Efficient Photometric Modeling of Complex Spacecraft Geometries toward Next-Generation Light Curve Analysis

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ABSTRACT

An extremely efficient method for synthetically generating high-fidelity space target photometric data is presented with applications to light curve analysis including attitude inversion, spacecraft shape estimation, and object association. An enabling feature of the technology is a model for rapidly determining where, for example, a deployed solar panel will cast a shadow on the spacecraft hub based on an appropriate-fidelity shape model. The presented technique represents a spacecraft's geometry via a macroscopic Finite Element Method (FEM), calculates where shadows are cast given the sun angle, and determines how much total light is reflected to an observer subject to its perspective on the target. Notably, the shadowing calculation is not only efficient, but also exact subject to model fidelity (i.e. no approximations exist in calculating shadow positions beyond those made in modeling the spacecraft geometry). After an overview of the technique is provided, applications are discussed and preliminary results are presented. Finally, a comparison between Scout's technique and Ansys Zemax is performed to demonstrate the precision and efficiency of the model.

1. INTRODUCTION

Among the many challenges to high-fidelity photometric analysis are prediction of shadowing and occlusions between elements in a scene. The prevailing technology in applications such as computer graphics is the Finite Element Method (FEM), which includes representing objects in a scene with surfaces comprising small elements that fit together to approximate a shape. In high-fidelity simulations, many rays of light are propagated, and element-to-element comparisons are performed to determine shadowing, occlusion, reflection, and other aspects of the scene. In order to accurately model photometrics, often millions of light rays and elements are applied, leading to an immense computational load necessitating optimized code deployed on parallelized compute architectures like a Graphics Processing Unit (GPU). High-fidelity analyses of simple scenes can still require seconds of computation time, precluding faster-than-real-time simulations or comprehensive photometric analysis (e.g. developing a holistic brightness model of an object given every illumination-observation angle and object orientation). Ansys Zemax [1] is an exemplar photometric analysis software that enables the high-fidelity ray tracing analyses described above.

Such FEM technologies are also applied for high-fidelity force and torque modeling for spacecraft on orbit and, therefore, precise orbit estimation and predication. Solar radiation pressure, for example, imparts force only on sunlit portions of a spacecraft face. For complex geometries, it is likely that the center of illumination — and therefore force — does not align with the body center of mass, meaning that complex forces and torques on the body will arise. Precisely estimating these orbit-attitude coupled effects offer promise for precisely estimating the orbits of attitude-controlled spacecraft as well as in propagating uncertainty for uncontrolled hazards on orbit. Technologies have been developed for this application that apply various shadowing models [4, 2, 3], but compromises are made in terms of fidelity, accuracy, and computational effort due to the lack of a precise, efficient model.

This paper outlines a novel occlusion model designed by Scout with specific applications to modeling spacecraft photometrics and dynamics. First, a high-level description of the technique is provided along with a discussion of how it would integrate with existing data inputs and follow-on analysis. A discussion of light curve analysis and other potential applications precedes a comparison of Scout's technology to Ansys Zemax.

2. TECHNIQUE OVERVIEW

The details of the technique are proprietary, so only a high-level overview is provided here. To begin with, consider an imaging scenario that consists of three separate elements as shown in Figure 1: an observer (left) images light from the sun (right) reflected by a target spacecraft (center). Note that the target spacecraft has concave geometries caused by the deployed panels, meaning light from the sun and to the observer can be blocked by components of the spacecraft. Regions where target components block light from impinging on others are called shadows, while areas with reflected light blocked by target components are called occlusions. The model outlined herein offers a method of precisely determining shadow and occlusion regions with orders-of-magnitude efficiency increases relative to industry standard software.

