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Orion GPS Post-flight Data Analysis Report

TestMaxus-4 Campaign

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Table of Contents

Scope

This report describes and discusses the Orion GPS flight data, recorded during the TestMaxus-4 campaign, of February 19th, 2001 at Kiruna/Sweden. It also includes a detailed comparison between the Orion GPS data and the data obtained by the Ashtech G12 GPS receiver flown by NASA as well.

1 Introduction

As part of the TestMaxus-4 campaign a novel GPS based tracking system for sounding rockets was first flown at Esrange, near Kiruna, Sweden on 19 Feb 2001. The flight unit comprises a modified ORION GPS receiver and a newly designed switchable antenna system assembled of a helical antenna mounted in the tip of the rocket and a two-blade antenna combination attached to the body of the service module. Besides the flight hardware a PC based terminal program has been developed to monitor the GPS data and graphically display the rocket's path during the flight. In addition, an Instantaneous Impact Point (IIP) prediction, employing the received position and velocity information, is performed.

Aside from the ORION receiver, an Ashtech G12 HDMA receiver and a BAe (Canadian Marconi) Allstar receiver, both connected to a wrap-around antenna, have been flown on the same rocket as part of an independent experiment provided by the Goddard Space Flight Center. This allows an in-depth verification and trade-off of different receiver and antenna concepts.

1.1 Orion GPS Receiver

Available experience with commercial-off-the-shelf (COTS) GPS receivers shows that various models can provide continuous tracking of sounding rockets under favorable conditions. On the other hand, large tracking gaps have likewise been observed, which indicates that temporary signal losses cannot be handled properly and that a reacquisition under highly dynamical motion is hard to achieve. To enhance the tracking robustness and reliability, adaptations of the standard receiver software need to be performed, which prohibits the use of most COTS receivers. The Mitel Orion receiver has therefore been selected for the implementation of a GPS based tracking system for sounding rockets, since it supports software modifications through the Mitel Architect development system [1].

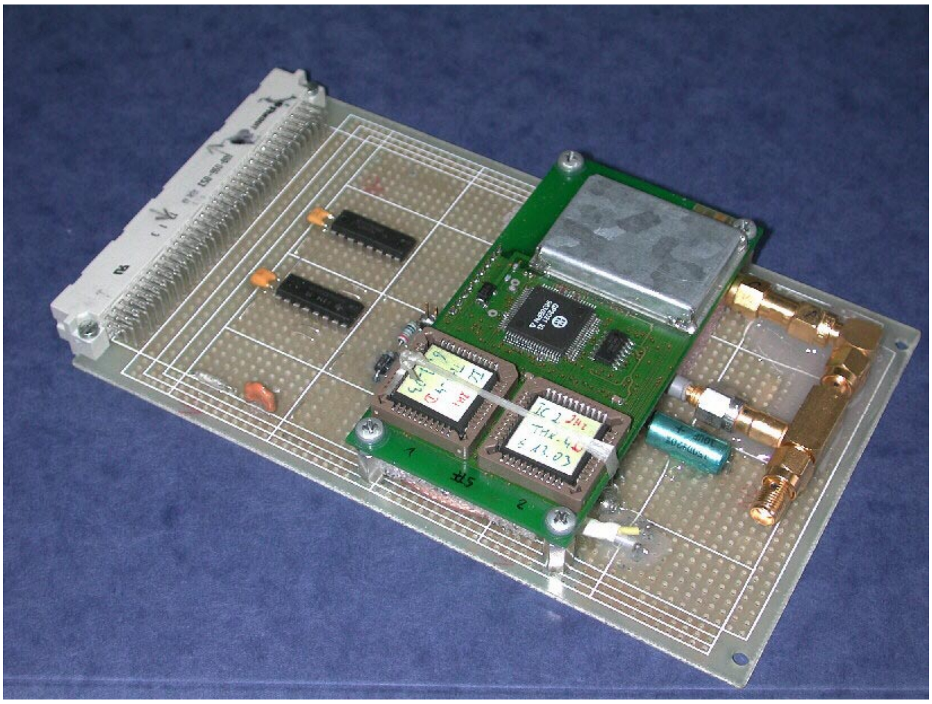

Fig. 1.1 Orion GPS receiver (Test Maxus-4 flight unit)

The GPS receiver has been built up at DLR/GSOC based on the ORION receiver design of Mitel Semiconductor. It employs the GP2015/2020 front-end and 12 channel correlator chipset as well as an ARM60B 32-bit microprocessor. The original firmware has been enhanced to cope with the highly dynamical environment of ballistic trajectories and the TM/TC interface has been adapted for space applications [2]. The Orion receiver unit flown as part of the Test Maxus-4 mission is shown in Fig. 1.1.

1.2 Antenna System

To support the different mission phases and to assess the suitability of different antenna concepts the rocket was equipped with a newly designed multi-antenna system [3]. 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 a pair of blade antennas mounted opposite to each other at the walls of the recovery module and combined via a power divider. This provided a near omni-directional coverage and allowed tracking of a sufficient number of satellites even for the tumbling motion of the payload module during the re-entry into the dense part of atmosphere.

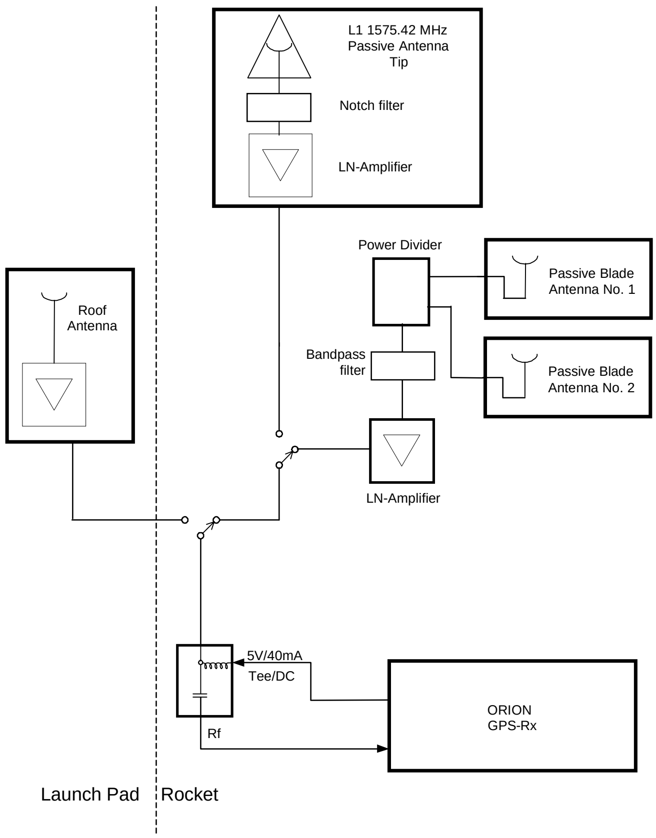

Fig. 1.2 Detailed view of the antenna system.

