

ANALYSIS OF SPECULAR REFLECTIONS OFF GEOSTATIONARY SATELLITES

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Abstract

Many photometric studies of artificial satellites have attempted to define procedures that minimise the size of datasets required to infer information about satellites. However, it is unclear whether deliberately limiting the size of datasets significantly reduces the potential for information to be derived from them. In 2013 an experiment was conducted using a 14 inch Celestron CG-14 telescope to gain multiple night-long, high temporal resolution datasets of six geostationary satellites [1]. This experiment produced evidence of complex variations in the spectral energy distribution (SED) of reflections off satellite surface materials, particularly during specular reflections. Importantly, specific features relating to the SED variations could only be detected with high temporal resolution data. An update is provided regarding the nature of SED and colour variations during specular reflections, including how some of the variables involved contribute to these variations. Results show that care must be taken when comparing observed spectra to a spectral library for the purpose of material identification; a spectral library that uses wavelength as the only variable will be unable to capture changes that occur to a material's reflected spectra with changing illumination and observation geometry. Conversely, colour variations with changing illumination and observation geometry might provide an alternative means of determining material types.

1 INTRODUCTION

In 2016, high temporal resolution photometry measurements using Bessel B, V, and R filters were obtained on ten geostationary satellites. Lightcurves and colour plots were produced with the aim of identifying patterns in the colour changes that occur to multiple satellites, particularly during specular reflections. The results demonstrate that the nature of colour changes during glints can vary significantly from one satellite to another. Rather than being able to determine material types by simply comparing observations to a spectral library, the orientation of the material with respect to the sun and the sensor must be understood too. If the material type is already known in advance, then the nature of the colour variation during a glint might allow the orientation of the material to be inferred.

2 EXPERIMENT SETUP AND PROCEDURE

Throughout the experiment, observations were taken using the 20 inch Officina Stellare Falcon Telescope Network (FTN) telescope located in Canberra, Australia, fitted with an Apogee Alta F47 camera. The telescope is mounted on a Paramount ME2 mount, and includes a nine slot filter wheel. Only standard Bessel BVR filters were used in the filter wheel for this experiment [2]. A more complete description of the FTN telescope setup is provided by Chun et al [3].

2.1 DATA ACQUISITION

Observations were conducted on a total of ten Geostationary satellites on six separate nights during August and September 2016. On all of the nights except for 05 September and 06 September there were two satellites visible in each of the images. Table 1 details the satellites that were observed throughout the experiment.

At the beginning of each observation session 15 bias frames, 10 dark frames of one minute exposure time, and 10 flat frames in each filter were taken. Master bias, dark, and flat frames were created by median combining the individual images. In addition, Landolt star fields were imaged either at the beginning or at the end of each observing session such that zero points could be calculated for each of the filter passbands and airmasses through which the target satellites were observed. The zero points were subsequently used

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| Date | Satellite | Bus Type |
|-----------|--------------|------------------|
| 11 Aug 16 | IRNSS 1G | I-1K |
| 11 Aug 16 | TDRS 9 | BSS-601 |
| 13 Aug 16 | IRNSS 1G | I-1K |
| 13 Aug 16 | TDRS 9 | BSS-601 |
| 26 Aug 16 | JCSat 3A | A2100AX |
| 26 Aug 16 | JCSat RA | A2100AXS |
| 26 Aug 16 | Yamal 300K | Ekspress-1000HTA |
| 26 Aug 16 | NSS 9 | GEOStar-2 |
| 27 Aug 16 | Optus C1 | LS-1300 |
| 27 Aug 16 | Optus D3 | GEOStar-2 |
| 05 Sep 16 | Chinasat 5A | A2100A |
| 06 Sep 16 | Intelsat 805 | AS-7000 |

Table 1: Satellites observed during the experiment.

to calibrate instrumental magnitudes to the standard apparent magnitude scale. Images were obtained of the target satellites with tracking turned off and the imaging sequence programmed into The Sky X, which automatically cycled through each of the filters.

