Data Processing of Microwave System R-400 on Board of the MIR Space Station

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In the end of 1996, on board of the MIR Orbital Space Station was activated the microwave system R-400 [1] (launched in orbit in the spring of the same year) as a part of the complex of research instrumentation for remote sensing of the Earth. The system provides for implemention of the experiments from the Priroda Project [2]. R-400 is a scanning radiometer that observes the earth's surface under an angle of 40^o relative to the vertical axis of the station while the scanning system provides 40 scans through 0.1 seconds with wideness of the scanning angle along the horizontal line 72^o; i.e. with respect to the movement’s direction, scanning is performed in the interval $[-36^o, +36^o]$. To obtain a correct picture of the observed earth stripe it is necessary to find with maximal accuracy the coordinates of the borders and the center of the spot, from which the device registers data at each given moment. The coordinate systems used for data processing are:

Oxyz - geocentric equatorial system with origin in the mass center of the Earth O,
axis **x** - directed to the point of the vernal equinox,
axis **z** - coincides with the axis of earth’s rotation directed to the north pole,
axis **y** - complements the system to a right-handed one;
Sabc — baro-centric orbital system (fig. 1a) with origin in the spacecraft mass center S,
axis **c** - collinear to the radius-vector along its increasing direction,
axis **b** - directed along the normal of the orbital plane,
axis **a** - complements the system to a right-handed one;
$S\alpha\beta\gamma$ - satellite system, stationary linked with the spacecraft construction axes, with origin in S;
$Or_o\varphi_g\lambda_g$ - geographic system, r_o - radius vector, φ_g - geographic latitude, λ_g - geographic longitude.

The problem of computing of the navigation data, needed for processing and visualization of the received information, can be divided in two separate processes:

a) estimation of the satellite coordinates $\mathbf{S(x_s,y_s,z_s)}$ and the velocity vector $\mathbf{v(x_v,y_v,z_v)}$ relative to **Oxyz** for a given value of the time **t**;

b) estimation of the spot center coordinates in **Oxyz** for the same moment **t**.

Since the first problem is a part of each research space experiment data processing task it is well-known. For this reason it will not be considered here. We will only assume that for any **t,** the values of $\mathbf{(x_s,y_s,z_s)}$ and $\mathbf{(x_s,y_s,z_s)}$

needed to find the coefficients of the transition matrix to migrate from **Sabc** to **Oxyz,** can be obtained calling some procedure.
The position of the instrument and the motion parameters of the scanning device are known relative to the satellite coordinate system **Sαβγ.** In general, the current orientation of the station, respectively of the device, must be determined by the help of angles: **θ=θ(t)** - rotation about an axis **b** (pitch), **φ=φ(t)** - rotation about an axis **a** (roll), **ψ=ψ(t)** - rotation about an axis **c** (hunting) that account for the current state of the axes of the satellite system relative to the orbital one. These angle values are calculated by processing the orientation system sensors' data (solar, star, magnetic, etc.). A method for estimation of the current orientation using data from solar sensors, a magnetometer, and angle velocity sensors can be found in [3].
In the case discussed here, the values of these angles are not available, but it is known that, before the beginning of the measurement cycle, the station is rotated so that the axes of the satellite system coincide with those of the orbital one, i.e. θ=φ=ψ=0.
To calculate the coefficients of the transition matrix to change from **Sabc** to **Oxyz,** we need the directivity cones of the angles between the corresponding axes. For the coordinates of the unit director vectors of the coordinate axes of **Sabc≡Sαβγ** relative to **Oxyz** we obtain:

$e_c(c_1,c_2,c_3)=\dfrac{\overline{OS}}{|OS|}$, т.е. $c_1=x_s/c,\ c_2=y_s/c,\ c_3=z_s/c,\ c=\sqrt{x_s^2+\ y_s^2+\ z_s^2}$;

$e_b(b_1,b_2,b_3)$ - normal to the orbital plane with an equation

$$m:\ \begin{vmatrix} x-x_s & y-y_s & z-z_s \\ x_v & y_v & z_v \\ x_s & y_s & z_s \end{vmatrix}=0,$$

