THE FORWARD SCATTER RADAR METHOD FOR DETECTING SPACE OBJECTS USING EMISSION OF EXTRATERRESTRIAL RADIO SOURCES

Vladislavs Bezrukovs(1), Nikolai Dugin(2), Karina Skirmante(1), Gints Jasmons(1), Jānis Šteinbergs(1)

(1) Engineering Research Institute Ventspils International Radio Astronomy Centre (ERI VIRAC) of Ventspils University of Applied Sciences, Inzenieru 101, Ventspils, Latvia. Email: vladislavsb@venta.lv
(2) Volga State University of Water Transport, Nesterova 5, Nizhny Novgorod, Russian Federation. Email: ndugin@yandex.ru

ABSTRACT

The radar-VLBI (Very Long Baseline Interferometry) method, based on the reception of signals of ground radar, reflected from an object, by a network of receiving stations, has been successfully applied in numerous experiments to observe space debris and asteroids. Authors propose enhanced radar-VLBI method, which uses the most powerful extra-terrestrial radio sources like the Sun and Cassiopeia A and the radiation from spacecraft transmitters as probing emission. Such construction of a bistatic location system significantly increases the probability of detecting an object in a situation where the forward scatter effect occurs. The Radar Cross Section (RCS) of an object in this case, in bi-static mode, is hundreds of times higher than the RCS for a traditional monostatic radar. An important point is that the scattered signal does not depend on the shape and material of the object. The method was validated by the series of successful experiments.

Keywords: space hazards, VLBI, near-Earth objects, asteroids, radio telescopes, LOFAR, data processing.

1 INTRODUCTION

The creation of effective optical and radar facilities for observing deep and near space is a priority task in the development of Earth space security systems. The asteroid-cometary hazards have been considered for a long time, but in recent years it has received increased attention both in connection with the fall of large meteoroids to the ground, and with the strong pollution of the near-Earth space with space debris.

The study is dedicated to the design and development of new radar techniques in combination with Very Long Baseline Interferometry (VLBI) method for the detection and high-precision positioning of near-Earth asteroids and comets, as well as space debris in near-Earth space. The proposed new scientific approach is providing unique results for bistatic radar object detection technology. The advantages of the proposed technique are that it can detect objects regardless of their shape and material, including "black bodies" that do not reflect incoming radiation. In addition, this method is able to detect objects that fly directly from the Sun to Earth and are not accessible to optical means of observation.

This task relates to exploratory research into the development of effective radar systems for detecting space hazards to Earth. General issues of asteroid and comet hazards are discussed in several papers [1, 2], where the main attention to searching of dangerous celestial bodies is focused on optical awareness tools. The existing optical space control systems have some disadvantages like night-time sky survey, weather dependence, impossibility of detecting objects approaching the Earth from the Sun direction. These determine the need to use other means of monitoring outer space, i.e., radars.

Since many years, the radar-VLBI method proposed by researches from "Research Radiophysical Institute of Lobachevsky State University of Nizhny Novgorod (NIRFI UNN), has been successfully tested on the international VLBI networks, and numerous experiments have been conducted to observe space debris objects in near-Earth space and asteroids at distances on the order of a lunar orbit [3]. The method is based on receiving signal, which is emitted by a ground-based planetary locator and reflected from a space object, by a network of radio telescopes operating in the VLBI mode. The Eupatorian RT-70 planetary locator and occasionally Goldstone locator were used. The most successful experiment can be considered as the location of the asteroid 2012 DA14, which passed within the geostationary orbit [4]. With relatively accurate targeting from optical telescopes, several sessions of radiation at a frequency of 5 GHz at distances from 50 thousand to 260 thousand kilometres to the asteroid were conducted. In subsequent processing, the accuracy of the object motion parameters was achieved, exceeding the accuracy of optical means.

As a development of the "traditional" radar-VLBI method, the use of millimetre range radio systems was proposed [5]. However, the high-power consumption of the transmitter, the need for additional targeting and the complex organization of the network of ground receiving points limit the use of this method too.

