CHALLENGES RELATED TO DETECTION OF THE LATENT PERIODICITY FOR SMALL-SIZED GEO DEBRIS

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Abstract. The urgent problem is to find signatures in addition to orbital parameters in order to identify space debris and to establish its lineage. Variability of the brightness is a typical feature of space debris. It is associated with an object's rotation or/and swinging around any arbitrary axis. The study of periodicity of light curves can yield valuable information about the nature of such objects. However, revealing the periodicity for debris, especially small ones, is not a simple problem. The signal-to-noise ratio is the determining factor in this study. We consider various frequency analysis methods applied to photometrical observational data of space debris at the 1.7-meter telescope of Sayan Observatory. The advantages of the nonparametric methods are shown. Some practical results are presented.

1. Introduction

The problem of space debris results in modernization and development of new space monitoring systems. However, most of them are meant for quality improvement and expansion of measurements of orbital elements. At the same time, gathering of non-coordinate data is an important problem related to the origination and evolution of space objects in near-Earth space. The main optical methods for obtaining non-coordinate data are the photometry and spectrometry of objects under investigation. These methods are based on measurements of the solar radiation reflected from elements of the satellite's construction. When these objects rotate, the reflected luminous flux is modulated due to different spectral characteristics and scattering indicatrix of the satellites' construction.

Examination of the temporal variations of an object's brightness allows us to obtain important information about object's construction and spatial orientation. Non-coordinate data are of special importance when examining small space debris with orbital parameters hard to define. These data are often the only possibility to determine the origin of an object and to identify it. Of great importance is the examination of periods of the object's proper rotation with the use of different methods for frequency analysis of time series.

2. Observations and processing

The study of space debris at Sayan Observatory of ISTP SB RAS started in 2007. Observations were made by means of the 1.7-meter telescope, AZT33-IR, with the CCD photometer connected with optical reducer of the Cassegrain focus of the telescope. The CCD photometer comprises the CCD camera S3C and the set of color filters, BVRI, similar to the standard Johnson-Cousins system, placed in front of it. Measurements were made in the tracking mode along ephemeris.

Selection of the exposure time is a key point of observations. On the one hand, detection of possible high-frequency variations in object's brightness requires measurements with the highest time resolution. On the other hand, the signal-to-noise ratio should be taken into account, when selecting the exposure time in order to obtain statistically significant values. The exposure time for filters R and V was from 1 to 5 s on average; that for the filter B was from 5 to 20 s. Duration of the series of observations depended on the expected period of brightness variation.

The aperture photometry method was applied for a preliminary processing of frames aimed at obtaining instrumental magnitudes. The Landolt standard fields, measured simultaneously with the object under observation, were used for converting data into the standard system. The final results of the processing are time dependences of the objects' brightness (light curves) adjusted to the standard BVR bands. In this study we use light curves obtained in V-band.

3. Frequency analysis methods and peculiarities of studying faint fragments

Most fragments of space debris can be characterized by brightness variability caused by their rotation. Frequency analysis methods should be applied to revealing the characteristics of the periodic variations of the reflected radiation. It is obvious that the choice between the different frequency analysis methods should depend on features of the time series under study.

When choosing a method for analysis, the following factors should be taken into account:

- signal-to-noise ratio;
- total amount of counts;
- average number of measurements during a period;
- form of the periodic oscillation;
- detailed temporal distribution of counts;
- availability of a priori information about the period and the oscillation form

(for more details, see [1]).

The frequency analysis methods can by divided into parametric and non-parametric [1, 2]. Methods of first type are based on the comparison of the time series under study with a certain oscillation specified in advance. The most famous method of this approach is the Fourier analysis comparing oscillations under study with harmonic ones. Though this method is widely applied, it has some restrictions. In particular, methods, based on the Fourier transform, yield bad results if the oscillations differ from the sinusoidal form.

Non-parametric methods are weakly sensitive to the signal form. These methods are based on construction of so-called phase diagrams by folding the time series with different values of trial periods. Periods, within which the scatter of points in phase diagrams is a minimum, are true. There are some non-parametric methods that differ in the value characterizing the data spread in the phase diagram. One of the widespread methods is based on the Abbe-Lafler-Kinman statistics [3] representing the sum of squares of differences in ordinates of consecutive points in the phase diagram.

