USE AND ANALYSIS OF DIFFERENT TYPES OF MEASUREMENTS AT TSUP FOR SOLVING THE NAVIGATION TASKS FOR THE MIR FLIGHT SUPPORT DURING ITS FINAL PHASE

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1. THE MAIN PURPOSE OF THE INTERNATIONAL COOPERATION FOR THE MIR DEORBIT SUPPORT

The ballistic and navigation support was one of the fundamental activities for the controlled deorbit of the Mir space station.

The basis of the ballistic and navigation support of the flight of the station in this phase was the problem of the determination and prediction of its orbit. The exact knowledge of the trajectory of the Mir station was necessary to guarantee the successful completion of the scheduled final deorbit operations and application of adequate measures in case of non-nominal situations.

An important characteristic of the final flight phase of the Mir station was, that final deorbit operations could only be carried out at sufficiently low altitudes. At the same time, with the station flying at these altitudes, there was no absolute confidence of reliable realization of the planned operations, as neither the design, nor the onboard systems and instrumentation of the Mir station were intended for functioning in these conditions.

An extreme consequence of unfavourable circumstances of the Mir flight at low altitude could be a failure to complete the reentry in a controlled fashion. In such a situation the Mir station would become an uncontrolled space object of high risk, whose return to Earth could result in serious negative consequences. The important problems were the precise prediction of both time and impact area for this space object, and operational information of the appropriate services and organizations, both in Russia, and in other countries. It would ensure acceptance of well-timed measures intended to minimize damage and minimize the negative consequences caused by surviving fragments (debris impact) of the Mir space station.

These circumstances, related to the control of the Mir station for a flight at low altitude, required to take measures which increase the reliability and quality of the ballistic and navigation support of the station in any situation during the final flight phase. As a result it was decided to involve additional sources of information, in support of nominal ground-based tracking systems, which would allow to ensure:

a) significant extension of the Mir coverage zone during its flight at low altitude.
b) improved reliability and accuracy of the navigation support during the final flight phase of Mir.
c) improved knowledge of the real Mir orbital motion during the preparation and execution of the deorbit operations.
d) Immediate prolongation of the operations with Mir as a high risk entry object in case of an emergency, which would no longer permit the controlled deorbit of Mir.

2. SOURCES OF ADDITIONAL NONSTANDARD INFORMATION

From the experience gained in earlier activities, data sources were selected which are important and fulfill the above stated requirements to accomplish the formulated tasks.

The most important data came from the Russian and US space surveillance systems. Their joint tracking of the Mir station allowed to control its orbital motion during all daily orbits.

Also it was recognized expedient to involve in a cooperative manner additional tracking facilities with good measurement and information characteristics:

a) the FGAN radar (Germany),
b) the phase direction finder "Rhythm" (Moscow region),
c) optical and laser systems (in Caucasus, Uzbekistan and Moscow region),
d) an astronomical system in Sayany (Siberia).

In order to satisfy the stringent accuracy requirements for the prediction of the Mir motion, a good knowledge of the most precise parameters of solar and geomagnetic activity was particularly important. The institutes IZMIRAN and IAG were in charge of providing the current values of indexes of solar and geomagnetic activity, their short- and long-term forecast, and also the quick delivery of these data

to MCC-M. In addition, the data for the indicated parameters were transmitted from ESOC to MCC-M.
The organizational and technical problems of communication and data exchange between sources of the information and MCC-M were solved. Because of the high requirements on efficiency and reliability for information exchange, preference was given to direct communication links. For some organizations voice communication was established in addition to direct lines. The scheme of the data exchange is shown in Fig. 1.

3. METHODS AND SOFTWARE FOR THE SOLUTION OF THE ORBIT DETERMINATION PROBLEM

In order to make the additional nonstandard information available for the activities of the ballistic and navigation support of the Mir station, special software for the following tasks was urgently developed:

- Acquisition and storage of the data received from different sources
- Interpretation of different types of additional information
- Use of the additional information, including their joint processing in the Mir orbit determination procedures.

The main principles for the solution of all types of ballistic and navigation tasks with the MCC-M software were the following:

I. Accepted spacecraft motion model:

- non-central Earth gravity field up to degree and order 8.
- For atmospheric drag the standard dynamical atmosphere model for Russian space missions was used.

Preliminary estimations had shown, that for the considered altitudes of Mir flight, and with the given accuracy requirements for the knowledge of its orbit, the influence of the Moon and Sun gravity field perturbation and other small perturbing factors can be ignored.

II. Numerical integration of differential equations of motion:

- A highly efficient method developed and realized in an elaborate software was applied.

This integrator is applicable for solving a wide spectrum of problems for ballistic and navigation support of all kinds of space missions. This high-order method with a high computing efficiency is based on an implicit interpolation - iteration scheme and can be adjusted to an arbitrary order of the approximation.

The main features of this method are:

a) achievement of any given accuracy and keeping this accuracy within a long-term period of integration of equation of space objects motion;

b) applicability of the method for the solution of differential equations with arbitrarily complex right-hand sides;

c) simplicity of the calculation with any required order and capability of changing this order within an integration step.

III. Measurements used for the orbit determination:

- RTS: $D, \dot{D}, A, \gamma$;
- RSSS: osculating orbital elements $\{q\}$, state-vectors $\{\vec{R}, \vec{V}\}$;
- Rhythm: $CosX$, $CosZ$;
- Optical: α, δ ;
- FGAN: D, A, γ, TLE ;
- USSPACECOM: TLE and S/V (state vector).

IV. Methods of measurement processing:

- weighted least squares method;
- separate and joint treatment of different kinds of measurements;
- option to include a priori information.

V. Solve-for parameters of the s/c motion:

- initial state-vector $\{R_0, V_0\}$,
- ballistic parameter S_b:

$$S_b = \frac{C_x A}{2m} g$$

$$(g = 9.80665[m/s^2])$$

4. ESTIMATION OF THE ACCURACY OF THE MIR STATION ORBIT DETERMINATION AND THE PREDICTION OF ITS MOTION

The accuracy of the Mir station orbit prediction depended both on the errors of the adopted model for the motion and errors of the orbit determination.

On the basis of the calculations carried out for the Mir station the orbit determination accuracy and orbit prediction accuracy was analyzed.

For the assessment of the orbit prediction accuracy the orbital coordinate system RNB was used: the R-axis is directed along the radius vector. The N-axis is also in the orbital plane, perpendicular to the R-axis, and is directed along the velocity vector. The B-axis - along the binormal to the orbital plane - completes the right-handed system. The accuracy of the orbit determination of the Mir station was computed with the method of covariance analysis.

4.1. Estimation of incorrect account of atmospheric drag influence on the Mir orbit prediction

Among the errors of the accepted motion model, the dominant influence on the accuracy of the Mir station orbit prediction is caused by the uncertainty in the parameters of the atmospheric model. More precisely, it is the errors in the forecast of solar and geomagnetic activity within the prediction interval of the Mir flight as well as the uncertainties in the knowledge of the ballistic parameter of Mir.
The influence of the uncertainties of the solar and geomagnetic activity indexes and the uncertainty of the ballistic parameter on the accuracy of the Mir station orbital prediction was evaluated for different phases of the flight. The estimated orbit errors of the Mir station are shown in Figs. 2 & 3 for the typical altitude H~250 km. In these figures the deviations of orbit parameters from the nominal ones are given for certain variations of the indexes of solar and geomagnetic activity and ballistic parameter. The nominal case takes into account the influence of the Earth gravity field (8×8) and atmospheric drag (standard atmosphere) calculated for real indexes of solar and geomagnetic activity and the ballistic parameter Sb = 0.033.

