The algorithm of processing and presenting the digital trajectory data obtained when launching rocket vehicles

S V Spitsyn¹, V I Potapov¹ and V P Koryachko²

¹ Department of special design bureau "Spectrum", Joint Stock Company Space Rocket Centre Progress, Gagarin Str. 59/a, Ryazan, 390005, Russia
² Department of Systems of Automated Design of Computational Tools, Ryazan state radio engineering university, Gagarin Str. 59/1, Ryazan, 390005, Russia

E-mail: spitsyn62@gmail.com

Abstract. This research aims at finding a generalized algorithm suitable for processing and presenting the trajectory digital parameters of consumer onboard navigation equipment which is used in the process of space rocket launches. Processing and analysis of digital telemetric information coming from the onboard equipment during the flight and containing digital frames of trajectory measurements is one of the priority tasks as it is the analysis of the path deviations of the rocket that makes a significant contribution to a complete and informative assessment of the launch results. It is suggested that the generalized processing and presenting algorithm which contains the initial stages of the primary processing (extraction of digital frame structures, extraction of trajectory parameters from the frames, mathematical transformations of extracted parameters) as well as determination of primary and secondary values are necessary for solving the trajectory task and, eventually, forming a unified digital stream for representing trajectory measurements, for obtaining results of processing in graphical representation software.

1. Introduction
Processing and analysis of digital telemetry information coming from the onboard equipment during rocket launches and containing frames of the consumer onboard navigation equipment (i.e. trajectory measurements) is one of the priority tasks, because it is the analysis of the trajectory deviations of the rocket that makes a significant contribution to a complete and informative assessment of the launch results. It is proposed to implement the following:

- to establish the general sequence of actions performed by the software set for processing of consumer onboard navigation equipment (CONE) digital parameters;
- to identify the stages of generating output CONE structures, including the steps of digital parameters extracting;
- to determine the primary and secondary values necessary to solve the trajectory task, as well as determine the methodology for their mathematical calculation;
- to determine the methodology for the transition between different coordinate systems;
- to establish a single unified format for presentation of trajectory parameters, used to transfer the results of CONE processing from processing software to graphic representation software.
2. Materials and Methods

2.1 Primary stages of processing and presenting CONE digital parameters

The CONE frame is considered as a fixed structure with an unchanged set of parameters. Generally, frames arrive asynchronously with respect to common telemetry information cycles, i.e. the beginning of the frame is not related to the beginning of the cycle, and the frequency of arrival of frames is not a multiple of the repetition rate of telemetric units. The frame is retrieved by the marker (sign of the beginning) and the control characteristic. The sequence of actions performed by the software when processing digital information is shown in figure 1:

![Diagram of telemetry information processing](image)

**Figure 1.** Processing sequence of telemetry information which contains CONE frames.

a) the substream of parameters is extracted from the digital devices addresses in the onboard telemetry system and, tied to time, is being written to the data array in the order in which they were extracted from the incoming telemetry stream (this function is assigned to the full stream processor preceding the CONE processing program in the technological chain);

b) after that we need to find frame structures markers. As soon as desired combination was detected we need to check the control characteristics of the CONE. The selected frame is logged into a file of digital structures and sent for further processing to extract the parameters of the product movement;

c) in the frame, the parameter is searched for by the address in the digital array (these addresses for CONE structure are fixed and determined by the CONE interface protocol for onboard telemetry system and processing methods pairing) - this is addressing, masking, and formation of the measuring word;

d) the conversion of the digital parameter code into physical quantities units by multiplying by the low-order coefficient \( K_{lo} \), in accordance with the formula:

\[
P_{\text{physical quantity}} = P_{\text{code}}K_{\text{lo}}
\]

e) the formation of trajectory parameters presentation stream (TPPS) for sending to a graphical view in the visualization software and trajectory measurements graphical representation software.

The following data is sent to the display as part of the TPPS:

1) navigation problem solution (if available - data readiness) to display flight models on maps and tables:

- the time for which a decision is given – it can be Moscow time, world coordinated (UTC), as well as GLONASS and GPS time (requiring an a priori correction to bring to UTC);
- three geocentric coordinates - usually in the system for a terrestrial ellipsoid;
- three projections of the velocity vector in the same geocentric system.

