DOI:http://dx.doi.org/10.18524/1810-4215.2020.33.207036

IMAGING POLARIMETRY OF GEOSTATIONARY SATELLITE EXPRESS-AM5

N. Kosaka[1], Y. Itoh[1], T. Saito[1], M. Tozuka[1],
T. Endo[2], T. Ando[2]

[1] Nishi-Harima Astronomical Observatory, Center for Astronomy, University of Hyogo, Hyogo, Japan, *yitoh@nhao.jp*

[2] Information Technology R&D Center, Mitsubishi Electric Corporation, Kanagawa, Japan

ABSTRACT. This paper reports on the optical imaging polarimetry of geostationary satellite Express-AM5. Precise optical polarimetry was carried out using the Nayuta 2-m telescope at Nishi-Harima Astronomical Observatory and a polarimeter. V-band images were continuously taken in 312 minutes. The degree of polarization decreased with time until the minimum phase angle was reached at midnight, and then, it increased until morning. This change in the degree of polarization is well explained by the reflection of sunlight from monocrystalline solar panels of the satellite and possibly from other satellite components such as the antenna dishes and/or bus.

Keywords: Polarization, Planets and satellites: individual: artificial satellite.

АНОТАЦІЯ. Штучні супутники мають спостерігати за допомогою різних астрономічних приладів. Отримавши колір супутника за допомогою фотометричних спостережень, можна оцінити поверхневий матеріал супутника. Кольори супутників, як правило, червоніші за сонячний спектр і супутники різних виробників мають різні кольори. Багато спроб ідентифікувати поверхневий матеріал супутника за допомогою дистанційного зондування було зроблено за допомогою спектроскопії. Ця стаття повідомляє про дослідження оптичної поляриметрії зображень геостаціонарного штучного супутника Землі Express-AM5. Високоточну оптичну поляриметрію проводили за допомогою 2-метрового телескопа Наюта (Nayuta) в астрономічній обсерваторії Ніші-Харіма (Nishi-Harima) та поляриметра. На протязі 312 хвилин у фотометричній смузі V послідовно отримувалися зображення цього супутника. Було отримано що ступінь поляризації зменшувалася з часом, поки близько опівночі не був досягнутий мінімальний фазовий кут, а потім ступінь поляризації супутника збільшувалася до самого ранку. Ступінь поляризації зменшувалася з початку спостережень, і залишалася на надзвичайно низькому значенні, менше 2%, між 22:51 і 24:42 (JST), а потім зросла до 14% у кінці спостережень. Кут поляризації зменшувався протягом ночі. Було досліджено поляризацію як функцію фазового кута супутника. Фазовий кут розраховували за допомогою веб-сайту Calsky. Фазовий кут зменшився з початку спостережень і досяг мінімуму 23,5° о 23:50 а потім збільшувався до самого кінця спостережень. Супутник показав великий ступінь поляризації під великим фазовим кутом. Для одного і того ж фазового кута ступінь поляризації була майже однаковою до і після мінімального фазового кута, що вказує на те, що компонент, що відбиває сонячне світло, був однаковим до і після мінімального фазового кута. Ця зміна ступеня поляризації добре пояснюється відбиванням сонячного світла від монокристалічних сонячних панелей супутника Express-AM5 і, можливо, від інших супутникових компонентів, таких як антенні тарілки та/або інші прилади.

1. Introduction

Artificial satellites have been observed using various astronomical techniques. By obtaining the color of the satellite through photometric observations, one can estimate the surface material of the satellite. Schmitt (2020) carried out optical B-, V-, R-, and I-band photometry of 61 geostationary satellites. They reported that the colors of the satellites are generally redder than the solar spectrum and that satellites from different manufacturers have different colors.