2 THE FORWARD SCATTER RADAR METHOD

In recent years, due to the emergence of low-visibility targets, the development of radar systems has focused on the bistatic scheme of construction of radar complexes [6, 7, 8]. Use of such configuration significantly increases the probability of detecting an object in the situation of occurrence of the "forward scatter effect" (hereinafter - FSR), which consists in the fact that when irradiating an object whose dimensions are several times greater than the wavelength emitted by the transmitter, the energy dissipated backwards is several orders of magnitude less than the energy dissipated forward along the irradiation line, regardless of the object shape and its material structure [9] (see Fig 1).

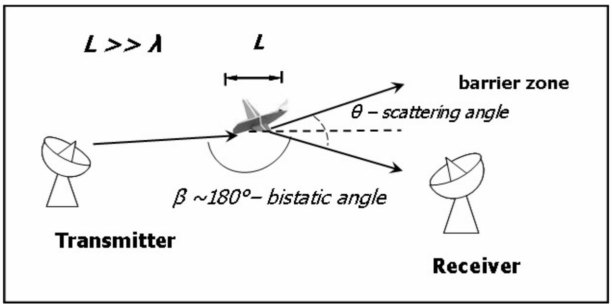


Figure 1. Schematic diagram of a "forward scatter" radar locator.

The patents [10, 11] explore the application of bistatic systems for the task of detecting celestial and extraterrestrial objects. On the basis of this research, schemes for the construction of complexes using VLBI technology were proposed. Important aspect is that the data processing procedure of these receiving complexes allows observations by single antennas, and the direct transmitter signal is a reference (i.e., useful in contrast to the currently operating radar systems, where it must be suppressed). It is also possible to use as probing radiation of the most powerful extraterrestrial radio sources and transmitters of interplanetary spacecraft and artificial satellites [12, 13].

The main difference in the operation of bistatic radars and radio astronomical systems is the different signal structure: radars use monochromatic radiation, the information about a moving object is contained in the Doppler frequency shift, in ground-based-space systems the sounding signal is noise (or quasi noise) and the spatial delay and interference frequency are measured in interferometric mode.

The reliability of the proposed forward scatter radar (FSR) method for detecting space objects can only be evaluated through experimental results.

3 VALIDATION OF THE METHOD BY EXPERIMENTAL OBSERVATIONS

The VIRAC radio astronomy infrastructure was used to validate the developed technique. Ventspils International Radio Astronomy Centre (VIRAC) was established in 1994 with the aim to promote research activities in radio astronomy, astrophysics and space sciences. The most important instrumental base for the centre comprised two fully steerable parabolic antennas, RT-16 and RT-32 (i.e. with the mirror diameter of 16 m and 32 m) and LOFAR-LATVIA station. The parabolic antennas were instrumented with two channel right circular polarization (RCP) and left circular polarization (LCP) cryogenic broad band receivers with frequency coverage of 4.5 – 8.8 GHz and instantaneous bandwidth of approx. 1200 MHz. Receivers are cryogenically cooled to 14 Kelvin which nominally achieves system noise temperatures of 30 to 50 Kelvin throughout the whole bandwidth. The "L band" receiver is available at RT-32 for observations at 1.40 to 1.72 GHz. It is an uncooled unit with dual (RCP and LCP) polarization channels and system temperature of 60 to 100 K. Both telescopes are ready for VLBI observations. Maximum azimuth and elevation tracking velocities are up to 5 degrees/s with RMS tracking accuracies 4 arcsec allowing to track near-Earth satellites. Since 2019, VIRAC obtain also Low Frequency Antenna array (LOFAR). It contains 96 low band (LBA) (10 - 90 MHz, total area 3200 sq.m) and 96 high band (HBA) (110 - 240 MHz, total area 2400 sq.m) antennas [14 – 16]. The VIRAC interferometer at Irbene – two radio telescopes RT-32 and RT-16, with baseline of about 800 m, was used to verify the developed method.

To apply observational techniques and data pre-correlation processing algorithms for near-Earth object detection using the FSR method, where four GNSS (Glonass, GPS, Galilieo, BeiDou) were used as sources of probing radiation. The number of these satellites is large enough, they are distributed evenly over the celestial sphere, move in well-known orbits, and emit signals at L-band frequencies. Aircrafts, the International Space Station (ISS) with a total geometric area of about 400 m^2 and large space debris fragments in highly elliptical orbits are suitable targets for observations. Aircrafts are relatively close to the receiving antenna (tens of km) and the scattered signal must have energy characteristics that allow the use of small antennas with wide antenna beams. Space debris fragments are at great distances from receiving sites, but their trajectories are sufficiently well-known to allow signal accumulation.

