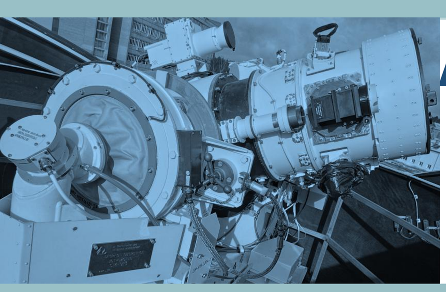
FEDERAL AGENCY ON TECHNICAL REGULATING AND METROLOGY

RUSSIAN METROLOGICAL INSTITUTE OF TECHNICAL PHYSICS AND RADIO ENGINEERING

STATE SCIENTIFIC CENTER OF THE RUSSIAN FEDERATION

$\tilde{y}_j = y_j - P_{n,j}(\vec{a})$



A new method for automated processing of rough measurements in satellite laser rangefinders

Igor Yu. Ignatenko, Igor V. Bezmenov

VNIIFTRI, Mendeleevo, Moscow reg., Russian Federation, Email: igig@vniiftri.ru

VNIIFTRI – National Metrological Institute

Federal State Unitary Enterprise (FSUE) "National Research Institute for Physical-Technical and Radio Engineering Measurements" (VNIIFTRI) is subordinated to Federal Agency on technical regulation and metrology of Russia. It has the status of the State scientific metrological center and is one of the main centers of the State standards of Russia. The VNIIFTRI plays role of the Main Metrological Center (MMC) of State service of time, frequency and EOP evaluation (SSTF).

Introduction

Satellite laser ranging(SLR) measurements are one of the tools to achieve high-precision synchronization of remote time and frequency standards, with the State Time and Frequency Standard and National Time Scale. Currently, the Main Metrological Center of the State Service for Time, Frequency and Determination of Earth Rotation Parameters (GMC GSVCH) has two scanning laser rangefinders (SLD): MMKOS "Sazhen-TM-BIS" and a new generation laser station "Tochka" [1], which are part of the GLONASS fundamental support system. Their connection with the State Special Standard of Unit Length and GMC GSVCH makes it possible to provide a direct metrological basis for measurements [2]. In order to obtain stable estimates, in particular, normal points, the measurement data at the preliminary stage of processing undergo a process of cleaning from outliers using trend building algorithms [3,4] and finding the optimal solution with the minimum number of rejected measurements [5,6]. The report, in particular, discusses the achieved results on the accuracy of the formation of normal points in conditions of an unfavorable effect on the measurements of external factors, such as refraction of the troposphere, background illumination, reception of a signal from satellite with low declination angles, etc. [7,8]..

Minimizing sets method for trend detection in noisy data in the polynomial class.

To obtain normal points related to the observed satellite, it is necessary to obtain and process a number of observations. The observations are a numerical series of values of pseudo-ranges to the spacecraft, obtained using a laser rangefinder at times synchronized with the National Time Scale. Since the presence of coarse measurements (outliers) in the observation data can significantly distort the final result, the detection and removal of outliers from the measurement series is a necessary part of data preprocessing.

The trend and outlier detection problems are tightly coupled. To find a trend, we first need to find outliers and eliminate them from the values of series ; after that, we need to find the desirable trend by adjusting some functions to the remaining values treated as reference ones. On the other hand, to detect outliers, it is necessary to know the trend. Initially, neither trend nor outliers are known. Both trend and outlier problems are found through iterations as described below. The trend-detection problem is traditionally solved as a result of searching for a trend in a predetermined functional class, for example, in the class of power polynomials, the coefficients of which are usually fitted to observation data in L_2 norm using the least squares method. However, the presence of outliers at the reference points by which the polynomial (or other function) is constructed can lead to significant distortion of the "true" trend values and, as a result, to incorrect detection of outliers [7].

To find the trend in the class of polynomials, one of the authors of this article developed a new minimizing sets method (see [3]), the main idea of which is searching a trend through a converging iterative process for finding reference points (for details see [9]).

