Space Flight Technology, German Space Operations Center (GSOC)
Deutsches Zentrum für Luft- und Raumfahrt (DLR) e.V.

Maxus-4
Orion GPS Tracking System

Flight Report

O. Montenbruck, M. Markgraf

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Prepared by :

O. Montenbruck, DLR/GSOC
Project Manager

M. Markgraf, DLR/GSOC
Lead Engineer

Approved by:

Th. Rupp, DLR/GSOC
Head Space Flight Technology

G. Schmitt, Kayser-Threde

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Scope

Within a joint project of DLR and Kayser-Threde, an Orion GPS receiver was flown onboard the Maxus-4 mission as part of the payload service module. This document provides a summary and evaluation of the GPS tracking data collected by the Orion GPS receiver, including a comparison with Ashtech G12 measurements recorded during the same flight.

1 Introduction

1.1 Mission Overview

The Maxus-4 rocket (cf. Fig.1.1) was launched from ESRANGE, Kiruna, on April 29, 2001 (11:28 UTC). The payload segment weighed a total of 803 kg and comprised seven material sciences experiments in five different experiment units:

- TEM 06-27M "Multi-Roll Instability of Thermocapillary Flow and Transition to Oscillary", (D. Schwabe,Univ. Giessen, Germany).
- TEM 06-4M "Pulsating and Rotating Instabilities in Marangoni Flows" (R. Monti, Univ. Naples, Italy).
- FOAMS, physics of foams (B. Kronberg, Ytkemiska Institutet, Sweden, and M. Adler, Univ. Marne la Vallée, France).
- TEM 02-5M "Application of a Rotating Magnetic Field for the Suppression of Time-dependent Marangoni Convection" (K. Benz, A. Cröll, P. Dold, M. Schweizer, University of Freiburg, Germany and T. Hibiya, S. Nakamura, NEC, Japan).
- TEM 06-26M "Crystallization of MFI type Zeolite from Clear Solution" (J. Martens, CEA, and Kirschhock, Univ. Leuven, Belgium).

A single stage Castor-4B motor carried the payload to an altitude of 703.4 km and allowed for a zero-g time of more than twelve minutes.

Fig 1.1 The Maxus-4 rocket has an overall length of 17 m. It employs a Castor-4B motor of 10 m size, which is able to carry an 800 kg payload to an altitude of 700 km

Due to problems in the guidance system, the flight path started to deviate from the planned trajectory from about 10 s after lift-off. As a result, the ground track was shifted in a westerly direction and the payload ultimately crossed the border before landing in Norway. Furthermore, the main parachute was destroyed after being deployed too early due to a malfunction, which resulted in a final sink rate of about 90 m/s. When telemetry was lost prior to touch down, the payload was located in a distance of 93 km from the launch site at

$$\lambda_{WGS84} = +20.046° \qquad \phi_{WGS84} = +68.627° \qquad h_{WGS84} = 2.8\ \mathrm{km}\,.$$

While the payload segment was badly damaged due to the abrupt deceleration, valuable data and samples required for the scientific post-mission analysis could still be recovered. Likewise, the Orion GPS receiver experienced no evident damage during touch down and was found to be electrically functioning after disassembly of the payload module.

1.2 Sequence of Events

Key events of the Maxus-4 mission are summarized in Table 1.1, which is based on reference data given in [1] and [2]. All times refer to Sunday, 29 April 2001 (day of year 119, GPS week 1112).

Table 1.1 Maxus-4 main events given in time since launch, UTC time, and GPS time

Event	h [km]	t [s]	UTC	GPS sec
Lift-off	0.3	0.0	11:28:00.0	41293.0
Approximate start of guidance problems	1.5	10.0	11:28:10.0	41303.0
Peak acceleration (13.7 g)	66.7	59.3	11:28:59.3	41352.3
Peak yerk (-7 g/s)	71.9	61.0	11:29:01.0	41354.0
Burnout (incl. motor chauffing)	87.0	65.0	11:29:05.0	41358.0
Tip ejection	91.4	67.0	11:29:07.0	41360.0
Motor separation	148.5	85.0	11:29:25.0	41378.0
ARCS valves enable	150.0	85.5	11:29:25.5	41378.5
Start of zero-g	185.1	97.0	11:29:37.0	41390.0
Apogee	703.4	454.0	11:35:34.0	41747.0
End of zero-g	121.2	830.0	11:41:50.0	42123.0
Spin-up	82.4	842.0	11:42:02.0	42135.0
Can removal; loss of GPS tracking	53.8	850.7	11:42:10.0	42143.7
Peak deceleration (38.5 g)	n.a.	867.0	11:42:27.0	42160.0
Heatshield release	n.a.	940.9	11:43:41.6	42234.6
GPS navigation re-acquired	ca. 4.5-5.0	943.2	11:43:43.2	42236.2
Loss of signal by DLR TM	2.8	961.0	11:44:01.0	42254.0

1.3 Orion GPS Receiver Unit

The Orion GPS receiver is a 12 channel L1 C/A code receiver based on the Mitel (now Zarlink) GP2000 chipset. The receiver software has extensively been modified by DLR/GSOC to support high-dynamics space applications [3]. For use on sounding rockets, a position-velocity aiding has been implemented [4], which allows the receiver to obtain coarse values of the instantaneous position and velocity from a low-order polynomial approximation of the nominal flight trajectory. Using the aiding concept, the receiver is able to quickly re-acquire tracking after temporary signal losses. A first test flight of the receiver on an Improved Orion rocket was successfully performed in Feb. 2001 as part of the Maxus-4 test campaign [5].

For use on Maxus-4, the standard interface board has been replaced by a tailor made interface board of Kayser-Threde (KT), which provides a suspension for the main board and fits into a standard housing unit (Fig. 1.2). The I/F board provides an RS422 output to the onboard data handling system, a bi-directional RS422 serial port connected to the ground support equipment (GSE) via umbilical cable before liftoff, an RS232 serial port for ground tests and a lithium backup battery.

Fig. 1.2 Orion GPS unit for the Maxus-4 flight. The main receiver board is embedded into the KT interface board featuring various serial line drivers and a backup battery. Total outer dimensions are 160 x 110 x 20 mm^3.

