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INTERNATIONAL NETWORK OF PASSIVE CORRELATION RANGING FOR ORBIT DETERMINATION OF A GEOSTATIONARY SATELLITE

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ABSTRACT. An international network of passive correlation ranging of a geostationary telecommunication satellite is considered in the article. The network is developed by the RI "MAO". The network consists of five spatially separated stations of synchronized reception of DVB-S signals of digital satellite TV. The stations are located in Ukraine and Latvia. The time difference of arrival (TDOA) on the network stations of the DVB-S signals, radiated by the satellite, is a measured parameter.

The results of TDOA estimation obtained by the network in May-August 2016 are presented in the article. Orbital parameters of the tracked satellite are determined using measured values of the TDOA and two models of satellite motion: the analytical model SGP4/SDP4 and the model of numerical integration of the equations of satellite motion. Both models are realized using the free low-level space dynamics library OREKIT (ORbit Extrapolation KIT).

Key words: orbit of geostationary satellite, DVB-S, TDOA

1. Introduction

Passive correlation ranging (PaCoRa) of geostationary satellites is considered by the European Space Agency (ESA) as an alternate to classical two-way radar ranging [1]. The ESA project with the same name had been performed by the SES company during Jun. 2010 – Jan. 2013. PaCoRa system receives a satellite‘s downlink signal by multiple ground stations located within the satellite‘s footprint. The signal's time difference of arrival (TDOA) is determined by the PaCoRA for each pair of the stations. Further the TDOA and known geographical coordinates of the stations are used to obtain the satellite's position and predict its orbit. According to the ESA the PaCoRa has some advantages compare to the classical method of ranging. In our opinion, three of them are the most important. 1) Rx-only: small antennas and standard RF front-end hardware required. 2) No uplink for ranging, therefore no impact on the satellite. 3) Orbit determination of own satellites and 3rd party satellites.

In the Research Institute "Mykolaiv astronomical observatory" (RI "MAO") the passive correlation ranging has been employed since the first experiment in Aug. 2011 [2, 3]. The method is considered as an independent method for tracking the future Ukrainian geostationary satellite "Lybid". Results of the passive correlation ranging of Eutelsat-13B are presented in the article. The results were obtained during 2015-2016 by an international network which consists of 5 stations located in Ukraine and Latvia.

2. International network of passive correlation ranging

Now the stations of the network are located in Kharkiv, Mukacheve, Rivne, Mykolaiv (Ukraine) and Ventspils (Latvia). The Rivne station had been located in Kyiv up to Feb. 2016. The Ventspils station has operated since Nov. 2015. The network has operated as a part of the four Ukrainian stations since Jan. 2015. The network also includes a data processing center, located in Mykolaiv.

The stations of the network have identical hardware and software. Each station consists of:

– The standard antenna-feeder system for the reception of DVB-S signals, with antennas of 0.9 m in diameter;

– DVB-S receiver (SkyStar1 or Skystar2) performed as a PCI-card and upgraded in terms of outputting of in-phase and quadrature signals from the receiver's quadrature detector;

– Single-frequency ThunderBolt-E GPS receiver;

– Digital USB-oscilloscope DSO5200A with 200 MHz passband and 9-bit ADC (Analog Digital Converter);

– Personal computer (PC) with USB and RS-232 ports, operable in Windows XP environment (1 GHz CPU clock rate; 1 Gb RAM, and 100 Gb HD capacity);

– Internet connection at data rate of at least 80 Kbytes per second.

The station software consists of:

– Standard software of the DTV-S receiver and digital USB oscilloscope;

– Open source software FileZilla (FTP-client);

– Special software for synchronized measurements by the GPS and for reading and archiving samples of the DVB-S signals on the PC hard drive.

