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OBSERVATIONS OF GEO AND LEO SATELLITES: RADIO ENGINEERING MEANS OF THE MYKOLAIV ASTRONOMICAL OBSERVATORY

The radio engineering means of the RI "Mykolaiv Astronomical Observatory" are fully passive. To track satellites, they use radio signals emitted by the satellites themselves. Thus, the following means were developed and put into operation: 1) Simple INTerferometer NETwork (SintNet) for monitoring the orbital position of geostationary (GEO) satellites; 2) Doppler station for clarifying the orbital elements of low Earth orbit (LEO) satellites.

Two SintNets operate now: European and Chinese. The European SintNet consists of 10 stations and tracks three co-located satellites simultaneously. The Chinese SintNet consists of four stations and tracks one satellite. The positional error (standard deviation) of satellites is about 200 m.

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The Doppler station operates in the frequency range 430...440 MHz. Signal spectrum analysis is used to determine the frequency F(t) of the radio signal emitted by an LEO satellite and received by the station at time t. The SGP4/SDP4 analytical model of the satellite motion is applied to analyze F(t) and to clarify the elements of the satellite orbit. Errors in measuring the Doppler frequency shift and time are 4 sm/s and 30 ms, respectively.

Keywords: *interferometer, geostationary satellites, low-Earth orbit satellites, Doppler effect.*

INTRODUCTION

The Simple Interferometer Network (SintNet) was initially developed at the RI «Mykolaiv Astronomical Observatory» as an independent radio engineering means for tracking future Ukrainian geostationary satellite Lybid. The first SintNet consisted of two stations and existed for 2 days in August 2011 [3]. At the same time, in 2010—2013, SES (Société Européenne des Satellites), together with Fraunhofer Research Institute, conducted the project named PaCoRa (Passive Correlation Ranging, European Space Agency). The PaCoRa system is considered by ESA as a high-precision alternative to active ranging radars [6]. As it turned out, the SintNet is a prototype of the PaCoRa system. Both systems are completely passive. They consist of geographically separated stations or terminals that synchronously receive payload signals of satellite TV emitted by tracked satellites. The coordinates of the satellites are determined from the known station coordinates and the measured values of Time Difference Of Arrival (TDOA). To calculate TDOA, correlation analysis of signals emitted by satellites and received by stations is used.

According to [10], the PaCoRa system of four stations should have a maximum error in calculating the coordinates of a geostationary satellite of approximately 119 m. This error was obtained as a result of the simulation. For the SintNet, our measurements show that the standard deviation of the TDOA is about 8.7 ns [4]. The orbital position (or orbital elements) of the satellite is determined using a numerical model of satellite motion and measured values of the TDOA obtained during 24h. The numerical model takes into account the gravitation of the Sun, Moon, and non-spherical Earth [7]. Herewith the standard deviation of the satellite's coordinates is about 200 m [2]. It has also been shown that the networks of three and more stations provide close coordinate precision of about 200 m [2, 11].

The urgency of the problem of clarifying the orbit elements of low Earth orbit (LEO) spacecraft has been increased sharply due to the appearance of a huge amount of satellites belonging to the Internet systems, which are being created now. About 16000 such satellites will be put into service by 2030 like OneWeb, StarLink, or TelSat. The Doppler station is designed to track low Earth orbit artificial satellites, emitting radio signals in the frequency range 430... 440 MHz, and to clarify orbit elements of the tracked satellites by measuring the Doppler shift of frequency of their radio signals. In the frequency range 430... 440 MHz, radio beacon signals of 18 LEO satellites were detected [8]. Thus, there is possible to solve the main methodological and technical issues of clarifying the orbital position of satellites by the Doppler frequency shift of their radio beacons. Obtained decisions may be used in other frequency bands, including frequency bands of the Internet systems.

1. SIMPLE INTERFEROMETER NETWORK

There are currently two SintNet in operation: the European and Chinese. The European SintNet consists of 10 stations and Chinese — 4 stations. Stations of the European SintNet are located in Ukraine (Mykolaiv, Rivne, Kharkiv, and Mukacheve), Latvia (Ventspils), and Italy (Pietramarina). Three stations are located in Mykolaiv and two stations each is in Ventspils and Rivne. Stations of the Chinese SintNet are located in Shanghai, Duyun, Urumqi, and Changchun [9]. Both SintNets have processing centers. The processing center of European SintNet is located in Mykolaiv and Chinese SintNet in Shanghai.

The Chinese network tracks one satellite, Apstar-6C, which is the only one in the cell at 134° of East longitude [11]. Until May this year, the European network tracked the orbital position of two satellites, Eutelsat-13B and C, located in the same cell at 13° E together with Eutelsat-13E. And this is despite the fact that the number of network stations allows tracking 3 satellites. The network cannot track Eutelsat-13E because it emitted only DVB-S2 signals, which cannot be processed correctly by DVB-S receivers of the stations [8]. Multistandard DVB-S(S2) receiver OMICOM was implemented on three stations in Mykolaiv, Ventspils, and Rivne in May, 2021. That allows now tracking all three satellites co-located in the same geostationary cell at 13 degrees of East longitude.