The overall flight configuration is illustrated in Fig. 1.3, which covers both the on-board and on-ground installation. For completeness the diagram also shows an Ashtech G12 HDMA receiver, which was operated independently by KT but shares the overall antenna system. To support the different mission phases, the payload segment has been equipped with a multi-antenna system. A helical antenna mounted in the tip of the rocket cone provided near hemispherical coverage during the ascent trajectory. After separation of the cone, an R/F switch connected the GPS receiver to an antenna mounted on the top of the canister of the recovery system. During the parachute phase the receiver was, finally, fed by an antenna mounted in between the four-leg bridle of the parachute. For ground operation, a separate antenna was provided on the roof of the launch complex and connected to the receiver through a supplementary R/F switch until lift-off. Thus, the receiver could be properly initialized to acquire all visible GPS satellites prior to launch.

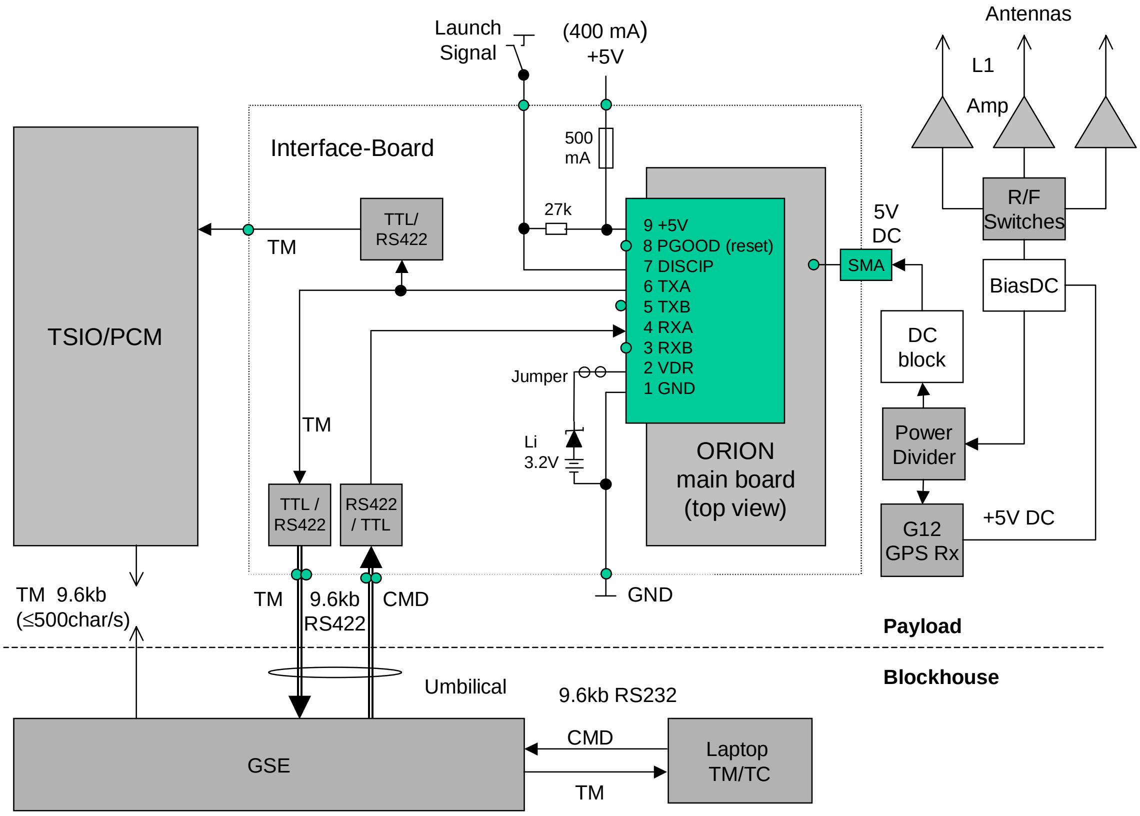

Fig. 1.3 Schematic view of the Maxus-4 GPS receiver interfaces and integration [6].

The GPS receiver's DISCIP pin is used as input for a liftoff signal provided by the payload. Prior to liftoff the DISCIP is connected to ground. Thereafter, the pin is left open which implies a high level due to the pull up resistor on the interface board. Changes in the pin state are sensed by the receiver software and used to store the time of lift-off required for the position-velocity aiding.

For the Maxus-4 mission the Orion GPS receiver was configured to compute and output a navigation solution (F40 message) at a 2 Hz rate. In addition, a channel status message (F43) was generated once per two seconds. No synchronization to the integer GPS (or UTC) second was activated, which causes uneven time tags of the individual measurements.

2 Flight Data

2.1 Tracking Status and Signal Acquisition

The Orion receiver tracked the position and velocity of the Maxus-4 payload from lift-off to landing with the exception of two outages related to antenna switching. 3D navigation was first lost for 5.5 seconds after the boost end (t=65.4 s to 70.4 s), even though one to two satellites were continuously tracked throughout this interval. Prior to the reentry, no tracking was available for 92 s after separation of the can, which took place at t=851 s. Position and velocity information was regained at 943 s, before telemetry transmission was ultimately terminated at t=961 s.