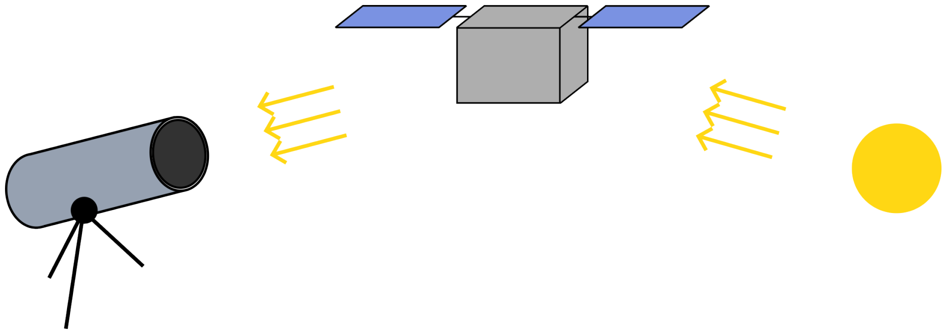


Fig. 1: Imaging scenario

At its core, Scout's approach is similar to the standard FEMs applied by existing industry software like Ansys Zemax. The primary differences are the size of the elements and the methods for analyzing occlusions between two elements. The technology is still under development (currently TRL 6) and is focused on applications to Geosynchronous Earth Orbit (GEO), so analyses discussed are limited to a single collimated light source and a box-and-panel model shown below in Figure 2.

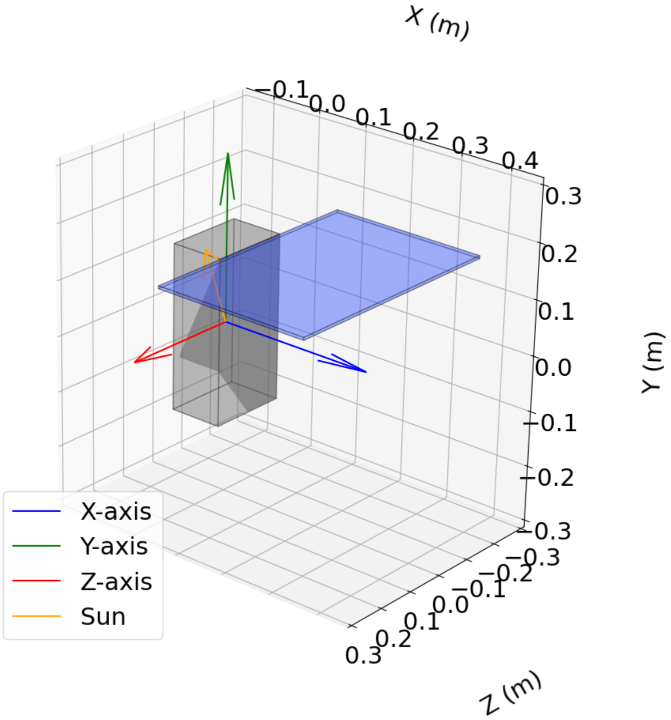


Fig. 2: Shadowing demonstration with simple box and panel geometry

In the image, a 3U cubesatellite hub (gray) with a deployed tri-fold solar panel (blue) is illuminated by the Sun, whose body-frame position is indicated. Note that all bodies are semi-transparent, allowing for visibility on all faces in a single image. Shown in dark gray are the shadows cast by the solar panel onto the hub calculated with Scout's technique (analysis takes roughly 4ms of computation time without code optimization or multi-threading). Note that 3 faces from the solar panel cast shadows onto two of the hub faces in this scenario. Occlusions are calculated using a nearly-identical process (though substituting the observer heading for the illuminator heading) and are indicated as overlaps between the blue panel and the gray hub visible because of the semi-transparency of the bodies. A final feature of note in Figure 2 is the overlap between the shadowed and occluded areas. These regions must be accounted for to avoid underestimating the amount of light reaching the observer. The process for implementing Scout's technique is shown in 3 with green boxes indicating input data, the blue indicating Scout's innovations, and the orange indicating arbitrary follow-on analyses.

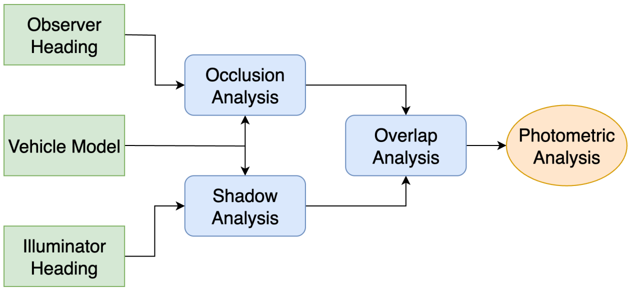


Fig. 3: Integration of Scout's occlusion model with standard photometric inputs and analyses

Integration of Scout's technology with a Bidirectional Reflectance Distribution Function (BRDF) model enables hyper-spectral light curve analysis and also has promise for extremely fast synthetic image rendering. The shadow locations are also critical for high-fidelity orbit-attitude couple dynamic analyses, as forces and torques from solar radiation pressure and, potentially, low Earth orbit atmospheric drag cannot be precisely modeled without this knowledge.