A detailed view of the utilized antenna system is provided in Fig. 1.2. Depending on the mission phase one out of three antenna systems (ground, tip, can) was connected to the RF input of the GPS receivers via a set of R/F switches. The switching between the different antennas was controlled via telecommand and a break wire. Each antenna carries its own pre-amplifier, powered by a dedicated current limited supply. To avoid interference with a Globalstar flight modem flown on the adjacent payload segment, a narrow bandpass filter was inserted into the R/F signal branch of the blade antenna system. Furthermore, a notch filter was inserted in the tip antenna branch to reject radiation from the S-band transmitters.

1.3 Flight Configuration

The Orion receiver was placed inside the DLR service module, which housed a data handling unit and telemetry system. In addition the two blade antennas were attached to the walls of the service module. Two independent modules provided by GSFC and SSC kept two NASA GPS receivers, a Globalstar modem and a secondary TM unit. The complete payload section is shown in Fig 1.3.

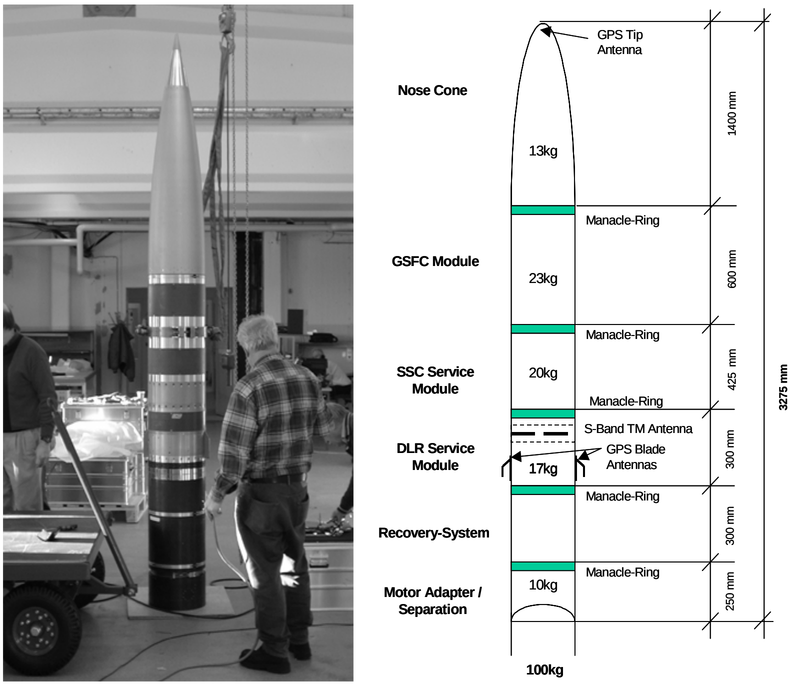

Fig. 1.3 The completely assembled payload before integration with the motor (*left*) and schematic view of the payload arrangement (*right*).

1.4 Mission Profile

The Test Maxus-4 rocket was powered by a single stage Improved Orion motor (*note*: by accident the rocket motor and the GPS receiver shared the same name). Key events of the mission are summarized in Table 1.1.

During the 24s boost phase, the rocket built up a spin rate of 3.8 Hz along the longitudinal axis. Accordingly, the rocket maintained a constant and stable attitude with a near zenith-facing tip. In the first 6s boost phase a maximum acceleration of 18g was reached, followed by a sustenance phase of 1g and 5g. After burnout a maximum rate of climb of 1100 m/s and a speed over ground of 280 m/s were measured. The rocket reached the apogee 2 minutes and 17 seconds after lift-off at an altitude of 81 km[1]. Briefly thereafter the spin was removed by a yo-yo system and the top cone as well as the motor have been separated (Fig. 1.4). The service and recovery module started a tumbling motion from about h=40 km downwards. Between 25 and 15 km altitude the module decelerated to sub-sonic speed before parachute deployment at h=5 km. The payload and nose cone landed at a distance of 60 km from the range and were finally recovered by helicopter.

[1] Due to a 3% underperformance of the motor, the Orion rocket did not reach the apogee height of 100 km expected in the pre-flight analysis.

Table 1.1 Key events of the Test Maxus-4 mission. All times refer to Monday, 19 February 2001 (day of year 50, GPS week 1102).

Event	h [km]	t [s]	UTC	GPS sec
Lift-off	0.3	0.0	06:02:00.0	108133.0
Peak acceleration 1st boost (17/18g)	1.8	4.5	06:02:00.5	108137.5
End of 1st boost phase	3.2	6.5	06:02:06.5	108139.5
Peak acceleration 2nd boost (4.8/5.8g)	15.9	21.5	06:02:21.5	108154.5
End of 2nd boost phase	19.2	24.5	06:02:24.5	108157.5
Apogee	81.4	137.0	06:04:17.0	108270.0
De-spin				
Start	81.4	140.3	06:04:20.3	108273.3
End	81.3	142.0	06:04:22.0	108275.0
Tip separation	81.1	144.8	06:04:24.8	108277.8
Motor separation	80.4	151.9	06:04:31.9	108284.9
Start atmospheric re-entry	ca. 41.0	230.0	06:05:50.0	108363.0
G12 begin loss of data	14.1	284.0	06:06:44.0	108417.0
G12 end loss of data	11.9	299.5	06:06:59.5	108432.5
Parachute release	ca. 5.0	367.0		
Loss of telemetry (at λ=+68.4057,φ=+21.0474, h=+535m)				

