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Observations of astronomical objects using radio (Irbene RT-32 telescope) and optical (Baldone Schmidt) methods

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Institute of Astronomy (University of Latvia) with Ventspils International Radio Astronomy Centre (Ventspils University of Applied Sciences) participation is implementing the scientific project "Complex investigations of the small bodies in the Solar system" which is related to the research of the small bodies in the Solar system (mainly focusing on asteroids and comets) using methods of radio and optical astronomy and signal processing.

To detect the rotation period and other physical characteristics of NEO objects using optical methods, 566 positions and photo-metric observations of NEO objects 2006 VB14 = Y5705 = 345705 (hereafter 2006 VB14) and 1986 DA = 6178 (hereafter 1986 DA) were obtained with Baldone Schmidt telescope in 2018. A Fourier transform was applied to determine the rotation period for asteroid 1986 DA. Value 3.12 ± 0.02 h was obtained. Observations confirm the previously obtained rotation period $P = 3.25$ h for 2006 VB14.

To detect weak ($\sim$0.1 Jy) OH maser of astronomical objects using radio methods, a researcher group in VIRAC adapted Irbene RT-32 radio telescope working at 1665.402 and 1667.359 MHz frequencies. Novel data processing methods were used to acquire weak signals. Spectral analysis using Fourier transform and continuous wavelet transform were applied to radio astronomical data from multiple observations related to weak OH maser detection. Successful observations of multiple galactic masers were carried out in 2019 and adapted Irbene RT32 radio telescope is ready for the observations of comets in the near future.

Keywords: Asteroids, comets, OH maser, rotation period, data processing

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1 Introduction

The surfaces of smallest planets and moons of the Solar system are covered with large number of craters created by asteroids. Every day the Earth is bombarded with more than 100 tons of dust and millimeter-sized particles from space. About once a year, a two meter sized asteroid hits the Earth's atmosphere, often creating a bolide event as the friction of the Earth's atmosphere causes them to disintegrate – sometimes explosively. The largest impact during this 20-year interval was the recent daytime Chelyabinsk event (in order of 500 kilotons) recorded over central Russia on February 15, 2013. This small asteroid that exploded in the atmosphere near Chelyabinsk, Russia was about 16 meters in size before it hit the Earth. About every 5 years a Chelyabinsk type event occurs. While that impact focused public attention on the potential hazards of Near-Earth objects' (NEO – asteroids or comets of sizes ranging from metres to tens of kilometres and its closest approach to the Sun is less than 1.3 AU) impacts with Earth, planetary scientists have long known that such events are just a part of Earth's geologic history. Scientific assessments of the risk of, as well as the hazards posed by, future impacts by comets or asteroids can link to several events on Earth. An article published in Nature (2013) by Peter Brown and his colleagues reported that astronomical surveys "have only discovered about 500 near-Earth asteroids that are 10–20 meters in diameter (comparable to the Chelyabinsk asteroid) of an estimated near-Earth asteroid population of around 20 million, implying that a significant impactor population at these sizes could be present but not yet cataloged in the discovered near-Earth asteroid population" [1]. The importance of the small body studies in the Solar system can be properly evaluated if we recall the volcanic eruption effects in Iceland, comparable to the effect caused by the fall of a small asteroid. The fall of an asteroid larger than 50 m will be a disaster that can stop the progress in the world for several years, but the fall of a 300 m and larger body can terminate the development of civilization on the Earth for several decades or even destroy the human race. At the 5th meeting of the PECS (Plan for European Cooperating States) Committee in on 27 of May 2009 in Esrin (Italy), the total number of NEO and hazard asteroids, is assessed as 66 000 [8]. NASA congress on 5 of March 2007 provided the assessment of the problem in Near-Earth Object Survey and Deflection Analysis of Alternatives. It concluded that only the wide ground base plus space sensor observations of Venus, like the orbit, can allow a more prompt solution of the problem, i.e. to discover the NEO asteroids (up to 90%) in the nearest future [7]. Finally, the research of asteroids manages to draw the attention of mass media, thus promoting the awareness of the importance of science, including astronomy among the public at large, and young people in particular.

