Use of Ground Stations of ERS Data Reception in the Interest of Space Situational Awareness

O.M. Kozhukhov
National Space Facilities Control and Test Center, Kyiv, Ukraine
O.V. Kalvatynskiy, D.M. Kozhukhov, A.P. Ozerian, V.M. Mamarev, I.V. Brukhno
National Space Facilities Control and Test Center, Kyiv, Ukraine

L.S. Shakun
Astronomical Observatory of Odessa I.I. Mechnikov National University

A.A. Zavada
Korolyov Zhytomyr Military Institute

ABSTRACT

The increase in the number of artificial space objects (SO) in near-Earth space leads to an increase in the number of sensors required to perform the tasks of space situational awareness (SSA). At the same time the number of not only classical radar and optoelectronic sensors is increasing, but also other types of sensors.

Recently, interest in passive radio frequency sensors for SO monitoring in different bands has increased significantly. One of the advantages of this approach is the ability to use existing stations to create them.

We propose the use of ground stations for receiving information from Earth remote sensing (ERS) satellites in X-band as additional sensors for obtaining the trajectory measurements of SO in order to increase the performance of space situational awareness tasks.

An algorithm for ERS satellites' orbit improvement was developed. It is based on the information from X-band reception stations using the search method of minimization of the objective function, and is formed on the LS method's basis. It allows to expand the region of convergence for the boundary value problem by reducing the requirements for the accuracy of the orbit's initial approximations and the amount of accumulated trajectory measurements.

The unbiasedness of the developed algorithm was tested on the basis of simulated trajectory measurements, preliminary researches were carried out using real trajectory measurements.

1. INTRODUCTION

After the launch of the so-called large constellations of spacecrafts (SC), the number of objects in low Earth orbits (LEO) began to increase even faster than before. Such a large number of objects requires much more effort for the safe use of operating spacecraft. This primarily concerns the prediction of dangerous collisions. Increasing the number of objects in orbit leads to an increase in the number of such collisions. The need to react to them (maneuvering) leads to excessive consumption of the propellant and thus reduces the time spent in orbit by a fully operational satellite. Reducing the number of collisions to be responded to is possible primarily through maximum accurate knowledge of the orbital position of objects in outer space. Thus, the requirements for the accuracy of the SC's orbits determination continue to increase. It, in turn, leads to the involvement of new sensors.

In recent years, conventional optical and radar sensors have been increasingly supplemented by radio frequency monitoring (RFM) facilities, which previously dealt primarily with space communications, data transmission and SC control. Now we are even talking about the creation of special networks of RFM sensors for use in the interests of SSA [2], [3]. Another way to expand the number of RF sensors for outer space monitoring is to upgrade existing facilities, such as stations for Earth Remote Sensing (ERS) data reception

2. TYPICAL GROUND STATION FOR ERS DATA RECEPTION AND PARAMETERS IT CAN MEASURE

2.1 General information about X-band ground stations

A typical ground station for ERS data reception consists of the following main elements (Fig. 1):
receiving antenna (usually a dish antenna with a diameter of 3 - 12 m);
frequency downconverter;
demodulator;
registration PC;
control PC.

The antenna tracks ERS SC through the ephemeris during data reception. The received signal with the carrier frequency f_r is fed to the frequency downconverter (Fig. 2), where it is transferred to the intermediate frequency f_i equal to:

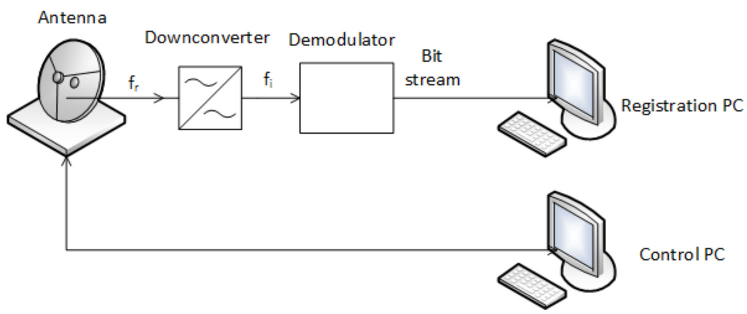


Fig. 1: Main elements of ground station for ERS data reception

$$f_i = f_r - f_{lo}, \tag{1}$$

where f_{lo} is a carrier frequency of the local oscillator.