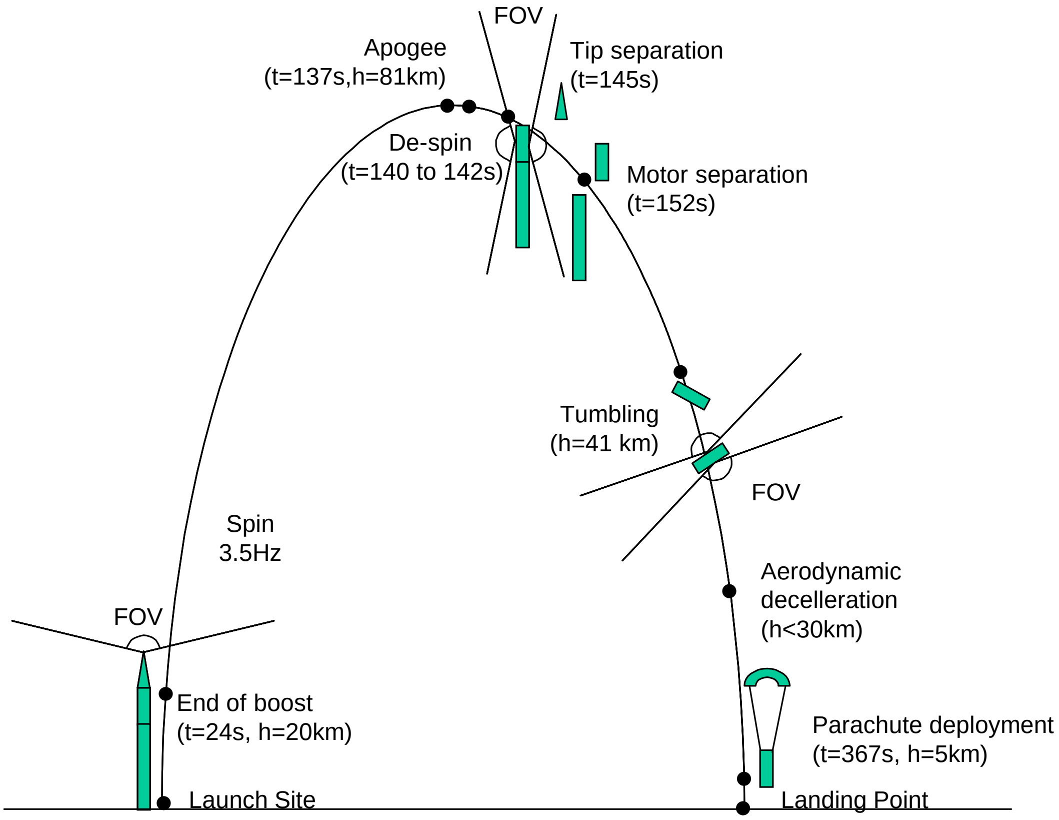

Fig. 1.1 Test Maxus-4 mission profile

2 Results and Analysis

2.1 Orion Tracking Analysis

The analysis of the overall received flight date has shown that the Orion receiver and the antenna system worked well during the entire flight. The receiver has continuously been in 3D-navigation mode from payload activation on the launch pad (20 minutes before lift off) to the time when DLR telemetry lost contact to the payload near landing. Typically, the receiver had between 10 and 11 GPS satellites in lock. Only during the first few seconds of the boost phase and during atmospheric reentry a loss of some satellites can be observed. In Fig. 2.1 the number of tracked satellites and the overall acceleration are shown versus time. The linear acceleration has not been directly provided by the Orion GPS receiver during the flight but was obtained by differencing the velocity measurements.

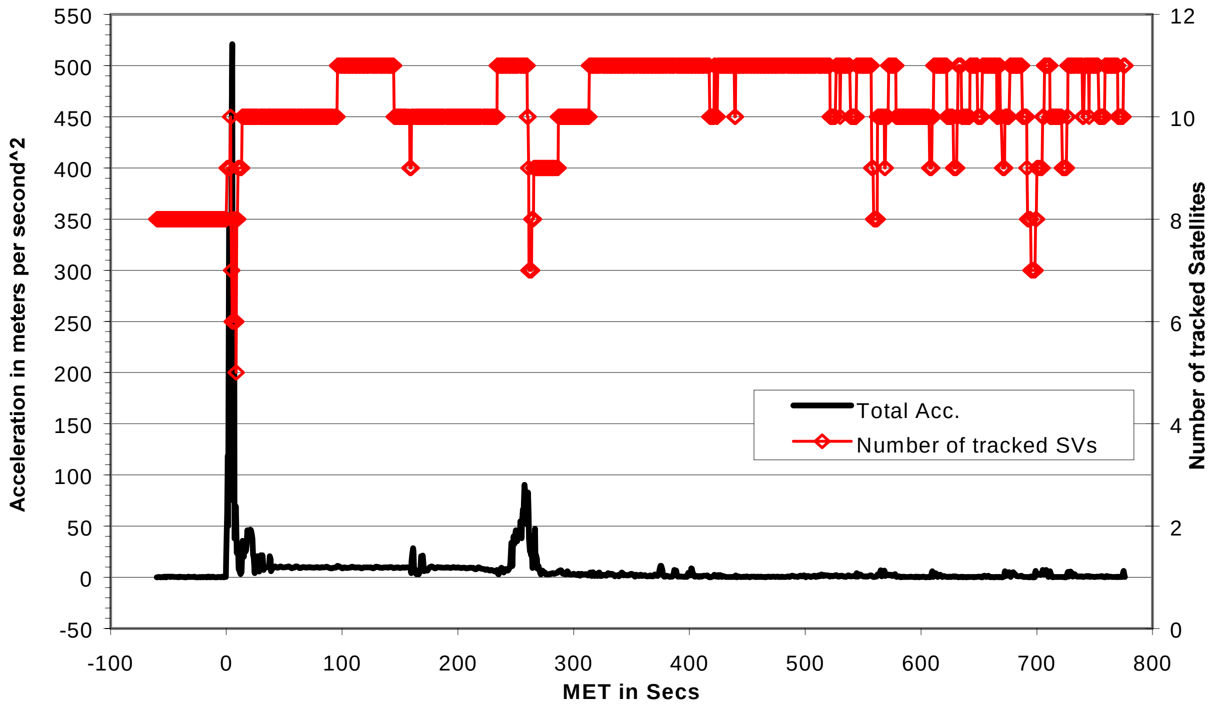

Fig. 2.1 History of number of tracked Satellites and linear acceleration during the Test Maxus-4 flight.

Fig. 2.2 shows the measured rate of climb, the speed over ground and the altitude versus time. Continuous tracking was even available near apogee, where at least short outages had to be expected due to the antenna switching at this time. Likewise, the tracking behavior during re-entry into atmosphere was expected to be critical due to the uncontrolled tumbling motion of the payload segment and pronounced sensitivity gaps in the unisotropic antenna pattern of the dual-blade antenna system [3]. While the performed ground tests indicated a moderate robustness in case of single axis rotation, the actual body motion and system performance during reentry could neither be simulated nor tested on ground prior to the mission.