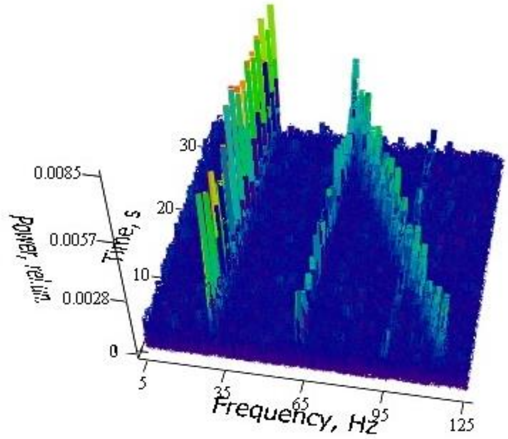
During preparation for test measurements several problems were revealed. To increase the sensitivity of the receiving complex it was desirable to use large diameter antennas, but with narrow antenna beams the difficulty of aiming at the object under study, especially at a fast-flying aircraft, increased significantly. Next is the choice of polarization of the receiving antenna. Natural radio sources have non-polarized radiation, receiving antennas can operate in any polarization. GNSS emits a signal in right-hand circular polarisation, the signal reflected from the object is in left-hand polarisation and the transmitted (diffracted) signal must retain the polarisation of the incident radiation. Operation in linear polarisation can solve this problem, but with substantial signal loss and the need for possible reconfiguration of the available receiving systems. The mode of operation and processing algorithms differ significantly from the traditional VLBI methodology, and consequently software upgrades are required.

A series of experiments were prepared and carried out on antennas of different effective areas in both single antenna and interferometer modes. During last year's several experiments were conducted also at the NIRFI VLBI site. In these experiments the single antenna 2 m in diameter with linear polarization was used. GLONASS and GPS signals highlight aircrafts flying along their corridor 40 km from the receiving complex in Nizhny Novgorod. The observation methodology and algorithms of experiment data processing were tested. Preliminary results show the presence of reflected signals [17].

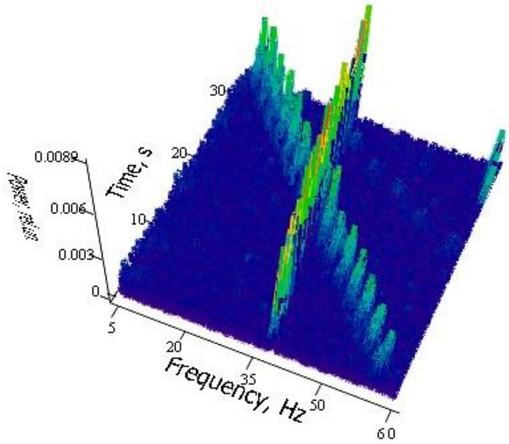
Further experiments were carried out using Irbene interferometer in 2021. The RT-32 radio telescope operates in two circular polarizations, while the RT-16 radio telescope operates only in RCP polarization. The targets were close-flying aircrafts and space debris objects in high orbits. During the experiments, the antennas tracked GPS and Galileo satellites and also recorded the passage of large space debris objects and the ISS through the antenna beam. The observations were processed for both single antennas and the interferometer modes. The most important task was to distinguish whether the signal was reflected or scattered from an object. The arguments in favour of a 'useful' signal were as follows: first, in numerous previous experiments on the reception of GNSS signals on the same antennas no such responses were found; second, the presence of a signal was determined only at the moment when an object flew over the irradiation line. The response characteristics were checked for consistency with the estimated values. Although there were some unforeseen response features, a "forward scatter" signal was observed with a high degree of probability.