When analyzing observed data, it is reasonable to calculate periodograms of both types, since they provide mutually complementary data on the process under study. The analysis is preceded by the following actions: the trend is removed from the initial series; values of the series are reduced to the zero mean and smoothed in order to remove random noise.

An important statement of the problem of the search for periodicity is the signal-to-noise ratio in basic data. The main noise sources have different nature:

1) statistical noise;
2) detector noise;
3) noise, resulting from atmospheric fluctuations.

Fig. 1 shows the precision of photometric measurements of the optoelectronic system (AZT33-IR+CCD-photometer) defined as a signal-to-noise ratio (SNR), depending on the exposure time (t_exp) and the object's brightness (m) in the spectral band V.

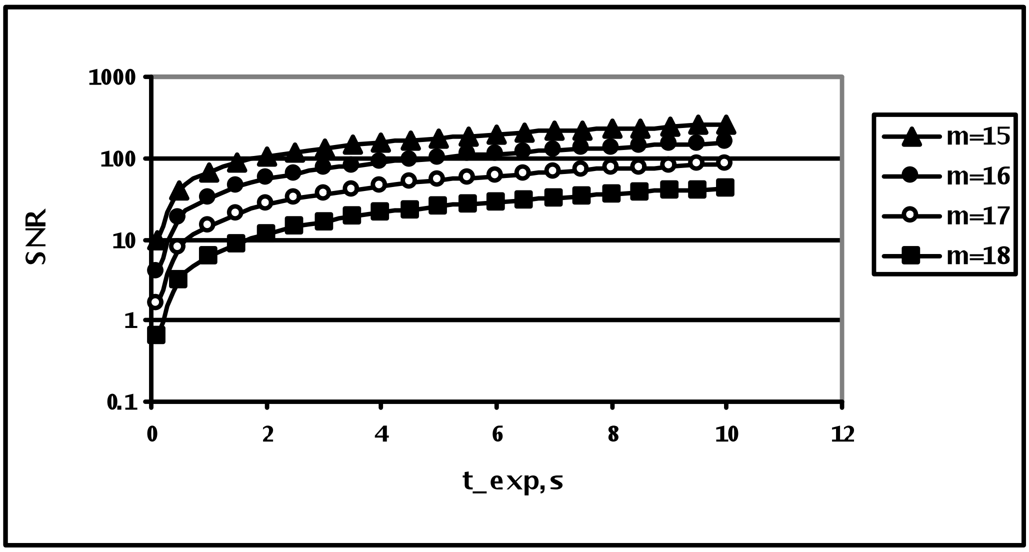


Fig.1 Signal-to-noise ratio for AZT33IR+CCD S3C.

For a 16th magnitude object with an exposure of 5 s, precision (depending only on static fluctuations of the registered flux and on detector noise) will be 1%. So we can obtain precise magnitude measurements of such an object in relatively short exposures. The measurement of fainter objects with the desired precision requires a significant prolongation of the exposure time. This leads to problems for determining short-term periods.

The noise resulting from atmospheric fluctuations is irremovable during CCD observations; consequently, photometric observations should be made under good astroclimatic conditions.

4. Results

This paper presents results of the investigation into the periodicity of the brightness variation of some fragments that formed after the explosion of the Russian communication satellite “Ekran 2” (10365/77-092001). Nine fragments of this spacecraft, with brightness from 13 to 18 magnitudes, have been catalogued by now. The biggest fragments demonstrate a regular character of light variations. Periods of the light variations of different objects are in the range from a few seconds to hundreds and thousands of seconds; their amplitudes, from a few magnitudes to tenths of magnitudes.

The amplitude of the light variations of the faintest fragments (V<16 mag) is 0.1-0.2 magnitudes (fig. 2). The noise amplitude of the faint fragments may exceed several-fold the variability amplitude and, thus, hampers search for a period. So the problem of periodicity of light variations of these fragments is still unsolved.