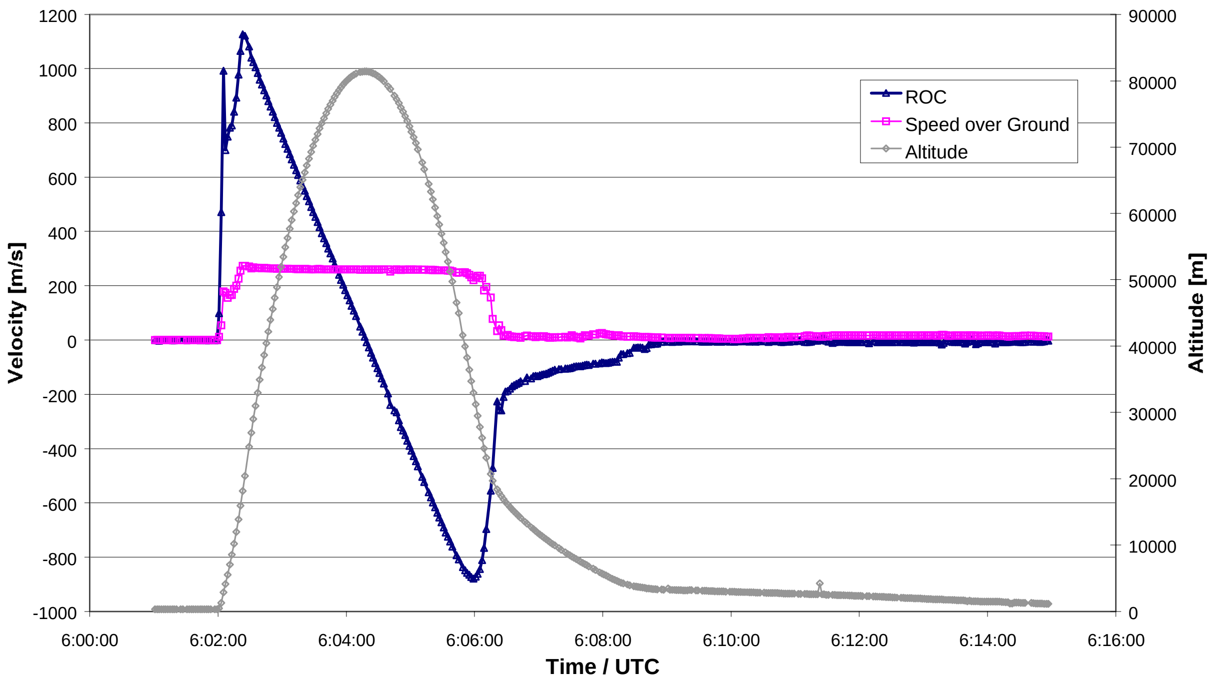

Fig. 2.2 Vertical and horizontal speed (*left scale*) and rocket altitude (*right scale*) during the mission.

Further information on the receiver and antenna system performance during the different flight phases can be obtained from the signal to noise ratios (SNR) recorded during the flight for the various channels. Fig. 2.3 illustrates SNR values of four representative satellites.

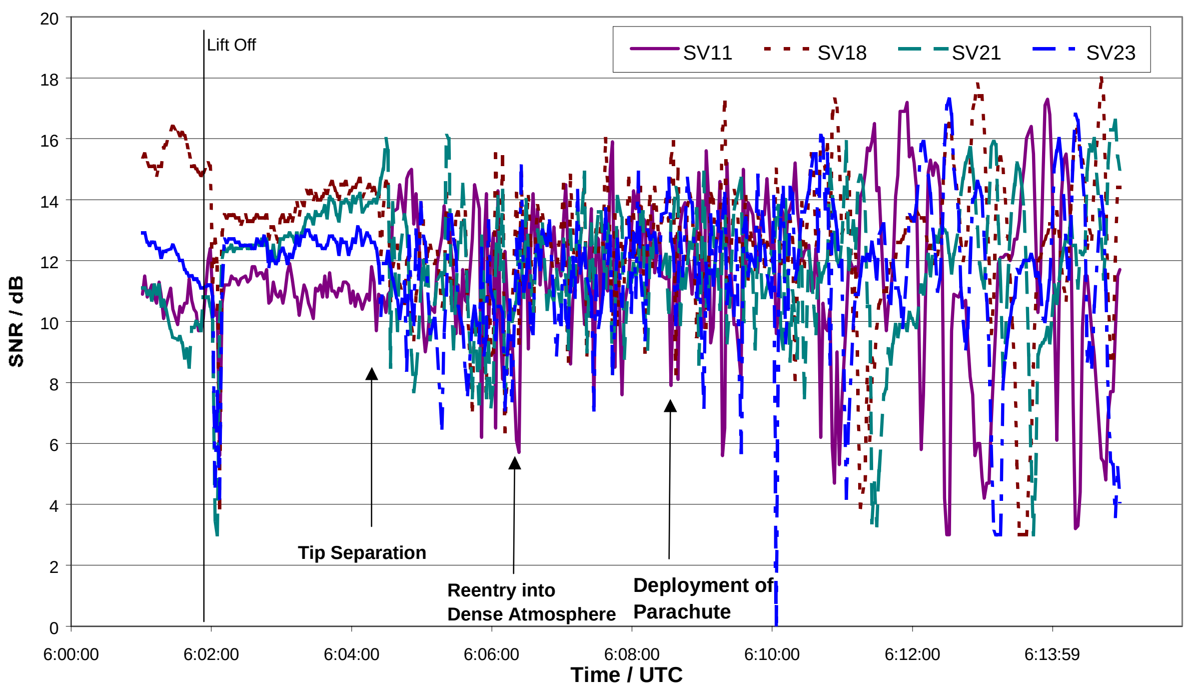

Fig. 2.3 SNR values for PRN 11, PRN 18, PRN 21 and PRN 23 in dB measured during the Test Maxus-4 flight.