From the other point of view the investigation of the properties of asteroids and comets are important for development of evolution theory of the Solar system and classification of small objects in the Solar system. Photometric studies of light curves of asteroids can obtain an additional information about size, rotation period, structure of objects, existence of craters and ice fields on the surface, which is very important data for space missions and for fantastic ideas about mining of minerals on asteroids [14]. The spectral observations can give information of chemical composition of asteroids and comets. The water condensation front (called the 'Snow line') shows that the Earth was not formed in a radial location where water can directly condense [5].

Water must have been delivered to the Earth from "elsewhere": exogenically, i.e., from asteroids and comets, or else endogenically, i.e., from accreting water-absorbed bodies. It is another motive to perform the research of the small bodies in the Solar system.

2 Observations of astronomical objects using optical methods

2.1 Observation and processing

Observations of NEO asteroids were made in 2018–2019 with 16.8 Mb camera STX-16803 installed on the Baldone Schmidt telescope, which has 1.2 m main mirror, correction lens 80 cm, focal length 2.4 m. In 2018, 1028 CCD images were obtained covering 200 square degrees of sky and 7 new asteroids were discovered. Common number of observed asteroids are 826. The Baldone observatory works at high declinations ($\delta > 50$ degrees), because the sky covering in this region is very weak (see Sky coverage map at https://www.minorplanetcenter.net/iau/SkyCoverage.html). Without monitoring of asteroids the aims and purpose of this research were to obtain the light curves of two NEO's 2006 VB14 and 1986 DA in order to determine their rotational period and corrected orbits.

The first observation of Aten-type asteroid 2006 VB14 in the Baldone Observatory (code 069) was made on 2018-10-14.05185 (MPS 930858), when distance till Earth was 0.09 au. All observations organized in the Baldone Observatory are described in Table 1. Results of observations in the Baldone were published in Minor Planet Supplement (MPS), which consists of total results of 99 astrometric and 332 photometric observations using stations over all world, including the Baldone station.

The first observation of Apollo-type asteroid 1986 DA in the Baldone Observatory (code 069) was made on 2019-04-17.84924,(MPS 991243), when distance till Earth was 0.201 au. All observations organized in the Baldone Observatory are described in Table 1. Results of observations in the Baldone were published in Minor Planet Supplement (MPS), which consists of total results of 33 astrometric and 132 photometric observations using stations over all world, including the Baldone station.

In order to reduce the images, flats, bias, and dark calibration images were taken each night. The program MaxIm DL was used to reduce and align the images. The flat-field images were taken against the twilight sky. The darks were exposed for the same time as the respective light images, two or three minutes for both asteroids. The red filter was used for observation. Afterward, the program MPO Canopus v10.2.1.0 [15] was used to perform differential photometry on the reduced data. For each data set, five stars were used for brightness comparison to the asteroid. Aperture photometry using a differential photometry technique was done to determine the brightness of comparison stars and the asteroid. The errors in magnitude for stars and asteroids were found and plotted in a phase diagram. Relative magnitude (the difference between brightness and average day brightness of asteroid) versus phase rotation, to create a light curve. 339 brightness measurements of 2006 VB14 and 130 for 1986 DA were obtained using "g" GAIA magnitudes of more than 30 reference stars.

Table 1 NEO asteroids observed at the Baldone Astrophysical Observatory.

Name	Date	Number of CCD images	MPS No
2006 VB14	14.10.2018	3	930858
	17.10.2018	3	930858
	17/18.10.2018	53	930858
	04/05.11.2018	40	936549
	28/29.11.2018	125	965727
	29/30.11.2018	108	965727
	30.11/01.12.2018	90	965728
1986 DA	16/17.04.2019	27	991243
	17/18.04.2019	25	991243
	22/23.04.2019	25	992907
	28/29.04.2019	34	994377
	05/06.05.2019	21	996904