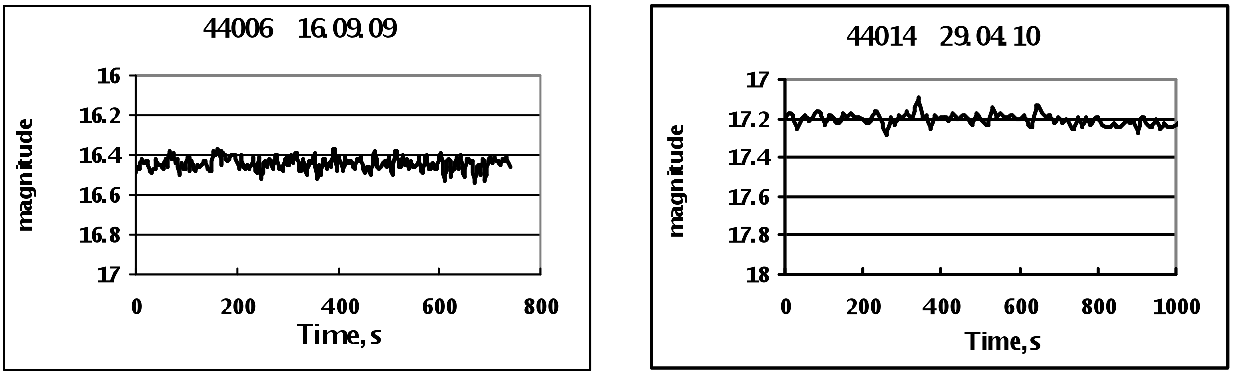


Fig.2 Typical light curves of faintest fragments of “Ekran 2”

Here we use the Fourier and Lafler - Kinman methods to investigate periodicity in light curves of different shapes.

4.1 Study of a quasi-sinusoid light curve as exemplified by the parent body of "Ekran 2" (No.10365/77-092001)

Light curves of “Ekran2” parent body have a simple form, close to a sinusoidal one, but with a slight difference between amplitudes of “even” and “odd” peaks (fig.3). The last fact suggests two maxima within the rotation period.

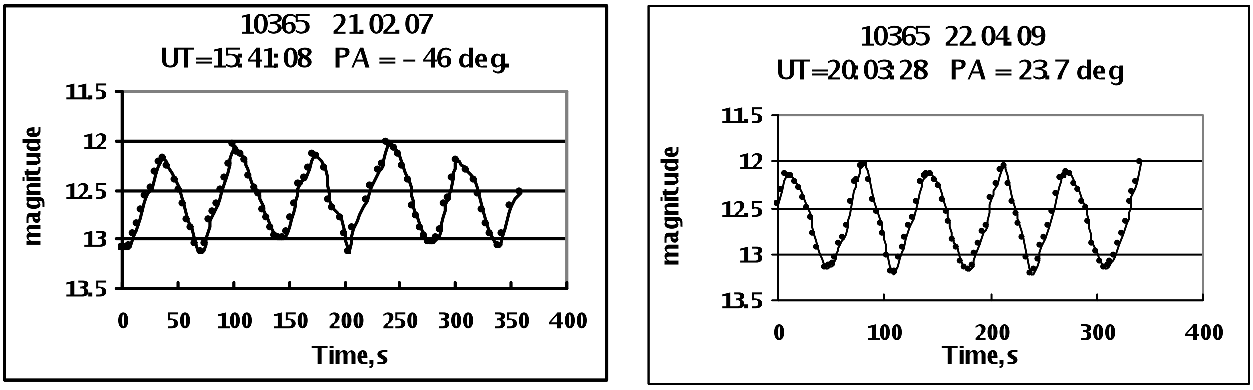


Fig.3 Examples of light curves of the parent body “Ekran 2”

Let us consider results of different frequency analysis methods, with a time series obtained from 22.04.09 as an example. When specifying the same range of periods, in the Fourier spectrum we observe one peak corresponding to the period 65.5 s (fig.4), whereas the main minimum of the Lafler-Kinman periodogram corresponds to the period 131.15 s (fig.5). (There is a minimum with less depth at the frequency corresponding to the second harmonics of oscillations).