In the case of power polynomials, the unknown trend is approximated by functions of the form

$$f_j : P_{n,j}(\vec{a}) = a_n \cdot x_j^n + a_{n-1} \cdot x_j^{n-1} + \ldots + a_0 \qquad j = 1, \ldots, N$$

where n – degree $\vec{a} = (a_0, \ldots, a_{n-1}, a_n) \in \mathbb{R}^{n+1}$ coefficients and $x_j = (t_j - t_1)/(t_N - t_1)$ normalized argument values: $x_j \in [0,1]$

The trend search is carried out in accordance with the strategy described in [3] by means of a double iteration process, as a result of which both the degree n (external iterations) and the reference points themselves (internal iterations) are found. We fix $L \le N$ – the number of desired reference values.

One step of an internal iteration loop at a fixed polynomial power n comprises:

a) Searching for coefficients $a_0, \ldots, a_{n-1}, a_n$ of the polynomial (1) by L reference values found at the previous iterative cycle (initially all N values of the series $\{y_j\}_{j=1}^N$ are considered reference);

b) Forming residuals $\tilde{y}_j = y_j - P_{n,j}(\vec{a})$ and searching for minimizing set $Y_{L,\min} = \{\tilde{y}_{j_1^*}, \ldots, \tilde{y}_{j_L^*}\}$ of length L in the series $\{\tilde{y}_j\}_{j=1}^N$

The minimizing set of length L is defined as the sequence that affords the minimum to standard deviation

$$Y_{L,\min} = \arg\min_{Y_L} \{\sigma_{Y_L}\}$$

where the minimum is taken over all sorts of sets of length L. Standard deviation and mean for the set are determined by standard formulas

$$\sigma_{Y_L} = \left((L-1)^{-1} \sum_{j \in \{k_1, \ldots, k_L\}} \left(\tilde{y}_j - z_{Y_L} \right)^2 \right)^{1/2}$$

$$z_{Y_L} = L^{-1} \sum_{j \in \{k_1, \ldots, k_L\}} \tilde{y}_j$$

c) Redefining the reference values set $Y_{L,\text{ref}} = \{y_{j_1^*}, \ldots, y_{j_L^*}\}$ in accordance with the found minimizing set and switching to the next iteration.

Iterations are performed until convergence is achieved, which, as proved in [3], always takes place. The resulting polynomial is considered as an approximation of an unknown trend.

When convergence is achieved, the number indices in both sets and coincide up to permutation. The final trend approximation $\tilde{f}_j$ is carried out on the resulting set of reference values. $N_{\text{out}} = N - \Lambda$

To detect outliers, an algorithm for finding the optimal solution $Y_{\Lambda,\text{opt}} = \{\tilde{y}_{k_1}, \ldots, \tilde{y}_{k_\Lambda}\}$ is applied to the differences $\tilde{y}_j = y_j - \tilde{f}_j = y_j - P_{n,j}(\vec{a})$ (see [5,6]). As a result, outliers will be all numbers of the original series $\{y_j\}_{j=1}^N$, for which $j \notin \{k_1, \ldots, k_\Lambda\}$.

The resulting number of detected outliers is equal to $N_{\text{out}} = N - \Lambda$. Since all outliers must be removed from further processing, then the more Λ, the lower the number of rejected data. The Λ length of the found optimal solution depends on L – the number of reference values: The L search strategy described in [4] is applied to choose L. It consists in finding the maximum of the dependence – the number of measured data cleaned up from outliers. For this, by the iterative procedure described above, for each value of the parameter L, there are a number of numbers Λ (N), Λ (N–1),..., Λ (Lmin) corresponding to different values of L starting with N and then decreasing by one to Lmin - the preset minimum permissible number of reference values used to build the trend.