The calculations for estimating the effect of incorrect atmosphere and drag parameters were made for the following cases:

a) the indexes of solar and geomagnetic activity are constant in the interval of prediction: F0 = 150, Ap = 10, F = 145, Sb = 0.033;

b) the indexes of solar and geomagnetic activity are constant in the interval of prediction: F0 = 175, Ap = 10, F = 180, (Sb = 0.033);

c) the real indexes of solar and geomagnetic activity in the interval of prediction were used; the ballistic parameter was Sb = 0.026;

d) the real indexes of solar and geomagnetic activity in the interval of prediction were used; the ballistic parameter was Sb = 0.038.

The analyses have shown, that the strongest influence of the incorrect prediction of atmospheric drag affects the forecast of the orbit of the Mir station along the N-axis, that is along its orbital motion. This error is increasing with time. For case b), the difference between the prediction and nominal orbit reaches within the first two days hundreds of kilometers. It was also found, that the errors of the forecast strongly depend on Sb (Fig. 2).

Fig. 3 shows the dependence of the Mir station osculating elements on variations of the indexes of solar activity and ballistic parameter (relative to the nominal) for an interval of 120 orbits.

4.2. Estimation of the accuracy of the Mir Space Station orbit determination

The accuracy of the orbit determination depends on types and composition of the used trajectory measurements (observation data).

For the orbit determination of the Mir station standard and non-standard observation data were considered. In the present paper the results of the estimation of the accuracy of orbit determination are presented for measurements from Russian Tracking Stations (RTS) located on Russian territory.

The accuracy assessment was based on the treatment of real tracking data, which were periodically collected. The orbit determination errors were computed from the covariance matrix which was obtained during the solution of the Mir orbit determination. For the calculation of the state-vector covariance matrix of errors at any epoch, the equations of motion and the corresponding variational equations were simultaneously computed by numerical integration. The orbit determination errors were projected on the axes of the orbital coordinate system.

In Fig. 4 the results of the Mir orbit determination accuracy are given for two typical altitudes: H ~ 300 km and H ~ 220 km. In the first case the orbit was determined from RTS measurements collected in cycles of the trajectory control during two days (3-5 orbits every day). In the second case measurements of current navigational parameters collected during 3-5 orbits in one day were used.

For both cases Fig. 4 illustrates the progressive increase of the component ΔN of the orbit determination error. For the other components of the orbital coordinate systems the errors do not have the tendency to increase and remain essentially smaller than ΔN.

The dependence of the accuracy of the orbit determination on altitude and on the composition of the measurements was demonstrated in Fig.4 as well.

5. PROCESSING OF NON-STANDARD MEASUREMENTS FOR THE NAVIGATION OF THE MIR STATION IN ITS FINAL FLIGHT PHASE

After data exchange agreements were reached with the sources of the non-standard information, the appropriate measurements began to enter MCC-M and were used in the navigation support.

Fig. 5 shows the quantity of non-standard measurements, received by MCC-M from various sources. Depending on the source of the information the number of orbits is indicated where measurements were made (for the "Rhythm" system and the TIRA radar) or the number of sets of orbital data (for RSSS and USSPACECOM).

The history of the Mir station reentry date predictions, obtained from the solutions of orbit determination including those obtained from the use of non-standard measurements, is shown in Fig. 6. The displayed curves are not smooth, which testifies the complexity of the prediction of the real motion of the Mir station. This is connected with the inaccuracy of the forecast of the atmosphere parameters, and of flight control operations with the Mir space station during the interval of prediction.

6. ANALYSIS OF THE QUALITY OF NON-STANDARD MEASUREMENTS AND EFFICIENCY OF USING THEM FOR THE MIR STATION NAVIGATION

After completion of the Mir station flight, all non-standard measurements received by MCC-M were analyzed to estimate the quality of this information and its value for the Mir station navigation. This analysis included the capabilities of these measurements for supporting the uncontrolled Mir station flight in its final phase up to entering the lower atmosphere and, if needed, to support emergency operations.

6.1. Estimation of the quality of the non-standard information

For the quality analysis of the non-standard measurements, the solutions of the Mir orbit determination, obtained from using only standard RTS tracking data, were selected as the basis.

The estimation of the quality of non-standard measurements was carried out as follows. For the selected non-standard measurements the basic solution closest to them was chosen. In the ideal case the analyzed measurements were found inside the measurement interval from which the basic solution was obtained. The values of selected non-standard measurements were obtained from initial conditions of the Mir station motion. At the measurement times the residuals (O-C) are calculated.

The quality of the non-standard measurements processed at MCC-M is shown for the following typical examples.

For the illustration of the quality of the TIRA (FGAN) radar data, two typical cases of observations for different Mir station orbital altitudes were chosen:

a) measurements collected on two orbits on 28.02.2001, at an orbital altitude H ~ 270 km;

b) measurements collected on four orbits on 20.03.2001, at a mean altitude of ~220 km

In Fig.7-8 the residuals (O-C) for the measured parameters: ΔD, ΔA, $\Delta\gamma$ are shown. For the measurements collected on 28.02.2001, the residuals do not exceed:

- for range - 300 m,
- for azimuth - 12′,
- for elevation - 20′.

For the measurements collected on 20.03.2001, the residuals do not exceed:

- for range - 200 m,
- for azimuth - 2′,
- for elevation - 20′.

For the "Rhythm" system Fig. 9 displays the residuals (O-C) for the measurements collected on 22.03.2001 on two orbits (№ 2316 and 2318). The residuals for the measured parameters cosX and cosZ do not exceed:

- for cos X - 0.0004,
- for cos Z - 0.0007.

For the analysis of the quality of the orbital data obtained from the Russian and the U.S. Space Surveillance Systems, the differences between measured and calculated parameters describing the Mir station motion in the orbital coordinate system R, N, B were computed. For this purpose the orbital parameters of the station entering MCC-M from RSSS in the format of the standard messages (as osculating elements or as state vector in the Greenwich coordinate system), were transformed to the state vector of the station (referred to the same time) in the inertial coordinate system J2000.

Similar transformations were made at MCC-M with the orbital data from USSPACECOM: the two-line elements (TLE) are presented in a form of state-vector (S/V) referred to the inertial coordinate system J2000.

The behaviour of the residuals ΔR, ΔN, ΔB, obtained from RSSS data, is shown in Fig. 10. The residuals for the

USSPACECOM data are shown in Fig. 11 (for TLE) and Fig. 12 (for S/V).
From these figures we may conclude, that for the orbital data obtained from the RSSS, the majority of the residuals are distributed within the limits of ±2 km, and only a few points (mainly - ΔN) have greater values.
For the orbital data produced by USSPACECOM as TLE and S/V the errors ΔR and ΔB stay within the limits of ±2 km. The discrepancies ΔN have a much greater dispersion, reaching in both cases 10 km.
The discrepancies in N correspond to an error of the position of the space object along its orbit or, equivalently, to an error of the time of passage of the ascending node.