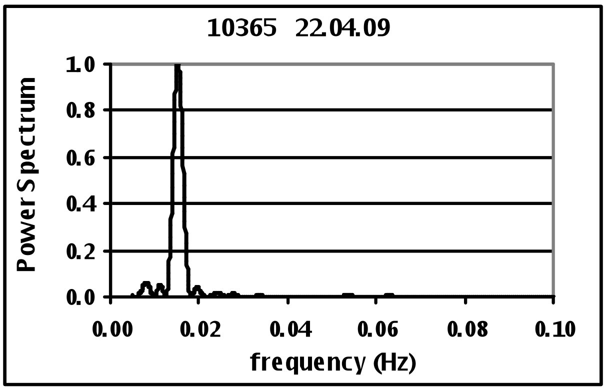


Fig.4 Fourier spectrum (maximum corresponds to the period 65.5 s)

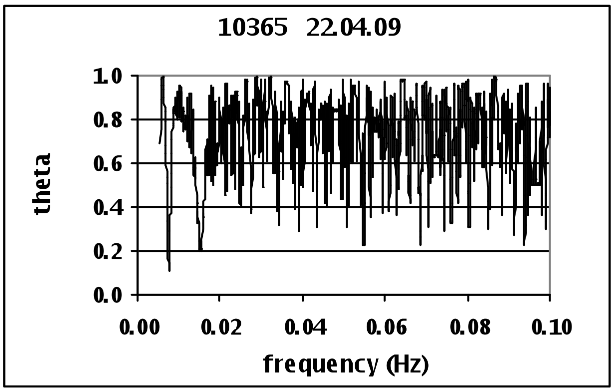


Fig.5 Lafler-Kinman periodogram (minimum corresponds to the period 131.15 s)

Fig. 6 presents the phase diagrams obtained by folding the data with the periods of 65.5 s and 131.15 s.

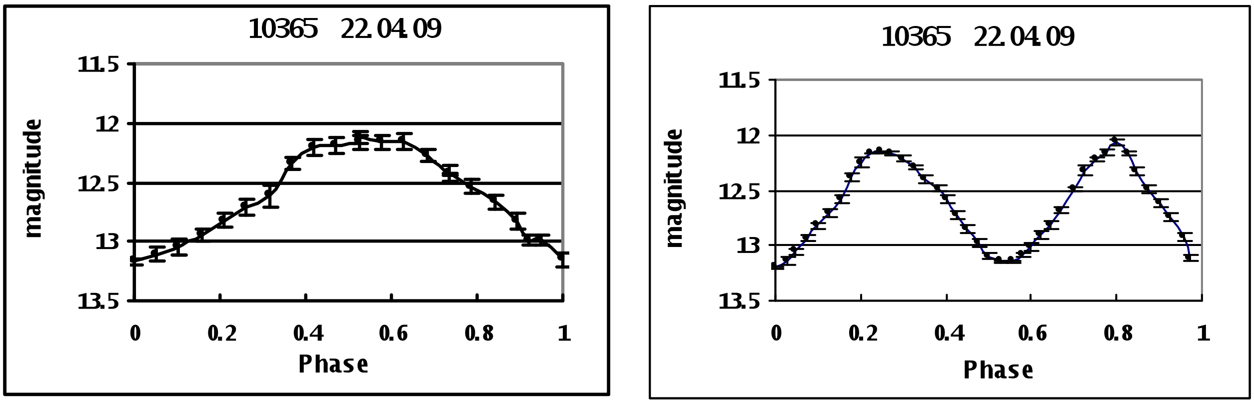


Fig.6 Phase diagrams obtained by folding the initial data for 22.04.09 with the periods of 65.5 s (on the left) and 131.15 s (on the right).

As evidenced by figure 6, folding with a period of 131.15 s provides the minimum data spread relative to the mean value (vertical lines in diagrams) and reproduces the exact shape of the original light curve. So we think that the last period is the real satellite rotation period.

Consequently, nonparametric methods should be applied for studying light curves with 2 peaks, since methods based on the Fourier analysis reveal the second harmonics instead of revealing the real period of rotation.

4.2 Investigation of a multiperiodic light curve by the example of the fragment of "Ekran 2" No. 11581/77-092008.

Light curves of the fragment of "Ekran 2" No. 11581 have a more complex shape and contain two periodical components (fig. 7).