The switching from the tip antenna to the blade antenna system at tip separation is clearly discernable from the suddenly increased SNR variation. The residual rotation rate of about 0.5 Hz left after the de-spin of the rocket, results in random like changes of the signal levels due to the antenna pattern. The average signal level, however, was at any time high enough to allow continuous tracking on all active channels down to an altitude of 40 km. Following the start of the atmospheric reentry the SNR variations exhibit a higher frequency and a moderately larger average value. Similar variations were also observed in the S-band telemetry link and are most likely related to orientation and spin rate changes during this mission phase. Several minutes after the main parachute deployment the payload system stabilized and the spin rate decreased to a few revolutions per minute. At the same time, however, more pronounced signal drops are encountered, which results in a rapidly changing number of tracked satellites below an altitude of about 2.5 km.

2.2 Receiver Performance Under High Dynamics

As mentioned above, a sudden drop in the number of tracked satellites occurred right after lift-off at 6:02 UTC. During this phase accelerations of up to 18g were encountered. While the receiver had constantly enough satellites in lock to compute a navigation solution, the obtained position and velocity values are notably degraded during the initial flight phase. This may be recognized both from a comparison of measured velocities with the nominal mission profile and a self-consistency test of velocity measurements and differenced position measurements. As shown in Fig. 2.4 for the WGS-84 z-velocity, the Orion navigation data exhibit a pronounced scatter for about 10 s that cover the primary boost phase. Thereafter the consistency of Doppler based velocity values and those derived from consecutive position measurements improves notably. An overall offset with respect to the nominal trajectory is readily explained by a 3% underperformance of the Improved Orion motor.

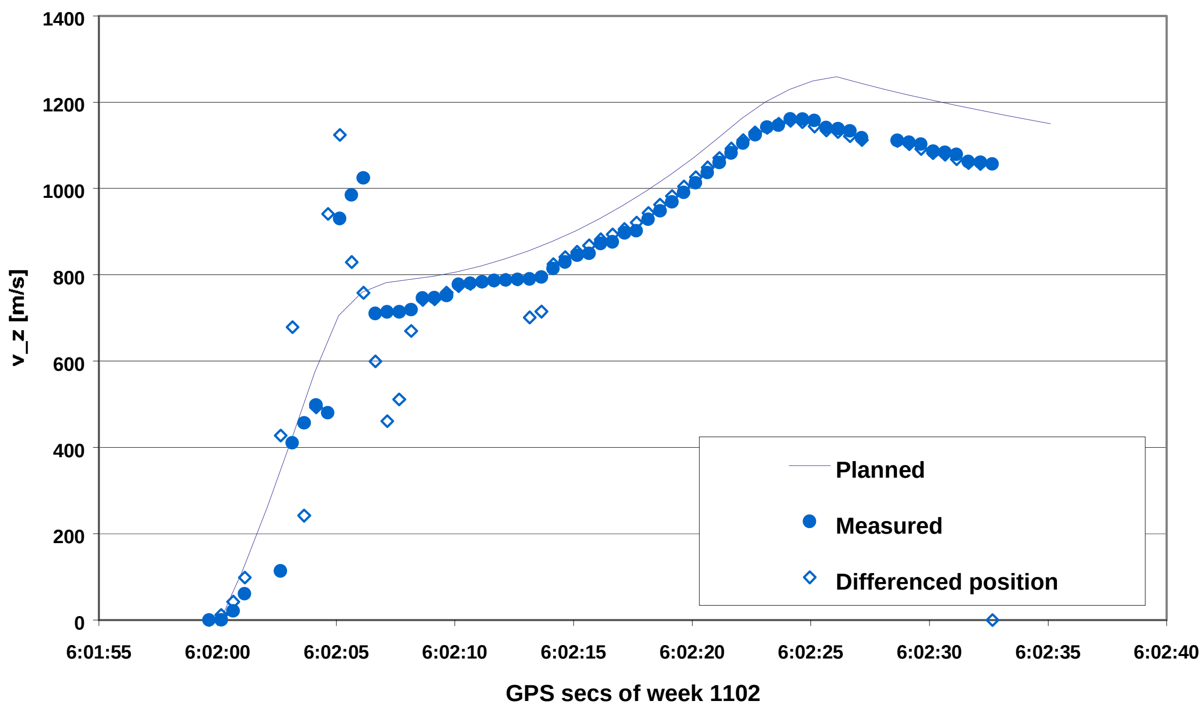

Fig. 2.4 Comparison of measured velocities with the nominal mission profile and a self-consistency test of velocity measurements and differenced position measurements during the thrust phase.

The observed phenomenon can be attributed to the physical acceleration forces during this phase and their impact on the GPS receiver's reference oscillator. Since the effect of the pure signal dynamic on the tracking behaviors has extensively been tested and analyzed in a wide spectrum of different simulation scenario it can be excluded as a cause for the observed phenomenon. In Figure 2.5 the oscillator error measured during the TestMaxus4 flight is displayed.