Detailed description of the station hardware and software is given in [3, 4]. The hardware and software allow each station of the network to record every second fragments of DVB-S complex signal, incoming from the quadrature detector, synchronously with PPS (Pulse-Per-Second) signals, incoming from the GPS receivers. It is shown in [3] that the complex signal should be transformed in a real signal taking into account the structure of DVB-S signal to obtain convolution and subsequently calculate TDOA. This transformation is performed on the stations now. The obtained real signal samples are archived and sent through the Internet in the data processing center. Here the correlation function of the real samples is computed and the value of TDOA is estimated by the following formula [5]:

$$\Delta\tau_i = \left(\frac{n_{xi}}{k \cdot f_n} + \tau_{PPSi}\right) - \left(\frac{n_0}{k \cdot f_n} + \tau_{PPS0}\right) - \Delta\tau_{hi}, \quad (1)$$

where $\Delta\tau_i$ – time difference of arrival the signals received by the i-th and 0 stations, n_{xi} – offset of the maximum of the correlation function from the beginning of the sample obtained by the *i*-th station, n_0 – given offset of the middle part of the sample obtained by the zero station, f_n – nominal sample rate of the ADC of the digital USB oscilloscope, k – measured factor between valid and nominal sample rates of the ADC, $\Delta\tau_{hi}$ – measured value of the difference of hardware delays of the stations, τ_{PPSi}, τ_{PPS0} – given initial delays of PPS signals of GPS receivers of the stations. The values of n_{xi} and n_0 are measured in counts of the sampling frequency. The size of the middle part of the zero station sample is equal to the sample size of a correlator and is always less than the sample size of the ADC. The ADC sample size is equal 10240 for the employed type of USB oscilloscope. The corresponding sample length is equal 200 µs for the sample rate f_n=51.2 МГц. The mentioned sample rate is close to Nyquist rate for the received signal. The coefficient k = 0.97655 is a constant for the given type of oscilloscope. Values of τ_{PPS} depend from geostationary position of tracked satellite and for Eutelsat-13B they are equal 1270 µs, –215 µs, 642 µs, 0 µs, 2660 µs and 888 µs respectively for the station in Kharkiv, Mukacheve, Rivne, Mykolaiv, Ventspils and Kyiv. The data processing center software has been written on Python to compute TDOA.

The special software has also been developed on Python to determine the orbit of tracked satellite using observed values of TDOA. Herewith orbit parameters are determined using the least square method (LS), namely, by minimizing the sum of squared differences of the observed and model values of TDOA. The LS equations are solved using the Levenberg-Marquardt method software-implemented in the Python function *leastsq* [6, 7]. The LS equations are also solved with respect to satellite coordinates in inertial coordinate system on an observing epoch. The satellite position is modeled using the free space dynamics library OREKIT (ORbit Extrapolation KIT) written in Java [8]. The developed software allows determination the satellite orbit using the SGP4/SDP4 (Simplified General Perturbation/Simplified Deep Space Perturbation) analytical model of satellite motion [9, 10], and using a numerical model of integrating the equations of satellite motion [11]. The SGP4/SDP4 model is used to determine the pseudo-keplerian elements of satellite orbit in the so called the two-line elements (TLE) format proposed by NORAD. The initial values of the satellite coordinates and velocity for this model are set in the TEME (True Equator Mean Equinox) coordinate system – the Earth-centered inertial frame used for determine the NORAD two-line elements. The following perturbations are taken into account under using the numerical model to determine satellite orbit:

– Three-body gravitational attractions of the Sun and Moon, JPL DE 405/DE 406 [12];

– Gravitational attraction of the non-spherical Earth (Earth gravity model EIGEN-6S, truncated to the 9th degree and order) [13].

The initial values of the satellite coordinates and velocity for the numerical model are set in the EME2000 (Earth's Mean Equator and Equinox) coordinate system which is also called J2000 frame.

The coordinates of the stations are necessary to determine the orbit. They are set in the Earth-fixed WGS84 system and are taken directly from the measurement data of GPS receivers used for synchronization of the stations. Initial values of the coordinates of tracked satellite are also originally set in the WGS84 assuming that the satellite is at the geographic coordinates of equal φ_{GSS}, λ_{GSS} = 0 and h_{GSS} = 36000 km, where φ_{GSS}, λ_{GSS} and h_{GSS} denote the longitude, latitude and height of the geostationary satellite. The satellite Eutelsat-13B is located in the geostationary cell at the longitude 13° East, therefore, φ_{GSS} = 13°.