4 RESULTS OF EXPERIMENTS

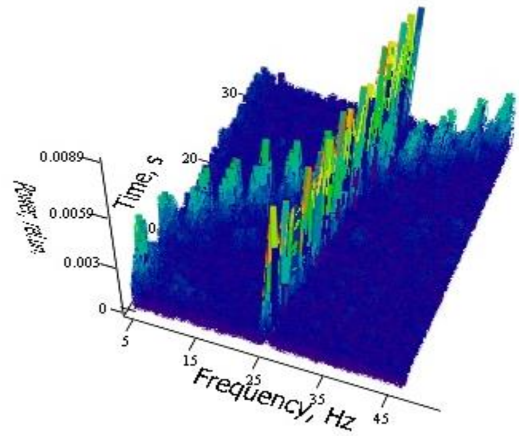
The example shows the results of data processing for the passage of a space debris fragment at an angular distance from the transmitter-receiver irradiation line of more than 1-degree (see Fig. 2 a) and Fig. 2 b) images). The figures are sequentially shifted in time by 30 sec; the estimated flyby time corresponds to Fig. 2 c) image. Each figure shows the output signal of the interferometer in the amplitude-frequency-time axis, plotted at an interval of 30 s. Two signals are clearly distinguishable: one from 1) a slow-moving GNSS, which has a nearly constant frequency due to compensation for frequency shifts and delays in processing; 2) a fast-moving object with an interference frequency that varies linearly with time.



a)



b)



c)

Figure 2. An example of passages of a space debris fragment in different time moments.

Successful correlations were obtained in more than 50% of observations, for example, observations with objects of different geometric areas, at different distances from the Earth and at different angular distances from the irradiation line. An important result of the experiments carried out at this stage of the work – to determine the methodology for processing the experimental data when both a single antenna and an interferometer are used for observations.

To perform simultaneous observations of aircraft and satellites an algorithm was developed which uses information from *data-live.flightradar24.com API,* computes the currently existing airplane flight trajectory and identifies the current aircraft position. The flight trajectory is extrapolated from current position for the next *n* points and the aircraft position is computed at the corresponding time, retrieving latitude and longitude values and the azimuth and elevation values relative to Irbene observatory. Using this data, nearest GNSS satellites that are visible in the same line-of-sight (within angular distance up to 5 degrees in azimuth/elevation) are identified.

This is achieved using the orbital parameters provided by *celestrak.com* for the GNSS type satellites and in each time moment, angular distance between aircraft and satellite is computed in an attempt to find the minimum possible distance. As a result, the best potential satellites to observe are identified, providing the user with satellite name, time moment for best possible observation, satellite latitude/longitude values, azimuth/elevation values for the telescope and radial distance between both objects. Code was developed using *Python* programming language and *pymap3d, geopandas, matplotlib, numpy, urllib, ephem* libraries. The *Google Colab* was used as a developing environment.

5 CONCLUSIONS

The application of the FSR effect uses scattering electromagnetic radiation on large objects and in this case, it is possible to increase the signal reflection from the object by orders of magnitude, thus increasing the probability and range of detecting celestial bodies that pose a threat to Earth. However, a significant disadvantage of this effect is the narrow scattering range, which needs to be taken into account in the observation planning stage. Narrow scattering range problem can be solved if multiple receivers are placed on the Earth's surface to increase the probability of receiving a strong scattered signal. The receiving network of antennas can also operate in standard VLBI mode, increasing instrument sensitivity and resolution. It should be noted that currently there is no alternative in radar systems for detecting distant and low-visibility objects and the investigation of the FSR method applications needs to continue to identify the feasibility for detecting celestial objects in deep space.

As the next step, authors consider possibility of using aperture synthesis systems with very high sensitivity to receive signals from celestial objects in deep space and the VIRAC's LOFAR (Low-Frequency Array) station in Irbene provides opportunities to continue the activities in this research area using low-frequency range. Should be noted that Irbene LOFAR station is a member of International LOFAR Telescope Network (ILT), thus providing the possibility to promote FSR methods in ILT consortium. Modeling shows that FSR approach with LOFAR technology has multiple advantages compared with parabolic antennas like radio telescopes RT-32 and RT-16: LOFAR has higher sensitivity, multiple beams and the single station beam is wider, allowing to process larger survey objects more quickly and it is more cost-effective to use, thus it will be possible to observe nearby aircraft, debris fragments in near space and asteroids using the emission from the most powerful extraterrestrial radio sources and satellite transmitters. In addition, combination of LOFAR and radar-VLBI technologies would allow to detect ionospheric fluctuation parameters which is required for higher precision of the object positioning.

The developed principles of the FSR method for VLBI complexes can be used in the worldwide system of protection against space threats and contribute to the solution of urgent tasks of space navigation.

6 ACKNOWLEDGEMENTS

This work was supported by Latvian Council of Science, project "The application of the forward scatter radar method for the detection of space objects" (lzp-2020/2-0101), being implemented in Ventspils University of Applied Sciences.