Each value of Λ (L) is obtained after performing the above iterative procedure and then finding the optimal solution. Further, the maximum of Λ (L) is found:

$$\Lambda^* = \max_{L_{\min} \le L \le N} \Lambda(L).$$

The maximum value of Λ* in this equality can be achieved at several values of L. Since L is associated with the number of reference values used to build a trend, then from all values of L for which the maximum possible value, denoted by L*, is choosed:

$$L^* = \max\{L : \Lambda(L) = \Lambda^*\}.$$

Example of application of the method to geodetic satellite measurements "AJISAI"

To check the effectiveness of the proposed method for clearing data from outliers, it was tested on real data obtained by Dr. Igor Yu. Ignatenko when he measured the pseudo-range to the geodetic satellite "AJISAI"(EGS) in 2019 using a laser rangefinder. Figure 1 shows the observations of the satellite when it passed the lower culmination (the nearest satellite orbit point to the observer). The time propagation *t* of the laser beam to and from the satellite in ms is plotted on the vertical axis; the time from the beginning of the day in s is plotted on the horizontal axis. The time interval of 50 seconds includes 5484 measurements of the time of propagation of laser beam to the satellite and back. In the offset rectangle, a small drop in the data is visible, which, however, has a significant negative impact on the distribution of differences obtained after the trend is removed.

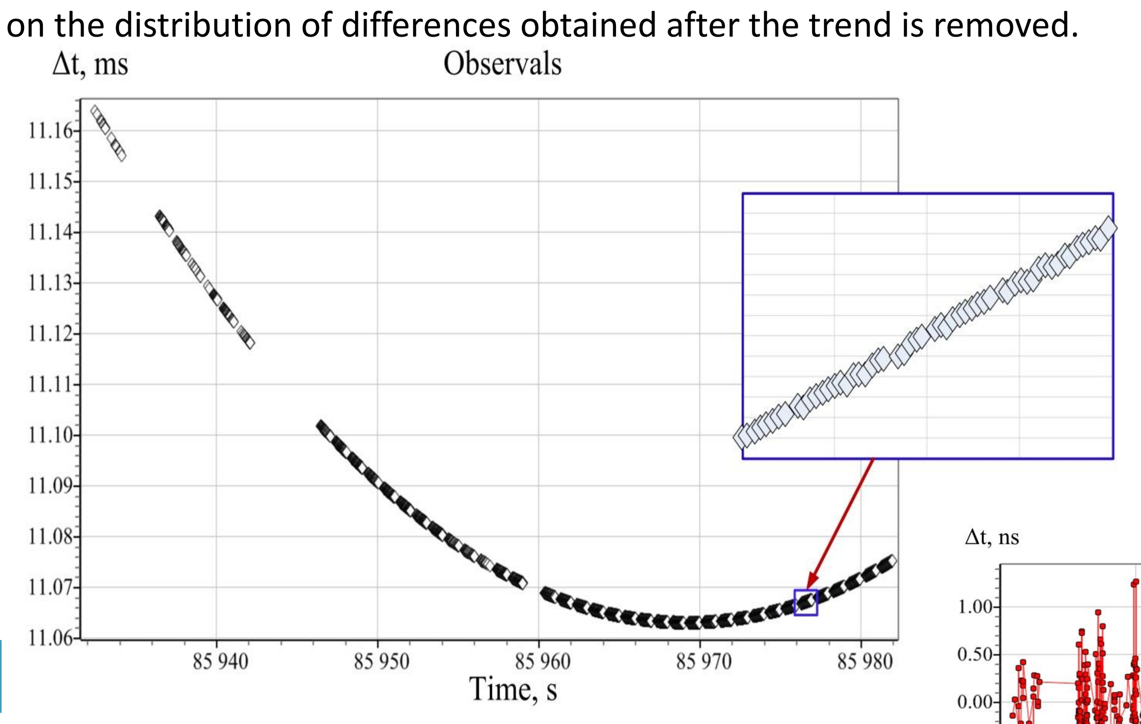


Figure 1. Pseudo-range measurement data to the AJISAI Satellite (EGS) using a laser rangefinder. The time of propagation of the laser beam to and from the satellite in ms are plotted on the vertical axis.The time from the beginning of the day in s is plotted on the horizontal axis.