The signal at the intermediate frequency is fed to the demodulator, where it is converted into a bitstream recorded by the registration PC.

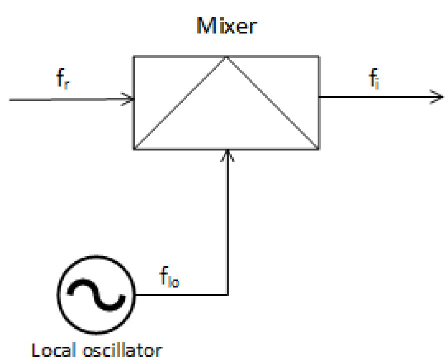


Fig. 2: Simplified downconverter block diagram

Most stations have the ability to keep a protocol of the ERS data reception session. It registers (with time-tagging) the direction of the antenna pattern, signal level, local oscillator carrier frequency, intermediate frequency, and other required parameters. The analysis of the protocol data can allow to obtain information about the position of the SC that transmits ERS data during the session.

2.2 Parameters can be obtained at the ground station for ERS data reception

2.2.1 Angular position of the satellite

As it is mentioned above, it is possible to obtain the positions of the antenna pattern at different points in time by analyzing the session protocol. These points correspond to the position of the SC transmitted the signal received by the ground station. These parameters are obtained in the topocentric horizontal coordinate system: azimuth (Az) and elevation (h). However, given that the values of these angles are recorded in the protocol simply as indicators of the angular sensors of the antenna, the errors in their estimation can be quite big (see sections 4 and 5).

2.2.2 Radial velocity of the spacecraft

As it is known, the radial velocity v can be obtained from the following expression:

$$v = \frac{c f_D}{f_t}, \tag{2}$$

where c is speed of light; f_t is the carrier frequency of the signal transmitted from the SC; $f_D = f_r - f_t$ is the doppler frequency shift.

If the value of f_t is known, then the value of f_r can be obtained from (1):

$$f_r = f_i + f_{lo}, \tag{3}$$

Thus, if the carrier frequency transmitted from the SC is known, the SC's radial velocity can be obtained directly using (3) and (2).

3. PECULIARITIES OF DOPPLER SHIFT AND RADIAL VELOCITY ESTIMATION AT UNKNOWN TRANSMITTED CARRIER FREQUENCY

In the general case, the carrier frequency transmitted from the SC may be either unknown or differ from the frequency specified in the documentation due to changes in the parameters of the SC's equipment. In this case, to determine f_t you can use the features of the change of f_D in time during the passage of the SC through the working area of the ground station. The graph of the f_D change in time is a monotonic curve with a specific S-shape, with a zero value at the point with the maximum elevation [4], [5]. Also, the passage time of the maximum elevation is the time when the derivative of this function acquires the maximum value [1]. The curve of change in time f_r has a similar shape, and at the point of the maximum elevation $f_t = f_r$. Thus, if we can set the time of passage of the maximum elevation by the SC and the value of f_r corresponds to this time, then we will determine the unknown value of f_t, and v according to (2) respectively.

It follows from the above, this dependence can be represented as a function of time t and the transmitted carrier frequency:

$$f_r = f(f_t, t).$$

If we choose as $f(f_t, t)$ a known function, that has properties correspond to the properties of the change f_r in time (we talked about them above), then it is possible to obtain a LS estimation of the SC's passage time of the maximum elevation t_0 and f_t respectively using the session protocol data with time and the corresponding value of f_r. After receiving the estimation of f_t, we can already obtain the corresponding estimates of v.

There are different approaches to obtaining similar formulas, for example [4], [5]. In this paper, we used the following model function:

$$f_r = f(f_t, t) = \frac{b_1 \arctan\left(b_2(t - t_0)\right)}{b_3} + f_t,$$

where b_1, b_2, b_3 are model coefficients determined through LS.

