Mars Global Surveyor Mapping Orbit Determination

Stuart Demcak* (primary point of contact)
818-393-7961
Stuart.Demcak@jpl.nasa.gov

Eric Graat
818-393-1289
Eric.Graat@jpl.nasa.gov

Pasquale B. Esposito
818-393-1264
Pasquale.B.Esposito@jpl.nasa.gov

Darren T. Baird
818-354-7791
Darren.T.Baird@jpl.nasa.gov

Mail and Fax address is the same for all of the above:
Jet Propulsion Laboratory
M/S 264-235
4800 Oak Grove Drive
Pasadena, CA 91109-8099

Fax: 818-393-3147

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*OAO Corporation

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Since the start of the mapping phase on March 9, 1999, the Mars Global Surveyor (MGS) spacecraft has been conducting a global scientific study of Mars' surface, atmosphere and magnetic and gravitational fields. The MGS mapping orbit is polar, nearly circular, frozen and sun synchronous. It has a period of 1.96 hours, with a mean altitude of 402 km. As of February 2001 MGS will have completed over 8600 mapping orbits in nearly two years of flight operations. Throughout this time the navigation team has been responsible for providing the MGS project teams with spacecraft ephemeris information, which is derived by analyzing X-band doppler tracking data. The methods and challenges of the orbit determination process are described in this paper.

The navigation team has two major responsibilities. First, it provides trajectories to the various engineering and science teams, which predict the future spacecraft position and velocity. These predicted trajectories are generated twice per week and are used for the following purposes: spacecraft command and sequence generation, Deep Space Network (DSN) antenna frequency and pointing, spacecraft onboard ephemeris and planning of science observations. The second is to generate a weekly reconstructed trajectory. It contains the actual spacecraft ephemeris over the previous week, which is used by the science teams in the analysis of science observations.

The accuracy of the orbit determination depends on correctly modeling the trajectory related forces and parameters. The spacecraft angular momentum desaturations (AMDs), which impart a velocity perturbation to the trajectory, are a major error source. AMDs are nominally performed autonomously onboard the spacecraft and occur about once every 7 hours. From the daily replay of engineering telemetry, the spacecraft team (SCT) generates a file describing each AMD event. There is a latency of 1.5-2.5 days in the delivery of this data to navigation. The velocity magnitude accuracies associated with these AMDs have been around 35-40%. Recent refinements by the SCT have reduced this error to 15-20%. However, for navigation to fit the doppler data to its typical accuracy of 0.1 mm/s, these errors must be less than a percent. Therefore, navigation must always estimate for each AMD to refine its value.

Information about future AMDs is not available from the SCT. This is the major source of error in the predicted trajectories delivered to the project. In addition, an important component of the predicted trajectory is greatly influenced by a small perturbation in a near zero component of the AMD. An AMD is theoretically executed along the spacecraft Z axis, which is nadir pointed to Mars. However, the AMDs also have a relatively small component along the spacecraft X direction (along the spacecraft velocity vector), which can significantly affect the downtrack or timing errors. Figures 1 and 2 give navigation estimates of the Z and X components of the velocity perturbation (16 mm/s and 2 mm/s, respectively) due to an AMD.

The other major error source, the gravity field, has been refined throughout the mapping phase. The original gravity field used for MGS was derived from Viking and Mariner 9 radiometric data. These spacecraft orbits were very different from MGS and provided little information about the gravity field around the Mars poles. Therefore, the field was inadequate for the stringent requirements needed by the MGS polar, low circular orbit. To help solve this problem, a two week gravity calibration phase was scheduled prior to the mapping phase. Navigation used data during part of this period to create an updated gravity field. This field was a dramatic improvement for the MGS doppler analyses. Further improvements in the gravity field were performed by the MGS radio science team. With the current field, the gravity is no longer a critical error source.