After appropriate calculations we obtain

$$b_1=b_x/b,\ b_2=b_y/b,\ b_3=b_z/b,\ b=\sqrt{b_x^2+\ b_y^2+\ b_z^2},$$

where $b_x=y_sz_v\text{-}z_sy_v,\ b_y=z_sx_v\text{-}x_sz_v,\ b_z=x_sy_v\text{-}y_sx_v$;
$e_a(a_1,a_2,a_3)$ complements the system to right-handed coordinate one, i.e.

$$a_1=b_2c_3\text{-}b_3c_2,\ a_2=b_3c1\text{-}b_1c_3,\ a_3=b_1c_2\text{-}b_2c_1$$

Note that, as far the orbit of the station is quite near to circular, e_a **almost** coincides with the velocity vector.
Now point **M** with coordinates (a_m,b_m,cm) in **Sabc**, relative to **Oxyz** will have coordinates:

$$x_m=a_1a_m+b_1b_m+c_1c_m+x_s$$

$$y_m=a_2a_m+b_2b_m+c_2c_m+y_s \qquad (1)$$

$$z_m=a_3a_m+b_3b_m+c_3c_m+z_s$$

Now, let us denote by $\mathbf{t_n}$ the start time of the n-th scan and let us assume (for definiteness) a left-right motion, i.e. at this moment the scanning head is initialized to the left end, ready to move right. Also, let us denote by $\lambda_k=\lambda_0-\mathbf{(k-1)}\Delta\lambda$ the angle between the axis **a** and the projection of the directivity device arrow on the plane **Sab**, with μ the angle between arrow and axis **-c**, with $\mathbf{t_k=t_u+(k-1)\Delta t}$ the time of the momentary (k-th) measurement, $\lambda_0=36^o$, $\Delta\lambda=72^o/39$, $\mu=40^o$, $\Delta t=0.1$sec, k=1.40. When $\mathbf{t=t_k}$, the vector l^k (fig.1b), collinear with the device directivity arrow, will have in S^kabc coordinates:

$$l_a=sin(\mu)cos(\lambda_k),\ l_b=sin(\mu)sin(\lambda_k),\ l_c=cos(\mu).$$

Then the line, representing the directivity arrow, will have parametric equation

$$\mathbf{g_k}:\ [\ \rho sin(\mu)cos(\lambda_k),\ \rho sin(\mu)sin(\lambda_k),\ -\rho cos(\mu)].$$

Replacing the coordinates of $\mathbf{g_k}$ in the equation of the sphere

$$\mathbf{s_k:(x-o_a)^2+(y-o_b)^2+(z-o_c)^2=r^2}$$

that approximates the earth ellipsoid (by Krasovsky), where $\mathbf{o_a,o_b,o_c}$ and **r** are respectively the coordinates of the Earth mass center in $\mathbf{S^kabc}$ and the radius-vector of the projection point, we achieve a quadratic equation for ρ. Solving the equation and denoting the smaller root by ρ_1, we obtain the coordinates of the center of the spot **P** in $\mathbf{S^kabc}$

$$a_p=\rho sin(\mu)cos(\lambda_k),\ b_p=\rho sin(\mu)sin(\lambda_k),\ c_p=-\rho cos(\mu),$$

from where, using (1), we can go over into **Oxyz,** and thus problem (b) is solved.

The boundary line of the spot on the earth surface for $\mathbf{t=t^k}$ can be determined by finding the coordinates of the cross-points of the sphere $\mathbf{s_k}$ and the generating arrow of a circular cone with a central axis $\mathbf{g_k}$, vertex **S** and cone angle δ. Similarly to the determination of g_k, we search for the coordinates of a vector through S, collinear with the generating arrow. For this reason, let us look at the system $Sl^il^jl^k$ where the orientation of l^i and l^j is not important. It can easily be seen that vector $\mathbf{h=h(\eta)}$ with coordinates

