NEOs offer a unique opportunity for polarimetric studies because they can be observed at much larger phase angles ($\alpha > 30°$) compared to Main Belt asteroids. At these large angles, the degree of linear polarization increases significantly (Fig. 3), enhancing the sensitivity of the method to surface properties characteristics and improving the accuracy of albedo estimation.

Polarimetry of NEOs at high phase angles represents a critical observational window for improving our knowledge of their physical properties, with direct implications for planetary defence and impact risk assessment.

5.1 Calibration of the relation between slope at inversion angle and albedo

The relation between albedo and polarization has long been known as the Umow law (Umow, 1905), which is linking the strength of the linear degree of polarization with the geometric albedo of the surface. Larger polarization values indicated lower albedo. However, most of the asteroids (Main Belt objects) cannot be observed at phase angles larger than 30° where the values of $P_{\rm r}$ are small and can even be null at the inversion angle or at opposition. Proxies to the Umow law have thus been developed and are mostly using the slope of the phase-polarization curve at inversion angle.

Many calibrations of the albedo versus slope at inversion angle have been published (Cellino et al., 2015, 2012, Masiero et al., 2012). All these calibrations assume that the relation between the slope at inversion angle and the albedo has to be linear in the log-log space. However, we are analysing the relation between two observables and there is no reason why this relation has to follow a physical law. Indeed, as we are adding more and more data, it is getting evident that the relation is not continuous.

Recommendation: A new calibration between albedo and the slope at inversion angle should be determined using all the new observations obtained in the last 10 years. This relation should not assume a linear relationship over the whole range of albedo or slope and should allow for discontinuities.

5.2 Calibration of the relation between polarization and albedo at high phase angles

Near-Earth objects, compared to Main Belt asteroids, can be observed at high phase angles. This is a key advantage because, at high phase angles, the estimation of geometric albedo becomes less dependent on the uncertain slope near the inversion angle. Instead, the polarization signal is strong enough that the albedo can be derived more directly, providing a more robust and less model-dependent measurement. This capability is particularly important for newly discovered or faint NEOs where complementary infrared data may be lacking.

In the recent years, a large number of NEOs have been observed in polarimetry. By comparing their observed linear degree of polarization with their albedo determined using independent techniques (radar observations, thermal observations, etc), a calibration between the observed linear degree of polarization at any phase angle and albedo has been

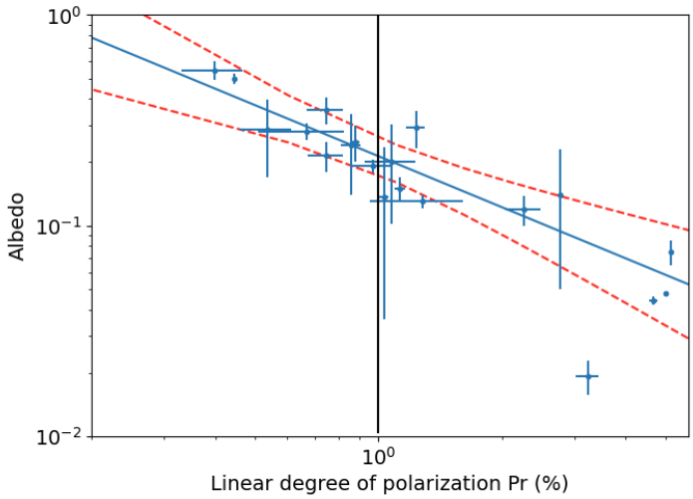

Figure 4: Example of the calibration between albedo and linear degree of polarization. The blue dots corresponds to the expected linear degree of polarization at 30° for NEOs that have been observed in polarimetry as a function of their albedo obtained through independent techniques. The blue line corresponds to the best linear fit between the linear degree of polarization and albedo. The vertical black line corresponds to an hypothetical observations of an NEOs displaying a linear degree of polarization of 1% at a phase angle of 30°. The intersection between the black and the blue line corresponds to the estimated albedo for this object (i.e $p_V = 0.21^{+0.05}_{-0.04}$).

established. Fig. 4 shows an example of calibration for a phase angle of 30°.

Recommendation: Polarimetric observations should be more widely used for albedo determination of NEOs and the calibration between albedo and polarization should be published so it could be used by the community.