The methodologies of both the reconstructed and predicted cases are similar but have some differences due to delivery requirements. In both cases a single batch, weighted least squares filter is used to fit the doppler data (see figures 3 and 4.) The fitting process estimates corrections to the spacecraft state (position and velocity), AMDs, and selected components of the gravity field. An AMD is modeled as a velocity perturbation in this process. The reconstructed deliveries analyze doppler data for which navigation has all of the available dynamic information -- most importantly AMD information. One and a half to two days (18-24 orbits) of doppler are fit for each orbit determination analysis. For the weekly delivery, these independent analyses are merged together to produce a week long reconstructed trajectory.

For predicted deliveries, the most recent good quality doppler data are analyzed. As a result, no AMD information is available for this type of analysis. Typically three orbits of doppler data are analyzed to reduce the chance of finding unmodeled AMDs in the data arc, which can cause significant problems in the analysis. Experience has shown that fitting less than one orbit results in a poor orbit prediction, especially if only 1-way doppler is available. If an unmodeled AMD exists within the fit timespan, the residuals (actual doppler observable minus computed observable) will usually be about twice as large as expected. The analyst will then have to manually search for the AMD. The AMD usually occurs during a period of no doppler data (e.g. geocentric occultation). In this case it is quite difficult to determine where the AMD occurs. On the other hand, if it occurs in the middle of doppler data, it is usually easy to detect. The analyst must also consider problems with doppler quality or spacecraft events. A poor fit could always be due to poor doppler data rather than an AMD. Furthermore, even a minor spacecraft event could cause a signature in the doppler data which, at first glance, could look like an AMD.

After the doppler analysis has been completed, the spacecraft trajectory must be integrated out to predict the spacecraft state typically over 20 days or 245 orbits. A constant acceleration model is used in the prediction to account for expected effects of future AMDs. This acceleration model is determined from the history of previous prediction trajectory accuracies, actual trajectory variations, and real-time doppler residual observations. By looking at doppler residuals calculated in real-time from the previous prediction delivery, one can estimate the effect of AMDs on the recent trajectory. The latest navigation reconstruction analysis is typically for a data arc three days in the past. So the real-time doppler residuals give much more current information on the behavior of the AMDs on the trajectory.

The accuracies of the reconstructed spacecraft ephemerides are less than 10 meters where accurate doppler data are available and increase up to 100 meters where no data exists. The predicted spacecraft ephemeris accuracies are most often examined with respect to the descending equator crossing time. This time or downtrack error is important for science observations and is mostly influenced by AMDs. The following table shows the descending equator crossing time error over three prediction time intervals (5, 10, 20 days) for four representative cases during the mapping phase.

Table 1: Descending equator crossing time (T_{deqx}) errors for four predicted trajectories.

Analysis Epoch	T_{deqx} *Error (seconds)* 5 day	*10 day*	*20 day*
1999/09/23	0.17	1.8	9.3
1999/11/11	0.09	-1.4	-8.0
1999/12/29	2.39	7.0	22.5
2000/03/02	0.51	1.3	-1.9

Figure Descriptions:

1) Navigation estimated values for the spacecraft Z component of the velocity perturbations due to the AMDs.

2) Navigation estimated values for the spacecraft X component of the velocity perturbations due tothe AMDs.

3) Initial "pre-fit" doppler residuals for a prediction analysis. These are the doppler residuals before any orbit determination analysis has been started (i.e. pass through).

4) Final "post-fit" doppler residuals for a prediction analysis. These are the doppler residuals after a converged orbit determination solution has been generated.

