

Thermal Simulation of Asteroid Surface Temperature and Yarkowski Effect

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ABSTRACT

The thermal environment on or near the surface of the solar system bodies, such as Near Earth Orbit (NEO) asteroids has important implications on future plans for a variety of solar system explorer missions. These missions aim to study asteroids, the primitive leftover building blocks of the Solar System formation process, to understand and potentially alter the course of an object that may threaten the Earth, or to demonstrate the technology to pave the way for man's return to Earth's Moon and beyond.

Previous work to determine the surface temperatures of asteroids has addressed the needs of astronomy by using the IR emission from the asteroid to determine its size. However this simulation assumes a theoretical spherical asteroid and not the complex geometries often observed. The simplification leads to inaccurate temperature prediction of details features of the asteroid surface which are of significance to vehicles and orbit prediction.

Astrium UK has been involved in various studies for spacecraft and landers that must operate within the demanding environment of these solar system bodies. During the course of these studies thermal simulation of asteroids themselves has been undertaken to determine the surface environment of irregular bodies and predict its effect on the orbit. Determination of asteroid surface temperature leads to improved determination of orbital

paths as the heat radiated from the surface can alter the course of these objects via the Yarkowski effect. Analytical models of the Yarkowski effect exist only for a few simple cases and a numerical thermal model of the real asteroid is required for accurate orbit predictions.

This paper discusses the thermal environment encountered on the surface of these solar system bodies including the effect this environment has on its own orbital motion.

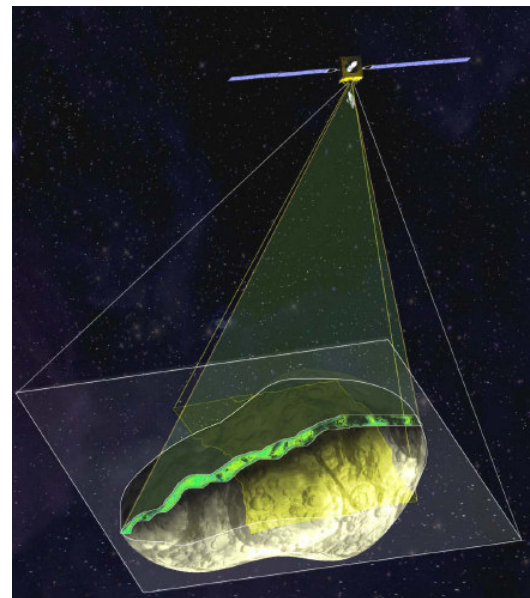


Figure 1. Apophis Explorer (APEX)

INTRODUCTION

Thermal models of Near Earth Objects (NEOs) such as asteroids (Figs. 1 and 2) have been also used to predict the thermal environment on a particular NEO surface, and have been an essential tool in determining the thermal environment for spacecraft operating near such bodies for a variety of studies undertaken. Asteroid surface temperatures can vary greatly, and for NEOs of interest the surface temperatures can exceed 400K. This is significant to spacecraft design as operations near the surface literally place the vehicle between a rock and a hot place.

However thermal modelling of NEOs has another important contribution to make in our understanding of the behaviour of asteroids. On April 13, 2029 asteroid Apophis will have a close encounter with Earth which could send it on a collision course with our planet. The probability of the collision with Earth can be ascertained if or if not the asteroid passes through the "keyhole" in the 2029 encounter.

Keyholes are defined as regions in near Earth space where if a NEO passes through them, it will definitely hit Earth at some time in the future [Ref 2, Ref 3]. The properties of the keyhole can determine the increase in energy that is required to successfully deflect the NEO after the pre-impact encounter. In the case of the 2029 encounter of Apophis, after passing through the keyhole, the energy required increases by 4-5 orders of magnitude. Therefore knowledge of the orbit of Apophis needs to be accomplished well before then to determine if any deflection is necessary.

Unfortunately, the orbit of Apophis is subject to a number of gravitational and non-gravitational perturbations, some of which are currently known or modelled with limited accuracy. One significant contribution to the orbit determination uncertainty is the Yarkowski Effect (YE) which alone can shift the position of Apophis by over 100 km between 2017 and 2029, outside the keyhole, which means it cannot be ignored in the orbit propagation models.

Since a 10% error in modelling non-gravitational perturbations like the YE can translate into more than 30 km error (3σ) in the position of Apophis in 2029, these perturbations need to be modelled with accuracies of a few percent, more than can be achieved by radio tracking alone. [Ref 4] The thermal properties of Apophis in particular are the dominant error contributor in YE estimations, so that a detailed understanding of the temperature distribution across the surface is necessary. Tracking the orbital evolution of Apophis alone is not sufficient to propagate the orbit path with the required

accuracy to determine if it will pass through the keyhole. Determination of the physical properties of Apophis along with simulation of the surface temperature evolution is necessary.