2) information about navigation satellites to form a diagnostic chart:
• satellite numbers characterizing their belonging to the global NAVSTAR or GLONASS systems;
• the state of the measuring channels - for example, lack of reception, synchronization of varying degrees (by code, by phase), participation in solving a navigation problem, disruption of reception and extrapolation;
• signal and noise levels[1].

3) conditional assessment of the reliability of information in percent. Since the visualization and graphical representation of telemetric information software expects coordinates to be superimposed on a specific terrestrial ellipsoid (to obtain geodetic latitudes, longitudes, and heights for positioning a trajectory point on a map), sending to a map is preceded by a Helmert transform for conversion from one rectangular geocentric coordinate system to another.

3. Results and discussion

3.1 Formation of output CONE structures

Figure 2 illustrates the algorithm of CONE digital parameters extraction - from the source TMI level to the frame structure of the original CONE parameter. The process of generating output structures includes the following subtasks:

• the formation of a substream of CONE words from the source telemetry information (in real time this is “short” stream of TMI “index-parameter” (SS), in non-real time this is full TMI stream). The formation of CONE words substream - is a sequential extraction of digital words of telemetric information related to navigation equipment. The substreams formed from the words in the order in which they arrive from the board. In relation to reportage (real time telemetry receiving from the onboard), the task of substream forming is to search for a parameter by index in the incoming telemetry short stream of the "index-parameter" format [2];

![Figure 2. Digital parameters extraction sequence.](image-url)

• extraction of the CONE output frame structure. This stage (extraction stage) is based on the markers and frames control characteristics (checksum) searching. Most types of CONE work asynchronously with onboard telemetry systems. Asynchrony lies in the fact that the size of the output CONE frame is not a multiple of the size of the subframe or TMS cycle, and the beginning of the CONE digital frame does not correspond to the beginning of the subframe or cycle. The frame marker is searched by sequential search of the words of the CONE substream,
then the checksum is checked (the calculation method is individual for each type of onboard equipment). At this stage, words that do not have the attribute of a measurement word are also cut off. The result of this operations is a sequence of frames aligned with the marker, eliminating unnecessary words between adjacent frames;

- **CONE** digital parameter processing includes the following:
  - extraction of digital frame parameters. The method of extracting one or another CONE parameter remains unchanged for a particular type of device - a task to address the values inside the frame is not required. The representation of words in the CONE (record format for integer values) depends on the protocol for pairing the CONE with onboard telemetry system and may differ from that adopted in personal computers. For example, there may be no additional code for negative values, it may require a rearrangement of the byte order (“Big Endian”);
  - conversion of parameter codes into physical quantity units [3]. The conversion lies in: multiplication by a coefficient (“low-order coefficient”) for parameters of a functional type, for example, projections of a velocity vector or geocentric coordinates. Although the coefficients are directly specified in the processing methodology, it is possible to correct them through the source data;
  - digital word masking - for logical signs such as the flag of using a particular coordinate system or the flag of readiness of navigation problem solution in two or three-dimensional space.
  - assessment of the quality of the CONE (this assessment does not cover the reliability of the source telemetry information, but the navigation problem solution received from the onboard along with the CONE data- by the flags readiness and the number of satellites in the solution);
  - the formation of the output TPPS for further sending to the consumer software.

### 3.2 Determination of primary and secondary values in solving the trajectory task

Thus, for graphical representation and visualization of the trajectory, the following quantities are required:

- 3 geocentric coordinates $Rx, Ry, Rz$- to form a trace on a 3D model. These quantities are contained in CONE frame and do not require additional calculations;
- module of the velocity vector. Since the geocentric coordinate system and the starting one are connected by a linear affine transformation, this module will be common for them, therefore, for its calculation, three projections of the vector $Vx, Vy, Vz$ which came in TPPS in the geocentric system, so it

$$ v = \sqrt{V_x^2 + V_y^2 + V_z^2}, $$

- acceleration - calculated as the derivative of speed with respect to time $a = \frac{dv(t)}{dt}$ for each projection of the velocity vector, then the acceleration vector is calculated as

$$ a = \sqrt{a_x^2 + a_y^2 + a_z^2}; $$

- latitude and longitude;
- spherical (elliptical) range from the starting position to the sub-satellite point;
- height (above the earth's ellipsoid) - used for graphs in time and in the trace of the trajectory in the axes of spherical range and height and is found by the formula

$$ h = \sqrt{R_x^2 + R_y^2 + R_z^2 - e^2} $$

where $R_x, R_y, R_z$ - geocentric coordinates; $e$ - eccentricity of the orbit.
\[ H = \frac{X_{GCS}}{\cos B \cos L} - N, \] where \( N = \frac{a}{\sqrt{1 - e^2 \sin^2 B}} \) - radius of curvature of the first vertical and \( a \) - semi-major axis of the earth’s ellipsoid [2].