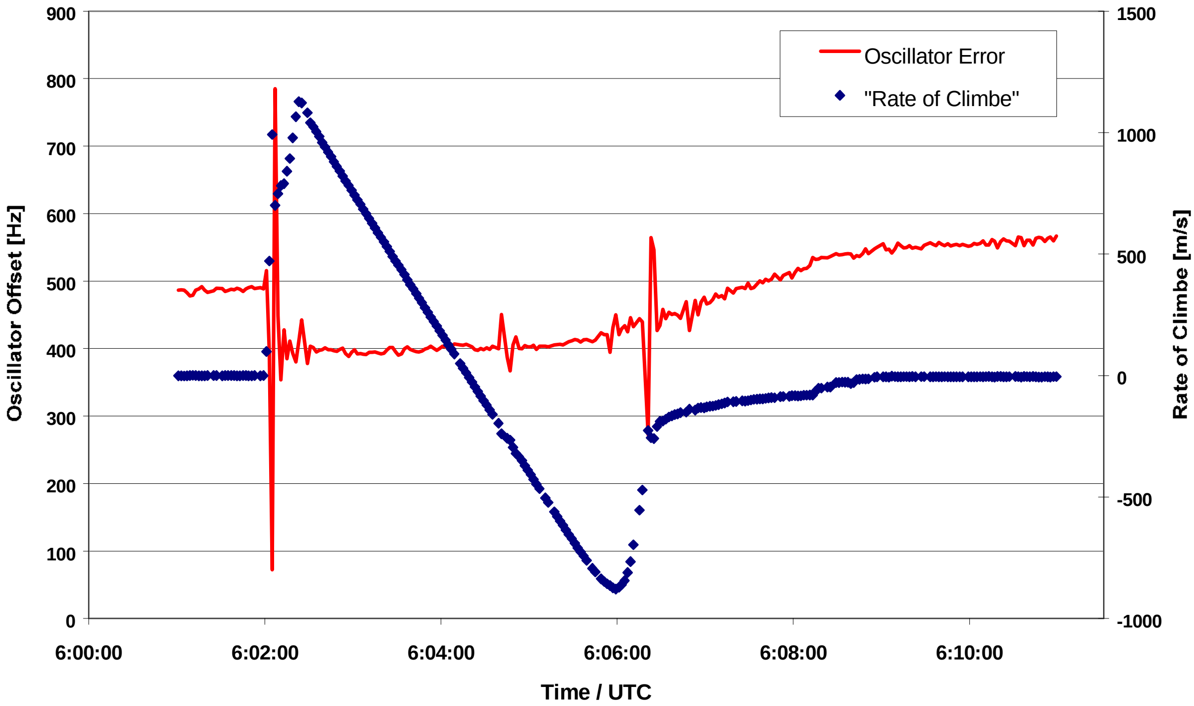

Fig. 2.5 Oscillator error in Hz in respect of L1 (*left scale*) and vertical speed (*right scale*) during the TestMaxus-4 flight.

Briefly after ignition one can observe large spikes in positive and negative direction in the frequency plot. After a few seconds in flight the oscillator offset stabilized on a value of about 100 Hz below the initial value. A similar but less intense effect appeared during the strong deceleration at reentry into the dense part of the atmosphere around 6:06:25 UTC.

Simultaneously with the beginning of the deceleration phase at 6:06:00 the average value of the frequency offset starts to increase slowly and stabilizes again during the parachute phase at a value of about 50 Hz above the initial offset. Until now no detailed explanation for this behavior is known. Since there are a lot of possible sources for this phenomenon like e.g. acceleration, vibration, and temperature changes, it is hard to conceive which perturbation affected the oscillator in which way. A further investigation of the oscillator behavior and potential means for improvement will be performed as part of future flight experiments.

2.3 Navigation Accuracy and Performance Comparison

The availability of Test Maxus-4 flight data from the two additional GPS receiver, provided and supported by NASA/WFF as mentioned above, allowed an in-depth verification and comparison of system performance and navigation accuracy between different GPS tracking concepts for sounding rockets. Unintentionally, a simple filtering algorithm for the single point navigation solutions, employed in the standard firmware of the Orion GPS receiver, was activated during the campaign. The filter forms a weighted average of subsequent velocity estimates and a weighted average of predicted and estimated positions under the assumption of a constant velocity, which contradicts the conditions during a sounding rocket flight. As a result a large degradation of the accuracy of the single point navigation solutions could be observed with activated filter. To arrive to a meaningful conclusion it was, therefore, necessary to reprocess the available Orion GPS raw data on ground to obtain unfiltered single point solutions for comparison with the onboard navigation solutions of the Ashtech G12 HDMA receiver.

2.3.1 Data Set

The recorded raw pseudoranges and Doppler measurements have been converted into the RINEX observation file format. Due to capacity limitations of the telemetry link, the GPS raw data have only been transmitted at 2 sec intervals.

For comparison, GPS navigation solutions obtained by the Ashtech G12 HDMA receiver at 0.5 secs intervals have been made available by NASA/WFF [6]. Due to carrier phase smoothing the G12 position and velocity data exhibit a notably lower noise level than those of the Orion receiver and the difference of both data sets is essentially representative of the Orion's tracking noise and measurement errors. Since the Orion s/w version employed during the Maxus test flight did not provide for an alignment of the navigation solution with integer GPS or UTC seconds, a quadratic approximation of the G12 trajectory data was used to obtain reference data at the Orion time stamps.

Table 2.1 Location of visible GPS satellites during the Maxus test campaign on Feb 19, 2001

	Lift-off		Landing	
PRN	**Az**	**El**	**Az**	**El**
2	107.3°	59.3°	98.6°	54.9°
7	136.8°	26.9°	132.9°	32.5°
8	103.5°	9.5°	105.0°	3.0°
9	263.2°	37.3°	261.1°	44.4°
11	51.2°	14.2°	45.6°	17.8°
14	322.4°	0.5°	321.9°	5.9°
18	318.5°	28.3°	310.6°	29.9°
21	338.0°	22.1°	331.8°	25.7°
23	285.2°	33.5°	277.3°	30.5°
26	197.6°	49.1°	193.1°	43.0°
31	17.4°	7.2°	15.0°	2.0°

In total, eleven different GPS satellites were visible during the flight, out of which 5 to 11 satellites could be tracked at any time. Elevation angles range from near 0° to a maximum of 60°.

2.3.2 Models

GPS satellite positions and velocities were interpolated from tabular ephemerides in SP3 format provided by the IGS. The "rapid orbit" data file (igr11021.sp3) is expected to provide a meter level accuracy in fair accord with the broadcast ephemerides available in real time.

Tropospheric range corrections have been computed from the relation

$$\Delta\rho_{\mathrm{trop}} = \frac{2.4224\mathrm{m} \cdot e^{-h/7.493\mathrm{km}}}{0.026 + \sin(E)} \tag{1}$$

applied in the standard Mitel firmware [1]. It accounts for the vertical density variation of the troposphere with a scale height of about 7.5 km and is non-singular for measurements collected above the mathematical horizon (0° elevation). Test runs performed with different values of the scale height resulted in a degradation of the Orion-G12 position differences, which provides empirical evidence for a similar refraction model in the G12 receiver software.

Ionospheric corrections of the observed pseudoranges were obtained from a thin layer approximation with vertical TEC values interpolated from a global IGS data set (codg0500.01i) for the time and location of interest. Since the maximum altitude of 80 km achieved by the Improved Orion rocket during the Maxus test flight is well below the ionospheric density maximum, the altitude variation of the total electron content was neglected and the full TEC value was applied to predict the ionospheric path delay from

$$\Delta\rho_{\text{ion}} = \frac{0.162\text{m} \cdot \text{TEC[TECU]}}{\sin(E_{\text{IP}})} \tag{2}$$

[7,8]. Here E_{IP} is the elevation of the GPS satellite at the ionospheric point, which marks the intersection of the line of sight with the ionospheric layer at 450 km altitude.

For small elevation angles, the inverse sine dependence in (2) implies a large amplification of the vertical ionospheric path delay and pronounced pseudorange corrections. In contrast to this, the standard Klobuchar model [9,10] makes use of a mapping function

$$\Delta\rho_{\text{ion}} = \Delta\rho_{\text{ion,zenith}} \cdot \left[1 + 16 \cdot (0.53 - E_{\text{IP}} / \pi)^3\right] \tag{3}$$

that exhibits no singularity at zero elevation angles but is constrained to about three times the vertical path delay near the horizon.