4. ACCURACY OF PARAMETER ESTIMATION

4.1 Accuracy of angle measurements

The main component of angle measurements errors depends primarily on the beamwidth θ of the station and the ”signal-to-noise” ratio (SNR) of the received signal [6] - [8]:

$$\sigma_\theta = \frac{\theta}{k\sqrt{2SNR}}$$

where σ_θ is the angle measurements error (for a symmetrical beam, it will be the same for both angles); k is the monopulse pattern difference slope.

This component of errors in the general case is much higher than others. For example, for $\theta = 1^\circ$ and $SNR = 12$ dB the angular measurement error is 2 mrad, and σ_θ =1.9 mrad [8]. Thus, in the first approximation, the other components can be neglected and due to the fact, that in the case under consideration, no monopulse technique is used, the coefficient k can be taken as equal to one or less.

4.2 Accuracy of radial-velocity measurements

In the general case, the accuracy of radial velocity measurements also depends on SNR [7], but in this case the radial velocity estimate is the result of indirect measurements and its error can be estimated from expression (2) as:

$$\Delta v = \left|\frac{\partial v}{\partial f_D}\right| \Delta f_D + \left|\frac{\partial v}{\partial f_t}\right| \Delta f_t = \left|\frac{c\Delta f_D}{f_t}\right| + \left|\frac{c f_D \Delta f_t}{f_t^2}\right| = c\left|\frac{f_t \Delta f_D + f_D \Delta f_t}{f_t^2}\right|, \tag{4}$$

where Δf_D, Δf_t are errors of estimating the doppler shift and the transmitted carrier frequency respectively.

From expression (4) it is clear that with equal errors in estimating the doppler shift and the transmitted carrier frequency, a higher carrier frequency helps to obtain a smaller error in determining v. It makes the X-band very attractive for such observations.

In turn:

$$\Delta f_D = \Delta f_r + \Delta f_t ; \Delta f_r = \Delta f_i + \Delta f_{lo},$$

where Δf_r is received carrier frequency determination error; Δf_i, Δf_{lo} are intermediate frequency and local oscillator frequency determination errors.

If we know the exact value of f_t, then $\Delta f_t = 0$, and in expression (4) only the first term remains:

$$\Delta v = \left|\frac{\partial v}{\partial f_D}\right| \Delta f_D + \left|\frac{\partial v}{\partial f_t}\right| \Delta f_t = \left|\frac{c\Delta f_D}{f_t}\right|.$$

5. RESULTS OF THE DEVELOPED METHOD VERIFICATION

5.1 Initial data

The verification was carried out on the basis of the PS-8.2 station for ERS data reception. It is part of the National Space Facilities Control and Test Center of the State Space Agency of Ukraine (Fig. 3). The main characteristics of the station are given in Table 1. The results of processing three passes (2020-June-04, 2020-June-05, 2020-June-06) for Terra SC (SSN ID 25994) were selected for verification.

5.2 Comparison of measurements and propagation of satellite’s positions and velocities

We used the Orekit library to predict the positions and velocities of the SC [9]. Prediction of satellite positions and velocities is usually performed in one of the inertial coordinate systems (for example, the TEME coordinate system is used for the SGP4 model [10]). Thus, to compare the measurements and the predicted positions and velocities of the SC, it is necessary to convert them into a coordinate system of measurements. In our case, the coordinate system of measurements is a horizontal coordinate system (azimuth and elevation) at the place of observation. To specify this coordinate system, we used the longitude, latitude and altitude of the observation station according to the GPS receiver data relative to the WGS84 ellipsoid and the associated coordinate system ITRF2014 [11].

Fig. 3: PS-8.2 station for ERS data reception

Table 1: The main characteristics of the PS-8.2 station for ERS data reception

Antenna diameter	5 m
Working band	7700-8500 MHz (X)
Local oscillator frequency	7425 MHz
Intermediate frequency band	250 – 1050 MHz
Number of ERS data reception channels	4
Beamwidth	30 arcmin
Antenna mount	Azimuth-elevation
Maximum azimuth slew rate	18 deg/s
Maximum elevation slew rate	4 deg/s

We also used the Orekit library to convert satellite positions and velocities between coordinate systems.