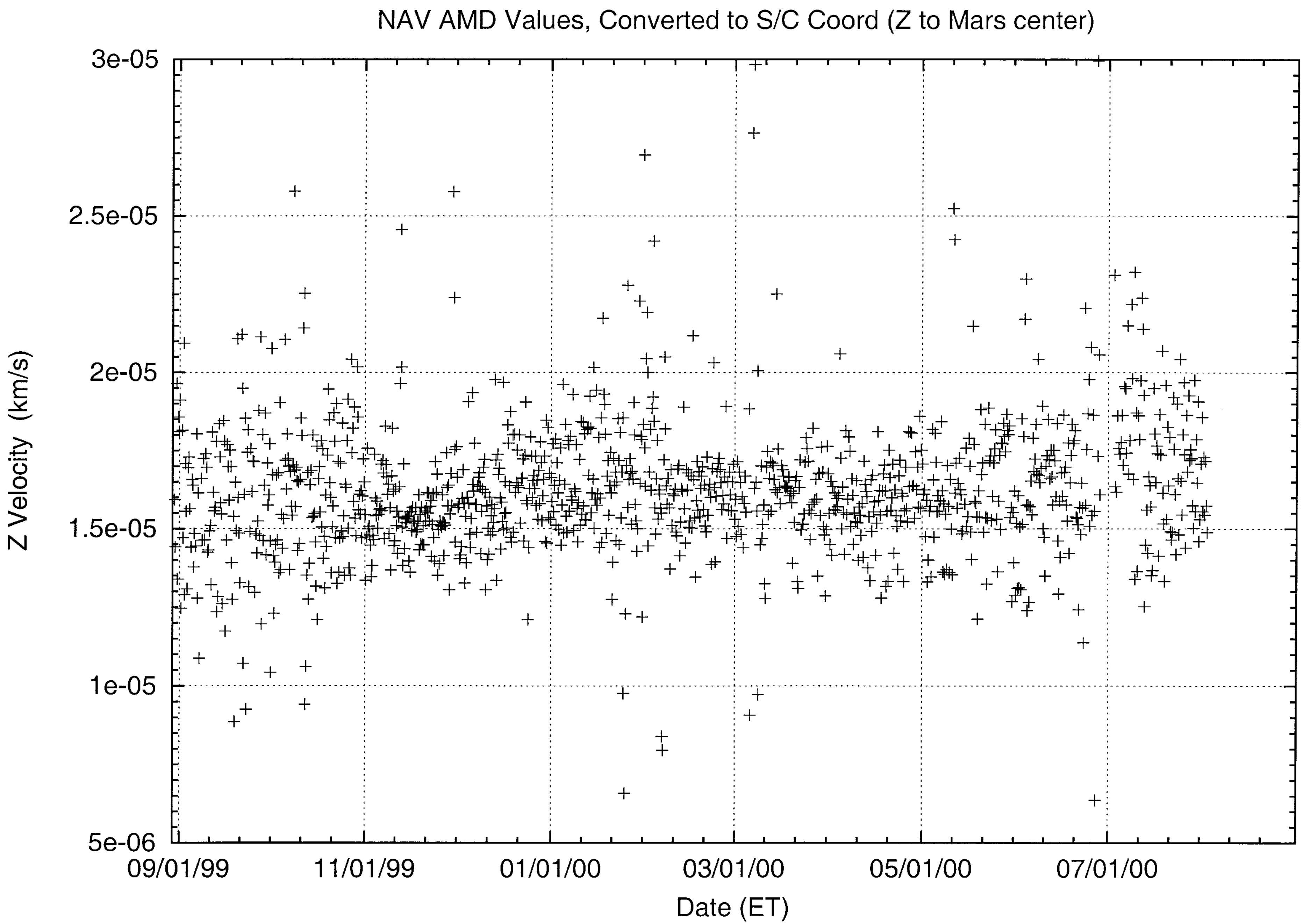
NAV AMD Values, Converted to S/C Coord (Z to Mars center)
Z Velocity (km/s)
3e-05
2.5e-05
2e-05
1.5e-05
1e-05
5e-06
09/01/99
11/01/99
01/01/00
03/01/00
05/01/00
07/01/00
Date (ET)