2.2 Periods

A Fourier transform was applied to determine the rotation period for both asteroids. Light curves were created also using MPO Canopus software. The rotation period 3.25 ± 0.02 h better fitted to our measurements for 2006 VB14. The period is in agreement with the earlier work [11]. The sharp fall of brightness in phases 0.3 and 0.8 and the brightness peak in phase 0.1 indicate the possible presence of a crater and the bright surface area (frozen gas field or water) on the asteroid surface, respectively (see Figure 1). The rotation period 3.12 ± 0.02 h better fitted to our measurements

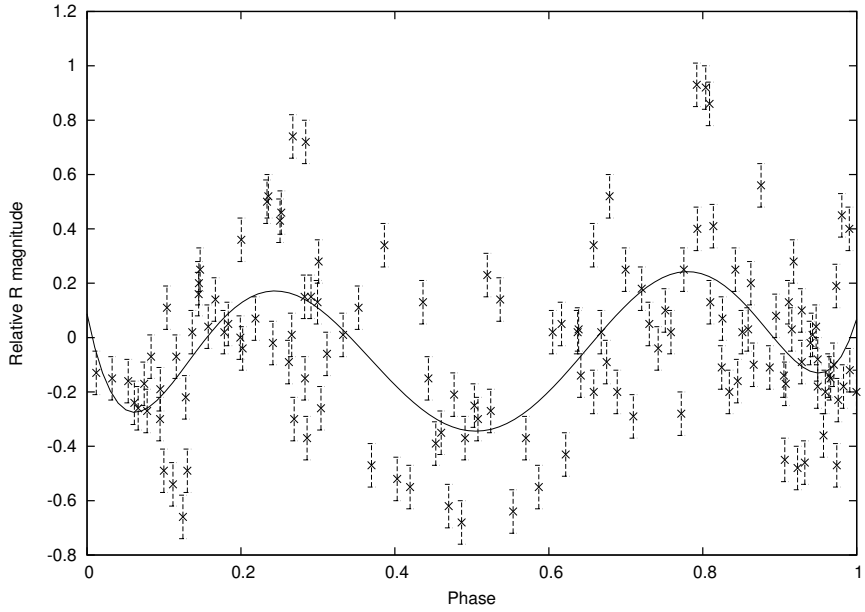


Figure 1 Light curve for NEO 2006 VB14.

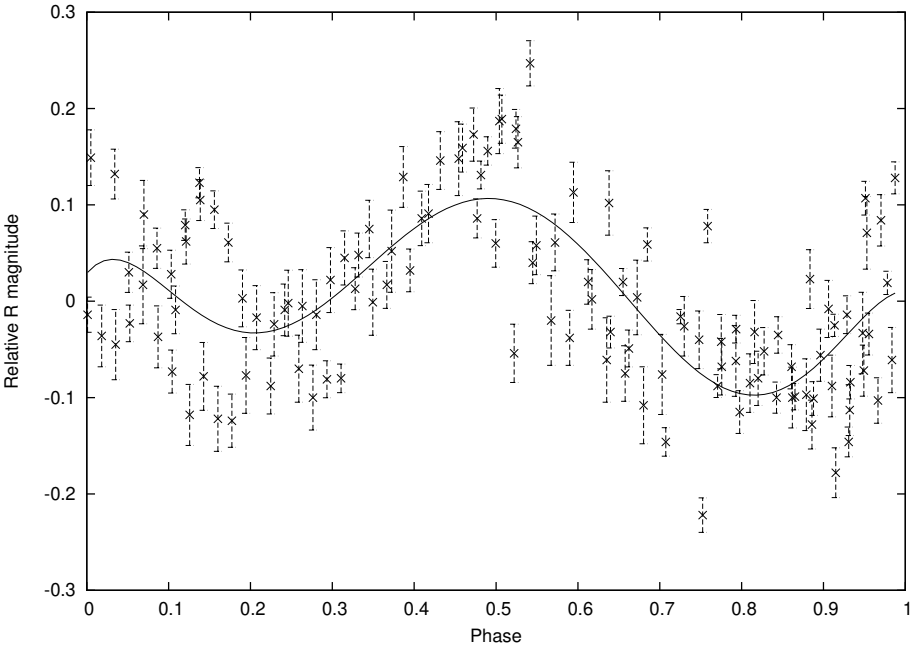


Figure 2 Light curve for NEO 1986 DA.

for 1986 DA. The similar reduction and processing procedure was used for 130 CCD images of asteroid 1986 DA. A Fourier transform was applied to determine the rotation period and the value 3.12 $\pm$ 0.02 h was obtained (see Figure 2).