Fig. 4 - 6 show the differences between the measured values: azimuth, elevation and radial velocity of the Terra SC and theoretical estimates, calculated by the SGP4 model. Two-Line Elements (TLE) with initial orbit data were taken from the USSPACECOM catalog [12] at the time of observations. It is seen that between the measurements and the theoretical estimate there are systematic differences at the level of a few tenths of a degree for measurements of angles and a few tens of meters per second for measurements of radial velocity. Based on the figures, it is possible to estimate the value of the random error of one dimension. We estimated for the angular measurements a random error of the order of 0.01 degrees and 1 m/s for the radial velocity.

5.3 Residuals between measurements and the average keplerian orbit for one pass

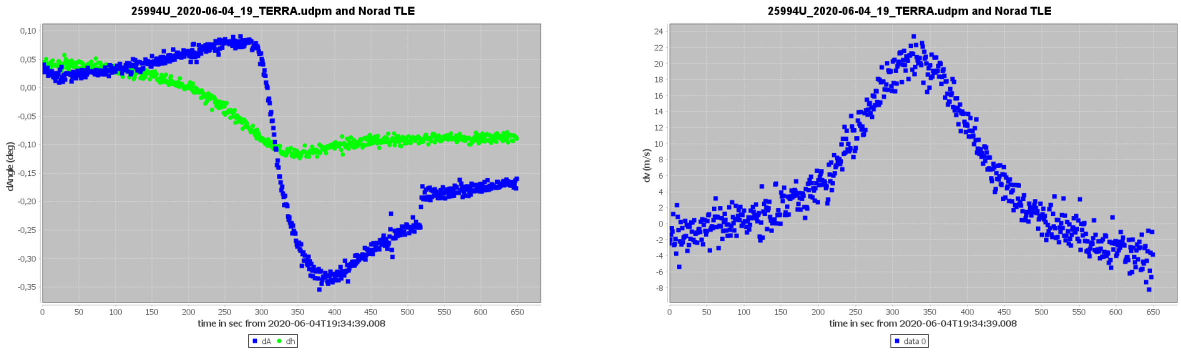
We made an attempt to estimate the elements of the average orbit in one pass. Due to the fact that the accuracy of one measurement of radial velocity is about 1 m/s, and the total duration of measurements for one pass is about 10 minutes, we decided to limit ourselves to Keplerian model of motion. At such time intervals, the average Kepler orbit must describe the observations with an accuracy that corresponds to the accuracy of the observation errors.

To estimate the initial elements of the average keplerian orbit, we used the LS estimate and minimized the functionality of the form:

$$\Phi = \sum_i \left(\left(\frac{Az - \hat{A}z}{w_{Az}} \right)^2 + \left(\frac{h - \hat{h}}{w_h} \right)^2 + \left(\frac{v - \hat{v}}{w_v} \right)^2 \right), \tag{5}$$

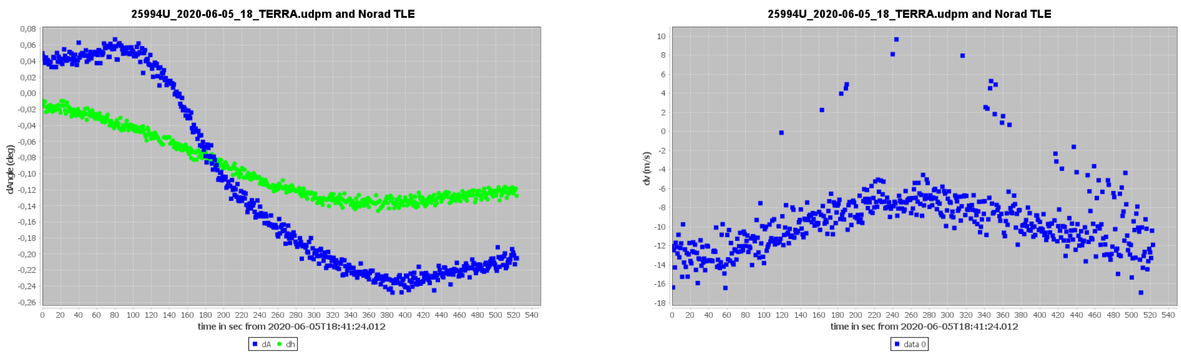
where Az is the azimuth; h is the elevation; v is the radial velocity; $\hat{A}z)$, $\hat{h}$, $\hat{v}$ are the LS estimates of the corresponding values; w_{Az}, w_h, w_v are a priori estimates of the accuracy of one measurement of the corresponding values.