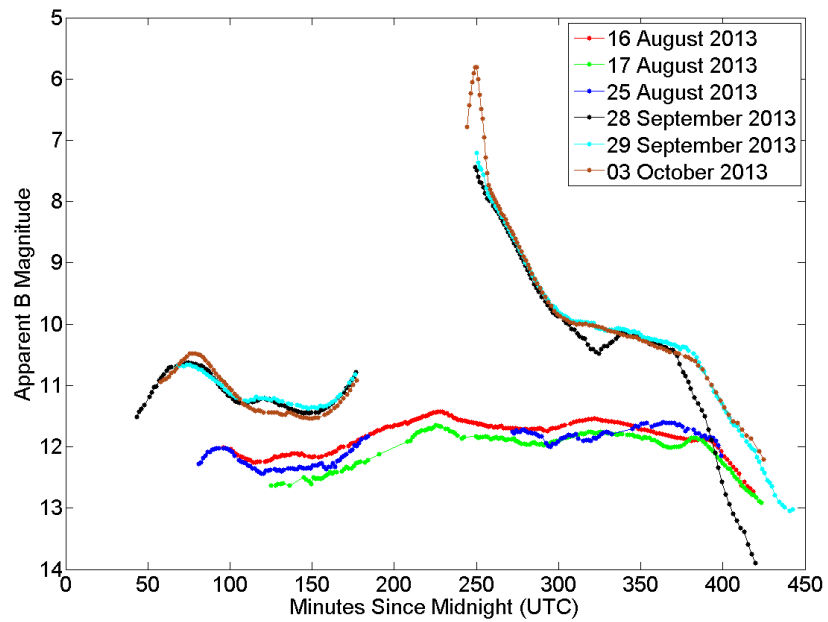
Throughout each night a signal level of between 5000 ADU and 10000 ADU was attempted to be maintained for the brightest pixel illuminated by the satellites being observed. The signal level was deliberately kept relatively low, without introducing unreasonably large errors, such that exposure times could be kept as short as possible, thus maximising the data rate. When the brightness was seen to increase markedly it was necessary to reduce the exposure time to avoid saturating any of the pixels; and when the brightness decreased the exposure times were increased to maintain sufficiently high SNRs. Typical exposure times were approximately 10-15 seconds for the R filter, 15-20 seconds for the V filter, and 20-30 seconds for the B filter, although exposure times were reduced significantly when the satellites were observed to be glinting.

Image processing was conducted using Mirametrics' Windows based Mira Pro X64 software program. The image reduction procedure involved subtracting the master bias and dark frames and applying flat field corrections to the data images. Instrumental magnitudes were calculated by using Mira's aperture tool. The nightly zero points were added to each satellite's measured instrumental magnitude to arrive at the apparent magnitude. All magnitude data were exported from Mira to Microsoft Excel, and then input to Matlab for plotting. For each of the satellites that were observed, lightcurves were constructed for each of the filter bands, as well as R-V, R-B, and V-B colour plots. Data points are generally spaced less than one minute apart on each lightcurve. To account for the fact that images were not taken simultaneously through each filter, the colour plots were created by interpolating between data points at every minute for each filter. The interpolated values of one filter were then subtracted from the interpolated values of another filter. Time (represented as minutes since midnight UTC) is placed on the horizontal axis for all plots.