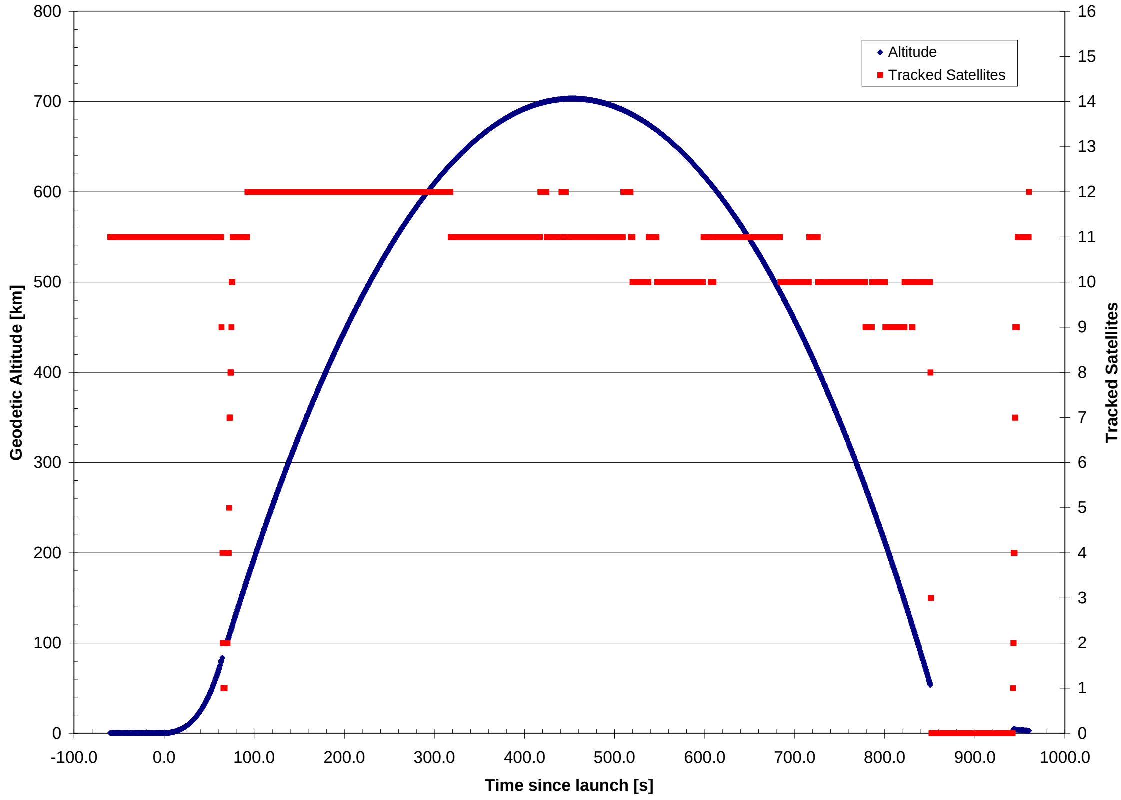

Fig. 2.1 Number of tracked satellites and altitude of the Maxus-4 payload as a function of the mission elapsed time

Throughout the boost and free flight phase the Orion receiver tracked between 9 and 12 satellites, yielding PDOP values better than 2.0. The slow decrease in the number of tracked satellites correlates with changes in the signal-to-noise (SNR) ratios (Fig. 2.2), which indicate a slow but notable change in the antenna boresight direction during the parabolic flight. While the SNR values of satellites PRN #3, #22, and #28 with azimuth values of 200° to 250° increases by typically 5 dB with time, a decrease of similar magnitude is observed for the majority of the other satellites. Out of these satellites, PRN #2, #8, and #27 were lost prior to reentry. Table 2.1 summarizes the GPS visibility conditions for the Maxus-4 flight considering the elevation limit of –15° that was configured in the Orion GPS receiver. A total of twelve different GPS satellites were visible during the flight with elevation angles between +10° and a maximum of +64°.

Table 2.1 GPS satellite visibility and tracking status during the Maxus–4 campaign (elevation threshold –15°)

	Lift-off		Landing		Status
PRN	**Az**	**El**	**Az**	**El**	
2	355.6°	-8.0°	353.0°	-1.7°	acquired at t=453 s
3	220.7°	64.3°	202.4°	61.5°	tracked
8	329.5°	21.4°	321.5°	20.5°	tracked
9	-	-	73.2°	-14.6°	-
10	26.4°	-11.9°	-	-	track lost at t=318 s
11	257.6°	-10.4°	258.0°	-4.1°	-
14	-	-	153.6°	-14.9°	-
15	97.9°	53.8°	95.2°	46.0°	tracked
17	84.7°	35.1°	84.5°	27.5°	tracked
18	124.0°	53.0°	111.9°	54.2°	tracked
21	174.9°	34.2°	171.2°	40.3°	tracked
22	202.0°	11.3°	199.2°	4.3°	tracked
23	107.9°	54.9°	96.0°	54.1°	tracked
26	42.8°	27.8°	35.0°	27.1°	tracked
27	305.5°	15.1°	299.1°	11.6°	tracked
28	254.5°	42.0°	244.6°	38.0°	tracked
31	281.7°	41.1°	275.0°	47.9°	-

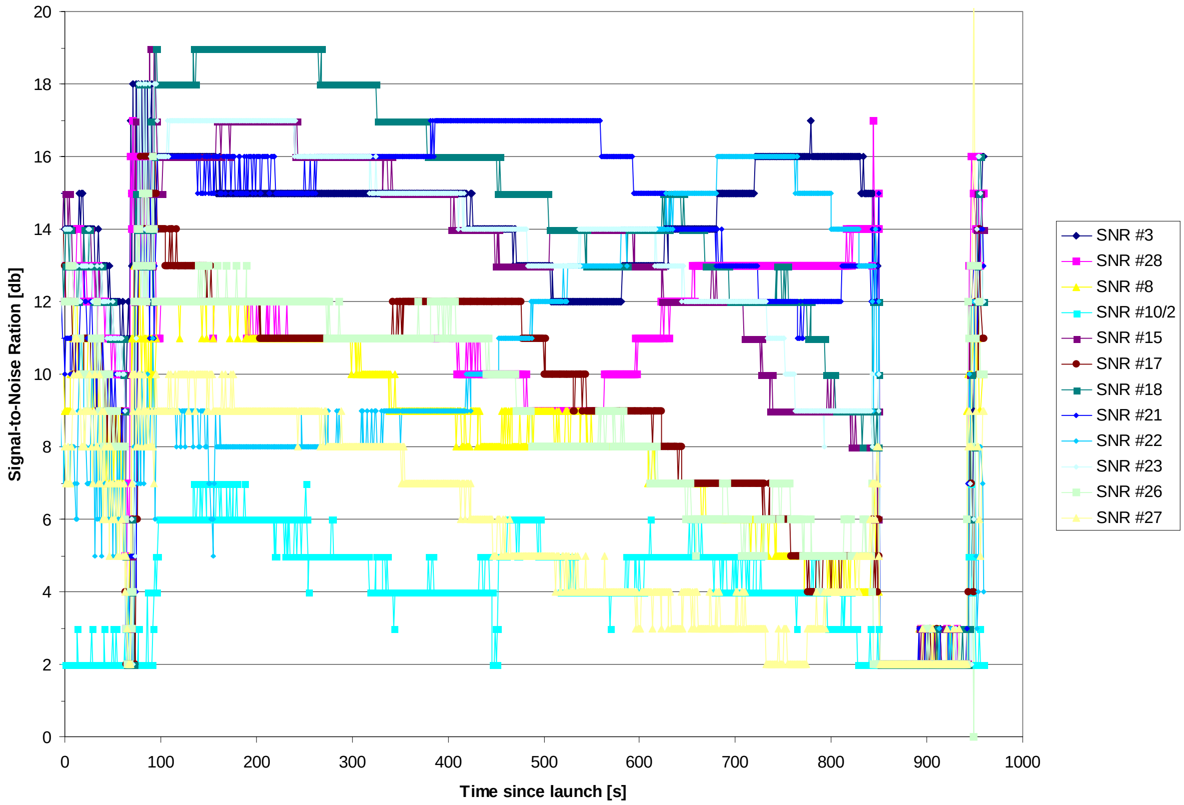

Fig. 2.2 Signal-to-noise ratio of GPS satellites tracked during the Maxus-4 mission

2.2 Ground Track and Instantaneous Impact Point

The Orion GPS telemetry was processed in real-time to obtain a graphical representation of the ground track and the instantaneous impact point (IIP). As illustrated in Fig. 2.3, the Maxus-4 rocket followed the nominal flight path for approximately 35 s. Thereafter, an increased West component of the thrust vector built up, which resulted in a sharp left turn of the instantaneous impact point.