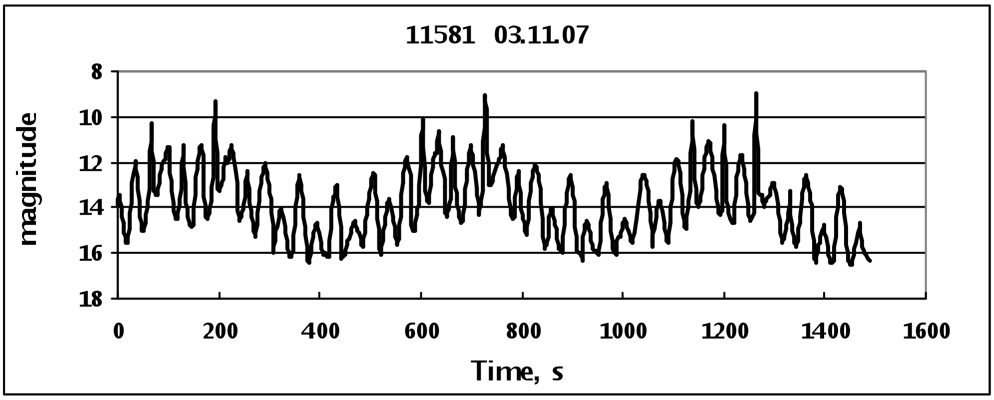


Fig.7 Example of light curves of the fragment No. 11581

The high-frequency component we associate with the object's rotation about the centre of mass; the low-frequency component - with the spin-axis precession.

The study of periodical structure of the light curves consisted of several stages.

1. Smoothing of the initial series in order to remove the high-frequency component (fig.8).

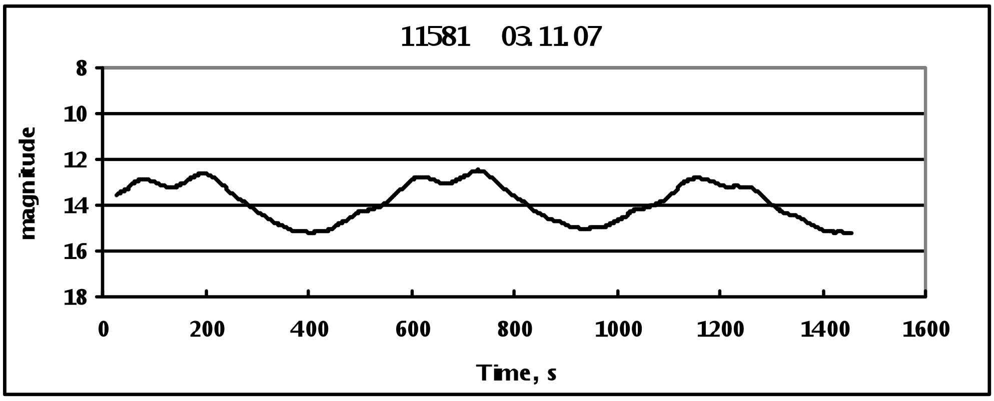


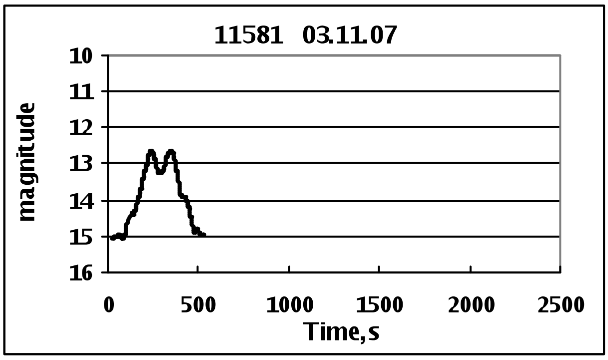
Fig.8 Low frequency component of the light curve

2. Definition of the low-frequency component's period.
3. Removal of the low-frequency component from the initial series ("prewhitening") and analysis of the residual series.

Both the Fourier and Lafler-Kinman methods provide similar results for the low-frequency component, whose form is close to sinusoidal. For the light curve of 3 November 2007 (Fig. 8), these are 522.4 s and 521.5 s, respectively.