$$[sin(\delta)cos(\eta),\ sin(\delta)sin(\eta),-cos(\delta)],\eta\in[0,2\pi]$$

is a generating line of a cone with central axis l^k and angle between them δ. To determine its coordinates related to $\mathbf{S^kabc}\equiv\mathbf{S^k}\alpha\beta\gamma$, we use the fact that the angle determines such a rotation of $\mathbf{S^kabc}$ that the axis **c** coincides with $\mathbf{g^k}$ and the unit vector of the negative semi-axis [0,0,-1] coincides with l^k. Really, when one rotates $\mathbf{S^kabc}$ about the axis **c** on an angle λ_k, after that, on an angle μ about the axis **b** for the transition matrix we obtain

$$\mathbf{W(0,-\mu,\lambda_k)}=\begin{pmatrix}\mathbf{cos(\lambda_k)cos(\mu)} & \mathbf{-sin(\lambda_k)} & \mathbf{-cos(\lambda_k)sin(\mu)}\\ \mathbf{sin(\lambda_k)cos(\mu)} & \mathbf{+cos(\lambda_k)} & \mathbf{-sin(\lambda_k)sin(\mu)}\\ \mathbf{sin(\mu)} & \mathbf{0} & \mathbf{cos(\mu)}\end{pmatrix}$$

from where it is easy to verify that l**=W(0,-μ,λ_k)*[0,0,-1].** Then, for the coordinates of h we will obtain $[h_a,h_b,h_c]=W*[h_i,h_j,h_k]$.

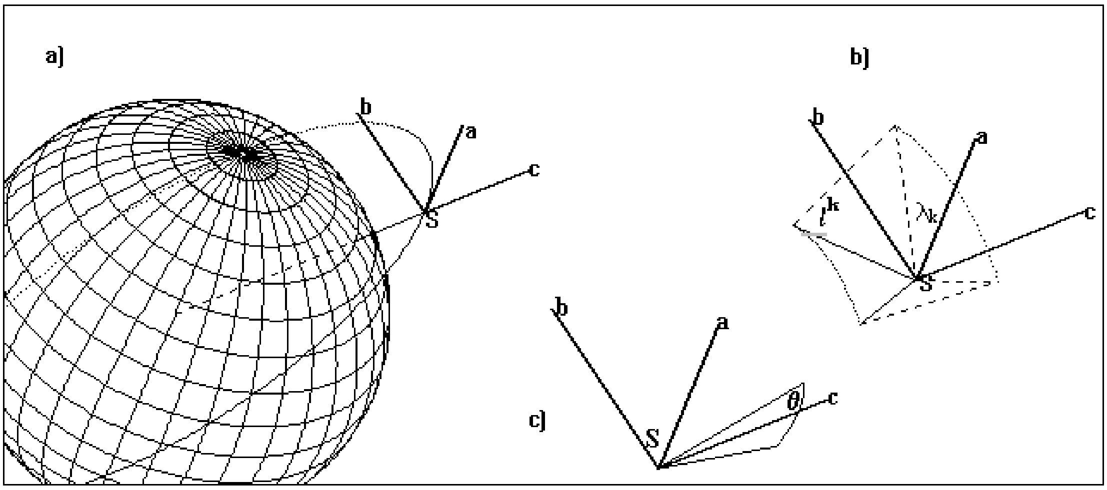

Fig.1

The formulae derived so far were obtained under the assumption **θ=φ=ψ=0**, i.e. **S^kabc≡S^kαβγ.** Let us now discuss briefly the case when this is not true, i.e. the stabilization of the station is disturbed and it drifts about its mass center **S**. Let us assume that one of the angles θφψ, e.g. θ, oscillating around the axis **b** (Fig. 1c), is not 0. The case **φ ≠0∩θ≠0∩ψ≠0** will differ only in the transition matrix coefficients of W(φ,θ,ψ). The coordinates of the unit directivity vectors $e_\alpha,e_\beta,e_\gamma$ of the coordinate axes of **S^kαβγ** are to be found from $\mathbf{e_\alpha,e_\beta,e_\gamma}$ by multiplication from the left with **W(0,θ,0)** and then formula (1) where $\mathbf{a_i}$, $\mathbf{b_i}$, $\mathbf{c_i}$ have been substituted respectively by α_I, β_I, γ_i, i=1..3, will perform the transformation from **S^kαβγ** into **Oxyz**. The equations for $\mathbf{g_k}$ and $\mathbf{s_k}$ remain the same, and the coordinates of the Earth center for $\mathbf{s_k}$ should be recalculated for **S^kαβγ.** As a result of the calculations following the algorithm described above we obtain a data set containing the measured values and their coordinates in **Oxyz**, from which a transition into geographical coordinate system **Orφλ** must be made where it is enough to remember only φ and λ (**r** can be obtained as a function of φ). However, the information increases considerably, because for each number of the incoming data we have added 2M+2 numbers. What amount of this information is to be stored in the data base (or another type of archiving) depends of the research problems to be solved as well as on the capacity of the PC. If the error resulting from the approximation of the outlines of the area by an ellipse is assumed tolerable and the points are selected properly, then M can be equal to 3.