- and others.

### 3.3 Transition between coordinate systems

When processing CONE parameters it is often necessary to present information in different geocentric coordinate systems on different terrestrial ellipsoids. Since CONE information usually comes in the WGS-84 system (World Geodetic System of 1984), i.e. in the system traditionally used to GPS parameters processing, it is required to present information in PZ-90 systems (Earth Parameters of 1990) or SK-42 (Krasovsky's ellipsoid of 1942), when processing the CONE parameters, Helmert transform must be used (this transform helps to convert coordinates from one coordinate system to another). The transition between coordinate systems is carried out according to the scheme shown in figure 3 i.e. through two Helmert transforms in a row [4].

![Figure 3. Geocentric coordinate transformation sequence.](image)

In the general sequence of conversion, the transition between geocentric systems is carried out before the presentation components i.e after receiving the TPPS in the original system in which the CONE operates. The transition between coordinate systems is carried out only in the CONE presentation software, distribution to external consumers is carrying out in the original system in which the CONE gives results. The Helmert transformation for the transition from one geocentric rectangular coordinate system to another has the form \( X_2 = (1 + \Delta m)A \cdot X_1 + B \), where \( X_2 \) - coordinates in new coordinates system, \( X_1 \) - coordinates in the source coordinate system, \( \Delta m \) – the number characterizing the deviation of the scale factor from unity in the transition to a new system, \( A \) – rotation matrix (matrix of guide cosines) of the form

\[
A = \begin{bmatrix}
1 & \omega_x & -\omega_y \\
-\omega_x & 1 & \omega_z \\
\omega_y & -\omega_z & 1
\end{bmatrix}
\]

- a simplified formula made up of the approximate equality of the angle sine to the angle itself at small values, \( \omega_x, \omega_y, \omega_z \) – rotation angles along the axes during the transition to a new coordinate system [5], or

\[
A = \begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix}
\]

- complete geometric formula in which

\[
a_{11} = \cos \omega_x \cdot \cos \omega_y , \\
a_{12} = \cos \omega_x \cdot \sin \omega_y + \sin \omega_z \cdot \cos \omega_x , \\
a_{13} = \sin \omega_z \cdot \sin \omega_y - \cos \omega_x \cdot \sin \omega_y \cdot \cos \omega_x , \\
a_{21} = \cos \omega_z \cdot \sin \omega_y - \sin \omega_z \cdot \cos \omega_x , \\
a_{22} = \cos \omega_z \cdot \cos \omega_y + \sin \omega_x \cdot \cos \omega_y , \\
a_{23} = \sin \omega_x \cdot \sin \omega_y + \cos \omega_z \cdot \sin \omega_y \cdot \cos \omega_x , \\
a_{31} = -\sin \omega_x \cdot \sin \omega_y - \cos \omega_x \cdot \cos \omega_z , \\
a_{32} = -\sin \omega_x \cdot \cos \omega_y + \sin \omega_z \cdot \cos \omega_x , \\
a_{33} = \cos \omega_x \cdot \cos \omega_y - \sin \omega_z \cdot \sin \omega_x .
\]
\[
a_{21} = -\sin \omega_z \cdot \cos \omega_y, \\
a_{22} = \cos \omega_z \cdot \cos \omega_x - \sin \omega_x \cdot \sin \omega_y \cdot \sin \omega_z, \\
a_{23} = \sin \omega_z \cdot \sin \omega_y \cdot \cos \omega_x + \cos \omega_z \cdot \sin \omega_x, \\
a_{31} = \sin \omega_y, \\
a_{32} = -\cos \omega_y \cdot \sin \omega_x, \\
a_{33} = \cos \omega_y \cdot \cos \omega_x, B - \text{shift (vector with coordinates } \Delta x, \Delta y, \Delta z). \\
\]