We estimated the initial elements of the average keplerian orbit in the space of Cartesian positions and velocities at the



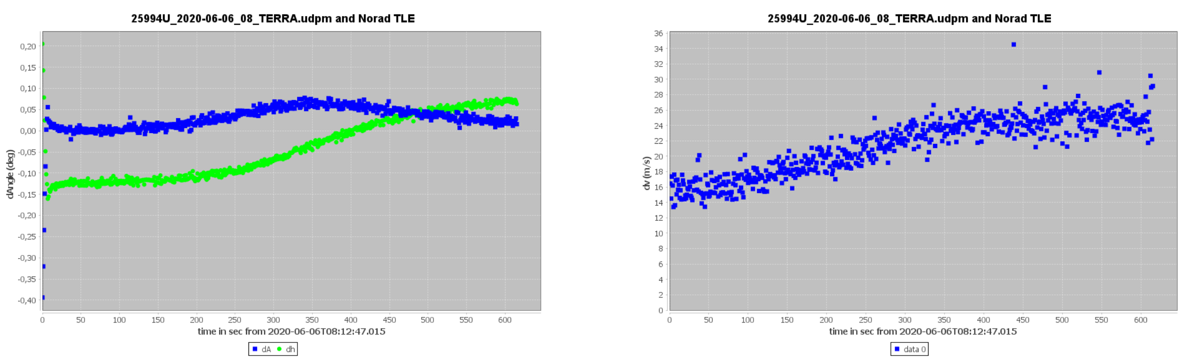
a) b)

Fig. 4: Residuals between Terra SC observations for 2020-June-04 and the SGP4 model prediction for TLE: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)



a) b)

Fig. 5: Residuals between Terra SC observations for 2020-June-05 and the SGP4 model prediction for TLE: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)



a) b)

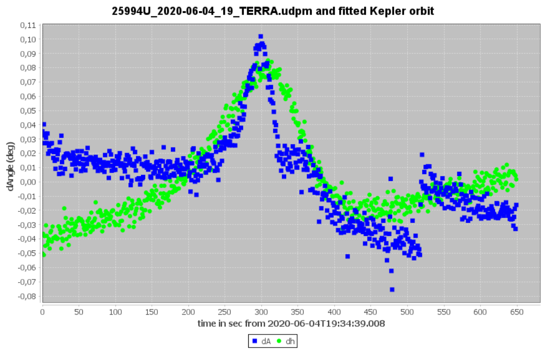
Fig. 6: Residuals between Terra SC observations for 2020-June-06 and the SGP4 model prediction for TLE: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)

initial moment of time (the moment of the mid-passage time) in the GCRF coordinate system.

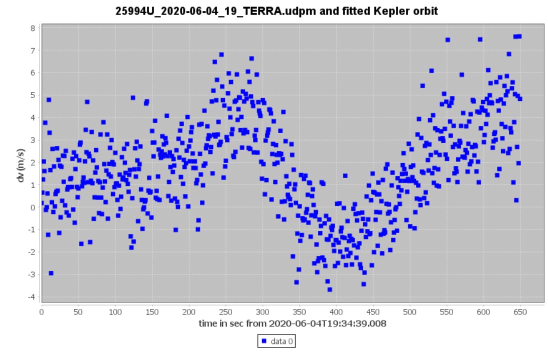
The Levenberg-Marquardt algorithm was used to solve the obtained nonlinear equations.

Orbit elements calculated on the basis of SGP4 prediction were used as the initial elements of the orbit.