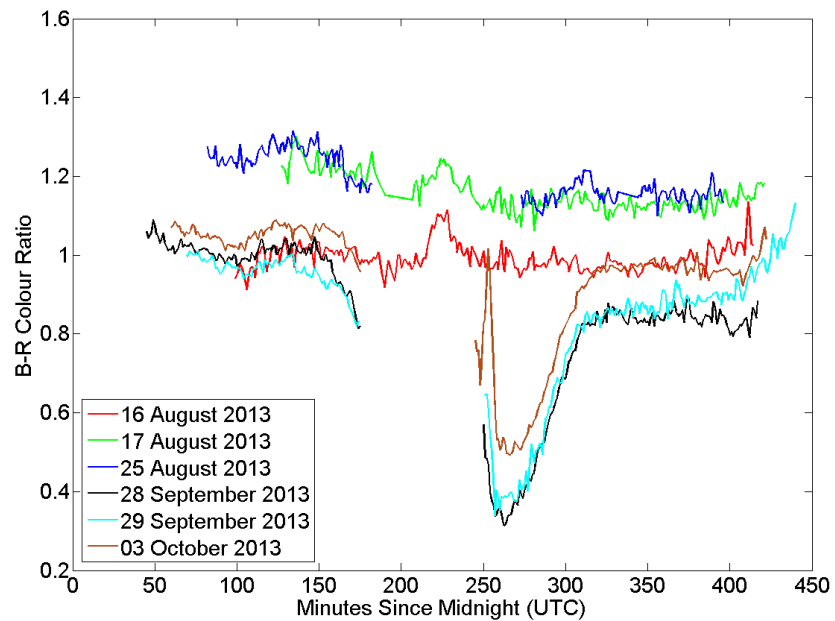
3 DISCUSSION

Many studies into the use of broadband photometry for satellite characterisation assume that the SED of light reflected off a given surface is invariant [4–10]. Bédard has presented evidence based on laboratory studies that this assumption is incorrect [11], and an experiment conducted by the author in 2013 supported that conclusion [1]. Results from the 2013 experiment, which analysed geostationary satellite lightcurves and colour plots obtained over multiple nights for each satellite, indicated that complex colour changes of significant magnitude can occur over short time periods, particularly during bright specular reflections. Figure 1 depicts sharp changes in colour variation for Intelsat-805 during bright glints, as well as subtle colour changes on nights that did not feature bright glints.

During the 2013 experiment, Intelsat-805 was observed by the author from the Royal Military College of Canada, Kingston, Ontario. Since then, Intelsat-805 has been moved to a new location above Eastern Australia, and it was observed again during this experiment. As can be seen in Figure 2, Intelsat-805 exhibits a similar colour variation during the bright specular glint off its solar array that it did during the



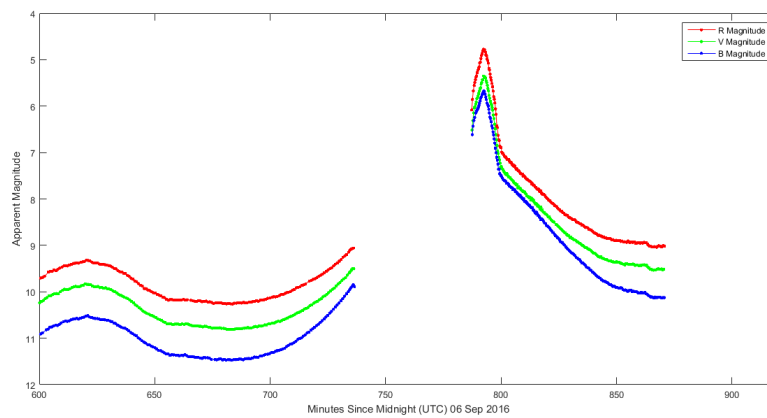
(a) Intelsat-805 B Band Lightcurve.



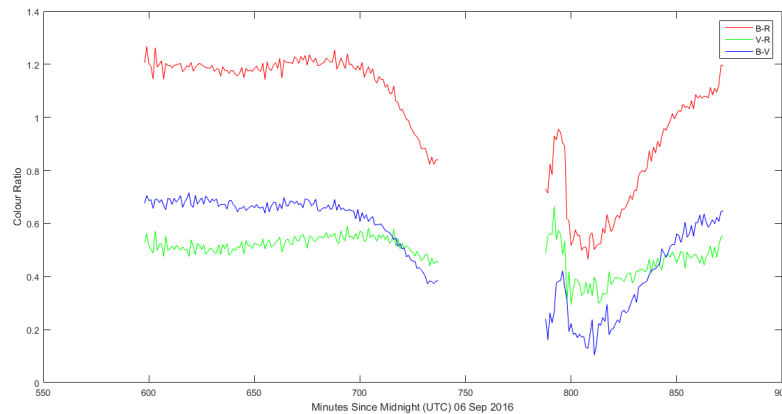
(b) Intelsat-805 B-R Colour Variation.

Figure 1: B Band Lightcurve for Intelsat-805 (a), compared with its B-R colour variation (b).

2013 experiment, whereby the colour initially becomes more blue before suddenly reddening markedly within 10 minutes of the centre of the glint.



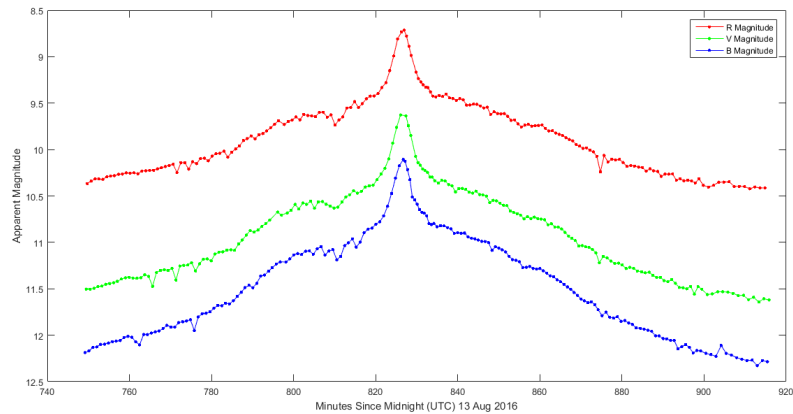
(a) Intelsat-805 B, V, and R Magnitudes.