3. APPLICATIONS

A primary application for Scout's model is precisely determining the amount of light reflected by a target as seen by a distant unresolved observer. Figure 4 shows a representative light curve calculated with Scout's model. Note that this simulation shows only the effects of including shadows — occlusions and overlaps are not considered, as the generalized algorithm for precisely determining these is not yet finalized.

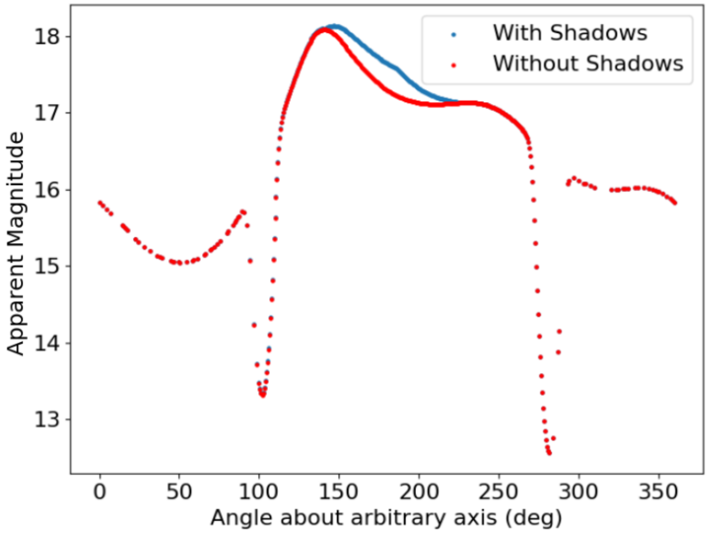


Fig. 4: Apparent magnitude simulation over time with/out shadowing included

In this simulation, the inclusion of shadows is primarily important at low magnitudes, though this is unlikely to always be the case. Spacecraft with complex geometries, like the International Space Station, have many reflective surfaces as well as appendages and components that can cast shadows onto other spacecraft surfaces. In these cases, there may in fact be sufficient observability resulting from the complex shadowing to facilitate light curve inversion. Scout's technique is especially applicable, as reinforcement learning and other machine learning approaches that show promise for light curve inversion depend on the generation of large sets of training data.

As discussed below in greater detail, Scout's technique takes roughly 5 milliseconds to perform a shadowing analysis like Figure 2 as opposed to 9 seconds for industry software. Therefore, assuming a comprehensive photometric characterization takes roughly $360^2 = 129,600$ analyses (assuming 1 degree grid-spacing for both observer and illuminator headings), Scout's technique is expected to take roughly 11 minutes, while industry software would require upward of 13 days of nonstop GPU time. Scout's technique is therefore an excellent candidate for generating labeled light curve training data toward applications including but not limited to light curve inversion, shape reconstruction, and capability and intent estimation.

Finally, Scout's technique may be especially promising for precise orbit determination, as shadowing and occlusion affect the forces and torques on orbiting bodies. If a spacecraft's attitude is controlled and known (e.g. a geosynchronous Earth orbit spacecraft with an orbit fixed orientation) the shadows and occlusions can be precisely determined with Scout's technique, mitigating this source of error when attempting to fit an orbit or predict where a spacecraft will be in the future.

4. COMPARISON TO INDUSTRY TECHNOLOGY

In this section, Scout's method is compared to Ansys Zemax, a representative industry software product for photometric modeling. The same box-and-panel model used in Figure 2 was replicated in Zemax and a collimated illumination source was placed at a specific location and angle to cast a shadow from the solar panel onto the hub, as shown in Figure 5a. Notice that the same face is shown in both images of Figure 5.

A major challenge with the FEM approach Zemax applies is the number of elements and rays required for high-fidelity analysis. The shadow results (blue) in Figure 5b are from a Zemax simulation with 10 million rays. Note the speckled regions at the top and bottom of the figure, evidence that an insufficient number of rays were cast to fully illuminate the face. The results shown in later figures are for simulations with 100 million rays. While the illumination region in 5a looks large for the orientation shown, it was sized specifically to ensure the maximum projected radius of the box-and-panel spacecraft would be fully illuminated.