It is important to note, that the time period, within which the measurements of the RTS facilities were made and the basic solution for the estimation of the non-traditional information quality was obtained, not always include the orbits, on which the estimated measurements of RSSS and USSPACECOM facilities were made. As a rule, the residuals belonging to the measurements of these facilities reached maximum values on orbits where no measurements were made by RTS.

6.2. Estimation of results of Mir station orbit determination using only non-standard measurements

It was of interest to estimate the navigation capabilities of non-standard measurements in real operations with the Mir space station in the final flight phase. For the navigation support an option was planned, when as a result of some non-standard situations without RTS measurements, the transition to the use of non-standard measurements should be made.
For this option the following cases were considered, where for the Mir station orbit determination only measurements were used from:

a) RSSS;

b) NASA (USSPACECOM);

c) ESOC (the FGAN radar).

The efficiency of the indicated non-standard measurements for the Mir station orbit determination was assessed by comparing the solutions obtained from non-standard measurements with the solutions of standard RTS measurements. For the comparison, the data taking periods for both type of measurements were approximately of equal duration and close to each other in time.

For the ballistic and navigation analysis orbital parameters were compared.

The results of the Mir station orbit determination with the non-standard measurements for the cases a) – c) are given in the Tables 1-3. For each case, four solutions of the Mir station orbit determination problem are presented for different data taking periods. The Mir station orbit parameters, presented in the Tables, are referred to the beginning of a certain orbit, where date and time (Moscow time) are given in the appropriate line. For each solution the measurement interval (in orbits) and number of orbits in this interval, where measurements were made, are indicated. From the analysis of the obtained solutions (Table 1) we may conclude, that for the control of the motion during the final flight phase and the final operations of the Mir station the necessary accuracy of the knowledge of its orbit would be achieved with measurements from the RSSS. From the results of Table 2 we can see the good accuracy of the Mir orbit determination using only USSPACECOM data. From Table 3 we conclude that the Mir orbit determination could be accomplished only with FGAN's TIRA radar data, provided that measurements on three to four orbits per day are available.

7. CONCLUSIONS

- Internal and at an international level, organizational and legal problems were solved to include additional data sources for the MIR deorbit navigation support.
- Data exchange channels were identified.
- Direct links with major data sources were established and tested.
- Urgent problems, solved in MCC-M:
  - a) Acquisition and storing of data received by MCC-M from different sources
  - b) Interpretation of different types of additional measurements
  - c) Utilization of all kinds of additional information, including their joint processing, in the MIR orbit determination procedure.
- Data acquisition and processing to support the MIR deorbit were nominally executed.
- In case of emergency, i.e. unavailable standard measurements from RTS, the use of non-standard measurement data for the Mir station orbit determination allowed to control its motion during the final phase of flight.
- An enormous experience was gained for the cooperation and joint operation of different organizations to accomplish complex tasks as a paradigm for the future.