While the use of (2) results in marginally smaller r.m.s pseudorange residuals, the best overall match between the postprocessed Orion and onboard G12 navigation solutions is obtained by application of the Klobuchar mapping function (3). Most notably, an average 5m shift in the z-direction may be observed upon exchanging the mapping function.

In view of prevailing uncertainties in the refraction modeling at low elevations, it has, furthermore, been decided to introduce an elevation threshold of 5° (as seen from the receiver location) for the incorporation of pseudorange measurements into the navigation solution. As a result, satellites PRN# 8, 14, and 31 contribute to the position estimate for only part of the data arc. Despite the higher position dilution of precision, the overall position accuracy is improved, however, as indicated both by the comparison with the Ashtech G12 solution and the notably reduced r.m.s. postfit pseudorange residuals.

2.3.3 Performance Comparison

The overall data arc may be divided into five major phases which differ in regard to the physical conditions and the achieved tracking accuracy (Table 2.2). These comprise the stationary phase at the launch pad, the boost and reentry phase during which the receiver is subject to high acceleration and yerk, as well as the free flight phase and the final descent, during which the receiver performs an essentially smooth motion under the action of moderate accelerations.

Prior to launch the receiver is located in a heavy multipath environment, which is immediately evident from the variation of the position solution over time. As a consequence of signal reflections, pseudoranges obtained at common measurement epochs exhibit r.m.s. errors of about 5 m and maximum offsets of up to 10 m with respect to the adjusted position. Over a 15 mins data arc before lift-off, the pre-launch position itself is determined with a standard deviation of 3.5m in the WGS-84 x- and y-direction as well as 12m in the z-direction.

Table 2.2 Deviation of postprocessed GPS Orion single point position solutions from Ashtech G12 reference values

Flight Phase	From [s]	To [s]	Mean [m] X	Mean [m] Y	Mean [m] Z	RMS [m] X	RMS [m] Y	RMS [m] Z	Max [m]
Launch site (h=0.3km)	-143.3	-1.3	0.9	2.2	4.9	3.6	2.2	14.7	39.7
Boost phase (h=0.3km to 19km)	0.7	24.7	8.8	3.9	-0.2	26.6	29.6	114.5	341.1
Free flight (h=19km to 81km to 39km)	26.7	232.7	-1.2	1.2	-0.3	1.0	0.8	3.1	12.8
Reentry (h=39km to 14km)	234.7	282.7	-6.2	8.3	0.7	20.4	25.8	19.9	120.1
Descent (h=12km to 2km)	300.8	438.7	0.6	1.9	0.7	1.3	1.3	2.4	6.9

During the boost phase, the Improved Orion rocket builds up a peak acceleration of about 18g in the body system. This results in an obvious degradation of the measured pseudoranges and the associated position solution with errors of up to 350m. It may, however, be noted that the position solution is again error free from t=15s onwards, even though the 6g maximum of the second boost phase is only attained around t=22s.

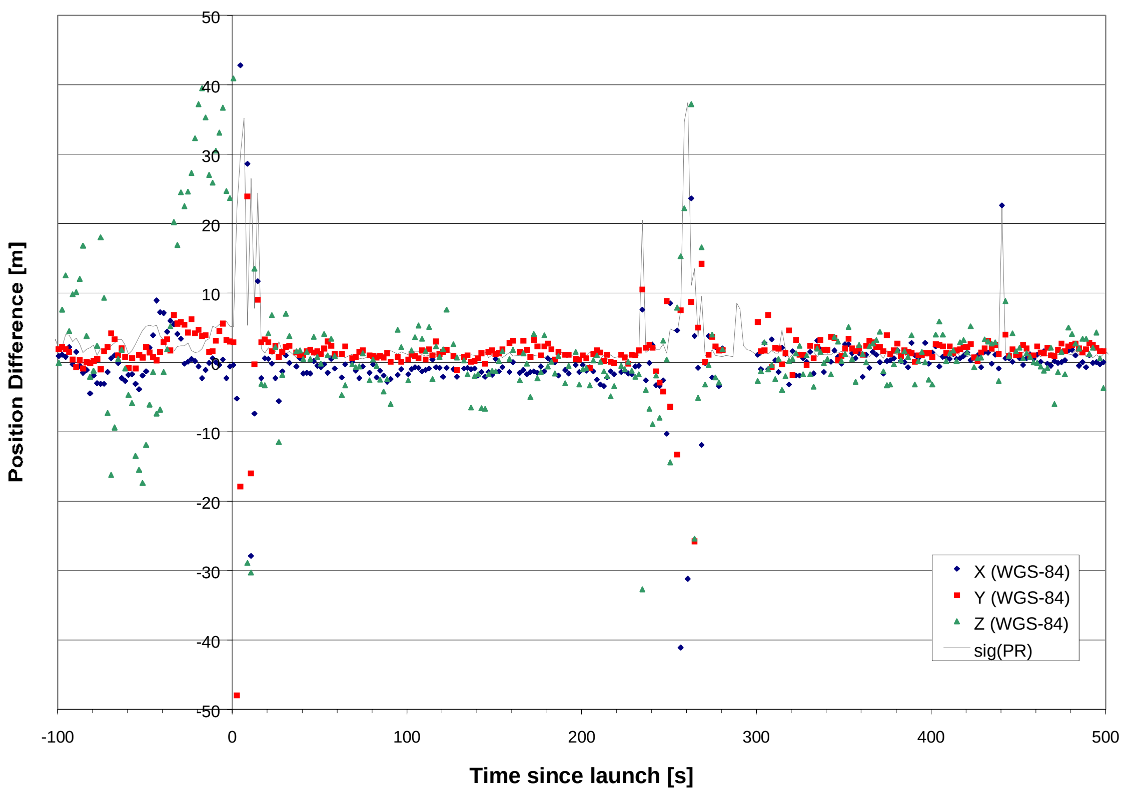

Fig. 2.6 WGS-84 position offsets from the Ashtech G12 reference data. The grey line represents the standard deviation of the pseudorange residuals with respect to the estimated positions. For improved consistency between Orion and Ashtech navigation solutions, the ionospheric corrections have been computed with the Klobuchar mapping function.