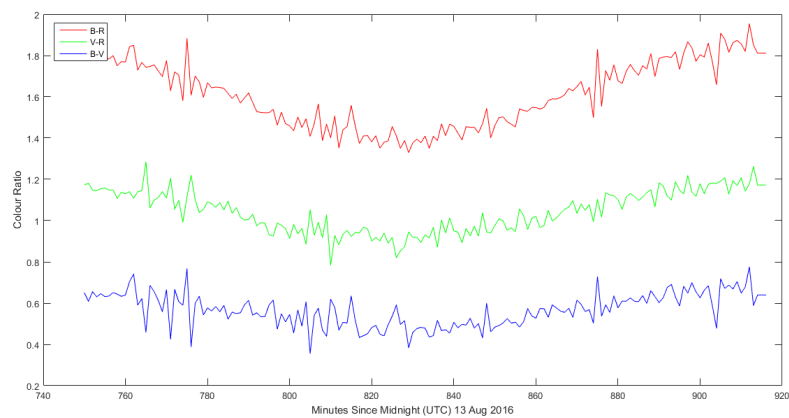
(b) Intelsat-805 Colour Plots.

Figure 2: B, V, and R lightcurves for Intelsat-805 (a), compared with its colour plots (b).

What remains unresolved, however, is which variables contribute to colour variations for a given satellite, and to what degree. During this experiment ten different satellites were observed, and colour plots produced, such that it could be determined whether any patterns exist regarding colour variation for different satellites. Some of the satellites, such as TDRS-9, exhibited a relative increase in shorter wavelength intensity during specular reflections, as is commonly associated with reflections off solar arrays [12]. In Figure 3 it can be seen that a glint of approximately one magnitude in brightness resulted in TDRS-9 becoming relatively more blue. A broad glint of approximately 3.5 magnitudes in Optus-D3's lightcurve, centred at approximately 840 minutes since midnight, also produced a significant increase in the shorter wavelength intensities, as depicted in Figure 4.

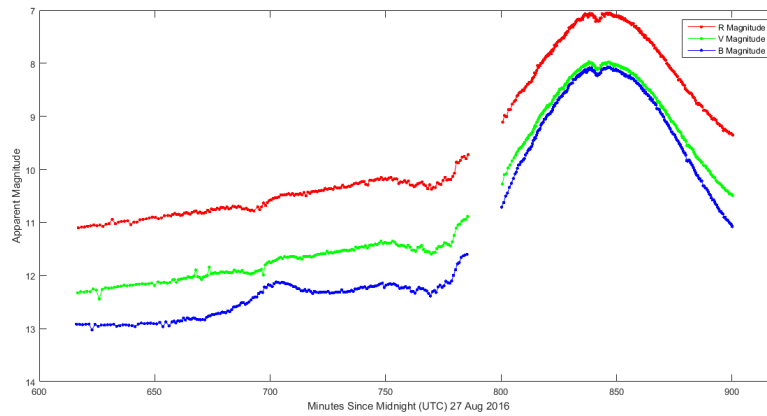


(a) TDRS-9 B, V, and R Magnitudes.

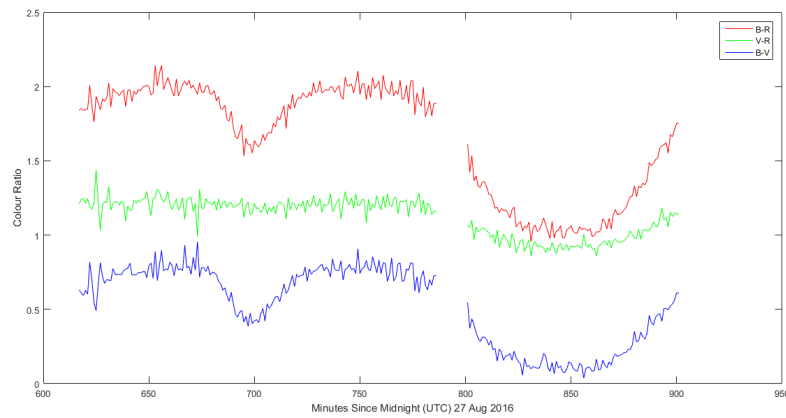


(b) TDRS-9 Colour Plots.