Table 2 presents starting orbital elements of the asteroids 2006 VB14 and 1986 DA computed with the non-gravitational parameter $A2$. For 2006 VB14 $A2 = (-1.19 \pm 1.26)E-14$ au/d^2 and for 1986 DA $A2 = (+3.24 \pm 2.98)E-14$ au/d^2.

Table 2 Initial nominal orbital elements of the asteroids 2006 VB14 and 1986 DA: a denotes the semi-major axis; e, eccentricity; angles i, Ω and ω refer to the Equinox J2000.0. Epoch: JD2458800.5 TDB = 13 November 2019. The orbital elements are computed with the non-gravitational parameter $A2$ [17].

Name	a, au	e	i, deg	Ω, deg	ω, deg
2006 VB14	0.7669388731	0.42123761	31.024613	258.7275473	346.441171
	6.2E-09	1.0E-07	1.5E-05	2.8E-06	1.7E-05
1986 DA	2.822145979	0.5818043231	4.3052158	64.636860	127.386722
	2.1E-08	2.2E-08	5.0E-06	6.6E-05	6.6E-05

The next closer proximity to the Earth of asteroid 2006 VB14 will take place on December 11 2057, when the distance to the asteroid will be 0.078. The next closer proximity to the Earth of asteroid 1986 DA will take place on April 13 2038, when the distance to the asteroid will be 0.198.

3 Observations of astronomical objects using radio methods

There are four known (1612.231, 1665.402, 1667.359 and 1720.530 MHz) hyperfine transitions of OH at 18 cm wavelength which have been used for 40 years, historically to observe comets. In 1973, the molecule OH in comet Kahoutek [2] was observed with Nancay 30 meter telescope. The 18 cm line is the result of an excitation from resonance fluorescence, whereby molecules absorb solar radiation and then re-radiate the energy. The OH molecule absorbs the UV solar photons and cascades back to the ground state Lambda doublet, where the relative populations of the upper and lower levels strongly depend upon the heliocentric radial velocity (the 'Swings effect') [4]. The result of observations of comets in 1.6 GHz frequency band by other astronomers [3, 6, 12, 13] show that the typical peak source flux densities of the comet are in the range of 4 to 40 mJy. Weakness of the radio signal is the main challenging factor. Assuming that the detection threshold is 3σ, at least 1.3 to 13 mJy noise floor is required.

3.1 Observations

Preparation of the Irbene RT-32 radio telescope includes design and installation of the dedicated low-cost L-band (18 cm wavelength) receiver, capable of receiving hyperfine transitions of the OH masers on comets. A suitable receiver was developed by VIRAC team and it consists of compact feed horn with dual circular polarized channels and parabolic reflector, which together with existing Cassegrain antenna forms triple mirror system. Uncooled low noise amplifiers are used for both channels (right and left circular polarisations), which allows us to achieve system noise temperatures of less than 60 K. Estimated aperture efficiency at 1.65 GHz is between 30 and 50 % which translates to RT-32 radio telescope gains of at least 0.1 K/Jy. The overall estimated sensitivity SEFD is between 650 and 900 Jy depending on the elevation of the antenna. Flux detection threshold levels were estimated (see in Figure 3). The calculated results of the noise floor *dS* vs *integration* show – the detection of the source with the flux density below 40 mJy is possible by an antenna (integration time $\sim$ 7.5 hours, spectral channel bandwidth BW = 10 kHz).

To verify the calculation of the model, multiple observations at 18 cm frequency band were performed in single and VLBI modes. Successful test observations in single dish mode were performed, which includes continuum calibration sources and OH spectral lines at 18 cm. To test the performance of the receiver and to verify the Solar System object tracking mode of the RT-32 control software, continuum observations of Venus were carried out at 28.12.2018 with central frequency of 1670 MHz and surface temperature of $\sim$600 K; total power BW was 20 MHz, angular size was $28''$, LCP and RCP channels were used and obtained flux density was 0.65 Jy. Observations of various Galactic maser sources (W75 S, U-Aur, G133P715, R LMi) with flux density in the range of 0.8 Jy to 3 Jy were performed in 2018 and 2019 to test Irbene RT-32 radio telescope receiving system sensitivity.