Fig. 7 - 9 show the residuals between the measurements and the average keplerian orbit, when the a priori values of the accuracy of one measurement for $w_{Az} = w_h = 0.01°$, $w_v = 1$ m/s. Comparing Fig. 4-6 and 7-9, we see slight

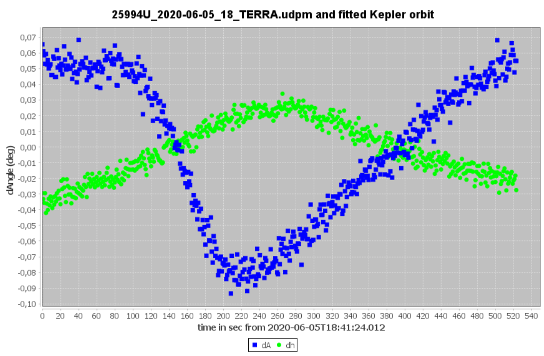


a)

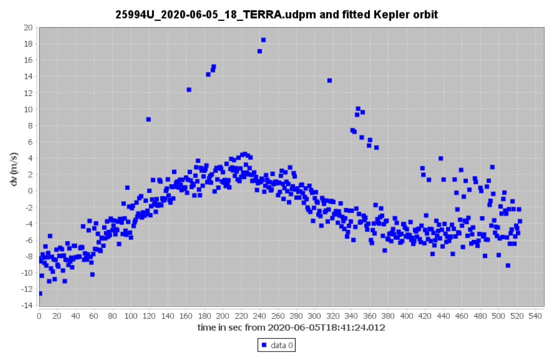


b)

Fig. 7: Residuals between Terra SC observations for 2020-June-04 and the prediction for the average keplerian orbit for $w_{Az} = w_h = 0.01°$, $w_v = 1$ m/s: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)

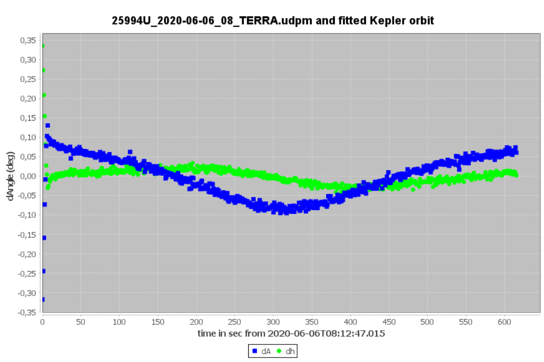


a)

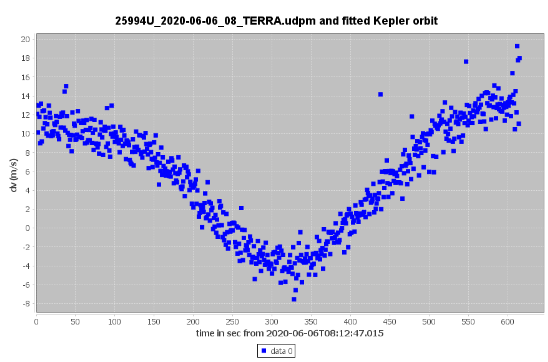


b)

Fig. 8: Residuals between Terra SC observations for 2020-June-05and the prediction for the average keplerian orbit for $w_{Az} = w_h = 0.01°$, $w_v = 1$ m/s: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)



a)



b)

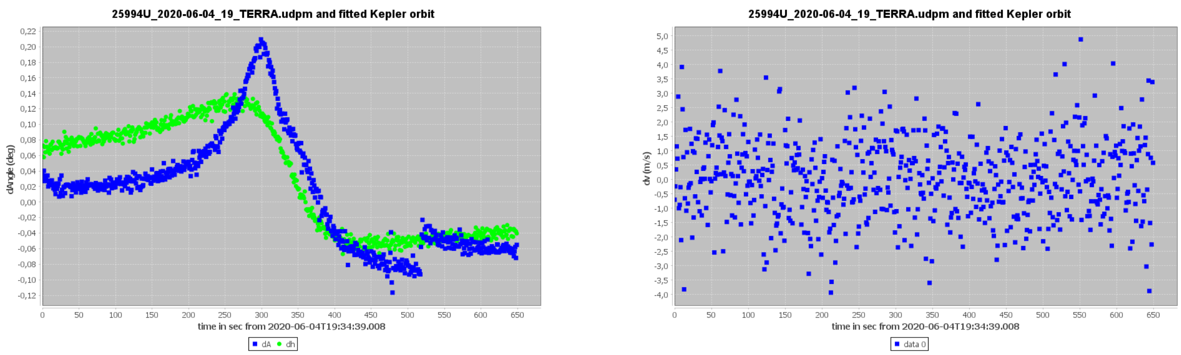
Fig. 9: Residuals between Terra SC observations for 2020-June-06 and the prediction for the average keplerian orbit for $w_{Az} = w_h = 0.01°$, $w_v = 1$ m/s: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)

