IMPLEMENTATION OF IMPROVED MAGNITUDE PARAMETERS FOR SOLAR SYSTEM PLANETARY EPHEMERIDES

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ABSTRACT. The joint publications of the U.S. Naval Observatory and Her Majesty's Nautical Almanac Office have integrated the Mallama & Hilton (2018) algorithms to improve planetary apparent magnitude and surface brightness values. Prior calculations were based on algorithms from the 1960s, except for Mercury and Venus (Hilton 2005). Physical ephemeris predictions are required for factors such as identification, exposure estimates, and offset between center-of-light and center-of-object. These improved algorithms will first appear in The Astronomical Almanac for 2021 and Astronomical Phenomena for 2022. The uncertainty in the V magnitude predictions ranges from 0.02 mag for Uranus to nearly 0.2 mag for Mars. There is room for improvement, and work is underway to further enhance these magnitude ephemerides is discussed. Renewed interest in planetary magnitude theory has implications for predictions of the characteristics of exoplanets and space navigation.

1. INTRODUCTION

Prediction of the apparent magnitudes and surface brightness of solar system bodies are required for factors such as identification, exposure estimates, and offset between center-of-light and center-of-object. Renewed interest in physics behind planetary magnitude has implications for predictions of the characteristics of exoplanets for missions such as HabEx (2019) and space navigation.

The joint publications of the U.S. Naval Observatory and Her Majesty's Nautical Almanac Office *The Astronomical Almanac* and *Astronomical Phenomena* provide these data. The algorithms used to predict the apparent magnitudes were, until recently, primarily drawn from Harris (1961). Hilton (2005) supplied the algorithms for Mercury and Venus. And the value $V(1,0)$[1] for Jupiter was drawn from Irvine et al. (1968).

The Harris algorithms were entirely empirical and ignored variations arising from albedo markings on the surfaces of Mercury and Mars. The predicted apparent magnitude for Mars had an uncertainty in V of about 0.3 mag. The uncertainty for the other planets was on the order of 0.1 mag. The large uncertainties made the predictions poor for planning purposes, and using empirical formulae, ignoring the physical properties of the planets made these algorithms useless as guides for applications to exoplanets.

2. NEW ALGORITHMS FOR THE ASTRONOMICAL ALMANAC

The 2007 edition of *The Astronomical Almanac* introduced the Hilton (2005) algorithms for predicting the apparent magnitudes of Mercury and Venus. Previous predicted apparent magnitude values for these planets were particularly inaccurate. The inferior positions of these two planets have made accurate photometric observations difficult because they must be made against a background that varies in both space and time. Figure 1 illustrates the problem. Modern data taken from CCD

[1] The body's apparent magnitude when it is 1 au from the Sun, 1 au from the observer, and at a phase angle of 0°.

and spacecraft observations are compared to the older data referenced by Harris. At small phase angles there is an offset of about 0.1 mag and there is a nonlinear trend maximizing at difference of about 0.4 mag at a phase angle of 120°.

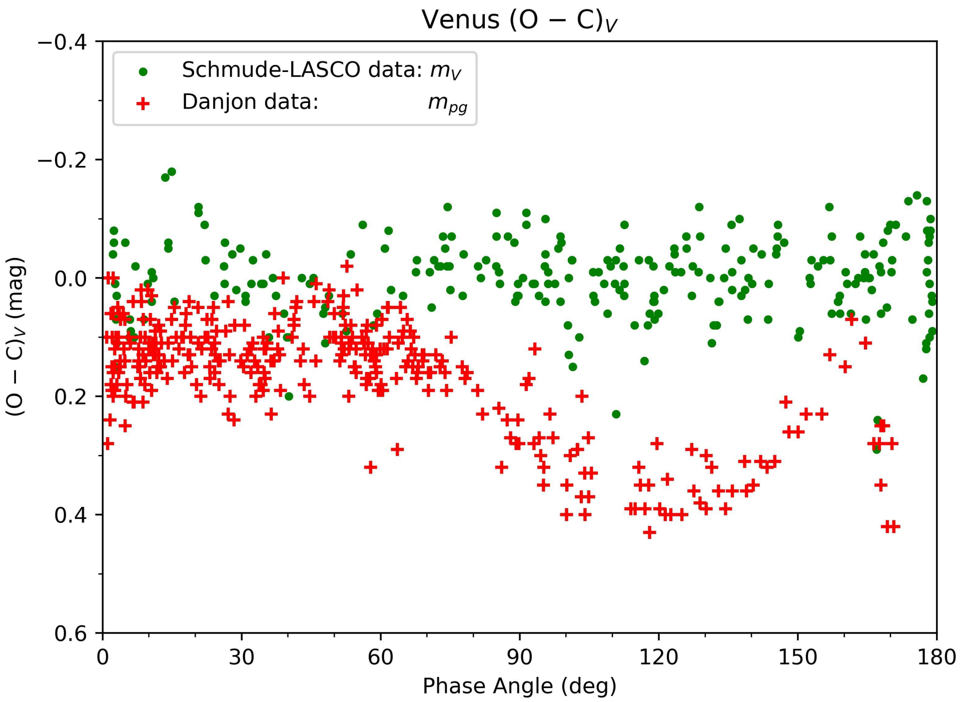

Figure 1: The (O − C)s for the modern CCD (Schmude) and spacecraft (LASCO) data and the older Danjon (1949) data. The predicted values were calculated using the Mallama & Hilton (2018) algorithm.