Figure 1

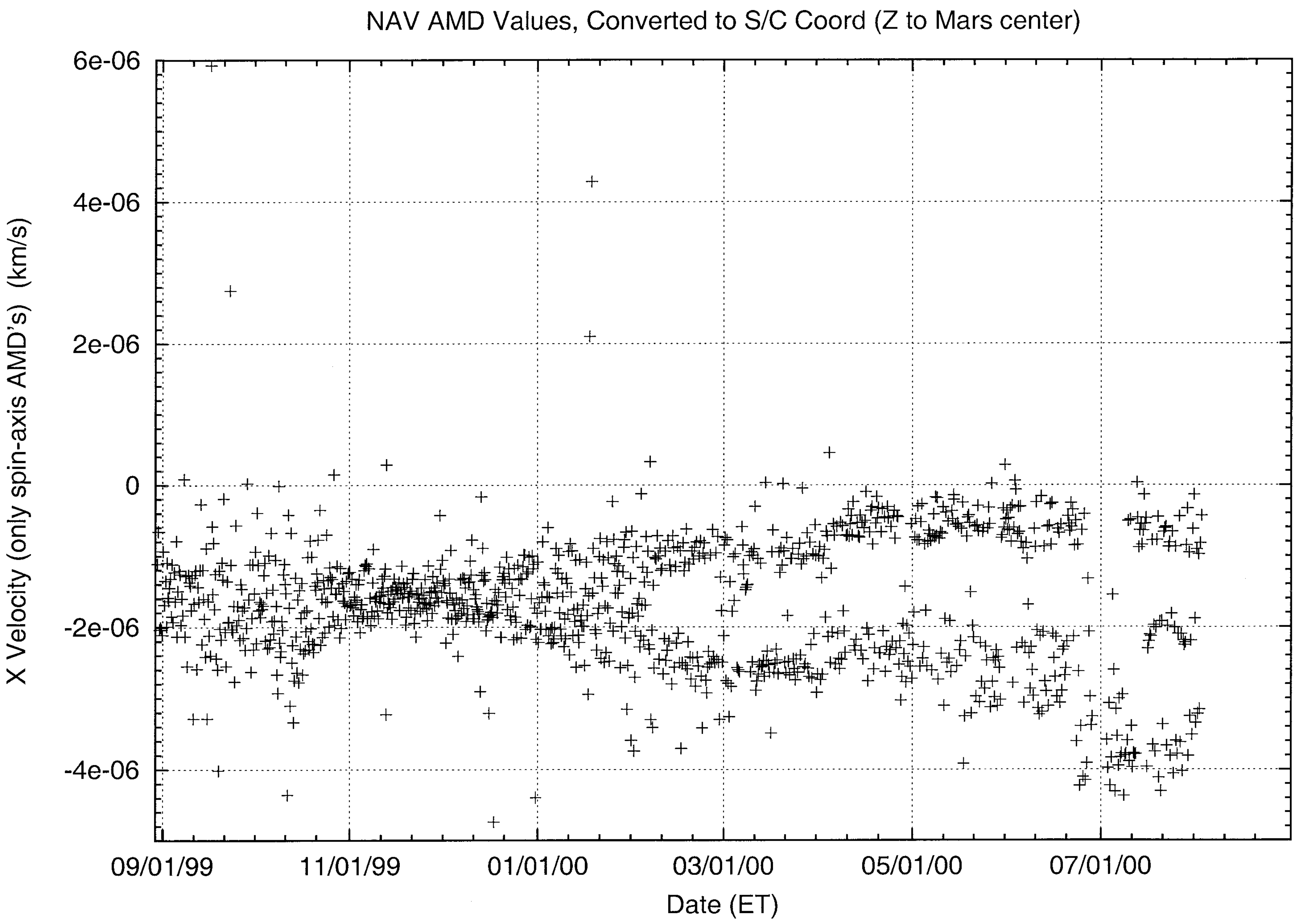
NAV AMD Values, Converted to S/C Coord (Z to Mars center)
X Velocity (only spin-axis AMD's) (km/s)
6e-06
4e-06
2e-06
0
-2e-06
-4e-06
09/01/99
11/01/99
01/01/00
03/01/00
05/01/00
07/01/00
Date (ET)