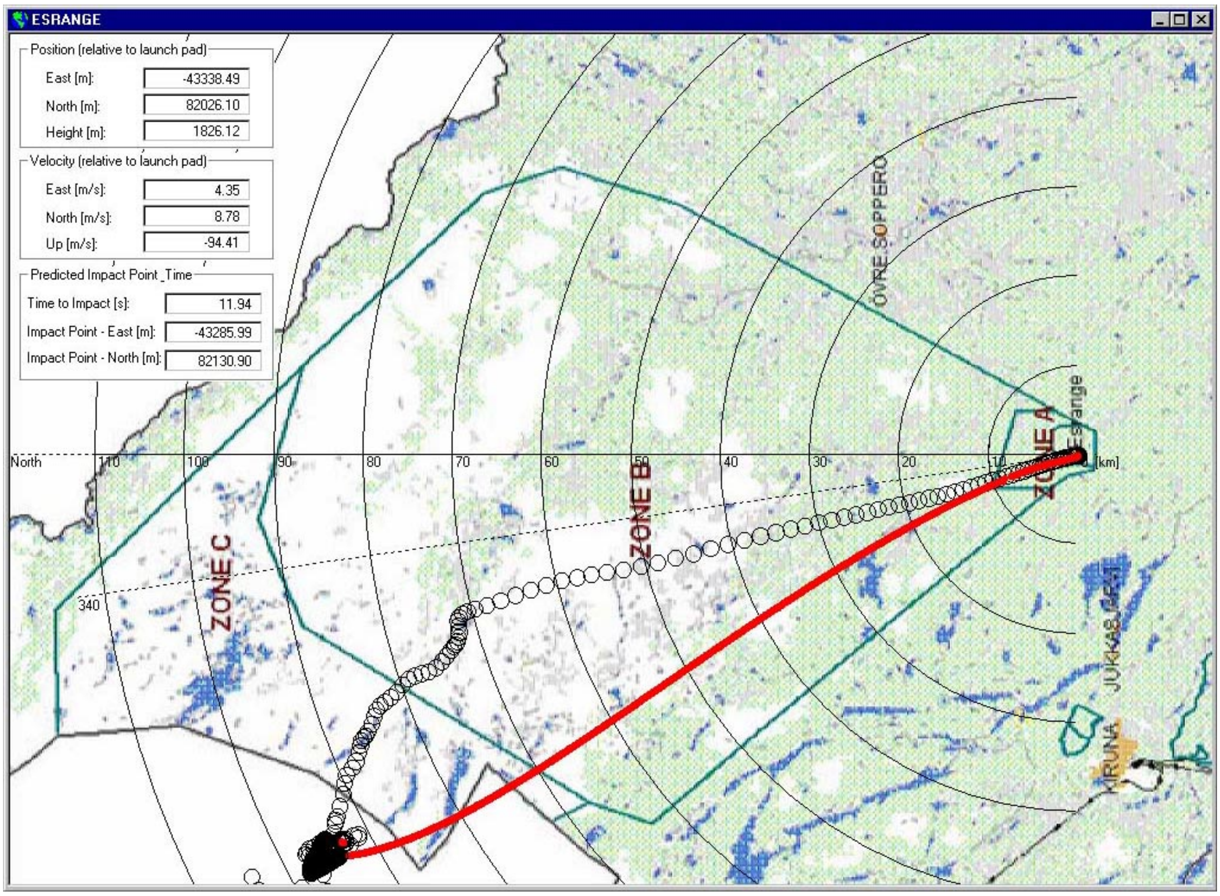

Fig. 2.3 Ground Track (red) and Instantaneous Impact Point (IIP; open circles) of Maxus-4 as derived from the GPS Orion navigation data.

The online IIP prediction provided a rapid indication of the off-nominal performance of the guidance system and the landing point across the Norwegian border. In view of the extended flight time of the Maxus-4 mission, the Coriolis correction has been considered, which minimizes the scatter of predicted impact points during the free flight phase.

For completeness, it is noted that the operational IIP prediction carried out by SSC Esrange based on Ashtech G12 navigation data is affected by discernible errors due to an inconsistent processing of spherical position and velocity data as well as a 0.25 s latency of the velocity information in the G12 POS data message.

The cross-track deviation between the nominal and actual trajectory amounted to roughly 30 km near the landing point. Obviously, the differences between the actual flight path and the reference trajectory used for aiding inside the Orion GPS receiver had no negative impact on the overall tracking performance.

2.3 Tracking Accuracy

The accuracy of the GPS Orion navigation solution was assessed by comparison with the Ashtech G12 HDMA data. To this end, the spherical coordinates given in the G12 POS message were converted to Cartesian WGS84 coordinates and interpolated for the uneven time stamps of the Orion navigation solution. A second order polynomial was applied to interpolate position values, while a linear approximation was used for the velocity values. In both cases, approximate accelerations were obtained from the Ashtech velocity data by a symmetric difference quotient. The resulting interpolation errors are essentially negligible with respect to the Orion data noise.

In the course of the analysis, an inconsistency of position and velocity information in the Asthech POS message became apparent, which required a correction of the G12 velocity time tags. The velocity data within a POS record refer to an instant of 0.25 s earlier than the given time stamp, while the position data bear the proper time tag. This inconsistency is easily recognized by forming second order difference quotients of the altitude and comparing the result with the climb rate provided in the POS message. The empirical evidence was later on confirmed by NASA/WFF (B. Bull, priv. comm.) and is related to the velocity computation algorithm employed in the XF02 release of the G12 firmware. An offset of 0.25 s in the G12 velocity data was therefore applied prior to the interpolation and comparison with the Orion measurements. For completeness, it is noted that no such inconsistency was encountered in comparison with NASA's G12 receiver during the Test Maxus-4 mission.