Many attempts at identifying the surface material of a satellite through remote sensing have also been made using spectroscopy. Jorgensen et al. (2004) presented the optical spectra of two satellites. One satellite exhibited a significant increase in reflectance in the wavelengths of the U- and B-bands. The authors considered this to be due to the presence and orientation of the solar panels. They also noticed a broad absorption feature at nearly 8500 Å in the spectra of both the satellites, which was attributed to the presence of aluminum.

Polarimetry is a powerful tool for investigating the surface of a solid body. An asteroid is an astronomical object with a solid surface reflecting sunlight. The reflected light is polarized, and by measuring the degree of polarization, one can estimate the size of the regolith on the surface. Kuroda et al. (2018) observed an extremely low-albedo asteroid in 1998, KU_2. They obtained linear polarization degrees of 44.6% and 44.0% at a phase angle (Sun–asteroid–observer angle) of 81.0° in the *Rc*- and *V*-bands, respectively. These values are the highest for the known airless bodies in the Solar system at similar phase angles. They attributed this high degree of polarization to a highly microporous regolith structure comprising nano-sized carbon grains on the surface of the asteroid.

An artificial satellite has a solid surface. Speicher (2015) observed eight satellites using a 20-inch telescope and a polarimeter. The polarimeter used had a polarizing beam splitter and took horizontally and vertically polarized images simultaneously. A large degree of polarization was observed during dusk and dawn and a small degree polarization at midnight.

Express-AM5 is an active geostationary satellite. This Russian communication satellite was launched in 2013, and it is located in the geostationary orbit at 140° east longitude. The satellite is three-axis stabilized.

In this study, we conducted optical imaging polarimetry of Express-AM5 using a unique polarimeter by which the fluxes of four polarimetric components were recorded simultaneously. We carried out the most continuous polarization measurements of a geostationary satellite to date.

2. Observations

Optical polarimetry of Express-AM5 was carried out on January 19, 2019 using a simultaneous imaging/spectroscopic polarimeter, called POL (Fujita et al. 2009), mounted at the Cassegrain focus of the Nayuta 2-m telescope at Nishi-Harima Astronomical Observatory, Japan (35.025° N, 134.336° E). POL has an unpolarized beam splitter and two Wollaston prisms, which divide light into four channels corresponding to linearly polarized light with polarization position angles of 0°, 45°, 90°, and 135°. The four channels were simultaneously captured in a single image. Each channel has a field of view of $\sim 0.7' \times 2.5'$. The optical magnitude of Express-AM5 was approximately 10 mag in the *V*-band. The celestial coordinate was calculated from a two-line element set. The satellite remained at 9.9° east from the south with an elevation of 48.9° in the sky. We observed the satellite between 21:46 and 27:48 (JST). A total of 162 frames were obtained with a 90-s exposure in the *V*-band. After observing the satellite, we observed HD 154892 as an unpolarized standard star and HD 154454 and HD 161056 as polarized standard stars (Turnshek et al. 1990). All images were taken at a position angle of −29.5° for operational reasons. The seeing size was approximately 1.5". Dark and flat frames were also taken. We think that the light reflected by the flat screen is polarized because a halogen lamp illuminates the screen in the dome from the lower side. We set the rotation angle of the Cassegrain rotator, to which the POL is attached, to 0°, 45°, 90°, and 135°, and took flat frames at each angle.

Data were processed with the Image Reduction and Analysis Facility (IRAF). The object frames were calibrated in a standard manner, namely dark subtraction and flat fielding with the dome-flat frames. The flat frames taken at four rotation angles of the Cassegrain rotator were combined into a single frame. The fluxes of the satellite and standard stars were measured using aperture photometry. The aperture radius was set to 2.5". We calculated the degree of polarization, P, and polarization angle, α, as follows:

$$\frac{Q}{I} = \frac{F_{0^\circ} - F_{90^\circ}}{F_{0^\circ} + F_{90^\circ}} \tag{1}$$

$$\frac{U}{I} = \frac{F_{45^\circ} - F_{135^\circ}}{F_{45^\circ} + F_{135^\circ}} \tag{2}$$