7 REFERENCES

1. Shustov, B.M., (2010). Asteroid-comet hazard yesterday, today and tomorrow // Астероидно-кометная опасность: вчера, сегодня, завтра, *M.:FIZMATLIT,* ISBN 978-5-9221-1241-3.

2. Chapman, C.R. & Morrison, D. (1994). Impacts on the Earth by asteroids and comets: assessing the hazard, *Nature*, vol, 367, pp. 33–40.

3. Nechaeva, M.B. et al, (2007). VLBI studies at the Radiophysical Research Institute, *Radiophysics and Quantum Electronics*, vol. 50, issue 7, pp.527-541.

4. Nechaeva, M.B. et al. (2015). VLBI Radar of the 2012 DA14 Asteroid, *Radiophysics and Quantum Electronics*, vol. 57, issue 10, pp.691-699.

5. Dugin, N. et al. (2013). Prospects for a millimeter-range multistatic radar system for asteroid hazard monitoring. *Environmental Bulletin of the Black Sea Economic Cooperation (BSEC) Science Centres* // Перспективы мультистатической радиолокационной системы миллиметрового диапазона для мониторинга астероидной опасности. *Экологический вестник научных*

центров Черноморского экономического сотрудничества (ЧЭС). No.4, vol. 2, pp. 44-49.

6. Chernyak V.S. (1993). Multi-position radiolocation. *Moscow: Radio and Communications* // Черняк В.С. (1993). Многопозиционная радиолокация. *Москва: Радио и связь*. pp. 416.
7. Merrill, I. Skolnik. (2008). *Radar Handbook*, McGraw-Hill Education.
8. Cherniakov, M. (Editor) (2007). *Bistatic radar: principles and practice*. 504 p, ISBN: 978-0-470-02630-4.
9. Ufimtsev, P.Ya. (1989). *Radio Engineering and Electronics* // Уфимцев П.Я. *Радиотехника и электроника*. Vol. 35, no.12. pp.2519-2527.
10. Antipenko, A.A. et al. (2010). *Radar complex*. Patent for invention No. 2422849 (RU 2 422 849 C1) dated 27.07.2011 (application number 2010106988, priority 24.02.2010). Publ. 27.06.2011, Bulletin No. 18. - 13.
11. Dugin, N.A., Blyakhman, A.B. (2016). *Radar complex for asteroid detection.* Patent for invention No. 2625542 (RU 2 625 542 C1), application No. 2016136255/28 (056981) dated 08.09.2016, published 14.07.2017, Bulletin No. 20.
12. Nechaeva, M., Dugin, N. (2017). Method of forward scatter radar in the task of near-Earth asteroids detecting. *BAASP 2017–5th International Scientific Conference "Baltic Applied Astroinformatics and Space data Processing"*. 23 – 24 August 2017, Ventspils, Latvia. Abst.P.29.
13. Dugin, N.A., Nechaeva, M. & Bezrukovs, V.V. (2022). Capability of Bistatic Radar Systems to Solve the Problem of Detection of Potentially Hazardous Celestial Objects. *Radiophys Quantum El* 64, 893–901 https://doi.org/10.1007/s11141-022-10187-y.
14. Bleiders M. et al. (2019). "Low-Cost L-Band Receiving System Front-End for Irbene RT-32 Cassegrain Radio Telescope." *Latvian Journal of Physics and Technical Sciences* 56 (3): 50-61. doi:10.2478/lpts-2019-0019.
15. Bezrukovs, V. (2016). "Time and Frequency Synchronization on the VIRAC Radio Telescope RT-32." *Latvian Journal of Physics and Technical Sciences* 53 (2): 14-19. doi:10.1515/lpts-2016-0009.
16. Bleiders, M. et al. (2020). "Spectral Line Registration Backend Based on USRP X300 Software Defined Radio." *Journal of Astronomical Instrumentation* 9 (2). doi:10.1142/S2251171720500099.
17. Dugin, N. et al. Capabilities of airborne objects radiolocation by spacecraft signals // Возможности радиолокации воздушных объектов сигналами космических аппаратов. // II *Russian Scientific Conference "Modern Problems of Remote Sensing, Radiolocation, Wave Propagation and Diffraction" - Murom 2018.* Conference Proceedings, pp.463-468.