3. Passive correlation ranging of Eutelsat-13B

As an illustration, in Fig. 1 the graphs of slant range differences $\overline{\Delta r}$ changed in time from May 18, 2016 to Aug. 16, 2016 are given for four pairs of stations Kharkiv-Mykolaiv, Mukacheve-Mykolaiv, Ventspils-Mykolaiv and Rivne-Mykolaiv.

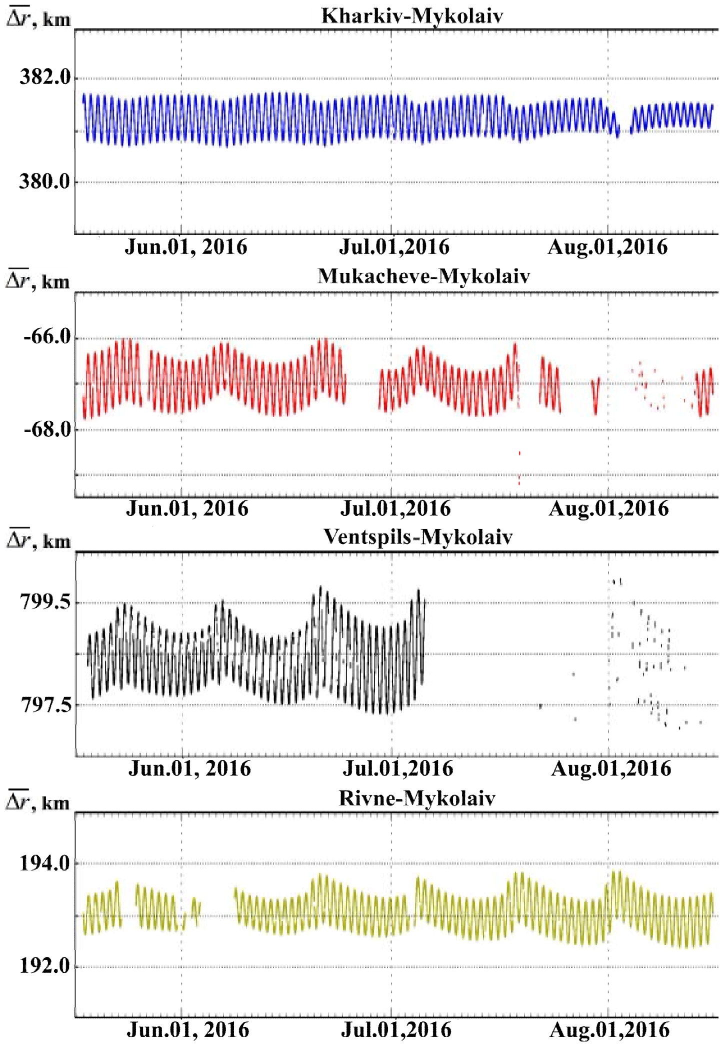
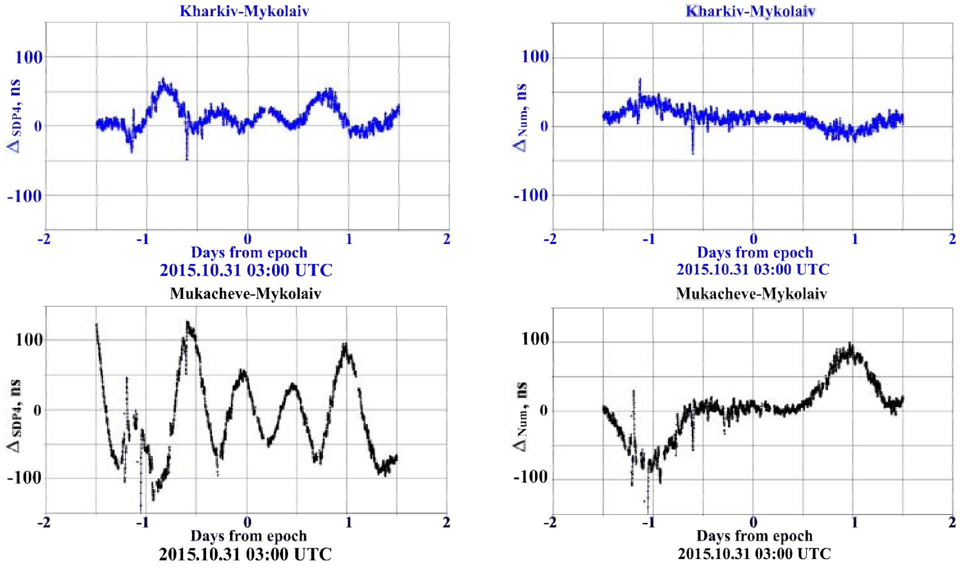