$$P = \sqrt{(\frac{Q}{I})^2 + (\frac{U}{I})^2} \tag{3}$$

$$\alpha = \frac{1}{2}\tan^{-1}(\frac{U}{Q}), \tag{4}$$

where F_θ is the flux density for the light polarized at θ, and Q/I and U/I are the normalized Stokes parameters. In astronomy, $\theta = 0°$ indicates north and $\theta = 90°$ indicates east. The degree of polarization of the unpolarized standard star was measured as 1.54 %. The polarization was caused by the telescope and/or instrument. We subtracted 0.0121 from Q/I and added 0.0095 to U/I such that the degree of polarization of the unpolarized standard star was zero. The same correction was applied to the data on the polarized standard stars and satellite. The measured degree and angle of polarization of the polarized standard stars were different from those described in the literature. The measured Q/I and U/I were transformed using the scaling and rotation matrix on the $Q/I - U/I$ plane; thus, the differences between the measured polarization and that described in the literature were minimum. Based on these differences, we consider the uncertainties to be 3/100th of the polarization degree and 5° in the polarization angle. The same matrix was applied to the satellite data. Among the 163 frames of the satellite data, background stars overlapped the satellite in 9 of the frames, and we did not further use these 9 frames.

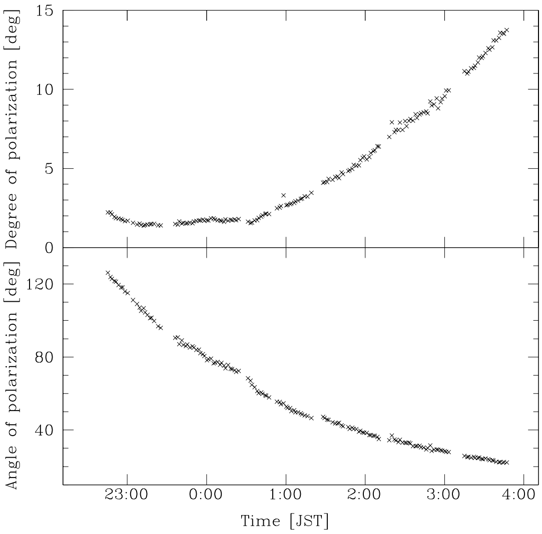

Figure 1: Degree and angle of polarization of Express-AM5 as functions of the observation time.

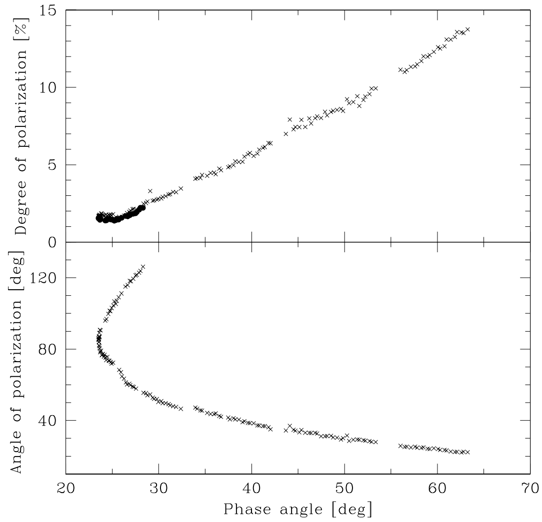

Figure 2: Degree and angle of polarization of Express-AM5 as functions of the phase angle. In the upper figure, the degree of polarization before the minimum phase angle is indicated by the filled circles and that after the minimum phase angle is indicated by crosses.

3. Results

The polarization of Express-AM5 was detected throughout the night (Figure 1). The degree of polarization decreased from the beginning of the observation, and remained at an extremely low value of less than 2% between 22:51 and 24:42 (JST) and then increased to 14% until the end of the observations. The polarization angle decreased throughout the night. Figure 2 shows the polarization as a function of the phase angle of the satellite. The phase angle was calculated using the *Calsky* website. The phase angle decreased from the beginning of the observations and reached a minimum of 23.5° at 23:50 and then increased until the end of the observations. The satellite showed a large degree of polarization at a large phase angle. For the same phase angle, the degree of polarization was almost the same before and after the minimum phase angle, indicating that the component reflecting the sunlight was the same before and after the minimum phase angle.