improvements in the structure of the residuals. On the one hand, previous experience tells us that the data of angular coordinates are usually quite unreliable and often burdened with various systematic errors. Moreover, the procedure of comparing measured angles and theoretical estimates does not take into account such effects as refraction. Given that much of the measurements are obtained at elevations less than 20 degrees, the effect of atmospheric refraction should be significant.

On the other hand, the measurement of the radial velocity based on the Doppler effect should not contain significant systematic errors.

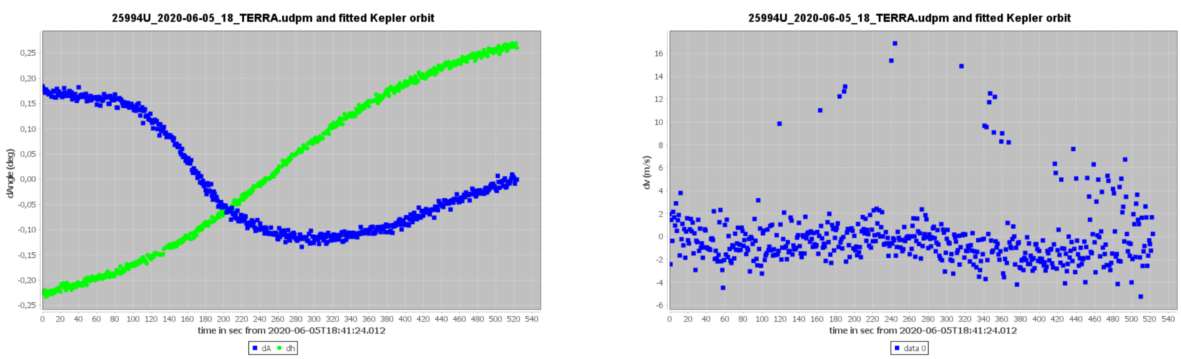
Based on these considerations, we increased the a priori errors for measuring angles by an order of magnitude to $w_{Az} = w_h = 0.1°$. It should have significantly offset the effect of systematic deviations for angular measurements, due to the reduction of the weight of residuals in the (5).

Fig. 10 to 12 show the residuals between the measurements and the average keplerian orbit, when the a priori values of the accuracy of one measurement for $w_{Az} = w_h = 0.1°$, $w_v = 1$ m/s. As it can be seen from Fig. 10 - 12, the



a) b)

Fig. 10: Residuals between Terra SC observations for 2020-June-04 and the prediction for the average keplerian orbit for $w_{Az} = w_h = 0.1°$, $w_v = 1$ m/s: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)

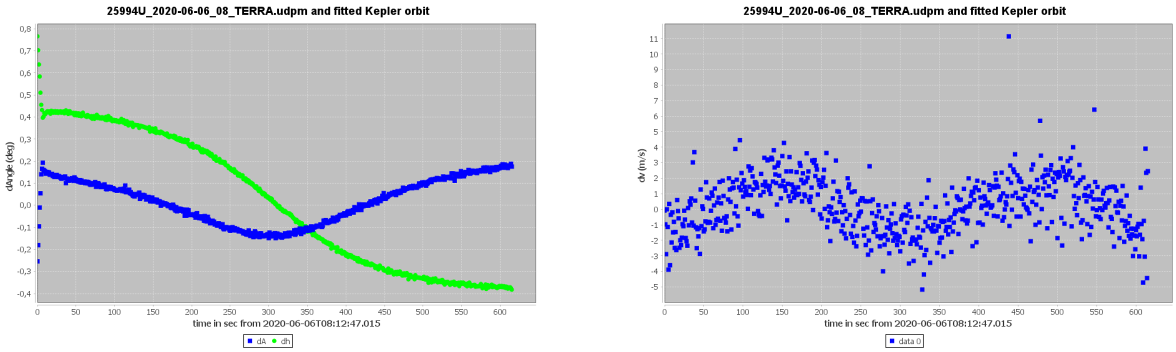


a) b)