Figure 1: Slant range differences for four pairs of stations (from top to bottom): Kharkiv-Mykolaiv, Mukacheve-Mykolaiv, Ventspils-Mykolaiv and Rivne-Mykolaiv. Observation time is from May 18, 2016 to Aug. 16, 2016.



(a) (b)

Figure 2: Residuals between model and observed TDOA for two pairs of stations (from top to bottom) Kharkiv-Mykolaiv and Mukacheve-Mykolaiv, and for two models: (a) – for SGP4/SDP4 model, and (b) – for numerical model. Fitting interval equals 24h.

Table 1. Mean and standard deviations of the residuals.

Model	Kharkiv-Mykolaiv		Mukacheve-Mykolaiv	
	$\overline{\Delta}$, ns	σ, ns	$\overline{\Delta}$, ns	σ, ns
SGP4/SDP4	11	±9	3	±39
Numerical	13	±5	4	±6

The slant range differences $\overline{\Delta r}$ is obtained by averaging every second values $\Delta r = \Delta\tau \cdot c$ on the interval of 60 s, where $\Delta\tau$ – the TDOA for given pair of stations and c – the speed of light in vacuum. Statistical analysis shows that for all four pairs of stations the median of standard deviation (SD) of Δr is ±2.6 m or ±8.7 ns for the TDOA SD.

The graphs of the TDOA residuals (Δ) between model and observed values are shown in Fig. 2 for the interval of ±1.5 days from the observing epoch 31.10.2015 03:00 UTC and for two pairs of stations Kharkiv-Mykolaiv and Mukacheve-Mykolaiv. Herewith the residuals obtained using the SGP4/SDP4 model are shown in Fig. 2 (a), and using the numerical model – in Fig. 2 (b). The interval for fitting the model and observed values was equal 24 hours.

From the data given in Fig. 2 (a) it follows that the SGP4/SDP4 residuals have significant periodic deviations on the fitting interval due to the inaccuracy of the model. The residuals graphs for the numerical model (Fig. 2 (b)) do not have significant periodic deviations on the fitting interval. Mean ($\overline{\Delta}$) and standard deviations (σ) of the residuals obtained on the fitting interval are given in Table 1. For both model there are significant deviations of the residuals outside of the fitting interval.

4. Summary

1. The monitoring of Eutelsat-13B was performed by the international network of passive correlation ranging during about a year from Nov. 2015 to Aug. 2016. The network consists of five stations received DVB-S signals and spaced at 1000 km along longitude as well as latitude .Single-measurement error (1 sigma) of the TDOA is equal about ±8.7 ns for the all pairs of the stations.

2. Special software was developed for determination orbital parameters by TDOA using the SGP4/SDP4 model and simple numerical model of satellite motion. Standard deviations and average values of the residuals between the model and observed TDOA are estimated for the pairs Kharkiv-Mykolaiv and Mukacheve-Mykolaiv. The numerical model is more accurate than the SGP4/SDP4 model. The standard deviations of the TDOA residuals on the fitting interval do not exceed ±6 ns for the numerical model. The fitting interval should be set more than 24 hours to increase prediction accuracy of the models.

3. The considering network could be a prototype of a system of ongoing monitoring of orbits of active geostationary satellites. This system may be cheap to implement and will be fully independent, do not tied to uplink stations.

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