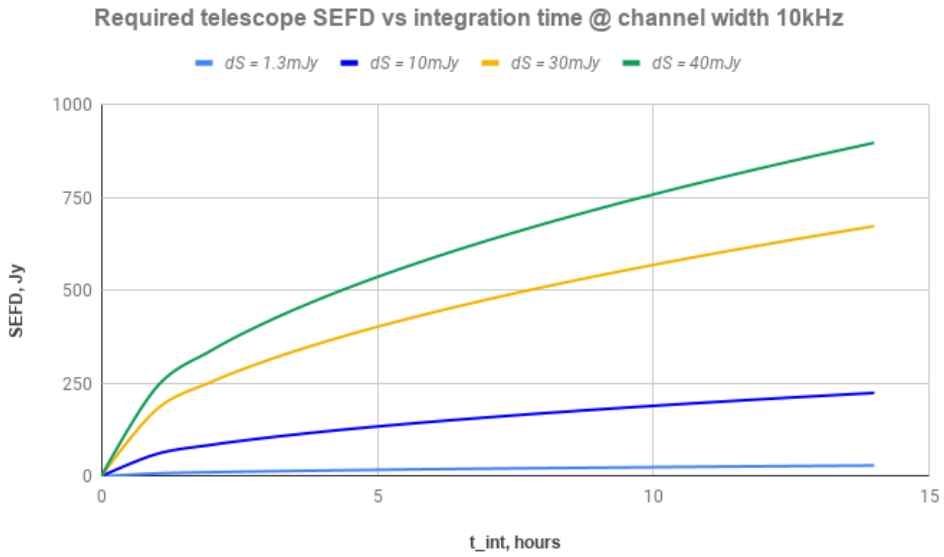


Figure 3 Irbene RT-32 telescope sensitivity requirements for comet observation in single dish mode.

3.2 Data processing and results

Single antenna mode – a spectrometer back end based on software defined radio USRP X300/310+TwinRX is used to record data using 16 bit+16 bit (real + imag part) per sample. For spectral data calibration, the frequency switching method [16] is currently used. Data processing is implemented to collect data using long integration time and to calculate as the result the spectrum of the object.

To check RT-32 readiness level for weak object observations, the Mira variable star R LMi was selected as the test object, which was successfully previous observed by Nancay Radio Astronomy Observatory, France [10]. Results from previous observations showed its spectral line at 1665 MHz with maximum 5 Jy and two locals maximums (2 Jy and 1 Jy) at 1667 MHz spectral line. Multiple observations were carried out to detect the object R LMi with the tuned Irbene RT-32 radio telescope receiver system. In April 16, 2019 two hour observation session at 1667 MHz frequency band showed strong emission line and unclear results in central frequency. Usage of multiple wavelet families showed the best results with rbio1.5 wavelet and 0.5 threshold. The obtained results demonstrate small maximum at central frequency (see Figure 4). In August 9, 2019 the second experiment session was organized where observation duration was 4 hours and frequency band was 1667 MHz. Strong emission line was detected and two maximum peaks (1.4 Jy and 1.1 Jy) were obtained using calibration algorithms, Fourier transforms and wavelet coif6 with threshold 0.5 (see Figure 5).