The high-frequency component has double peak structure like in the previous case. The main maximum of the Fourier spectrum also falls on the second harmonics of the rotation period (33.4 s for the series under investigation). There is also an additional peak with a lower power, corresponding to the period of about 67 s. The main minimum of the Lafler-Kinman periodogram corresponds to the period 67.3 s .

Let us now consider results of folding of each component of the initial series with the previously founded periods for the two data sets obtained in 2007 and 2009 (Fig. 9, 10). We plot the time on the abscissa instead of the oscillation phase in order to show the real value of periods.



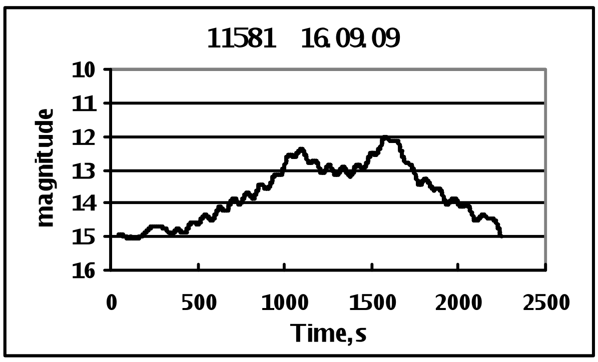
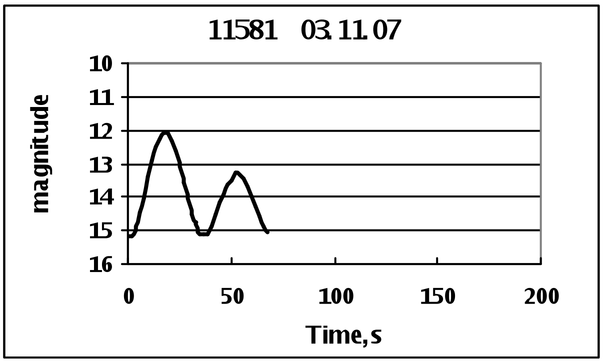


Fig. 9 Average light curves for low-frequency



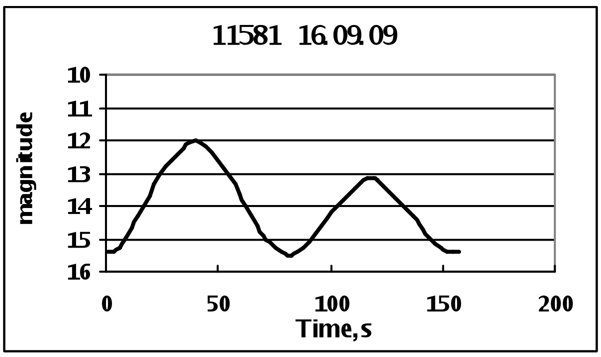


Fig. 10 Average light curves for high-

component for two dates of observation. frequency component for two dates of observation.

Note that the shape of mean light curves stays nearly constant during the entire period of observations, whereas values of both periods increased several times! (period of precession from 521s to 2280 s; period of rotation – from 67.3 s to 155 s).

4.3 Study of the light curve having a complex shape by the example of the fragment of "Ekran 2" No. 12996/77-092009.

The fragment of "Ekran 2" No. 12996 displays fast brightness variability (Fig. 11).

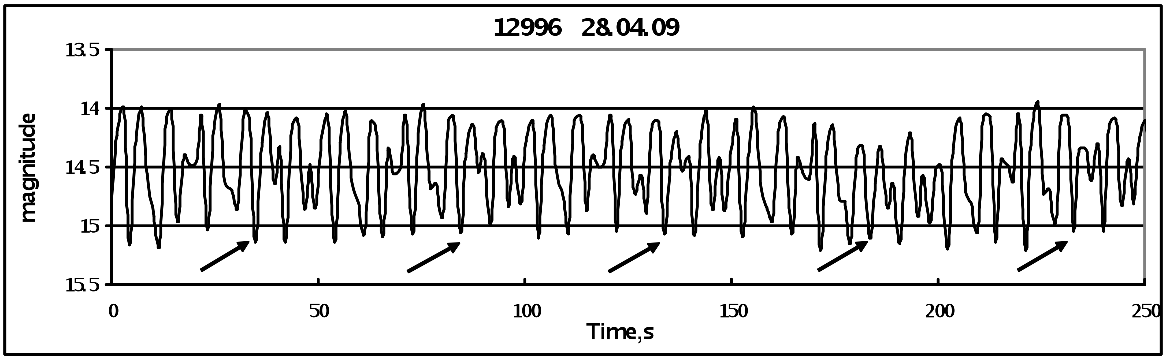


Fig.11 Example of light curves of the fragment No. 12996

Fourier spectrum for this series shows one peak corresponding to the period 6.2 s (fig.12)