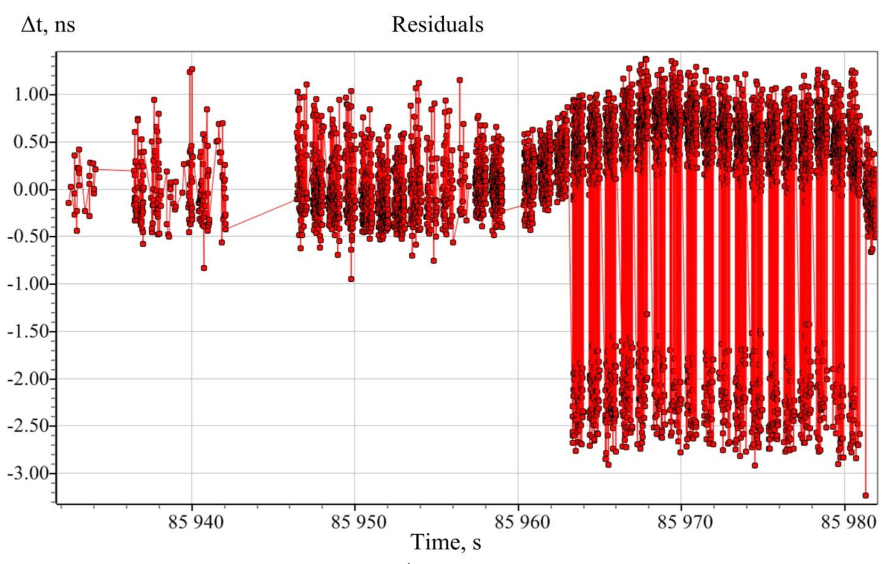


Figure 2. Residuals $\tilde{y}_j = y_j - P_{n,j}(\vec{a})$ obtained after trend removal. The trend approximation was carried out by a polynomial of the 8th degree, fitted to all N measurements treated as reference ones. The time in ns is plotted on the vertical axis. The time from the beginning of the day in s is plotted on the horizontal axis.

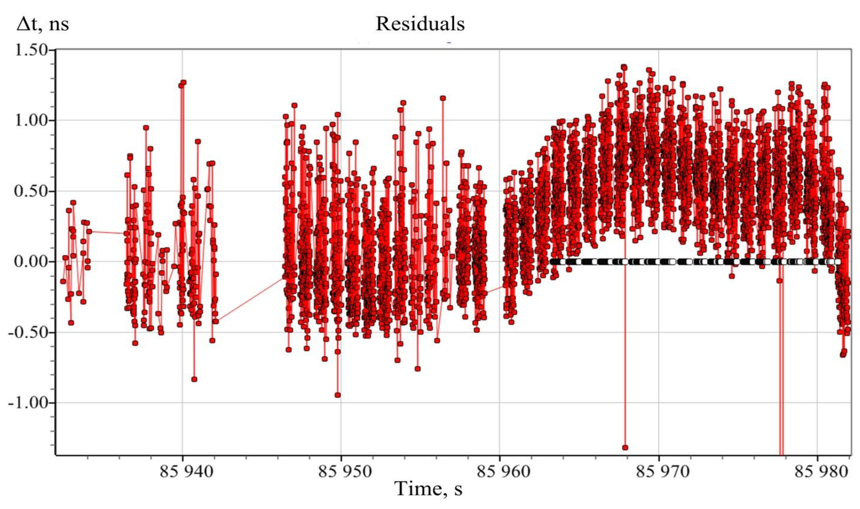


Figure 3. Residuals $\tilde{y}_j = y_j - P_{n,j}(\vec{a})$ obtained after detection and removing outliers. The positions of the detected outliers are marked with white circles.

This satellite was chosen as one of the worst ones in terms of the dynamic range of the received signal. Moreover, at the culmination, the signal strength is often so strong that it can overload the input path. This is manifested in the form of the so-called "second track" in the series of measurement data (see Figure 2). Figure 2 shows the deviations of measurement data from the trend in the case when a polynomial approximating of an unknown trend was built for all measured values treated as reference ones.