6 Other

During the workshop, it became evident that albedo values are often presented based on taxonomic classifications, rather than on direct observational methods such as thermal infrared or polarimetric measurements. However, this distinction is not always made explicit, which can lead to confusion. While these taxonomically inferred albedo estimates are extremely useful—especially when no direct measurements are available—there is currently no consensus on which values to use or how they should be presented within the community.

A key point of discussion was the need for a standardized, community-endorsed set of albedo values associated with taxonomic types, which could be transparently and consistently used across studies. One proposed approach is to select a set of benchmark objects that are well-characterized in both spectral taxonomy and directly measured albedo. From these, one could derive empirical albedo probability distributions for each taxonomic class.

Alternatively, a more comprehensive method involves leveraging all available spectroscopic and albedo data in a probabilistic framework, such as the approach developed by Mahlke et al. This method assigns probabilities of an object belonging to different

taxonomic classes, which can then be used to derive weighted albedo distributions for each class. With this framework, when a new spectrum is obtained, its probabilistic classification across taxonomic types can be used to compute a corresponding probability distribution of albedo—offering a more nuanced and statistically grounded estimate.

Recommendation: Standard albedo probability distributions for each taxonomic type should be defined. This could be done by either selecting benchmark objects with well-determined taxonomy and measured albedo, or by applying a probabilistic framework (e.g. Mahlke et al., 2022) that uses all available spectroscopic and albedo data to derive class-dependent albedo distributions. These standardized distributions should be transparently documented and made available for consistent use across the community.

7 Conclusions

The EU-ESA Workshop on the Size Determination of Near-Earth Asteroids (NEAs) highlighted the pivotal role of accurately determining asteroid sizes within the broader framework of planetary defence. A central theme across all sessions was the need for consistent methodologies, improved data quality, and collaborative infrastructures that can support reliable and unbiased size estimates.

From a photometric standpoint, the community consensus was to shift from outdated models such as the HG phase function to more modern systems like HG^*_{12}, which better represents the diversity of asteroid phase behaviours and are grounded on more extensive observational datasets. Likewise, observers are encouraged to conduct measurements in the V band when possible or apply recent band correction models (e.g. Hoffmann et al., 2025) to reduce systematic biases when using alternative bands. A more precise and physically meaningful definition of the H magnitude was also proposed, accounting for aspect and rotation effects.

The need for low phase angle observations was emphasized repeatedly. These observations are essential for constraining the H magnitude and, by extension, the size. The community strongly recommended that surveys prioritize acquiring data at or near opposition, even if only occasionally, to fill this critical gap in the current observing strategies.

In terms of data management and infrastructure, the lack of a central photometric and thermal observations repository analogous to the Minor Planet Center for astrometry was identified as a major limitation. A standardized submission process and centralized archiving of photometric and thermal observations data would enable better exploitation of existing observations and foster reproducibility and consistency in size determination efforts.

Crucially, the workshop reaffirmed the central role of thermal infrared observations as the most robust and widely accepted technique for determining asteroid sizes, especially when high-quality data from space-based observatories are available. These observations provide direct and physically grounded constraints on the size and albedo of small bodies, and their accuracy is further improved when combined with reliable absolute magnitude (H) measurements. In parallel, polarimetric techniques—though observationally more demanding—were recognized as an important and underutilized tool to constrain albedo and surface properties, particularly in cases where thermal infrared data are lacking or limited. The integration of polarimetry into multi-technique workflows can help reduce

degeneracies and improve the reliability of size and albedo determinations.

The role of shape modelling and spin state reconstruction was also recognized as essential for interpreting both photometric and thermal data. Shape models help correct projection effects and rotational variations that can otherwise bias size estimates, especially when relying on sparse data or single-epoch observations.

Finally, the workshop fostered a strong spirit of collaboration between the planetary defence and planetary science communities. The complexity of asteroid size determination demands a multi-technique approach and the establishment of long-term observational strategies, coordinated campaigns, and data-sharing protocols. The recommendations set forth in this report provide a path toward more accurate, reliable, and timely characterization of potentially hazardous asteroids—thereby strengthening our planetary defence capabilities.

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