Fig. 11: Residuals between Terra SC observations for 2020-June-05and the prediction for the average keplerian orbit for $w_{Az} = w_h = 0.1°$, $w_v = 1$ m/s: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)

reduction of the role of systematic error in the angle measurements allowed to completely eliminate the systematic trend in the residuals of radial velocity for measurements for 2020-June-04 and 2020-June-05. In the measurements for 05.06.2020 there is a significant amount of emissions, which probably indicates the presence of episodic problems in the measurements. For observations on 2020-June-06, the systematic trend for radial velocity was not completely eliminated. It may be due to a slightly more pronounced systematic trend for angular coordinates. In general, it can be concluded that the measurement of the radial velocity at the ground station has an error of one measurement of about 1 m/s and has no significant systematic trends within the random error of one measurement.

The angular coordinates of the satellite are not measured well enough, which is manifested in the presence of noticeable systematic trends in the residuals relative to the average orbit.



a) b)

Fig. 12: Residuals between Terra SC observations for 2020-June-06 and the prediction for the average keplerian orbit for $w_Az = w_h = 0.1°$, $w_v = 1$ m/s: a) angular residuals (azimuth (dA) and elevation (dh)); b) radial velocity residuals (dv)

6. CONCLUSIONS

Ground stations for ERS data reception can be used as additional means of radio frequency monitoring of outer space.

It is possible to obtain angular coordinates (azimuth and elevation) and radial velocity observing active spacecraft by ground stations.

Determination of the radial velocity by the doppler frequency shift is possible even in the absence of accurate values of the frequency transmitted from the spacecraft.

The accuracy of determining the radial velocity is much higher than the accuracy of determining the angular coordinates.

Further efforts should be made to improve the accuracy of the obtained measurements: to improve the time tagging accuracy, to improve the methods for determining angular coordinates and radial velocity and so on.

7. REFERENCES

[1] D. Richmond and K. Raichle. Doppler Curves in Satellite Tracking and Characterization, *AMOS Technical Conference Proceedings* , 2018.
[2] M. Werremeyer, S. Clark, J. Dorny and V. Pascente. Sensor Network for Global Monitoring of Spacecraft Situational Awareness, *AMOS Technical Conference Proceedings*, 2019.
[3] B. Lal et al. *Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)*, Institute for Defense Analyses, 2018.
[4] I. Ali, N. Al-Dhahir and J. E. Hershey. Doppler Characterization for LEO Satellites, *IEEE Transactions on Communications*, 46, 3, 309–313, 1998.
[5] Z. Tabakovic. Doppler Effect in Non-GSO Satellite Propagation, 1999. (https://bib.irb.hr/datoteka/39128.p0767.PDF).
[6] S. Kingsley and S. Quegan. *Understanding Radar Systems 1st Edition*, SciTech Publishing,1999.
[7] G. R. Curry. Radar Essentials. *A Concise Handbook for Radar Design and Performance Analysis,* SciTech Publishing, 2012.
[8] G. R. Curry. *Radar System Performance Modeling, 2nd Edition*, Artech House, 2004.
[9] https://www.orekit.org/ .
[10] D. Vallado, P. Crawford, R. Hujsak and T. Kelso. *Revisiting Spacetrack Report # 3*, AIAA, 2006.
[11] Z. Altamimi, P. Rebischung, L. Metivier, and X. Collilieux. ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, *J. Geophys. Res. Solid Earth*, 121, 6109– 6131, 2016 (DOI:10.1002/2016JB013098).
[12] https://www.space-track.org .