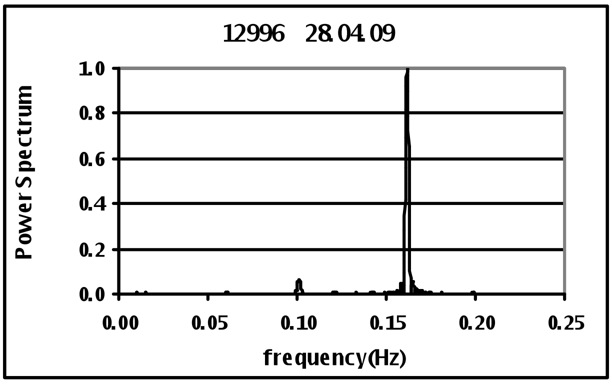


Fig.12 Fourier spectrum of the time series for the fragments No. 12996

However, the detailed consideration of the light curve reveals structures that repeat every 50 seconds (depicted by arrows in the figure 11). This led us try to find the rotation period with the Lafler-Kinman method, by specifying the range of trial periods near 50 s. A period of 49.5 s was thus found. Folding of data with this period resulted in the phase curve that reproduced the structure of the initial series in detail (Fig. 13).

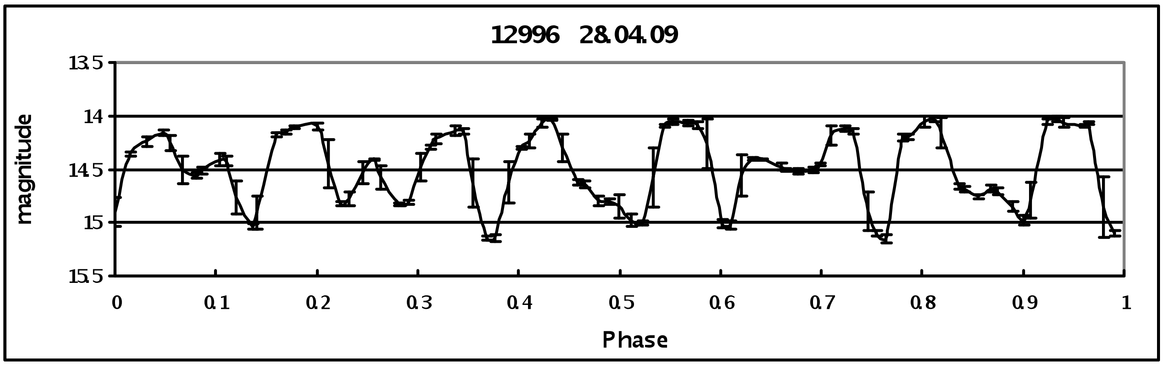


Fig.13 Phase diagram for a period 49.5s

Conclusion

Most fragments of space debris display periodic light variations in the range from a few seconds to hundreds and thousands of seconds. Long-term series with short exposures are required to determine such periods. Hence, the requirements for equipment and a technique for obtaining observation series are as follows: possibility to register luminous fluxes with high time resolution and to track object during a long-term period of time. An important aspect of problem of the search for periodicity is the signal-to-noise ratio in the initial data. The noise amplitude of faint fragments may exceed by several-fold the variability amplitude, and thus hampers the search for a period. To study small GEO debris, medium and large aperture telescopes with high-sensitivity radiation detectors should be used.

The frequency analysis of the time series of the brightness of some fragments of "Ekran 2" is performed with the Fourier and Lafler-Kinman methods. The Lafler-Kinman method turns out to be the most preferable for the study of non-sinusoidal light curves.

Analysis of phase diagrams, obtained by folding the light curves with known periods, enables us to study the light curve's structure in detail and to reveal its characteristic properties.

References

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