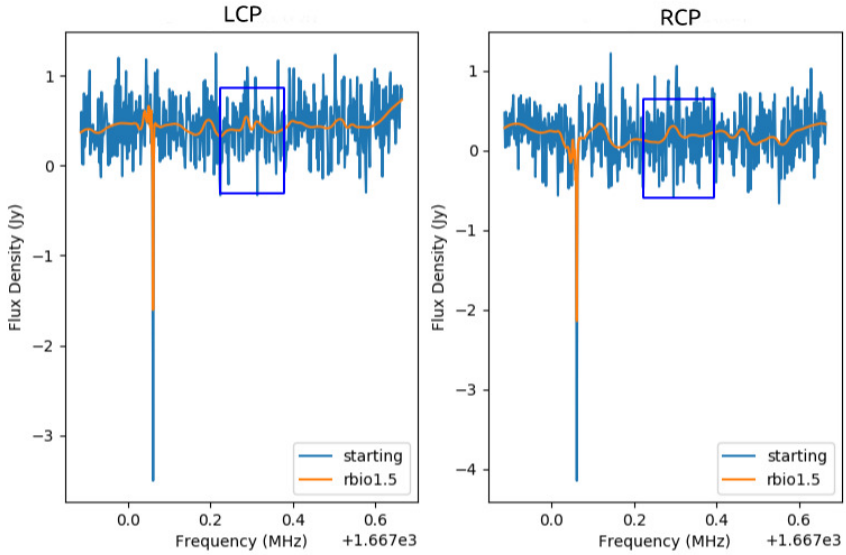


Figure 4 Left and right circular polarisations (LCP and RCP) of object R LMi were used on April 16, 2019. Spectre (line in blue) and rbio1.5 wavelet with threshold 0.5 (line in orange) are shown.

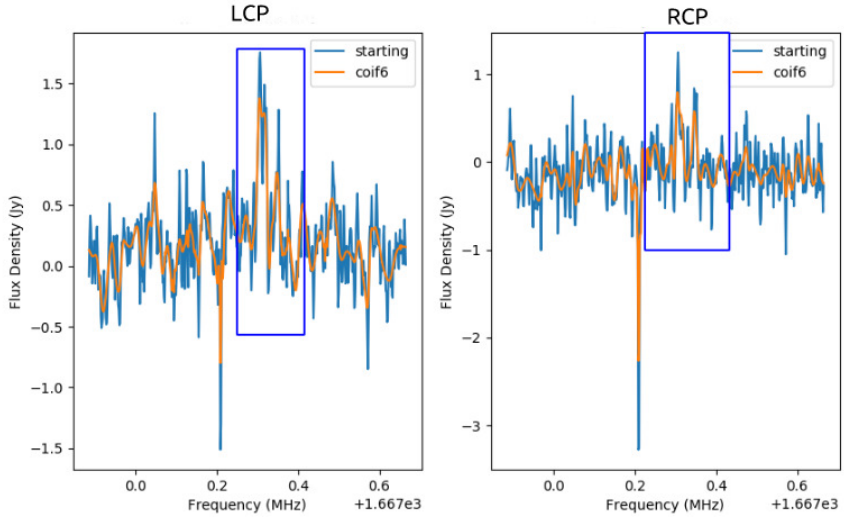


Figure 5 Left and right circular polarisations (LCP and RCP) of object R LMi were used on August 9, 2019. Spectre (line in blue) and coif6 wavelet with threshold 0.7 (line in orange) are shown.

4 Conclusion and future work

Optical observations of NEO objects 2006 VB14 and 1986 DA were organized with the Baldone Schmidt Telescope and computation results of the rotation period and

other physical characteristics of the observed objects were successfully obtained.

Radio astronomical observations of OH masers of comets can be a very challenging task. The upgrade of the L band receiver was performed to observe comets. Multiple data processing methods were developed to acquire a weak signal – from observations of single antenna and VLBI. Tuned telescope receiving system and developed data processing tools in future will be applied for interstellar comet 2I/Borisov with its close perihelion at 1.94 AU on 2019-12-07 and comet 2P/Encke with its close perihelion at 0.3302 AU on 2020-06-17. Previous experience with acquiring and processing data from the DA14 asteroid [9] on February 15, 2013, offers a good experience to develop methods for the comets OH maser location detection and its behavior approaching the Sun, in addition to developing new methods for measuring delay and frequency of interference using hyper-fine transitions of OH molecules. Observations of small bodies are possible with the best available accuracy when optical and radio methods are combined. Data processing from two independent simultaneous measurements (e.g., usage of Kalman filters) allows us to reduce human errors in sporadic sources.

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