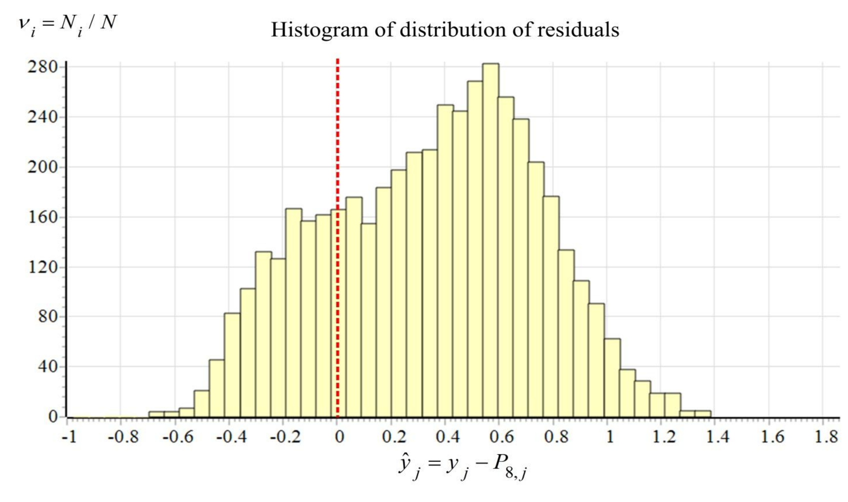


Figure 4. The histogram of the residuals $\tilde{y}_j = y_j - P_{n,j}(\vec{a})$ An asymmetry of the distribution and the bias of the average estimate are visible.

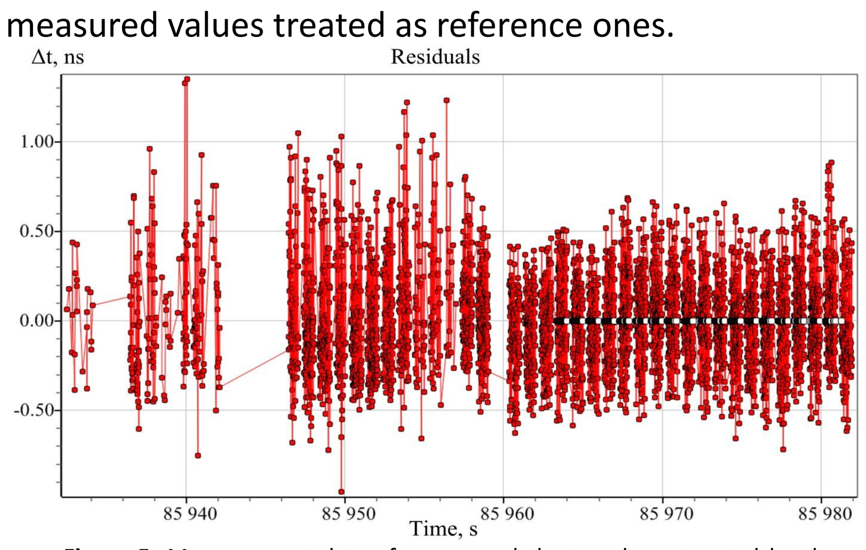


Figure 5. Measurement data after removal the trend constructed by the minimizing sets method [3]. The time in ns is plotted on the vertical axis. The positions of the detected outliers are marked with light circles.

Figure 6 shows a histogram of the distribution of residuals. The resulting estimate of the distribution center is unbiased and consistent.