Table 2.2 Mean tracking errors and standard deviations of the Orion navigation solution as compared to the G12 reference data

Phase		x [m]	y [m]	z [m]	vx [m/s]	vy [m/s]	vz [m/s]
Pre-launch (t<0s)	Mean	0.3	-1.2	-9.3	0.1	0.0	0.3
	σ	4.5	3.6	9.2	0.1	0.1	0.4
Boost (0s<t<60s)	Mean	1.5	0.9	-1.9	0.1	-0.1	0.6
	σ	2.7	1.3	6.0	1.1	1.3	2.9
Post boost (60s<t<85s)	Mean	5.6	13.0	-4.5	2.4	4.4	6.4
	σ	25.4	18.3	52.2	22.0	14.1	45.0
Free Flight (85s<t<845s)	Mean	3.7	1.4	-2.8	-0.1	-0.1	0.0
	σ	4.0	1.4	5.2	0.3	0.2	0.5

As illustrated in Table 2.2, the Orion and G12 navigation solutions agree to roughly 10 m and 0.5 m/s during the pre-launch free flight phase. Only moderately larger velocity errors are encountered during the boost phase, and major tracking errors may only be observed right after the end of boost. As discussed in Sect. 2.4, this behavior is most likely attributed to mechanical stress of the quartz oscillator at the time of maximum yerk..

A detailed view of the position and velocity errors of the Orion receiver (as referred to the Ashtech G12 solution) is given in Figs. 2.4 and 2.5. Slightly increased position errors during the pre-launch phase are most probably attributed to multipath effects caused by reflections in the vicinity of the launch pad. At t=318 s, a discontinuity in the position difference is encountered, which relates to the loss of the low elevation (<-15°) satellite PRN 10 by the Orion receiver. Overall, the observed differences between the Orion and G12 navigation solution are within expectations and readily understood by differences in the set of tracked satellites as well as the modeling of atmospheric path delays. In addition, no filtering or carrier phase smoothing is applied in the Orion navigation solution, which results in a higher noise level.

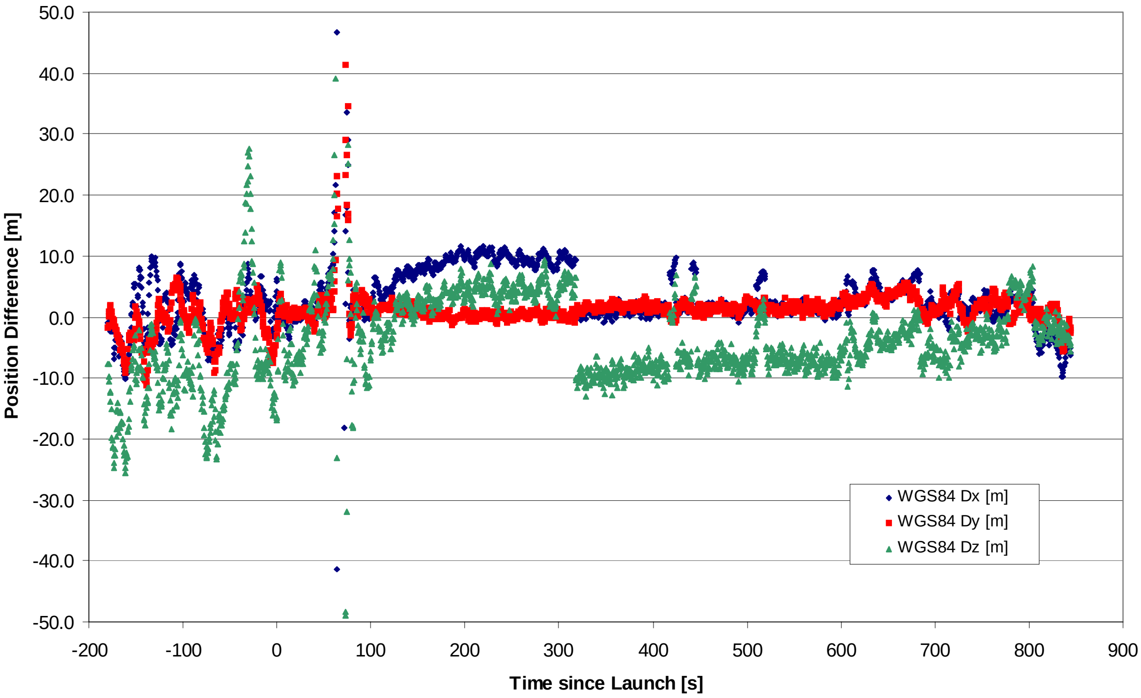

Fig 2.4 Mean offsets and standard deviations of the Orion position solution as compared to the G12 reference data

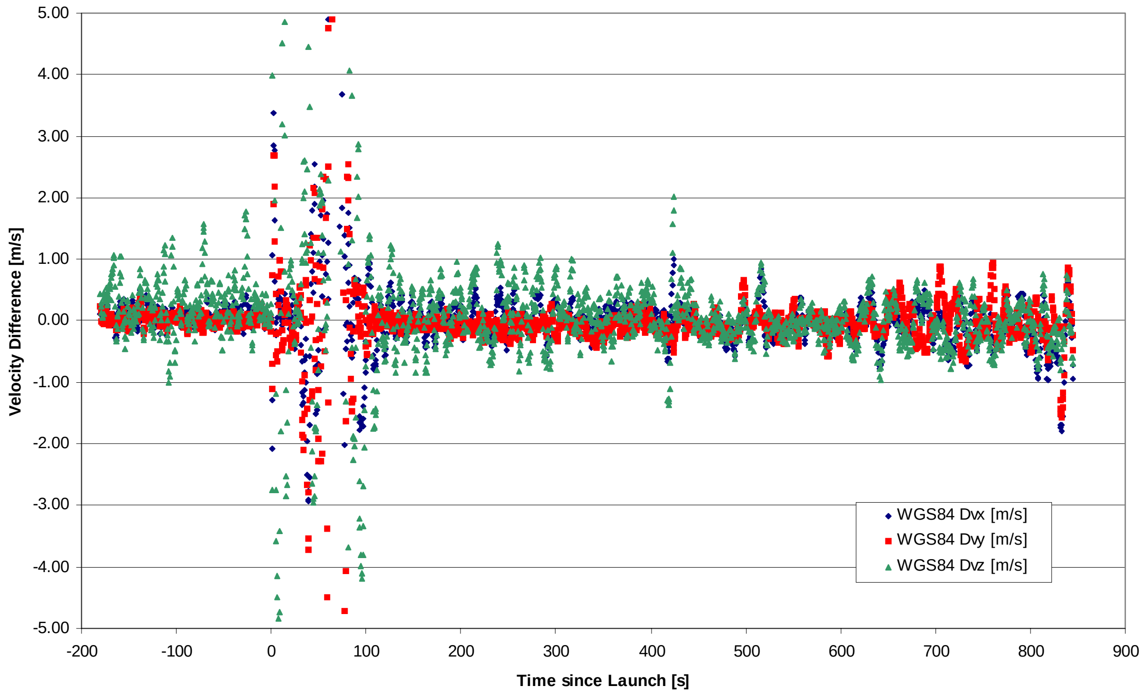

Fig 2.5 Mean offsets and standard deviations of the Orion velocity solution as compared to the corrected G12 reference data

2.4 Boost Phase

For further analysis of the tracking behavior under high dynamics, the boost phase of the Maxus-4 mission is discussed in more detail. As shown in Fig. 2.6, the rocket achieved a peak climb rate of 3283 m/s around 64 s after lift off. The north velocity component increased for 38 s up to a maximum of 208 m/s but was subsequently reduced to half this value at the boost end.