4. Discussion

The polarization of light reflected by the satellite components was investigated with laboratory measurements. Beamer (2018) measured the polarization of light reflected by a monocrystalline solar panel, a polycrystalline solar panel, a cylinder and a cubic box as a model of a satellite bus, a painted dish antenna, and a painted dish antenna with a fiberglass wire mesh. The intensity of light reflected by the sample in a specific direction was measured using a power meter. The bus and antennae of a geostationary satellite are nadir pointing. To measure the light reflected from the bus and antenna components, those and the power meter were mounted on a rail. A halogen lamp was set separate from the rail, and by changing the orientation of the rail with respect to the halogen lamp, the incidence angle of light to the sample was changed. The solar panels of a geostationary satellite are oriented towards the sun. For measurement, the solar panel was not mounted on the rail but was set normal to the halogen lamp. The reflection angle of the light to the solar panel was changed as the power meter moved. They measured the degree of polarization using an incidence or reflection angle between 15° and 83°. The monocrystalline solar panel showed a degree of polarization of less than 2% at a reflection angle between 20° and 30° and a degree of polarization of $\sim$ 10% at a reflection angle of $\sim$ 60°. The painted dish antenna, the cylinder bus, and the cubic bus showed a degree of polarization of $\sim$ 10% even at a small angle of incidence. The polycrystalline solar panel and dish antenna with a wire mesh exhibited a low degree of polarization at all incidence and reflection angles.

Cognion et al. (2013) claimed that the sunlight reflected from the front of the solar panels dominates the reflection light of a satellite at a phase angle below 85°.

The degree of polarization of Express-AM5 is $\sim$ 2% at a phase angle less than 30° and 13% at 60°. This degree of polarization is roughly consistent with that of the light reflected by a monocrystalline solar panel. We consider the polarization of light reflected from Express-AM5 to be mainly caused by its solar panels.

Nevertheless, the observed degree of polarization of Express-AM5 is 2%–3% larger than the measured degree of polarization of a monocrystalline solar panel. Different solar panels may exhibit larger degrees of polarization. Horváth et al. (2010) indicated that solar panels made by different companies exhibit different patterns of polarization. Száz et al. (2016) verified that an anti-reflective coating changes the polarization properties. Other satellite components, i.e., the bus or dish antennae, may also contribute to the polarization. Endo et al. (2016) found a $B-V$ color variation of approximately 1 mag for Express-AM5, indicating the reflection of sunlight by multiple components. Express-AM5 has three 1.2-m diameter dishes and three larger dishes. All dishes have smooth surface. The diameter of the larger dish seems to be twice that of the small dish (Amyotte et al. 2013). The total surface area of six dishes is 17 m^2, which is larger than the projected area of the bus. The area of the solar panels of Express-AM5 is 84 m^2. If 20% of the reflected light comes from the antennae and 80% from the solar panels, the degree of polarization increases by approximately 2%–3% at a phase angle of 30° and 1%–2% at a phase angle of 60°, compared to the reflection solely by the solar panels.