Both SintNets have identical hardware and software. The composition and main characteristics of the equipment and software of SintNet stations are given in [5]. The stations have the standard antenna-feeder system for the reception of DVB-S(S2) signals. Most stations of both SintNets have antennas with a diameter of around 1 m. An important feature of the stations is the use of standard digital satellite television DVB-S(S2) receivers, modified in terms of the signal output from their quadrature detectors, as well as digital oscilloscopes as external ADCs. Synchronization of measurements is carried out using GPS receivers ThunderBolt-E. The error of the PPS (Pulse-Per-Second) signal is 15 ns. It should be noted that 4 stations of the European SintNet have computers that work under Windows-XP, and computers of the other 6 stations under Windows-7. The processing center in Mykolaiv has a more powerful computer (64-bit processor, 32 cores, 32 GB memory, and a 3 TB hard disk for saving primary observation data). Description of the processing center software of TDOA and orbit determination of tracked satellites is given in [4, 10]. The existing SintNet software allows the completely automatic acquiring of observational data and their transfer from the stations to the processing center. For further data processing and calculation of TDOA and orbital elements, it is necessary to run the appropriate programs manually.

Positions of the satellites were calculated to confirm a fact of tracking all three co-located satellites by the European SintNet. Orbital elements obtained by the network on May 29-30, 2021 were used to calculate the positions. Herewith, the distances between the satellites varied in the range from 7 to 81 km, which significantly exceeds the error of SintNet coordinate determination, equal to 200 m. So, the European SintNet really tracks now all three co-located satellites, and the implementation of multistandard receiver OMICOM allows now tracking satellites regardless of the standard of signals they emit.

As a result of continuous observations, catalogs of daily values of orbital elements (numerical model) for Eutelsat-13B (since Feb 2015), Eutelsat-13C (since Sep 2018), and Eutelsat-13E (since May 2021) were obtained.

2. DOPPLER STATION

A detailed description of the Doppler station hardware and software is given in [1, 9]. The station consists of a 10-sections antenna omnidirectional in the upper hemisphere, a unit of antenna switches, and software defined radio (SDR) that includes a personal computer and receiver. Microchip Realtek RTL2832U is used in the receiver as a demodulator of radiofrequency signals of terrestrial digital television and radio “DVB-T+DAB+FM” (Digital Video Broadcasting-Terrestrial + Digital Audio Broadcasting + Frequency Modulation). The antenna switch allows switching antenna sections automatically from the computer according to the azimuth and elevation of a tracked satellite. The satellite coordinates are calculated using TLE-orbital elements from https://www.space-track.org.

A synthesizer has recently been developed and implemented. Using the synthesizer solves two problems: 1) increasing the frequency stability of the receiver and 2) measuring the frequency and time of the received radio beacon signals. The synthesizer forms two signals: an external 28.8 MHz reference signal for the receiver and a pilot signal. The external reference signal replaces the internal one of the receiver. The pilot signal is used to estimate the frequency and time of signals received by the station. Both signals are phase-locked to the signal of 10 MHz generated by the GPS receiver. The pilot signal consists of 1 Hz packages of 100 kHz pulses. The PPS signal of the GPS receiver is used for forming the 1Hz packages. The pilot signal is applied to the input of the receiver along with signals of satellite radio beacons.

There are two modes of the Doppler station operating: real-time and post-processing [1, 9]. In real-time, three tasks are now performed: 1) automatic tracking one of a given number of low-Earth-orbit artificial satellites, 2) recording payload and pilot signals into wav-files, 3) synchronization of computer time using GPS. The criterion for selecting a satellite for tracking is the closest passage of the satellite to the station. Program TSIP_SYN is used for the time synchronization of the Doppler station computer by

GPS. The program was specially developed earlier to synchronize the computer time of SintNet stations [3]. This program provides the difference between the time of the computer and GPS at a level not exceeding 0.5 seconds. As an illustration, a screen of the station computer during registration (recording) satellite radio beacon and the pilot signal is given in Figure. The radio beacon signal emitted by the OSCAR-19 satellite is marked by digit 1 and a 100 kHz harmonic of the pilot signal by 2.

During post-processing, the next tasks are performed by analyzing the wav-files: 1) determination of frequency and time corrections; 2) searching satellite radio beacon signal and determining radio beacon frequency as a function of time *F*(*t*) using the corrections of frequency and time; 3) clarifying orbital elements using measured function *F*(*t*) and orbital elements from *space-track.org* as the initial approximation. Internal errors in measurements of Doppler frequency shift and time synchronization have been obtained during the determination of frequency and time corrections. The relative frequency error does not exceed 10^{-10}, and the timing error is less than 30 ms, while the frequency error is about 0.06 Hz or 4 cm/s in the 430-440 MHz frequency range.