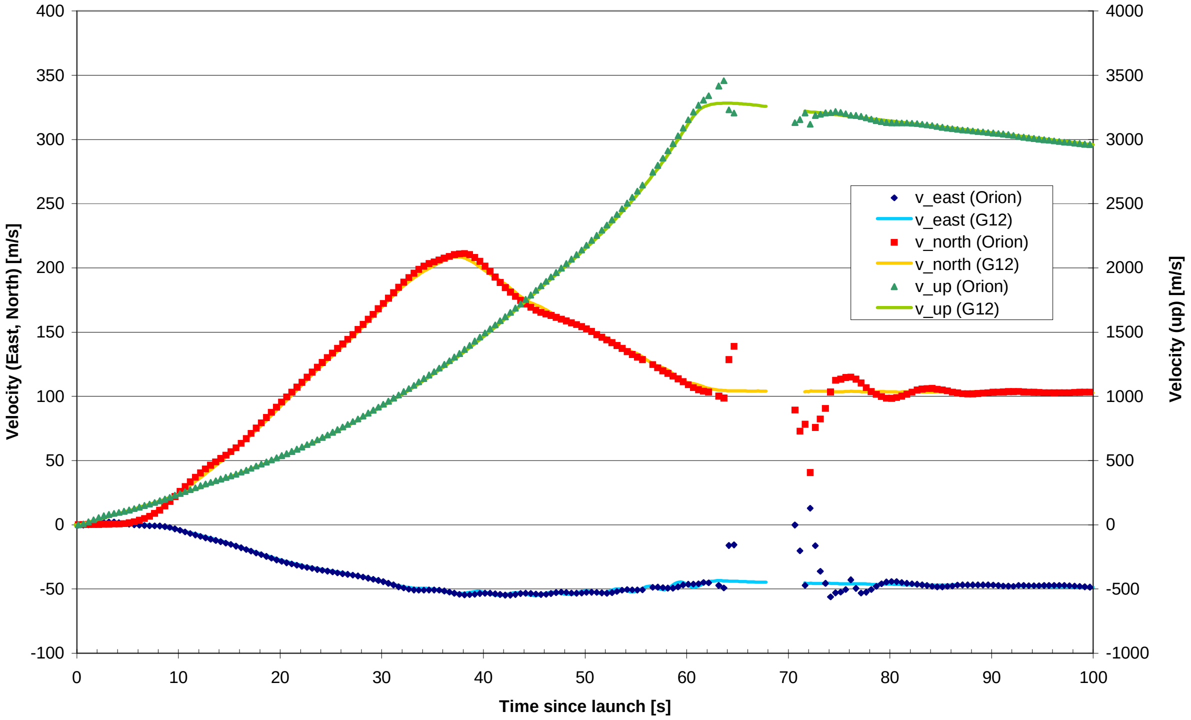

Fig 2.6 Velocity profile during the first 100 seconds of the Maxus-4 flight. The Orion navigation solution is indicated by individual markers, while the Ashtech G12 solution is depicted by solid lines. Note the different scales employed for the east and north components on the on hand (left scale) and the up component (right scale) on the other hand.

Near burn out (t~63s), an overshooting of the Orion velocity solution may be observed in comparison with the G12 data, which provides a first indication of tracking problems under high acceleration changes (yerk). About 2 seconds later, the Orion receiver lost tracking, while the G12 receiver continued to provide data up to the disconnection of the tip antenna (t~68 s). Following the interrupt, the Orion regained 3D navigation a t~70.5 s, while the G12 tracking data were available slightly later (t=72 s).

A comparison of both velocity solutions once again shows notable Orion tracking errors and exhibits a damped sine characteristic with a relaxation time of 10-15 seconds. Since signal simulator tests conducted earlier have not revealed a similar behavior, the tracking problems are best explained by a response of the employed reference quartz to mechanical stress following the instant of maximum yerk. This conclusion is further supported by a comparison of the vertical acceleration and the observed oscillator offset of the Orion receiver given in Fig. 2.7. Both tracking and oscillator errors are observed jointly in response to acceleration changes of up to +4.5 g/s and –7 g/s near the boost start and end, respectively.

For completeness the horizontal (east and north) components of the acceleration vector are given in Fig. 2.8. It may be observed that the small oscillatory acceleration in the second part of the boost phase is less well resolved by the Orion receiver, which is only partly explained by the lower output frequency of the velocity data (2 Hz versus 5 Hz). It is therefore suspected that the tracking loops are less responsive than those of the G12 HDMA receiver and a better adaptation of the loop bandwidths to the dynamical conditions is suggested.