Figure 3: B, V, and R lightcurves for TDRS-9 (a), compared with its colour plots (b).



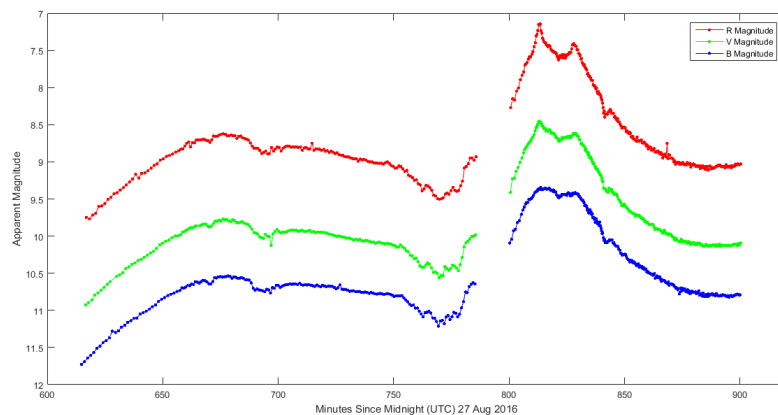
(a) Optus-D3 B, V, and R Magnitudes.



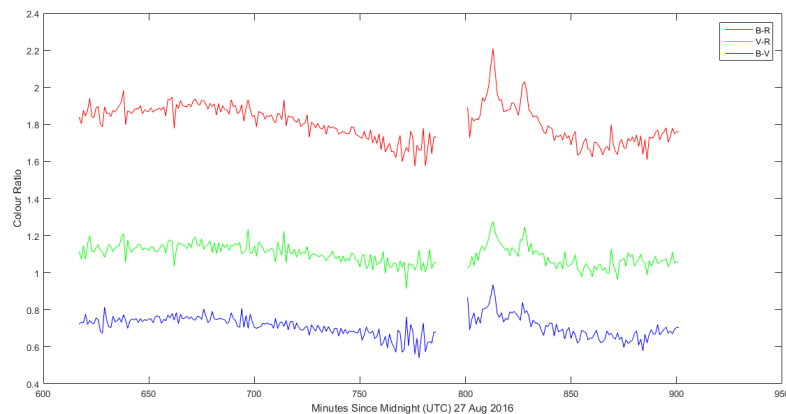
(b) Optus-D3 Colour Plots.

Figure 4: B, V, and R lightcurves for Optus-D3 (a), compared with its colour plots (b).

Other satellites, however, exhibited opposite colour variations during glints. Optus-C1, for example, showed an increase in longer wavelengths across a glint of approximately two magnitudes brightness, as seen in Figure 5. If it is assumed that the main glints in each of these lightcurves are all caused by specular reflections off solar arrays, then the colour changes indicate that bright reflections off solar arrays do not always result in the colour becoming more blue. The colour was also observed to become relatively more red during the main glint for NSS-9. It is tempting to conclude that colour changes during glints might provide a relatively simple means of identifying particular solar cell types, however Bédard has previously demonstrated that the reflected spectra off common spacecraft materials can be significantly dependent on the illumination angle [11]. Whilst it remains possible that colour changes could assist in identifying material types, the illumination and observation geometry needs to be taken into account as well. Conversely, if the solar cell type is already known, the nature of the colour change might provide a means of inferring the orientation of the solar arrays with respect to the sun.



(a) Optus-C1 B, V, and R Magnitudes.

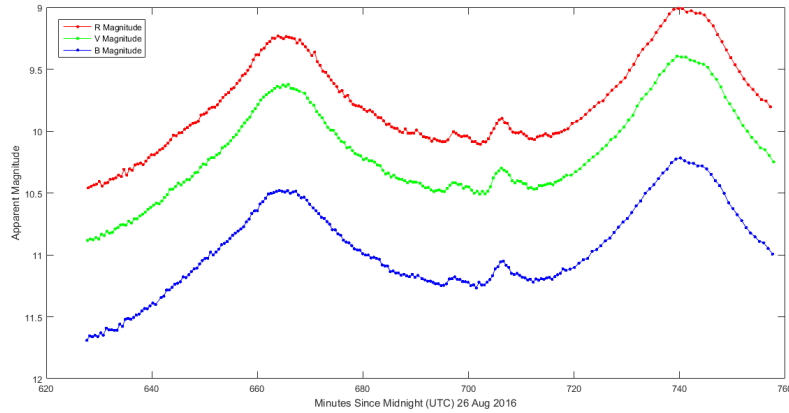


(b) Optus-C1 Colour Plots.