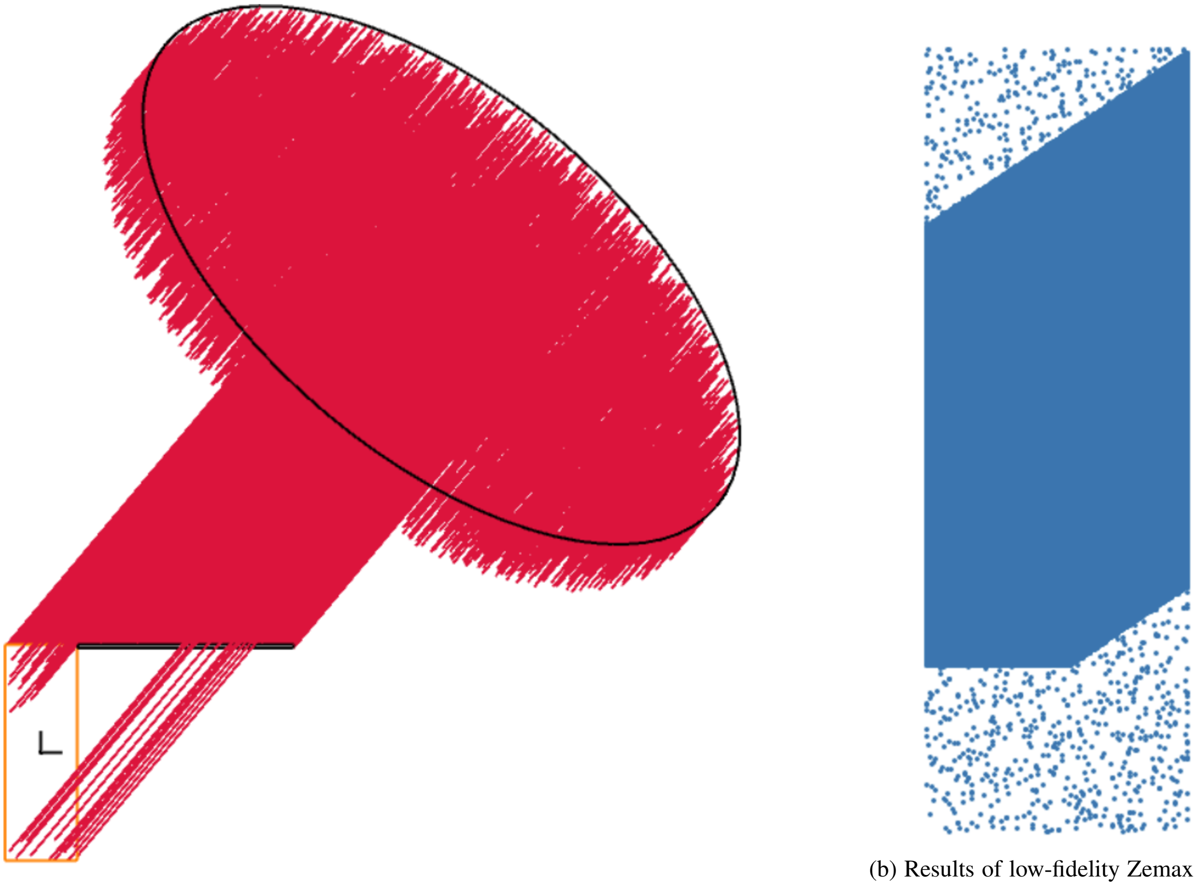
Figures 6 and 7 show the results of the comparison between Scout's solution and that derived by Ansys Zemax. The red points indicate areas where Zemax predicted shadows while the colored edges outline the areas Scout identified. In Figure 7, the multiple outlined areas are where individual components shadowed each face. Scout's technique took roughly 5 milliseconds on a single thread of a CPU for this analysis, while Zemax took 9 seconds while using the GPU on a personal laptop. The simulations show excellent agreement, with slight edge effects that result from Zemax's discretized FEM analysis — the most obvious errors are the rough diagonal edges visible because of the grid-based discretization approach Zemax applies.

5. CONCLUSION

A method for computing shadows and occlusions in photometrics scenes is presented. Application to light curve analysis was presented, demonstrating that shadowing must be accounted for to accurately measure reflected brightness. Additionally, improvements to precise orbit determination were identified that are specifically enabled by Scout's technique. Finally, a comparison to industry standard software was presented, showing that Scout's technique matches result down to machine precision while running 1000x faster on a CPU than industry software runs on a GPU.

6. REFERENCES

[1] Ansys Inc. *Ansys Zemax OpticStudio User Guide*. Ansys Inc., Canonsburg, PA, 2025. Available from: https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/Zemax/v242/en/OpticStudio$_{U}ser_{G}uide/index.html$.