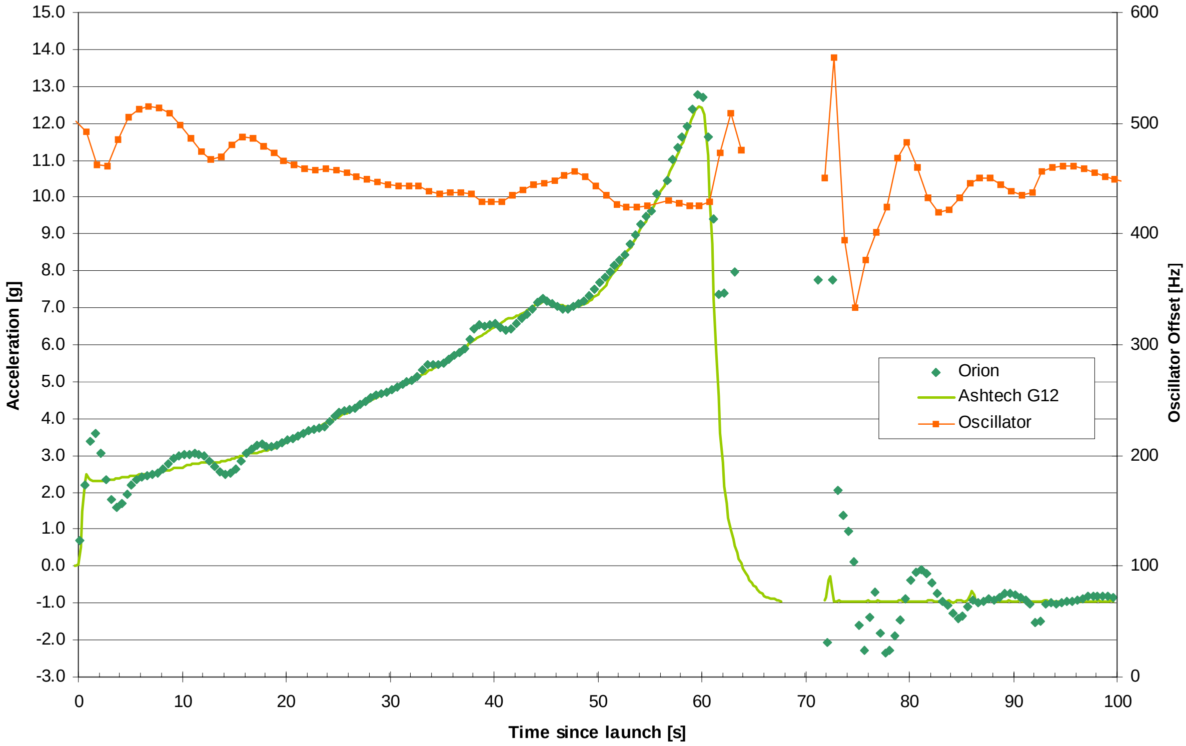

Fig 2.7 Vertical acceleration (left scale) and oscillator offset (right scale) during the Maxus-4 boost phase. Accelerations have been derived from measured velocities using symmetric difference quotients.

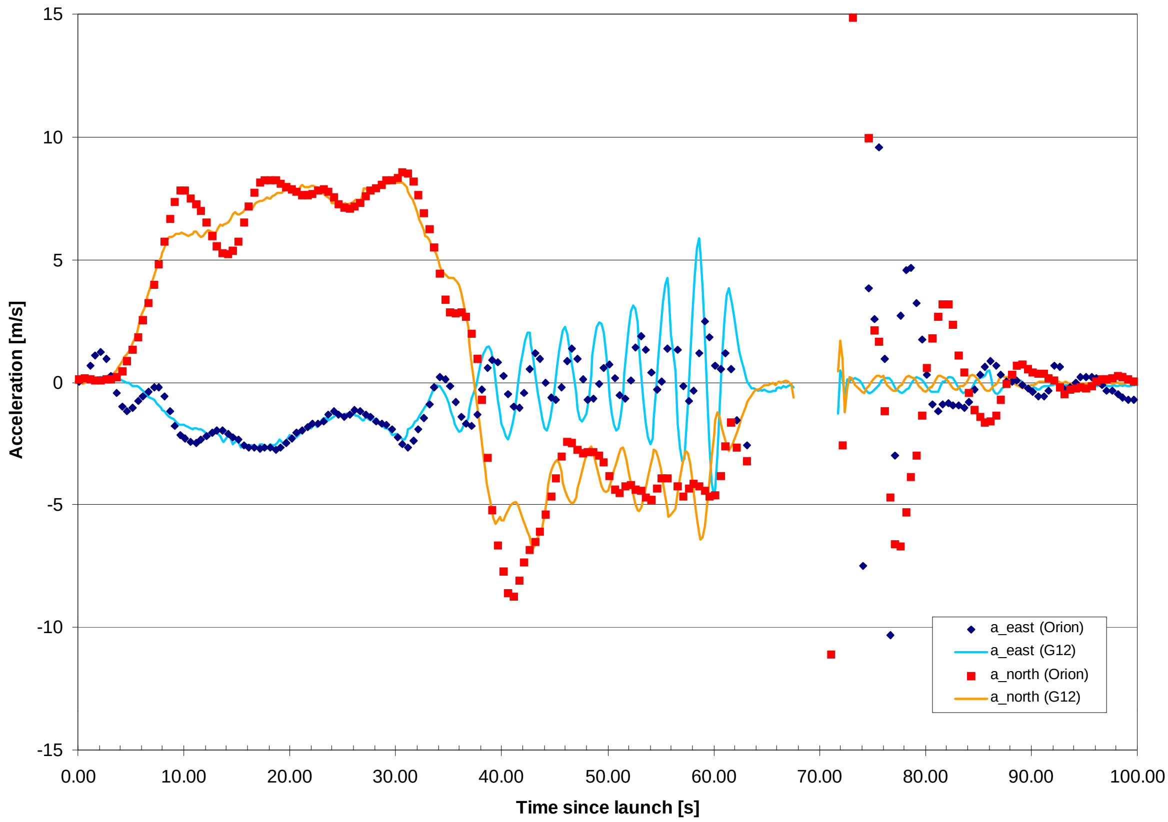

Fig 2.8 Horizontal acceleration during the Maxus-4 boost phase.

2.5 Parachute Deployment

As mentioned in the introduction, no GPS tracking was available during the reentry of the Maxus-4 payload due to the lack of an antenna, after the canister on top of the recovery system had been removed. At an altitude of roughly 5 km (t=940.9 s) the heatshield was finally released and the drogue parachute was deployed. The main parachute was planned to be released 16 s later, after which GPS tracking would again be possible via a patch antenna located in between the four leg bridle of the main chute. However, due to a malfunction of the stage line the main parachute was deployed to early and destroyed consequently.