Speicher (2015) measured the polarization of eight satellites. The polarimeter had a polarizing beam splitter and two optical CCDs, allowing the simultaneous collection of two-channel polarimetry data. The instrument was set to obtain horizontally polarized ray, F_{h}, and vertically polarized ray, F_{v}; then, $S_1/S_0 = (F_{\mathrm{h}} - F_{\mathrm{v}})/(F_{\mathrm{h}} + F_{\mathrm{v}})$ was calculated. Because an alt-azimuth telescope was used and an instrument rotator was not applied, S_1/S_0 differed from Q/I. Two polarized images were obtained for each satellite every 15 min with a 20-s exposure. A negative S_1/S_0 was observed with a large absolute value during dusk and dawn and with a small absolute value at midnight. A negative S_1/S_0 with a large absolute value indicates strong vertical polarization. They considered that the bus or antennae exhibited strong vertical polarization, whereas the solar panels provided only a small contribution to the overall optical signature during dusk and dawn owing to their edge-on geometry. However, as shown in Figure 1, the polarization angle of light reflected by Express-AM5 changed over time because the scattering plane rotated over time. A measurement of linearly polarized light with four polarization angles is mandatory for the polarimetry of a satellite.

When the phase angle is at its minimum, the projected point of the satellite onto the Earth, the projected anti-solar point on the Earth (the anti-sub solar point), and the observer are along a single line. This line is an intersection of the scattering plane and the Earth's surface. Both planes are orthogonal. The position angle of this line is $90^\circ + \tan^{-1}(\frac{35.025^\circ}{134.336^\circ - 140^\circ}) = 9.2^\circ$ west from the north. Assuming a vertical polarization to the scattering plane, the polarization angle of the reflection light is 80.2° at the time of the minimum phase angle. The minimum phase angle was observed at 23:50, and the measured polarization angle was 85.9° at that time. The angle reached 80.2° approximately 10 min later. Because the uncertainty of the measurement is 5° in terms of the polarization angle, we do not consider a discrepancy of 5.7° to be significant.

Unpolarized light is 100% polarized if the incidence angle equals the Brewster's angle. Because the refractive index of a vacuum is 1 and that of a solar panel glass is 1.5, the Brewster's angle of a solar panel is 56°. Speicher (2015) reported that there was no significant increase in the degree of polarization at a phase angle of 56°. In our observations, we also did not find such an increase. Speicher (2015) speculated that an anti-reflective coating on the surface of the solar panel reduces the total reflected light, creating a small polarization. However, as noted by Beamer (2017), a solar panel of a satellite always faces the sun, and thus, the incidence angle of sunlight does not equal the Brewster's angle even when the phase angle is 56°.

Each component of a satellite has its own color. The antennae of Express-AM5 are white, black, or gold, whereas the solar panels of some satellites are bright in the blue and ultraviolet wavelengths. A bus consists of numerous materials. Multi-band imaging polarimetry may resolve the shape, orientation, and surface material of a satellite.

5. Conclusion

We measured the polarization of sunlight reflected by the Russian geostationary satellite, Express-AM5. The degree of polarization in the V-band ranged from less than 2% at approximately the minimum phase angle to 14% at the end of the observations. The polarization vector rotated clockwise in the sky. We concluded that the solar panels, and possibly the antenna dishes and/or bus, contribute to the polarization of the reflected light.

Acknowledgements. This study was supported by a fund from Mitsubishi Electric Corporation.

References

Beamer, D. K.: 2018, *Ph. D. Thesis, University of Dayton*
Cognion, R. L.: 2013, *Proc. of AMOS Conf.*
Endo, T. et al.: 2016, *Proc. of AMOS Conf.*, 922
Fujita, K., Itoh, Y., Mukai, T.: 2009, *Adv. Space Research*, **43**, 325
Horváth, G. et al.: 2010, *Conservation Biology*, **24**, 1644
Jorgensen, K., Africano, J., Hamada, K., et al.: 2004, *Ad. Sp. Res.*, **34**, 1021
Kuroda, D., Ishiguro, M., Watanabe, M., et al.: 2018, *Astron. & Astrophys.*, **611**, A31
Schmitt, H. R.: 2020, *Adv. Space Research*, **65**, 326
Speicher, A.: 2015, *Ph. D. Thesis, University of Denver*
Száz, D. et al.: 2016, *J. of Insect Conservation*, **20**, 663
Turnshek, D. A., Bohlin, R. C., Willamson, R. L. II: 1990, *Astron. J.*, **99**, 1243