3. DISCUSSION

Further upgrading the hardware and software of the European SintNet may be proposed to increase its consumer value, namely:

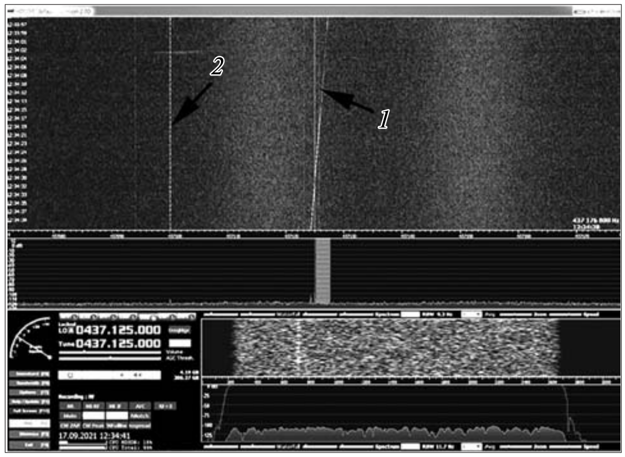
• upgrading the SintNet software for completely automated processing of the observation data up to orbital elements determination;

• implementing DVB-S(S2) receiver OMICOM on all network stations;

• developing WEB-service for ongoing representation of orbital positions of tracked satellites;

• improving network accuracy using a more accurate reference oscillator for observation synchronizing and analog-digital converting.

Clarified orbital elements of tracked satellites are not obtained yet after the synthesizer has been implemented in the Doppler station composition. Earlier, as a result of clarifying satellite orbital elements, the reduction of the difference between measured and model values of the radial velocity was obtained on average by 1.6 m/s [9].



HDSDR program screenshot with payload signal of an OSCAR-19 radio beacon (1) and a 100 kHz harmonic of the pilot signal (2)

CONCLUSIONS

1. Now, European SintNet consists of 10 stations and simultaneously tracks three satellites Eutelsat (13B, 13C, and 13E), co-located in a 13 ºE cell, including a satellite (Eutelsat-13E) that emits only DVB-S2 signal. Tracking of Eutelsat-13E has become possible due to the implementation of the multi-standard DVB-S(S2) receiver OMICOM at three network stations in Ventspils, Rivne, and Mykolaiv.

Catalogs of daily orbital elements (numerical model) for Eutelsat-13B, Eutelsat-13C, and Eutelsat-13E were obtained as a result of continuous observations since Feb 2015, Sep 2018, and May 2021, respectively.

The existing software of the SintNet allows the completely automatic acquiring of observation data and their transfer from the stations to the processing center.

2. Doppler station of RI "MAO" allows automatically tracking only one low-Earth-orbit artificial satellite out of a given number at a time. The criterion for selecting a satellite for tracking is the closest passage of the satellite to the station. The synthesizer is developed and implemented to provide forming:

• the 28.8 MHz reference signal of the RTL2832U receiver of Doppler station,

• the pilot signals, which are the 1 Hz packages of 100 kHz pulses.

The signals are phase-locked to the signal of 10 MHz generated by the station GPS receiver.

The software has been developed and implemented for the measurements of frequency and time using pilot signals. Internal errors in frequency and time measurements have been obtained. The relative frequency error does not exceed 10^{-10}. The error of time measurement is less than 30 ms. The development will make it possible to clarify the orbital elements of satellites taking into account the measurements of frequency and time. An external comparison of orbital positions of tracked satellites is planned to be carried out using data from optical observations and the ILRS (International Laser Ranging Service).

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СПОСТЕРЕЖЕННЯ GEO- І LEO-СУПУТНИКІВ РАДІОТЕХНІЧНИМИ ЗАСОБАМИ НДІ «МИКОЛАЇВСЬКА АСТРОНОМІЧНА ОБСЕРВАТОРІЯ»

Радіотехнічні засоби НДІ МАО повністю пасивні. Для відстеження супутників вони використовують радіосигнали, які випромінюють самі супутники. Таким чином, розроблено та введено в експлуатацію: 1) проста мережа інтерферометрів (SintNet) для моніторингу орбітального положення геостаціонарних супутників (GEO); 2) допплерівська станція для уточнення елементів орбіти низькоорбітальних супутників Землі (LEO).

Сьогодні працюють дві мережі SintNet: європейська і китайська. Європейська мережа SintNet складається з 10 станцій і відстежує три супутники одночасно. Китайська мережа SintNet складається з чотирьох станцій і відстежує один супутник. Похибка визначення координат супутників становить близько 200 м.

Допплерівська станція працює в діапазоні частот 430...440 МГц. Вона використовує аналіз спектру сигналу для визначення частоти $F(t)$ радіосигналу, що випромінюється супутником LEO і приймається станцією в момент часу t. Для аналізу $F(t)$ та для уточнення елементів орбіти супутника застосовано аналітичну модель руху супутника SGP4/SDP4. Похибки вимірювання допплерівського зсуву частоти та часу становлять 4 см/с і 30 мс відповідно.

Ключові слова: інтерферометр, геостаціонарні супутники, низькоорбітальні супутники Землі, ефект Допплера.