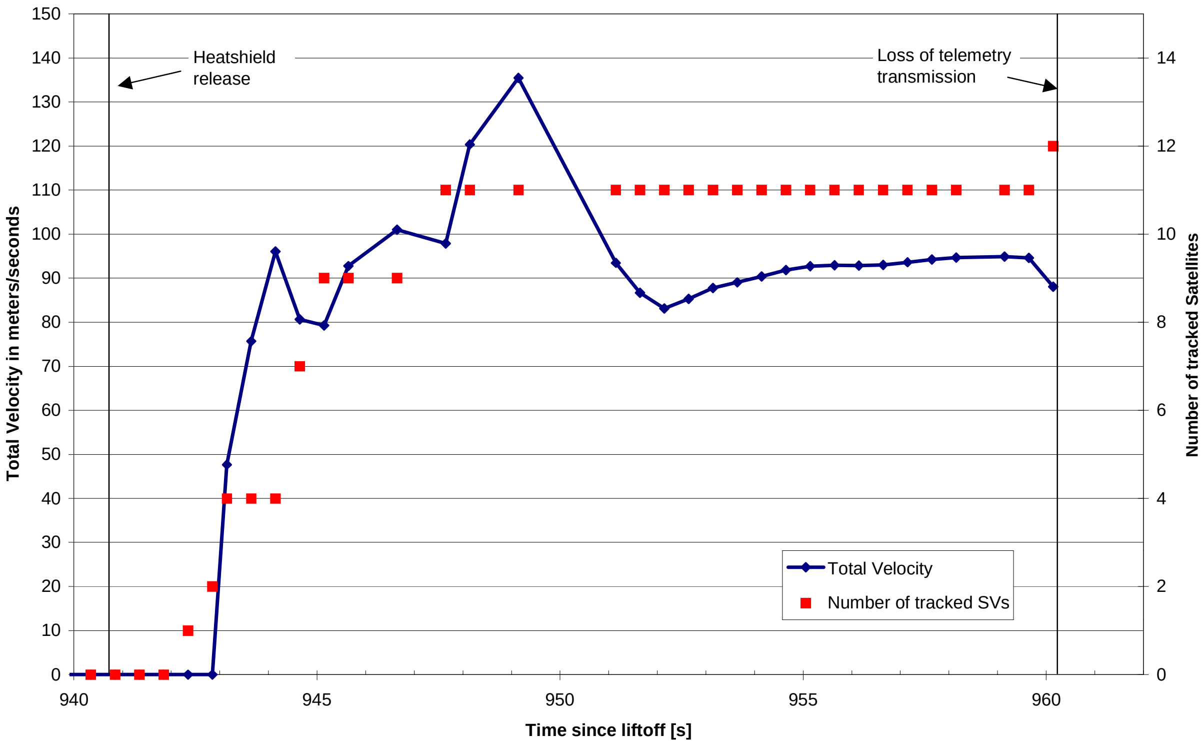

Fig 2.9 Number of tracked satellites and total velocity during the Maxus-4 parachute phase.

This is well illustrated by the signal acquisition and navigation data of the Orion receiver collected prior to touch down (Fig. 2.9). Within 1.5 s after the heatshield release, a first satellite was acquired and 3D navigation was achieved about another second later. Since no tracking would have been possible from an antenna wrapped inside the packed main parachute, the main chute must have been prematurely released. In view of the known oscillator problems, tracking data collected during the first ten seconds are apparently unreliable, while stable and self-consistent position and velocity measurements are available from t=953 s onwards. Prior to the loss of telemetry a sink rate of about 90 m/s was observed.

No reference solution is available during the parachute phase, since the Asthech G12 receiver failed to reacquire signals during the short time available. Apparently, the receiver had no information on the velocity drop during the reentry and tried to predict expected signal Doppler shifts using the last measured velocity (ca. 3300 m/s) prior to the can removal. On the other hand, the position-velocity aiding performed in the Orion receiver contributed to the rapid reacquisition and the immediate availability of tracking data after the deployment of the parachute antenna.

Summary and Conclusions

Within a joint project of DLR and Kayser-Threde, an Orion GPS receiver was flown onboard the Maxus-4 mission as part of the payload service module. The receiver employs a Doppler aiding concept to support the high signal dynamics encountered in sounding rocket applications. During the Maxus-4 mission the Orion GPS receiver shared a common tip, can, and parachute antenna system with the Ashtech G12 HDMA receiver, which was used for operational real-time tracking and IIP prediction.

The Orion GPS receiver performed as expected and provided accurate tracking data for real-time IIP prediction and post mission trajectory analysis. Following the premature main parachute deployment, the receiver was able to quickly re-acquire tracking, which turned out to be highly important for an understanding of the recovery system problems. The suitability of the Doppler aiding concept was fully validated. The receiver had no problems at all to follow the off-nominal ascent trajectory but exhibited an excellent reacquisition time after signal outages.

Deficiencies of the receiver have been encountered during phases of high yerk, i.e. during rapid changes of the acceleration. This is primarily attributed to mechanical stress on the employed crystal oscillator and alternative TCXOs will, therefore, be tested in future flights. In addition the current settings of the loop bandwidths will be reassessed to better match the observed dynamics. To obtain an improved coverage of the overall flight path by GPS tracking, the use of alternate antenna systems as well as on-board recording of GPS data in flash memory is, furthermore, suggested.

References

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Annex

A.1 Trajectory Polynomials

The following command sentences define the trajectory polynomials used for the representation of the nominal Maxus-4 trajectory inside the Orion GPS receiver software:

```
ˆLT18˜
ˆF51 0    +0.000 +2245875.5   +11.8606  +2.599629  +866832.3    +7.7294  +0.602120 +5886908.8   -11.8314 +12.4239247F˜
ˆF51 1   +15.000 +2246640.3   +73.9585  +3.060247  +867082.7   +15.4905  +0.563912 +5889564.0  +359.9480 +16.9747016D˜
ˆF51 2   +30.000 +2248461.5  +169.1171  +7.968254  +867453.6   +35.7290  +2.925725 +5898819.1  +881.8189 +24.87251577˜
ˆF51 3   +39.000 +2250638.8  +324.3873 +13.131226  +868016.3   +92.0283  +5.085391 +5908780.8 +1334.6992 +30.15022575˜
ˆF51 4   +45.000 +2253113.0  +448.8486 +17.574885  +868777.8  +138.6207  +7.670469 +5918016.4 +1615.4529 +41.64358761˜
ˆF51 5   +62.400 +2266338.6 +1077.2238  -1.530970  +873563.8  +412.8634  -0.656835 +5958992.0 +3115.1845  -4.1263947F˜
ˆF51 6  +250.000 +2414733.0  +507.5536  -1.392133  +928045.6  +168.1380  -0.550448 +6398699.5 +1579.4015  -3.7400437D˜
ˆF51 7  +460.000 +2459928.8   -73.3741  -1.397495  +939146.8   -61.1954  -0.502837 +6565465.8   +18.8766  -3.73837876˜
ˆF51 8  +650.000 +2395292.3  -596.9810  -1.548898  +909349.3  -250.2349  -0.508158 +6433449.3 -1381.5102  -4.13432571˜
ˆF51 9  +874.000 +2183618.2    +0.0000  +0.000000  +827758.7    +0.0000  +0.000000 +5915922.7    +0.0000  +0.00000063˜
ˆET11˜
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