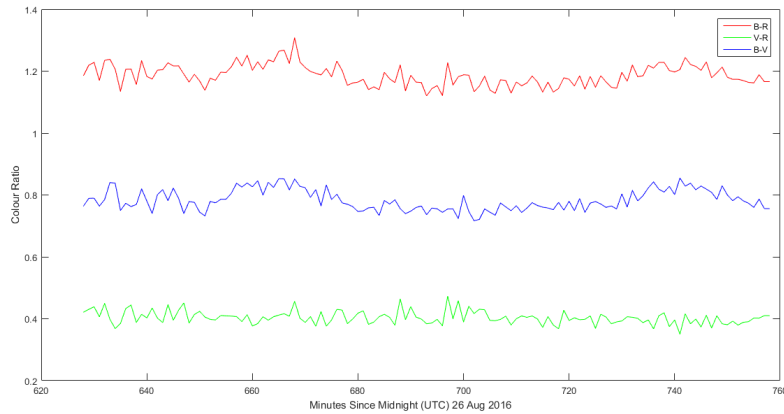
Figure 5: B, V, and R lightcurves for Optus-C1 (a), compared with its colour plots (b).

In addition to some glints causing the colour to become either more red or more blue, some satellite glints caused barely perceptible colour changes. For example, Yamal-300K's lightcurve, at Figure 6, displays two broad glints centred at 665 minutes since midnight and 740 minutes since midnight, however its colours barely change throughout the observation period. The broad glints, spaced well apart, are not characteristic of how geostationary satellite solar array glints are commonly understood to appear. Glints off geostationary satellite solar arrays are usually narrower in appearance, with sharper peaks, and if there is more than one peak they are usually spaced much closer together. The reason for this is that satellite solar arrays exhibit

highly specular reflections and usually track the sun quite closely. As can be seen in Figure 7 Yamal-300K has two antennas located either side of the main satellite bus. Although this experiment obtained insufficient data to conclusively determine the source of Yamal-300K's glints, it is possible that they were caused by the antennas rather than the solar array. Further investigation is warranted to determine whether glints caused by satellite antennas can be differentiated from glints caused by solar arrays by the nature of the colour changes that they produce.



(a) Yamal-300K B, V, and R Magnitudes.



(b) Yamal-300K Colour Plots.

Figure 6: B, V, and R lightcurves for Yamal-300K (a), compared with its colour plots (b).

4 CONCLUSION

During this experiment ten geostationary satellites were observed over six separate nights with the aim of determining whether any patterns could be identified regarding how colours vary during specular reflections. The satellites' colours were observed to vary in a variety of different ways. In some cases the colours became more blue during glints, and in other cases the colours became more red, even when the glints were likely to be off solar arrays. Intelsat-805's colour became markedly more blue before sharply reddening again at the centre of the glint, and in other cases significant brightness changes resulted in almost no apparent colour change at all. Further investigation is required to determine all of the relevant variables that contribute to how a given satellite's colour will vary during specular reflections, however it is apparent that it is not feasible to use a simple spectral library that has wavelength as its only variable to identify material types.

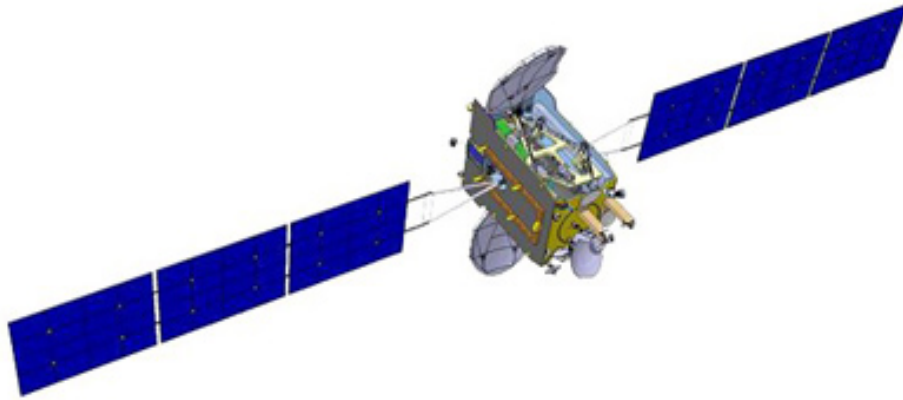


Figure 7: Yamal-300K [13].

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