(a) 3D view of Zemax simulation

(b) Results of low-fidelity Zemax simulation

Fig. 5: Zemax simulation results

[2] Carolin Früh and Moriba K Jah. Coupled orbit–attitude motion of high area-to-mass ratio (hamr) objects including efficient self-shadowing. *Acta Astronautica*, 95:227–241, 2014.

[3] Patrick W Kenneally and Hanspeter Schaub. Fast spacecraft solar radiation pressure modeling by ray tracing on graphics processing unit. *Advances in Space Research*, 65(8):1951–1964, 2020.

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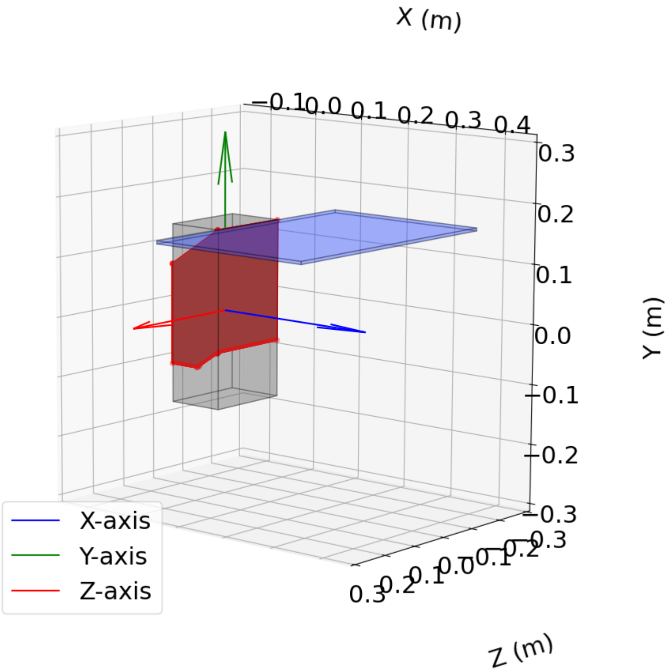

Fig. 6: 3D representation of Scout and Ansys Zemax comparison

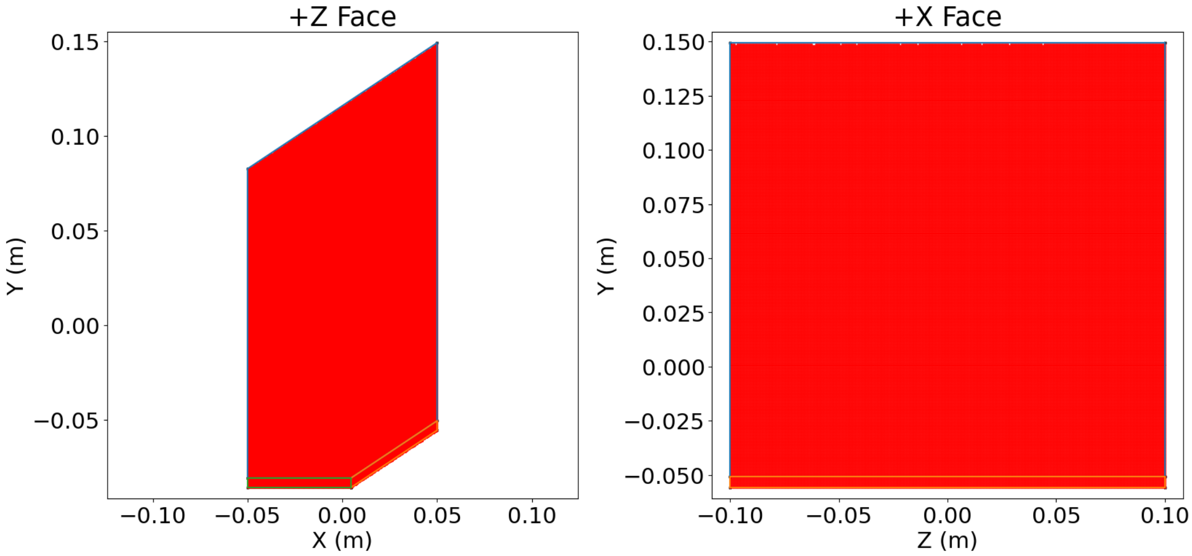

Fig. 7: 2D representation of Scout and Ansys Zemax comparison