Figure 2

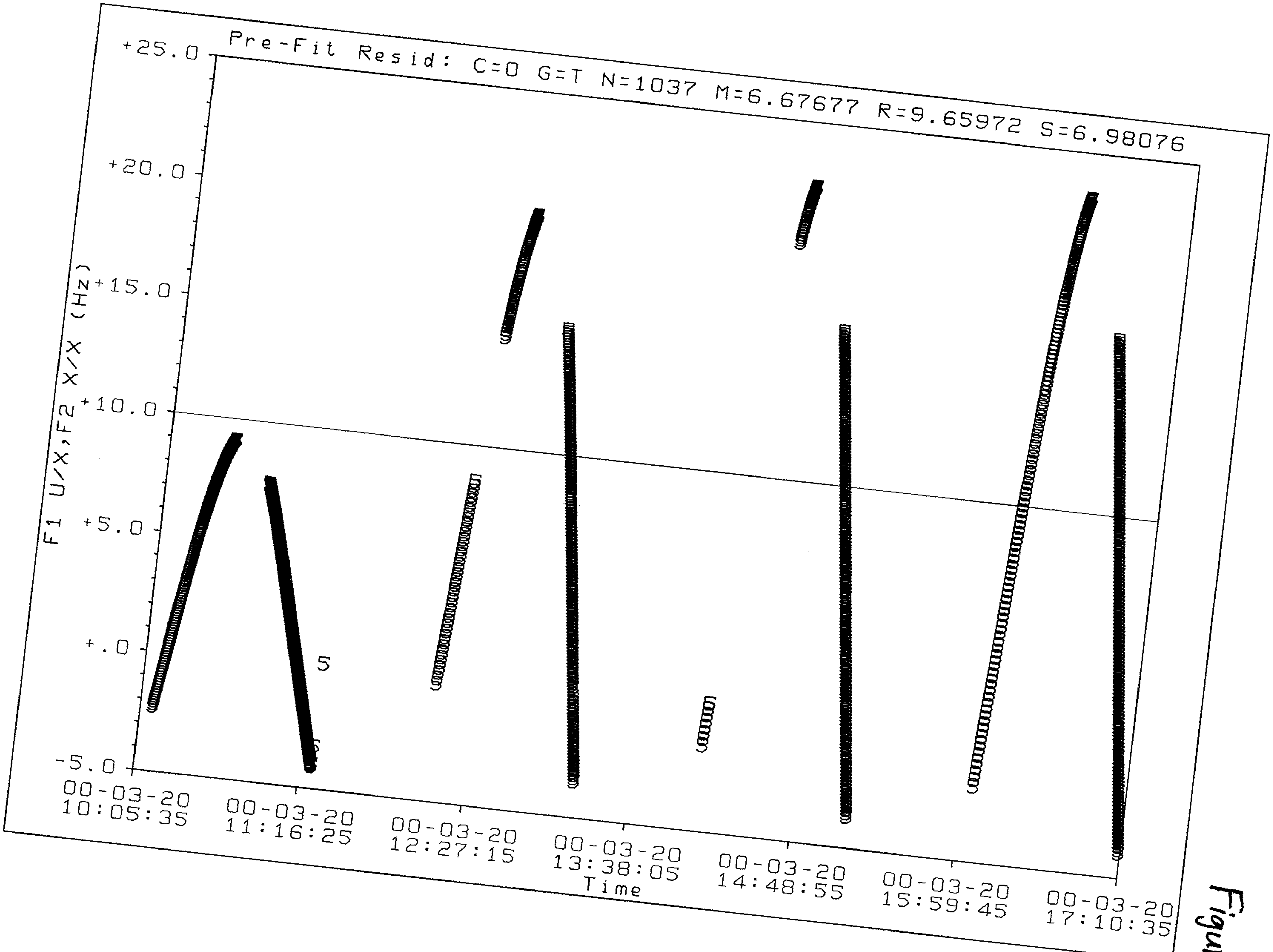
Pre-Fit Resid: C=0 G=T N=1037 M=6.67677 R=9.65972 S=6.98076
F1 U/X,F2 X/X (Hz)
+25.0
+20.0
+15.0
+10.0
+5.0
+.0
-5.0
00-03-20 10:05:35
00-03-20 11:16:25
00-03-20 12:27:15
00-03-20 13:38:05
00-03-20 14:48:55
00-03-20 15:59:45
00-03-20 17:10:35
Time
5