Starting with the 2021 edition of *The Astronomical Almanac* all of the prediction algorithms will be replaced with those from Mallama & Hilton (2018). Table 1 gives the 1 σ_V uncertainties in the predicted apparent V magnitudes for these algorithms. Both Mercury and Mars have significant albedo markings. The algorithm for Mars attempts to correct for these (see § 2.1.), but no correction has been applied for Mercury. Venus has a glory near inferior conjunction (see § 3.1.) that was not incorporated into its algorithm.

2.1 Mars

Mars is still a significant problem. It is not clear that the current parameterization of Mars' algorithm is optimal. It contains terms to account for Mars' variation with sub-Earth longitude and season. The seasonal term includes changes such as changes in the size of its polar caps and cloud cover. It also accounts for changes in its sub-Earth latitude. The rate of change with longitude is variable and may be as great as 0.039 mag hr^{-1} in V. The rate of change of the seasonal term also varies greatly. Its maximum rate of change is only 0.0042 mag day^{-1} in V. The difference in the rates of change is primarily caused by the large difference in the rate of change of the angular velocity of rotation, 350°.8 day^{-1}, compared to Mars' tropical year angular motion, 0°.524 day^{-1}. The variations in magnitude are similar for the two terms. The difference between the minimum and maximum rotational magnitudes is 0.11 mag, and the difference for the seasonal magnitudes is 0.14 mag.

The tabular interval for the apparent magnitude of Mars in *The Astronomical Almanac* is four

Planet	σ_V
Mercury	0.079
Venus	0.069
Mars	0.074
Jupiter	0.042
Saturn (planet and rings)	0.042
Saturn (planet alone)	0.244
Uranus	0.024
Neptune	0.034

Table 1: Standard deviation uncertainties of the revised predictions for apparent V magnitudes of the planets.

days, 3.8986 martian sidereal rotations. Thus the sub-Earth longitude at the tabulation interval is slowly regressing on average. This regression could give the user a false idea of how Mars' apparent magnitude changes, so the sub-Earth longitude correction will not be included in the tabulation but will likely be included in other products with a finer time resolution.

Mars also has major dust storms that can obscure its entire disk and reduce its apparent V magnitude by up to 0.2 mag. These dust storms can also reveal and conceal albedo markings making semi-permanent changes in its albedo as a function of sub-Earth longitude and latitude.

3. FUTURE WORK

A predicted value accurate to 0.1 mag is likely adequate for planning purposes. However, the algorithms for Mars and the ball of Saturn alone do not meet this modest goal and the algorithms for Mercury and Venus are require an accuracy of 0.03 mag for our products. Improving the predictions will require developing improved algorithms, which will require knowledge of the light-scattering physics of the surfaces and/or atmospheres of the individual planets as input.

3.1 Exo-planets

Another aspect is the planets of the solar system can serve as a testbed for direct observation of exoplanets, *e.g.* HabEx (2019). Too little light is received to make spectroscopy or spectrophotometry possible. Leaving wideband photometry as the best tool to learn about their atmospheres.

For example, the uncertainty in the predicted apparent magnitude of Uranus is 0.02 mag in V. The algorithm for predicting its apparent magnitude is a function of the observer's sub-Earth latitude. Spectroscopy of Uranus shows that the proportion of methane in its atmosphere is a function of latitude and is the source of its change in apparent V magnitude.

Venus is another good example where incorporating our detailed knowledge of a solar system planet can lead to better understanding of an exo-planet through wideband photometry. Sulfuric acid droplets in its atmosphere contribute to two phenomena:

- First, excess light is scattered towards the observer at large phase angles resulting in an *increase* in its apparent magnitude at phase angles between about 165° and 172°.
- Second, a glory is observed at phase angles less than about 10°. Figure 2 is an example of a glory arising from water droplets viewed from an airplane. The physics of a glory are similar to that of a rainbow. Light is scattered away from a phase angle of 0° resulting in a wavelength dependent deficit at very small phase angles as opposed to a surge in the apparent magnitude.

Figure 2: A glory arising from cloud water droplets. Photo credit: Brocken in a glory - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2204135.

The existence of the glory was only recently appreciated (García Muñoz et al. 2014), and the new algorithm does not model it. A better algorithm including the glory should be able to significantly reduce the (O − C)s in Venus' V magnitude.

3.2 Other Wavelengths

The ability to predict the apparent magnitudes of the planets in other bands, particularly the near infra-red is significantly worse. The uncertainty in the apparent magnitudes of the outer planets is about 0.05 mag in R and 0.06 mag in I. The primary obstruction to improvement in these bands is insufficient data rather than the algorithms. There are insufficient data for Mercury, Venus, and Mars in R and I to provide even preliminary predictions.

4. REFERENCES

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