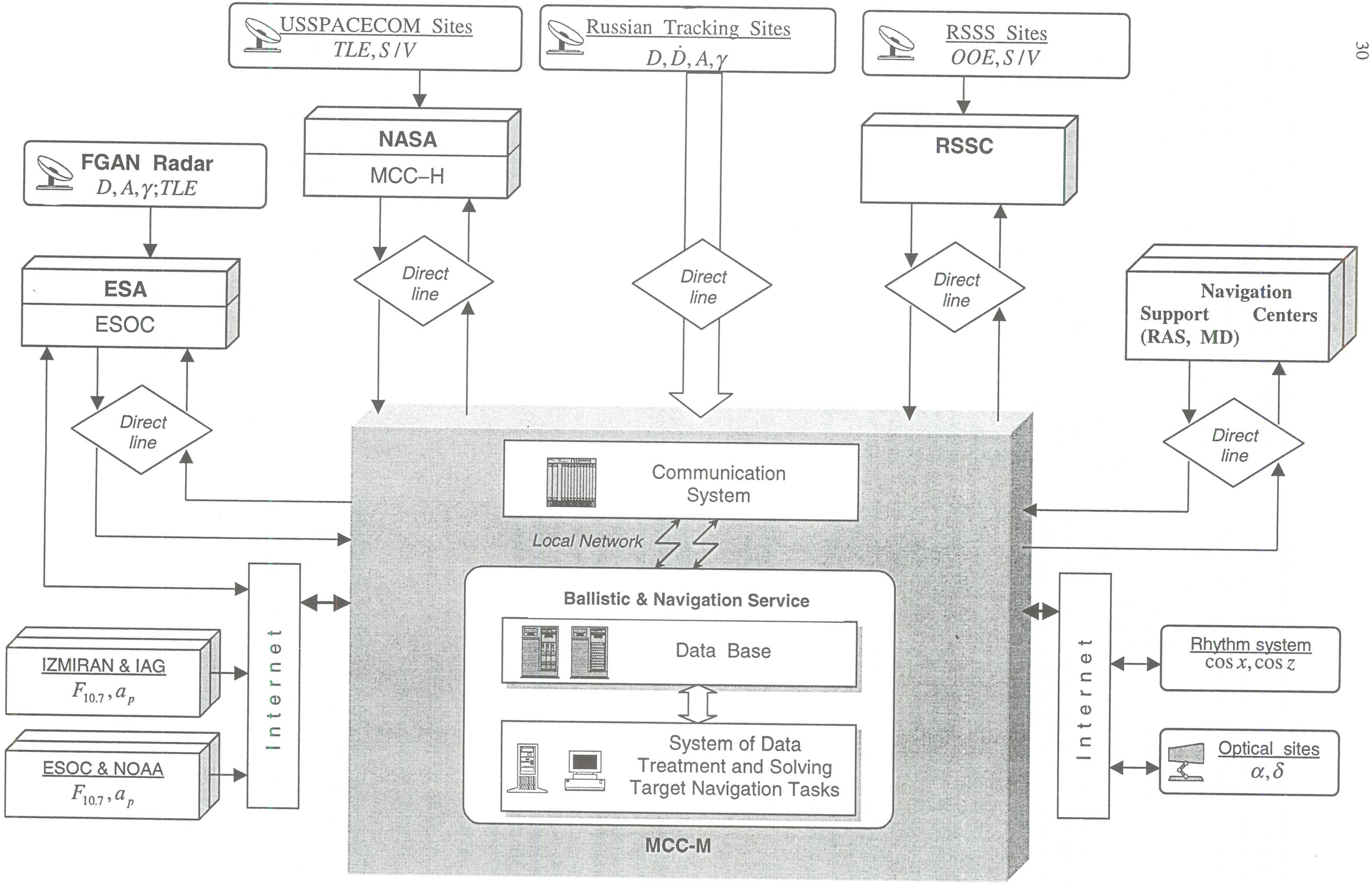


Fig.1. Scheme of data exchange for navigation support of MIR flight final phase

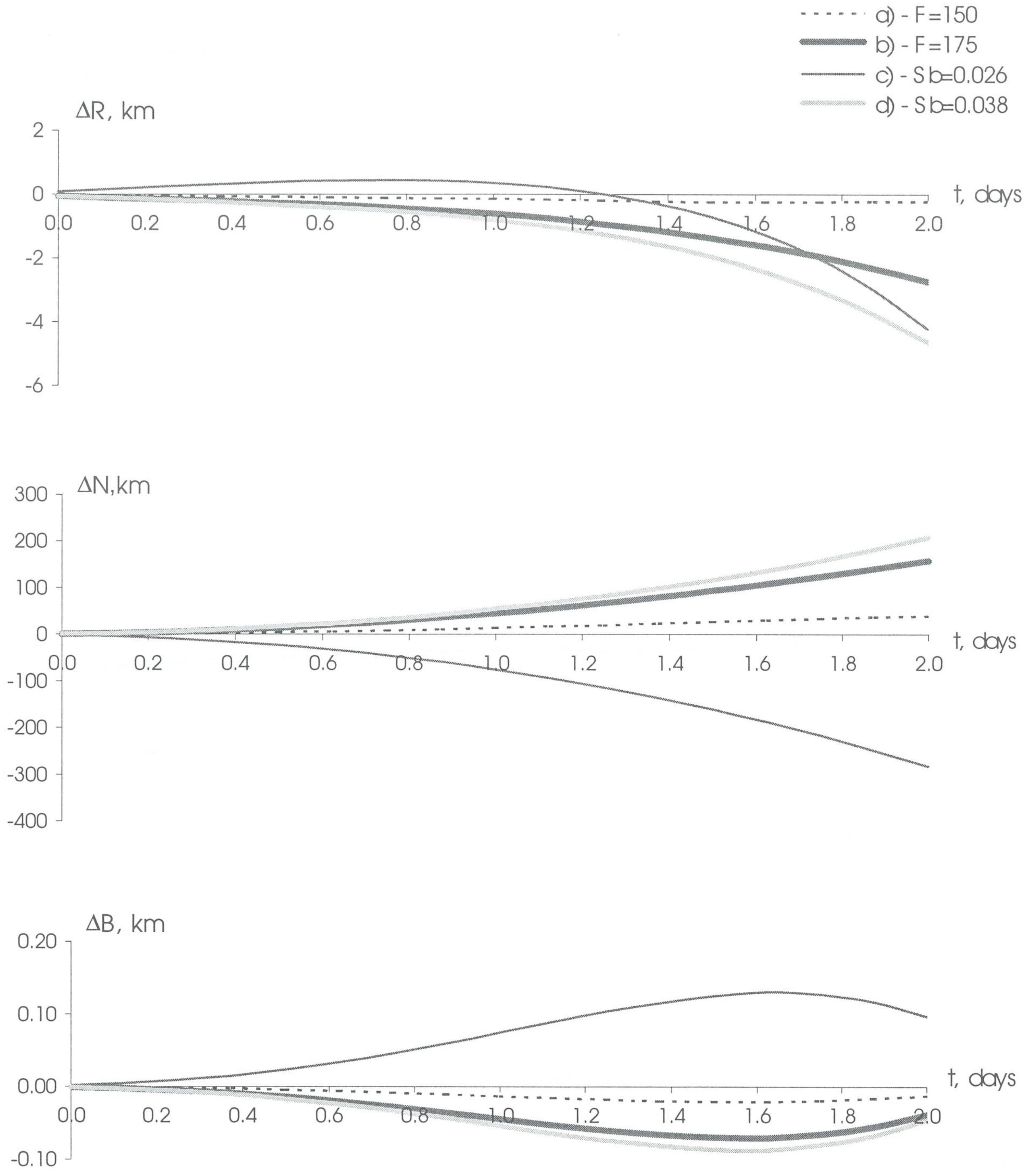


Fig.2. Effect of the atmospheric drag uncertainty on the MIR motion prediction (original Sb=0.033; H~250 km)

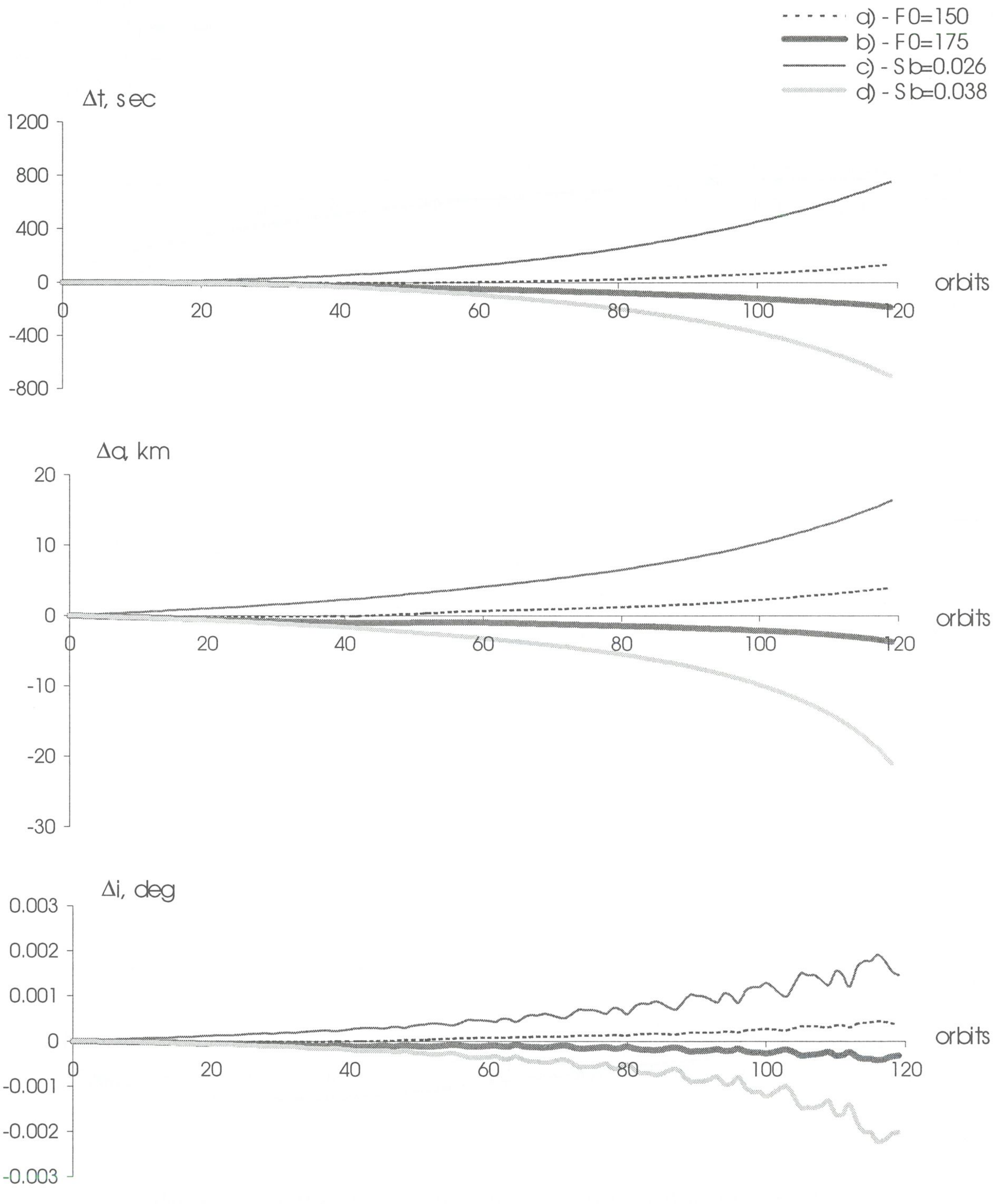
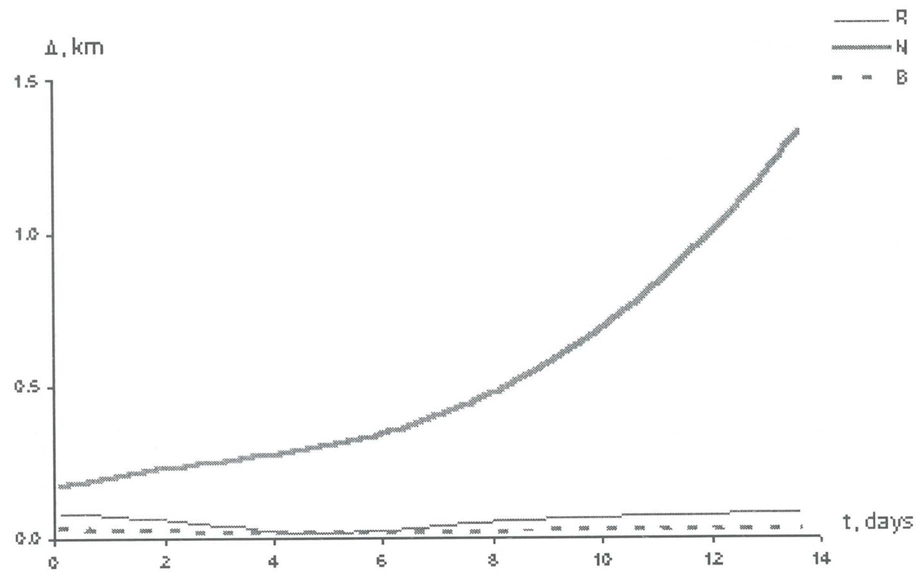
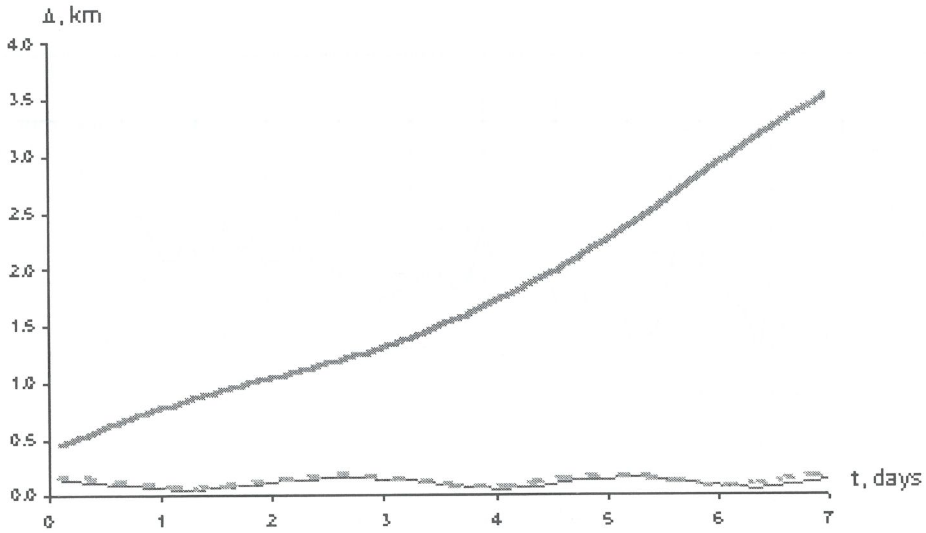