Figure 3

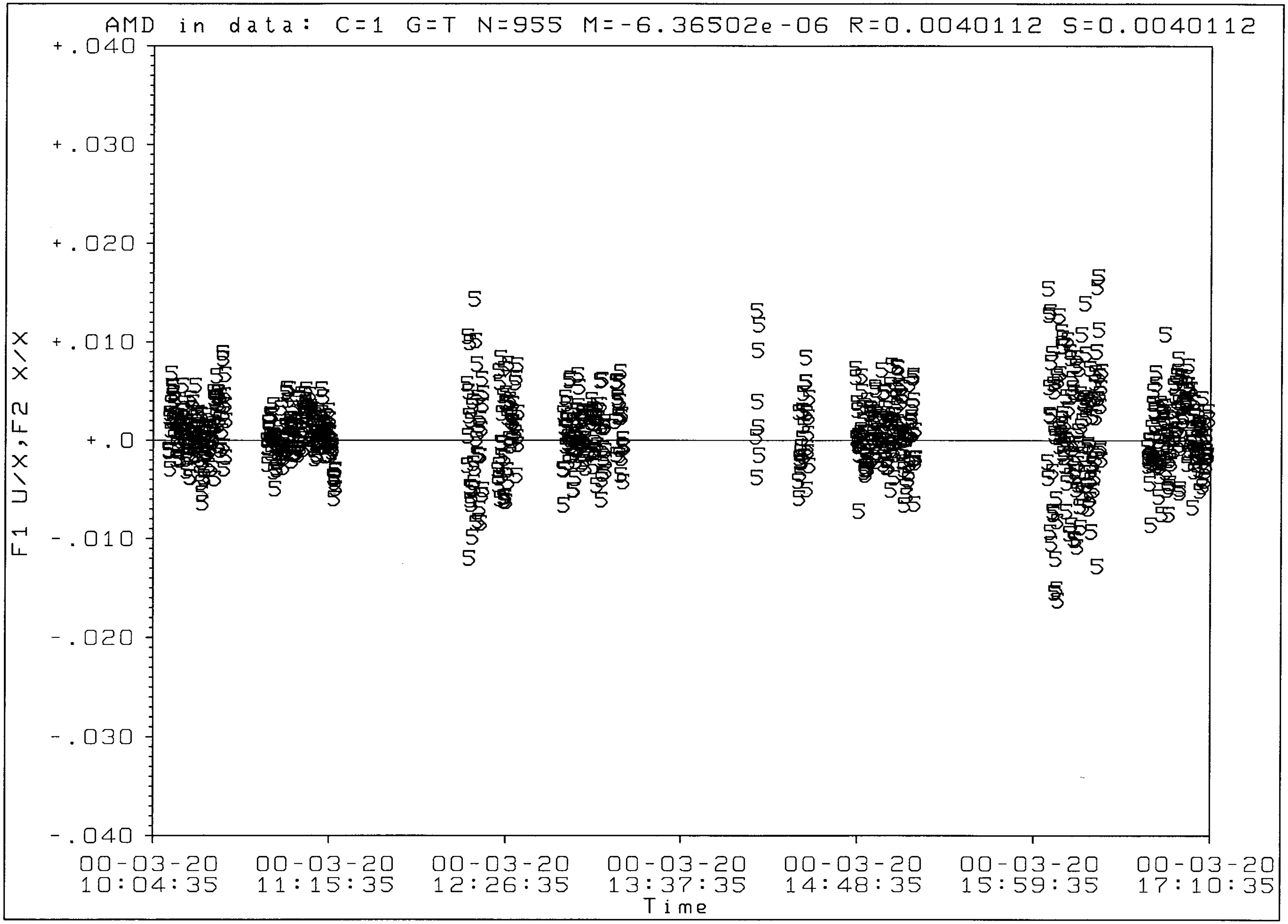
AMD in data: C=1 G=T N=955 M=-6.36502e-06 R=0.0040112 S=0.0040112
+.040
+.030
+.020
+.010
+.0
-.010
-.020
-.030
-.040
F1 U/X,F2 X/X
00-03-20 10:04:35
00-03-20 11:15:35
00-03-20 12:26:35
00-03-20 13:37:35
00-03-20 14:48:35
00-03-20 15:59:35
00-03-20 17:10:35
Time

Figure 4