3.4 Trajectory parameters presentation stream format

For CONE processing results transferring from processing programs to trajectory information graphical representations means, trajectory parameters presentation stream (TPPS) format is suggested. In real time, transmission is carried out via UDP broadcasting to the specified ip address and port, in non-real time - through a file [6]. The TPPS format frame is as follows (C ++ programming language notation, data types for the processor architecture such as x86, alignment of the structure is “to the byte”) [7]:

```c
#pragma pack(1)

// Navigation satellite record
struct tSatInfo12 {
    char numSat; // GPS or GLONASS satellite number
    float SN; // signal-to-noise level represented in dB / kHz (default is 0)
    float tilt; // elevation angle (if information is not available, the default is 361);
    char status; // condition in processing. Codes - according to the pairing protocol
    char NSS; // word number
    float range; // pseudorange from the phase center of the CONE antenna to the satellite
    float fDoppler; // Doppler frequency, Hz
    float dF; // increment of the phase integral over the time interval dt
    char flags; // from low bit – ephemeris suitability, satellite health flag
    char antenn; // CONE antenna number on which the satellite signal is received
};

// Trajectory parameters presentation stream frame (TPPS frame structure)
struct tTriFrame12 {
    long marker1; // first marker
    unsigned short marker2; // second marker
    char idSrc; // information source identifier
    float zeitReg; // relative frame registration time
    double zeitCoord; // time for solving the navigation problem UTC (SU), in sec. from midnight
    char quality; // quality (reliability rating from 0 to 100%)
    double Rx, Ry, Rz; // three geocentric coordinates (in meters)
    double Vx, Vy, Vz; // three projections of the velocity vector (in meters per second)
    char numChannels; // number of CONE channels
    float GF; // geometric factor
    char flags; // from the least significant bit - equipment health, data availability, 3D solution
    char Nsat; // the number of channels of navigation satellites
    char reserve[]; // reserved
    unsigned checksum; // control characteristic - the sum of all bytes of the TPPS frame, // except for this checksum attribute
};
```
tSatInfo12 channels[];  // information about navigation satellite channels

4. Conclusion
In addition to the proposed generalized algorithm for processing and presenting the parameters of the
digital trajectory of the on-board navigation equipment of the consumer, the article also proposes a
single unified format for representing the trajectory parameters, recommended for transferring the
results of CONE parameters processing from processing programs to graphical presentation software.
Using the proposed format in combination with the use of the considered algorithm, which includes the
stages of primary processing of digital CONE parameters, converting digital parameter codes into units
of physical quantities and generating output CONE structures, significantly increases the accuracy and
reliability of the field tests’ results evaluation in terms of trajectory information.

References
[1] Balashov S and Spitsyn S 2019 Processing, analysis and presentation features of trajectory
measurements during rocket launches Vestnik of Ryazan State Radio Engineering University 69 175-84 DOI: 10.21667/1995-4565-2019-69-175-184
[2] Spitsyn S and Tovpeko A 2019 The algorithm for targeting calculation Radiotekhnika 8311(18)
28-34 DOI: 10.18127/j00338486-201911(18)-04
[3] Spitsyn S, Tovpeko A and Tikhomirov A 2019 Algorithm for trajectory measurement processing
when carrying out rocket launches Vestnik of Ryazan State Radio Engineering University 70
118-26 DOI: 10.21667/1995-4565-2019-70-118-126
[4] Tovpeko A 2015 Architecture and operating principle of the measuring equipment controlsystemfor providing rocket launches Vestnik of Ryazan State Radio Engineering University 5111(18) 72-89
[5] Spitsyn S and Tovpeko A 2018 Main quality indicators for measurement gathering and processing
systems of space launches providing Mezhdunarodnyj nauchno-tekhnicasj forum STNO-
2018 5 211-7
[6] Spitsyn S and Tovpeko A 2019 Problems of targeting calculation for measuring tools when
providingrocket launches Mezhdunarodnyj nauchno-tekhnicasj forum STNO-2019 31 25-30
[7] Spitsyn S 2020 Trajectory processing and measurements analysis when conducting field tests
Mezhdunarodnyj nauchno-tekhnicasj forum STNO-2020 5 189-95