Fig.3. Effect of the atmospheric drag uncertainty on the MIR orbit evolution (original Sb=0.033; H~250 km)



Orbit altitude H~300 km (accuracy prediction for 14 days)



Orbit altitude H~220 km (accuracy prediction for 7 days)

Fig.4. Estimation of the MIR orbit determination accuracy

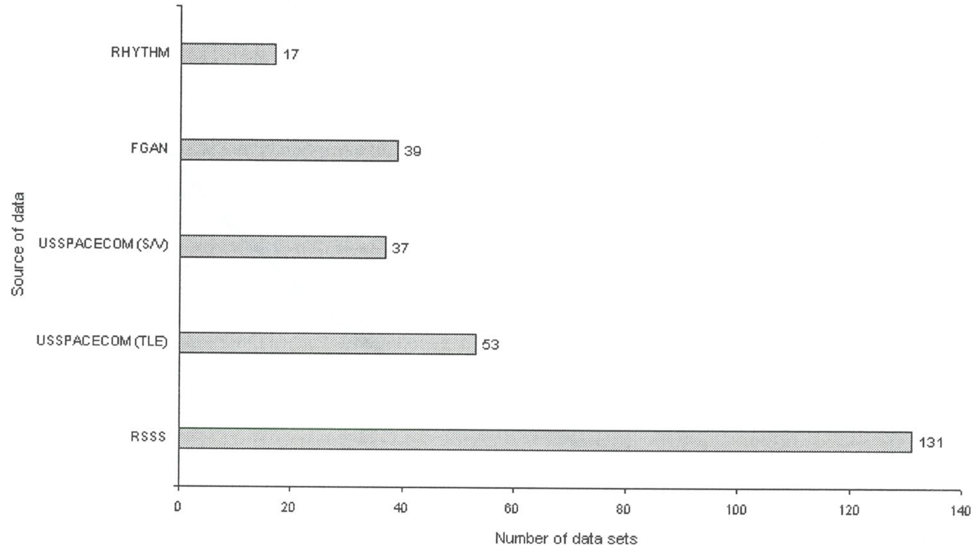


Fig.5. Amount of the measurement passages/orbital sets entered into the MCC-M during 01.02.2001 - 23.03.2001