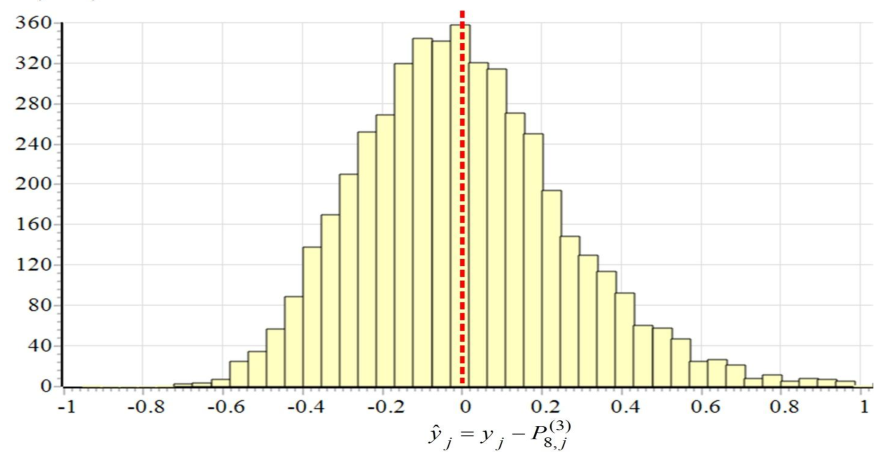


Figure 6. Histogram of distribution of residuals. The average estimate is consistent and unbiased.

References

Ignatenko I. Yu.: Mendeleevo, Russia. In: Section 8 ILRS Network of International Laser Ranging Service (ILRS) 2016-2019 Report. Noll C. and Pearlman M. (eds.). 2020, pp. 8-66 - 8-68. NASA/TP-20205008530, NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Ignatenko I. Yu., Zhestkov A.G.,Slegel V.R., Emelianov V.A Metrological aspects of laser-ranging me3asurements. VIII International Symposium "Metrology of Time and Space". September 14-16. 2016, SaintPetersburg, Russia.

Bezmenov I. V. Effective Algorithms for Detection Outliers and Cycle Slip Repair in GNSS Data Measurements // Chapter 9 in the book "Satellite Systems: Design, Modeling, Simulation and Analysis". Edt. by Tien M. Nguyen. IntechOpen. London. UK. 2021. PP. 177-209. ISBN: 978-1-83968-373-2. DOI: 10.5772/intechopen.73789.

Bezmenov I.V., Drozdov A.E., Pasynok S.L. (2022) A Strategy for Finding Outliers in Noisy Data Series Including an Unknown Trend. *Meas Tech* 65: 339–345. https://doi.org/10.1007/s11018-022-02085-6

Bezmenov I.V. (2023) Method of Cleaning Outliers from Measurement Data: Search for the Optimal Solution with the Minimum Number of Rejected Measured Data. *Meas Tech* 66: 14–23. https://doi.org/10.1007/s11018-023-02184-y

Bezmenov I.V. (2024) Fast algorithm for cleaning highly noisy measurement data from outliers, based on the search for the optimal solution with the minimum number of rejected measurement data. *Metascience Aerosp* 1: 110–129. https://doi.org/10.3934/mina.2024005

I.V. Bezmenov, I.Yu. Ignatenko, S. L. Pasynok. New Methods for Achieving Advanced Accuracy in Time and Coordinate Measurements // Transactions of IAA RAS. — 2022. — Issue 60. — P. 12–20.

Ignatenko I.Yu., Bezmenov I.V. Применение новых методов обработки для повышения точности результатов лазерно-локационных измерений в условиях действия неблагоприятных внешних факторов. // Тезисы докладов X всероссийской конференции с международным участием «КВНО-2023», 17-21 апреля 2023 г., Санкт-Петербург. С. 85.

Bezmenov I.V. Trend detection in time series of measurement data in solving problems in space geodynamics and other research areas[J]. *Metascience in Aerospace*, 2024, 1(3): 268-291. doi: 10.3934/mina.2024012

Conclusions

An effective method for processing noisy SLR measurement data in conditions of adverse external factors has been developed. Its main advantages are:

– significant reduction of asymmetry of measurement data distribution after removal of polynomial trend;

– minimization of outliers.

The next step is to improve the method by selecting trend-fitting functions taking into account known models of the Earth's gravitational potential.