Figure 2. Asteroid Ida

YARKOWSKI EFFECT

Solar radiation that is absorbed by a body is subsequently re-emitted as thermal radiation. As the body rotates, the infrared emission from the surface can lead to an asymmetric force in the along-track direction, which can modify the orbit of the body significantly, particularly over long periods of time [Ref 5]. The asymmetric force is a product of the rate of both the rotation of the asteroid and the thermal capacity of the surface (Figs. 3, 4). For a slow spinning asteroid with a surface of low thermal capacity the surface temperature distribution will remain evenly distributed around the sub-solar point, resulting in the direction of the IR force to be aligned with the solar flux direction (typically the centre of the orbit). However for a faster spinning asteroid with a higher surface thermal capacity the temperature distribution across the surface is asymmetric as the dawn side of the surface warms up faster than the afternoon side cools down. This results in the asymmetric direction of the IR force as it does not point in the direction of the solar flux.

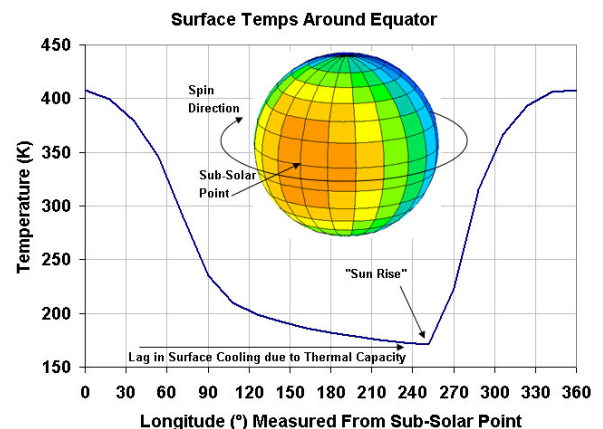


Figure 3. Temperature Distribution around Asteroid

However for a fast spinning asteroid with a high surface thermal capacity the temperature distribution across the surface approaches an isothermal distribution, reducing the asymmetric IR force.

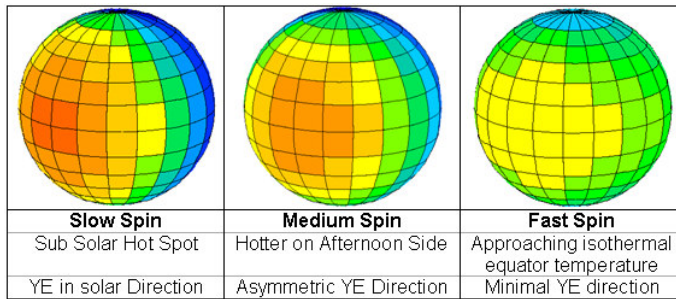


Figure 4. Variation in Surface Temperatures

Therefore accurate simulation of the temperature distribution across the asteroid surface is required for correct determination of the magnitude and direction of the YE force.

The IR force that leads to the Yarkowski effect for an asteroid surface element is calculated via:

$$F = \frac{P_{\text{radiated}}}{2 \cdot c}$$

Where c is the speed of light and the IR power radiated is:

$$P_{\text{radiated}} = A_{\text{surface}} \cdot \epsilon_{\text{surface}} \cdot \sigma \cdot (T_{\text{surface}}^4 - T_{\text{space}}^4)$$

The radiated IR force is integrated across the surface of the asteroid taking into consideration the vector of the surface element normal.

Typically the influence of the Yarkowski Effect is difficult to observe due to its small magnitude (milli-Newton), however it has been observed directly on the orbit of asteroid 6489 Golevka using radar ranging [Ref 1]. The Yarkowski Effect is in general more pronounced for NEOs smaller and lighter than Apophis. Considering that NEOs of size as small as tens of meters still represent a very significant problem in case of an impact with Earth, there is a whole class of objects for which an accurate estimate of the YE is required, if their orbit is to be predicted with certainty.

PARAMETERS THAT AFFECT SURFACE TEMPERATURE

The temperature distribution on any particular object is a function of many asteroid parameters:

Solar Environment

A key driver, the greater the incoming solar flux on the surface the warmer it is and the greater the IR force. Related to this is the asteroid surface absorptivity as this determines the input energy received by the object. Typically NEOs such as asteroids have a very high surface absorptivity due to the nature of their material.

While it may look reflective at night, the Moon and other NEOs have optical properties similar to black paint. The Moon itself reflects 7% of the light from the Sun, which while a small percent of the incident visible light, relative to other objects at night it appears bright.

Thermal Inertia

Thermal inertia determines the response of the surface to the environment conditions. Thermal inertia relates thermal conductivity (k), surface layer density (ρ) and specific heat capacity (c) of the surface material and is expressed as:

$$I = \sqrt{k \cdot \rho \cdot c}$$

The magnitude of the thermal inertia determines the response, spatial and temporal, to the heat input. For example a dusty surface will lead to a wider variation in surface temperatures as it is highly insulative leading to rapid responses to changes in external flux (akin to the external layer of MLI), while a rocky surface has a much greater lag in response. This leads to one of a greater unknowns in the modelling of the asteroid surface, as the properties of the surface material are difficult to determine via remote observation. Assumption is required based on observation of visited asteroids, however for accurate determination of the surface temperature distribution and the YE missions such as APEX propose detailed close proximity observation of the surface temperatures over a extended duration to determine the thermal inertia based on the variation in temperature.

Spin

The rotation state of the asteroid is significant as it dictates how the heat is distributed across the surface and the direction it is subsequently radiated. The orientation of the spin axis determines diurnal and seasonal effects, while the rotation period sets the frequency at which input energy is applied