In the discussed algorithm, it is indirectly assumed that the telemetry and read-write data systems behave normally. But in fact, maybe due to an error

in the system exchanging data with the buffer storage (memory) of the telemetric system, the data from the strobes whose numbers lies in the intervals [9-16] and [25-32] repeat the information of the preceding strobe group, i.e. [1-8] and [17-24], respectively. So, at the input of the data processing system, “authentic” is only the data from [1-8], [17-24] and [33-40]. (Let us note that exactly this situation was the reason to discuss the problem of coordinates estimation of the spot boundaries, thus obtaining the possibility to consider the instrument as a tracing one).
It is natural to try to recover missing data with the help of mathematical methods and the problem we want to solve can be described in two ways:
- to recover the indications of the n-th scan by using only data from the same scan,
- except for the indications of the n-th scan, scans from 2K neighbor scans are used, $K \geq 1$.
The plots shown below represent the results from solving the first problem by the spline approximation procedure.
In Fig. 2, orbit No292 from 26.01.97, or a “tracing” version is shown. The non-realistic behavior of the color range is due to the inadequate reproduction of RGB-set by BW-printing.
In fig. 3, a fragment of the same orbit is shown.

Literature:

1. T. Nazarski, G. Dimitrov, Ch. Levchev, The Basic Principles Determining the Operation of the Microwave Scaning Radiometric System R-400, Turk. J. of Physics, 19(1995), pp. 1059-1062.
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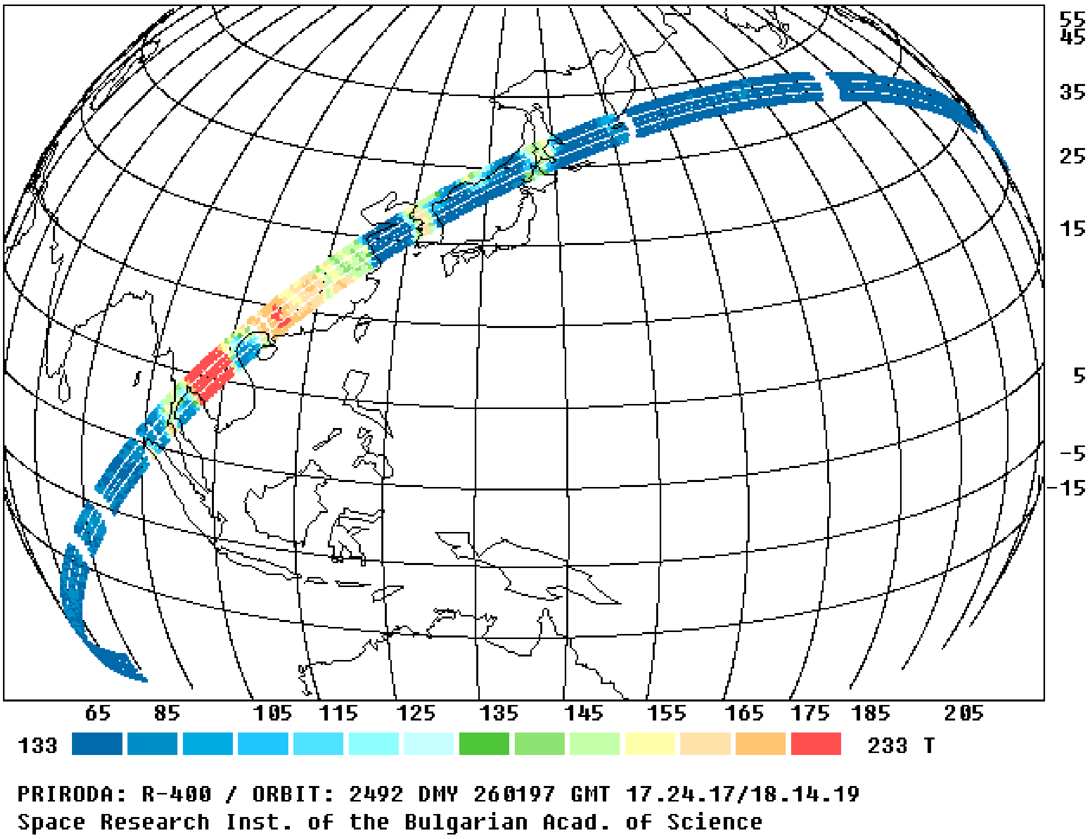
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fig2.