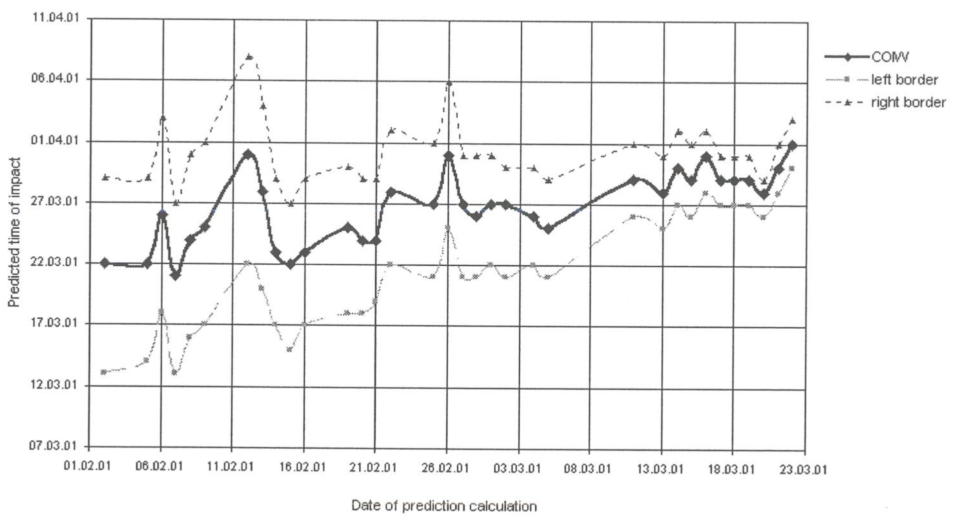


Fig.6. MIR re-entry prediction history according to the MCC-M solutions

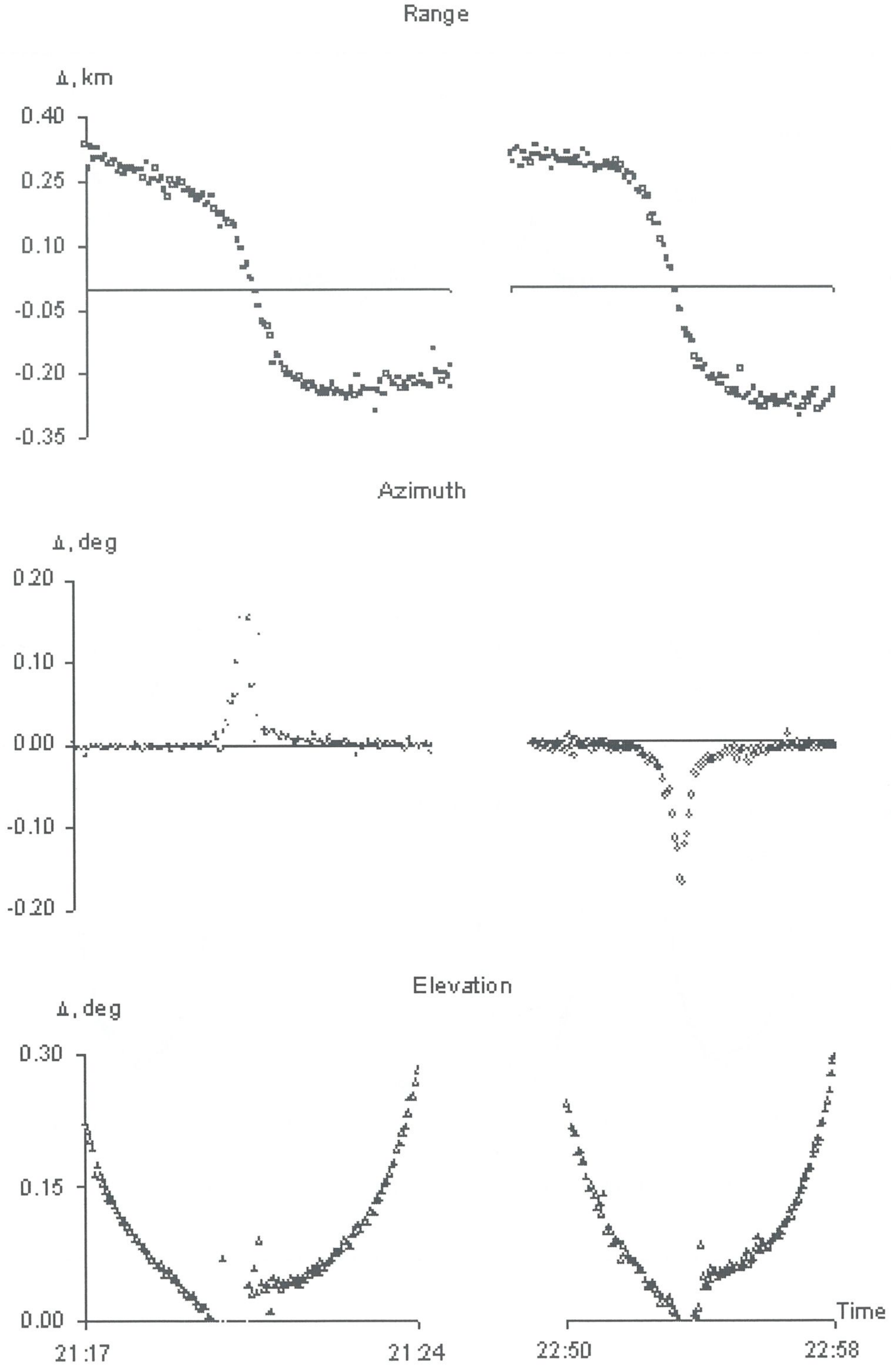


Fig.7. Residuals of the FGAN radar data from RTS solution
(for 28.02.2001)

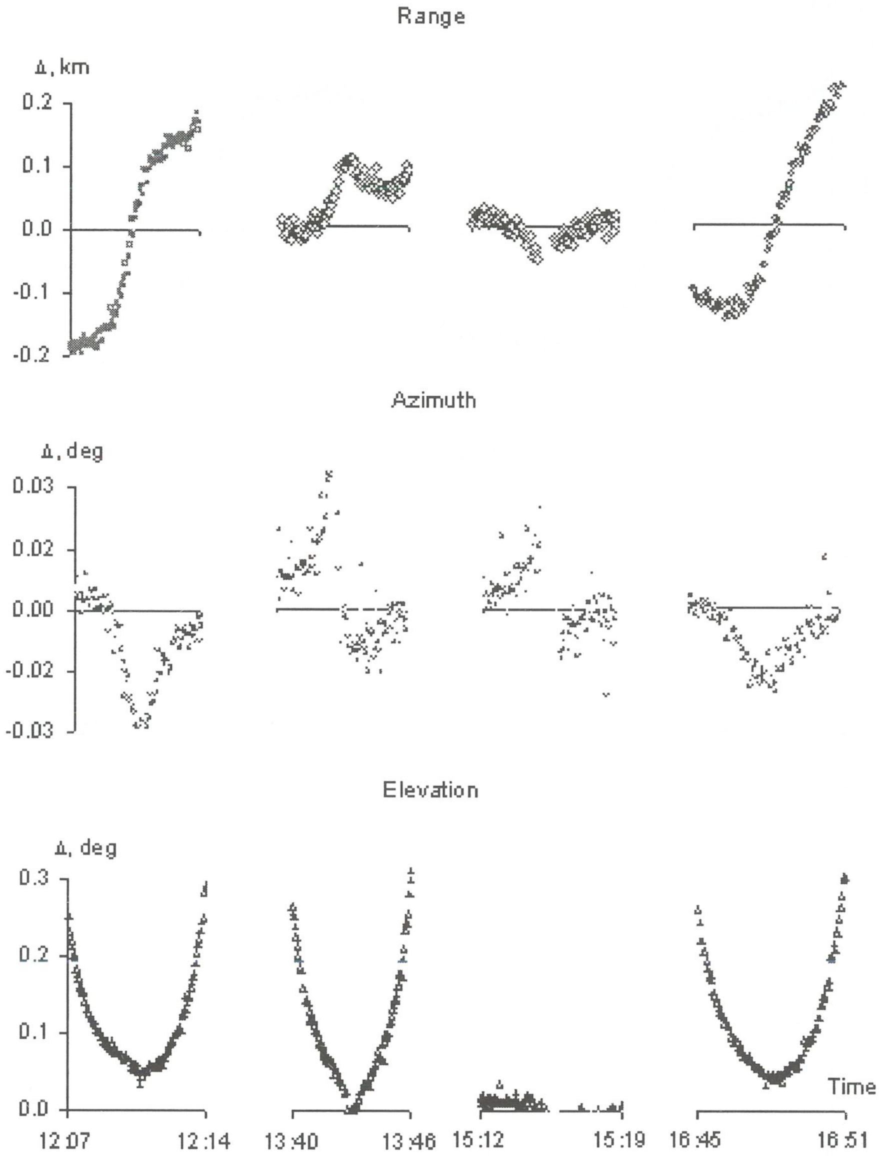


Fig.8. Residuals of the FGAN radar data from RTS solution (for 20.03.2001)