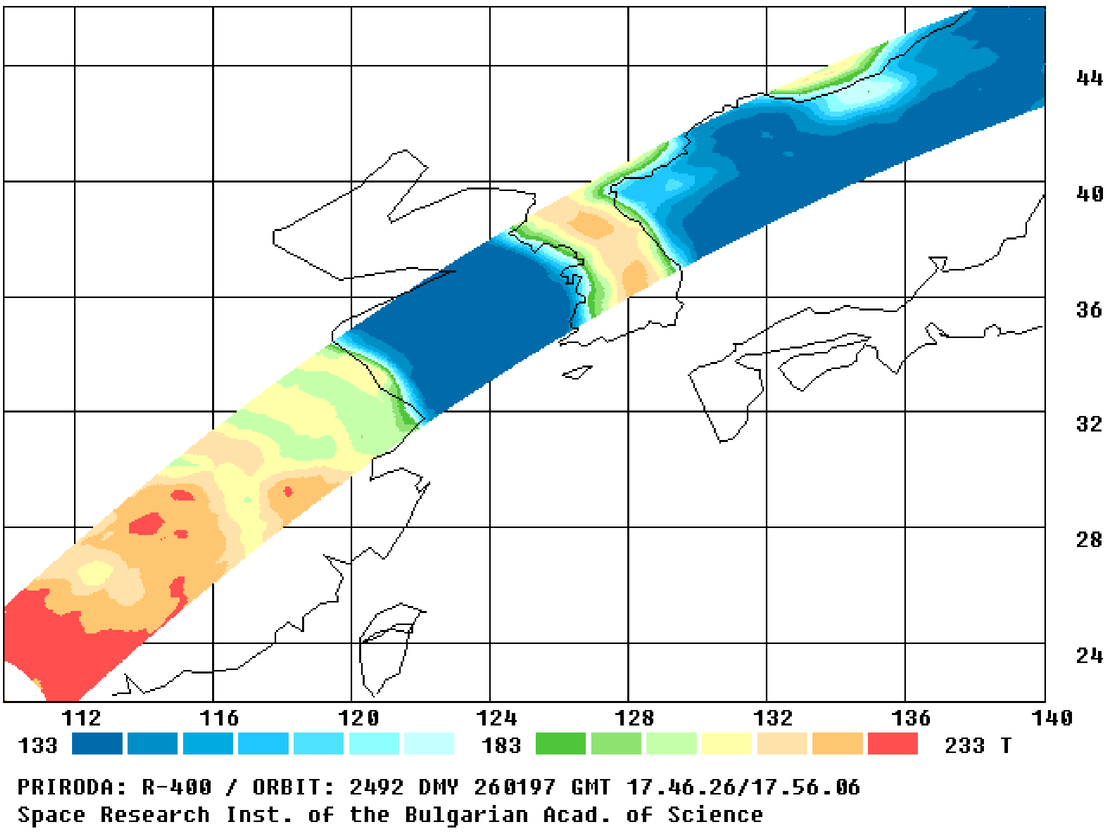
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fig 3

The paper describes an algorithm solving the task for calculation of the coordinates of some geometric sections on the Earth's surface resulting from some experiments for remote sensing of the Earth from space. The suggested algorithm is an essential part of the data processing software of the R-400 microwave system on board of the MIR Orbital Station.