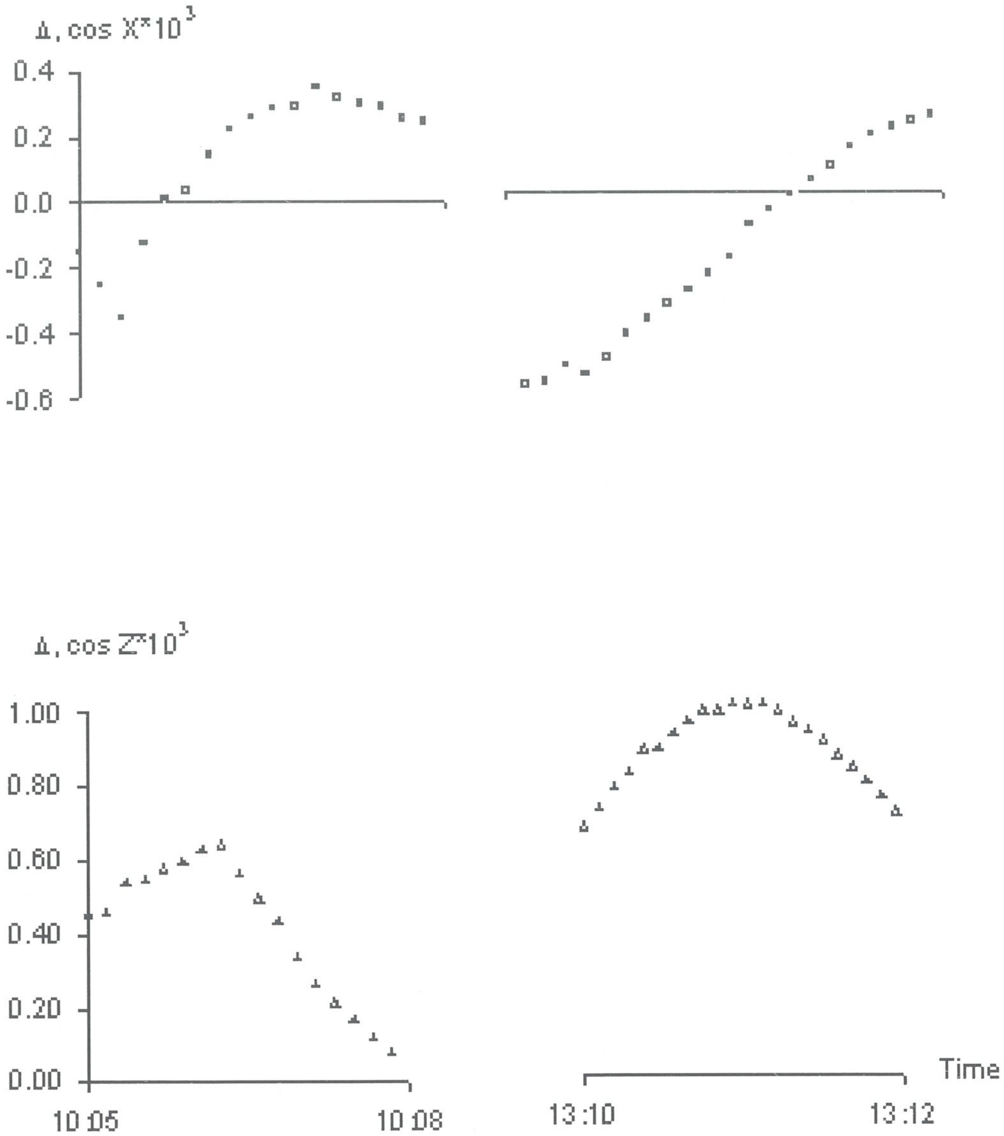


Fig.9. Residuals of the "Rhythm" system measurements from RTS solution (for 22.03.2001).

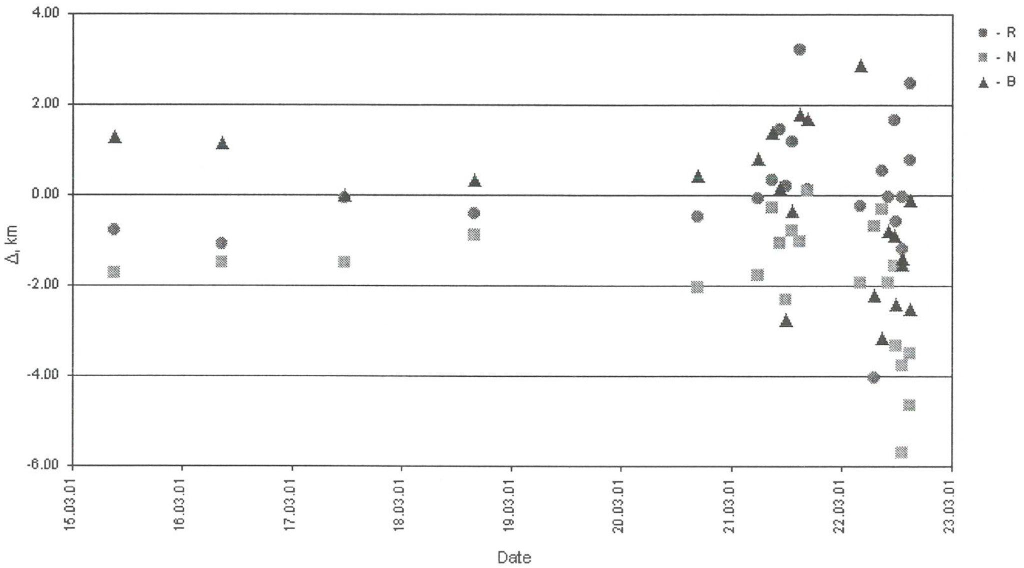


Fig.10. Residuals (in RNB) of the RSSS' orbital data from RTS solution

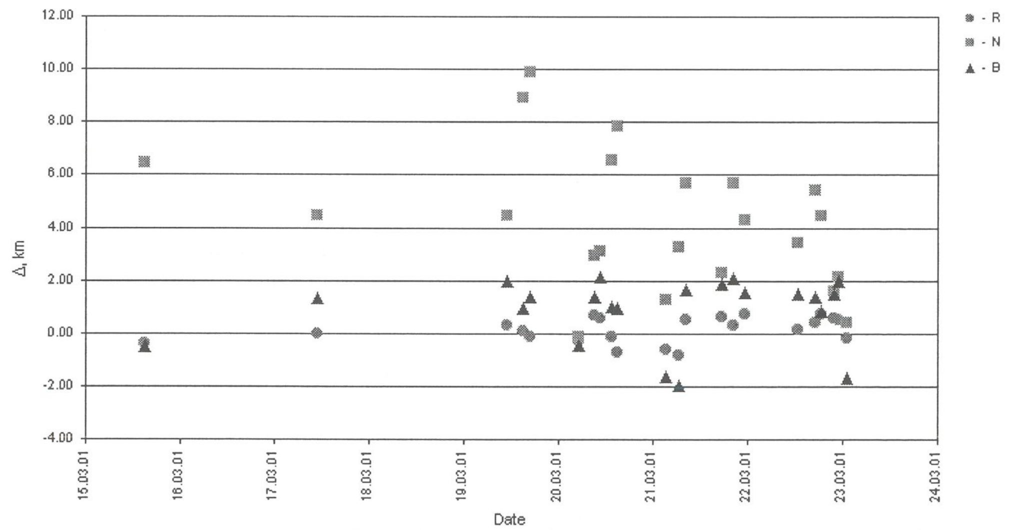


Fig.11. Residuals (in RNB) of the USSPACECOM TLE from RTS solution

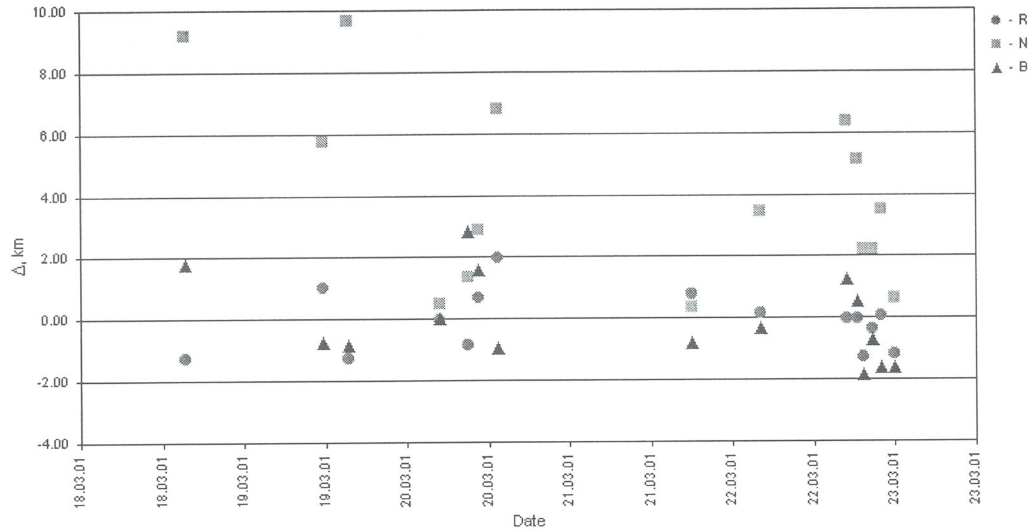


Fig.12. Residuals (in RNB) of the USSPACECOM S/V from RTS solution

Table 1. Comparison of the MIR orbit determination results obtained from measurements of Russian tracking sites (RTS) and the RSSS

	Solution 1		Solution 2		Solution 3		Solution 4	
	RTS	RSSS	RTS	RSSS	RTS	RSSS	RTS	RSSS
Orbits	2090-2109 (8)	2111-2154 (5)	2169-2171 (4)	2170-2175 (10)	2185-2187 (3)	2187-2218 (3)	2231-2236 (6)	2236-2256 (3)
Date, *yy.mm.dd*	2001.03.09		2001.03.13		2001.03.14		2001.03.17	
t_Ω, *hh.mm.ss,sss*	17.09.01,249	17.09.01,465	12.02.11,256	12.02.11,328	10.21.30,307	10.21.30,605	11.11.42,369	11.11.42,062
T, *min*	89,471	89,472	89,395	89,309	89,264	89,263	89,108	89,110
i, *deg*	51,661	51,654	51,658	51,651	51,656	51,651	51,658	51,653
Ω, *deg*	323,808	323,804	303,994	303,979	298,272	298,265	281,761	281,743
H_e, *km*	254,252	254,186	247,428	247,351	245,174	244,142	237,621	237,759
H_{max}, *km*	254,252	254,186	247,428	247,351	245,174	244,142	237,621	237,759
H_{min}, *km*	247,57	247,79	239,38	239,58	237,29	238,49	230,29	230,31
Sb, $m^3/(kg\ s^2)$	0,02701	0,02804	0,02909	0,03176	0,02553	0,02857	0,02730	0,02993

Table 2. Comparison of the MIR orbit determination results obtained from measurements of Russian tracking sites (RTS) and the USSPACECOM TLE

	Solution 1		Solution 2		Solution 3		Solution 4	
	RTS	TLE	RTS	TLE	RTS	TLE	RTS	TLE
Orbits	2263-2270 (8)	2267-2277 (7)	2280-2286 (7)	2279-2293 (9)	2299-2304 (6)	2294-2308 (7)	2314-2316 (3)	2317-2325 (6)
Date, *yy.mm.dd*	2001.03.19		2001.03.20		2001.03.21		2001.03.22	
t_Ω, *hh.mm.ss,sss*	09.12.27,154	09.12.27,082	04.29.04,566	04.29.04,500	17.30.57,830	17.30.57,039	09.47.36,638	09.47.36,627
T, *min* c	88,996	88,996	88,941	88,941	88,808	88,805	88,764	88,764
i, *deg*	51,655	51,657	51,652	51,645	51,654	51,647	51,655	51,647
Ω, *deg*	271,297	271,280	266,904	266,885	258,436	258,414	254,710	254,694
H_e, *km*	231,549	231,803	228,595	228,642	221,595	222,133	219.108	219.364
H_{max}, *km*	245,940	244,40	242,77	243,03	235,55	235,40	233,08	233,42
H_{min}, *km*	225,39	225,60	223,06	222,96	216,81	216,22	215,11	214,83
Sb, $m^3/(kg\ s^2)$	0,02770	0,03138	0.03170	0.03139	0,02277	0,02548	0,02015	0.01668

Table 3. Comparison of the MIR orbit determination results obtained from measurements of Russian tracking sites (RTS) and FGAN radar data

	Solution 1		Solution 2		Solution 3		Solution 4	
	RTS	FGAN	RTS	FGAN	RTS	FGAN	RTS	FGAN
Orbits	2263-2270 (7)	2269-2272 (4)	2280-2286 (7)	2285-2288 (4)	2294-2300 (7)	2301-2304 (2)	2314-2317 (4)	2316-2320 (5)
Date, *yy.mm.dd*	2001.03.19		2001.03.20		2001.03.21		2001.03.22	
t_Ω, *hh.mm.ss,sss*	12.10.26,305	12.10.26,256	11.53.43,374	11.53.43,257	11.35.40,675	11.35.40,672	09.47.36,637	09.47.36,557
T, *min*	88,987	88,987	88,913	88,913	88,825	88,829	88,765	88,765
i, *deg*	51,657	51,656	51,656	51,656	51,656	51,656	51,656	51,656
Ω, *deg*	270,621	270,620	265,212	265,210	259,793	259,794	254,710	254,709
H_e, *km*	231,041	231,114	227,048	227,351	222,485	222,592	219,129	219,302
H_{max}, *km*	245,341	245,309	240,767	241,004	236,267	236,376	233,176	232,862
H_{min}, *km*	225,139	225,090	221,735	221,467	217,721	217,996	215,160	215,086
Sb, $m^3/(kg\ s^2)$	0,02841	0,02893	0.03170	0.03296	0,02670	0,03296 *)	0,01830	0.01805

*) Sb was not improved