During the parabolic free-flight phase, which starts around t=25s and lasts for roughly 200s, the navigation solution exhibits a meter level accuracy in the x- and y-coordinates, while the standard deviation of the z-axis is about 3m. Similar results are later on obtained for the descent from 12km to 3km altitude (t=300s..500s).The peak errors during these phases amount to roughly 13m and 6m, respectively. As may be recognized from Fig. 2.6, the position solution shows no indication of a degradation after the separation of the tip antenna near apogee (ca. t=137s) and the subsequent switch to the dual blade antenna system.

The good quality of The Orion tracking data during the quiescent flight phases is also evident from the r.m.s. residuals of the pseudorange measurements with respect to the adjusted positions. Representative values range from 0.5m to 1.5m (average 1.1m) during the parabolic flight, which is consistent with the observed scatter of the navigation solutions and a position dilution of precision of 0.7 (x-/y-axis) to 2.1 (z-axis). Given the absence of multipath reflections in free space, the Orion receiver is thus able to achieve a tracking performance in-flight that has otherwise only been observed in a purified signal simulator test bed.

For completeness, we mention that individual spikes in the navigation error near t=235s and t=441s are caused by errors in individual pseudorange measurements at times of signal reacquisition. To provide an unbiased view of the Orion tracking performance these data have not been removed within the postprocessing.

Similar to the early boost phase, notable tracking errors can again be observed during the atmospheric reentry phase. Between an altitude of 39 km and 14 km, the payload experiences a net acceleration of up to 7g and individual position solutions are found to be off by up to 120m. Between t=284s and t=299.5s no reference solution from the Asthech G12 receiver is available due to a temporary loss of data. As indicated by the standard deviation of the pseudorange residuals, the Orion receiver is likewise affected by tracking problems during this time frame. No loss of track appears, however, and a minimum of seven satellites remains continuously in lock.

Table 2.3 Deviation of postprocessed GPS Orion single point velocity solutions from Ashtech G12 reference values

Flight Phase	From [s]	To [s]	Mean [m/s]			RMS [m/s]			Max [m/s]
			X	Y	Z	X	Y	Z	
Launch site (h=0.3km)	-143.3	-1.3	0.0	0.0	-0.3	0.2	0.1	0.8	2.6
Boost phase (h=0.3km to 19km)	0.7	24.7	-3.4	-10.6	-37.9	11.2	21.7	86.1	258.4
Free flight (h=19km to 81km to 39km)	26.7	232.7	0.0	0.0	0.1	0.4	0.8	1.2	6.3
Reentry (h=39km to 14km)	234.7	282.7	-2.8	2.6	3.3	12.9	20.1	16.5	77.3
Descent (h=12km to 2km)	300.8	438.7	0.0	-0.1	-0.3	1.8	2.2	1.8	12.0

Supplementary to the position measurements discussed so far, a summary of the Orion single point velocity solutions is given in Table 2.3. Again, it is obvious that the tracking accuracy is strongly degraded during the boost and atmospheric reentry phase, where the accelerations of the receiver and the associated mechanical stress are most pronounced. While the r.m.s velocity errors are typically on the order of 1 to 2 m/s during quiescent phases, peak errors of up to 350 m/s are encountered during the boost phase. During the parabolic flight phase individual pseudorange rates are accurate to 0.3 m r.m.s. which closely resembles the quality obtained in signal simulator tests. A detailed view of the achieved velocity solutions is given in Fig. 2.7.

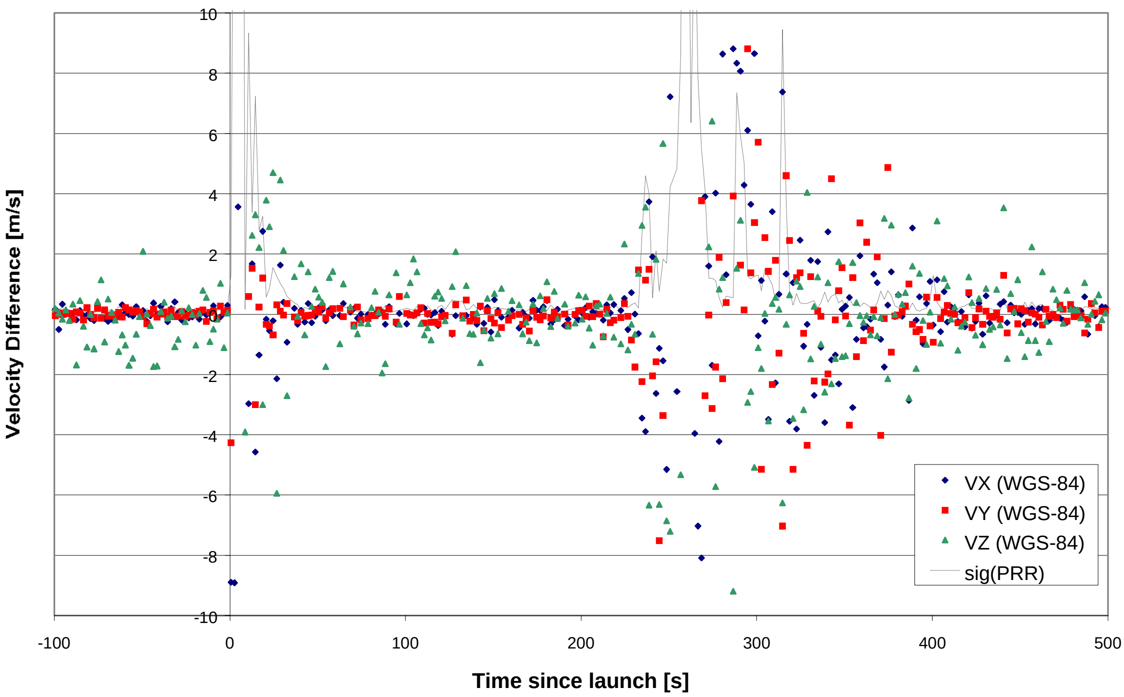

Fig. 2.7 WGS-84 velocity offsets from the Ashtech G12 reference data.

3 Instantaneous Impact Point Prediction

Besides the use of GPS derived position data for the post-mission analysis of scientific experiments onboard a sounding rocket, GPS can also contribute to range-safety operations. An experimental Instantaneous Impact Point (IIP) prediction has therefore been performed during the Test Maxus-4 campaign. It employed position and velocity data provided by the Orion receiver to compute (in real-time) the expected touch down point under the assumption that the booster is no longer active. A screenshot of the display is shown in Fig. 3.1.

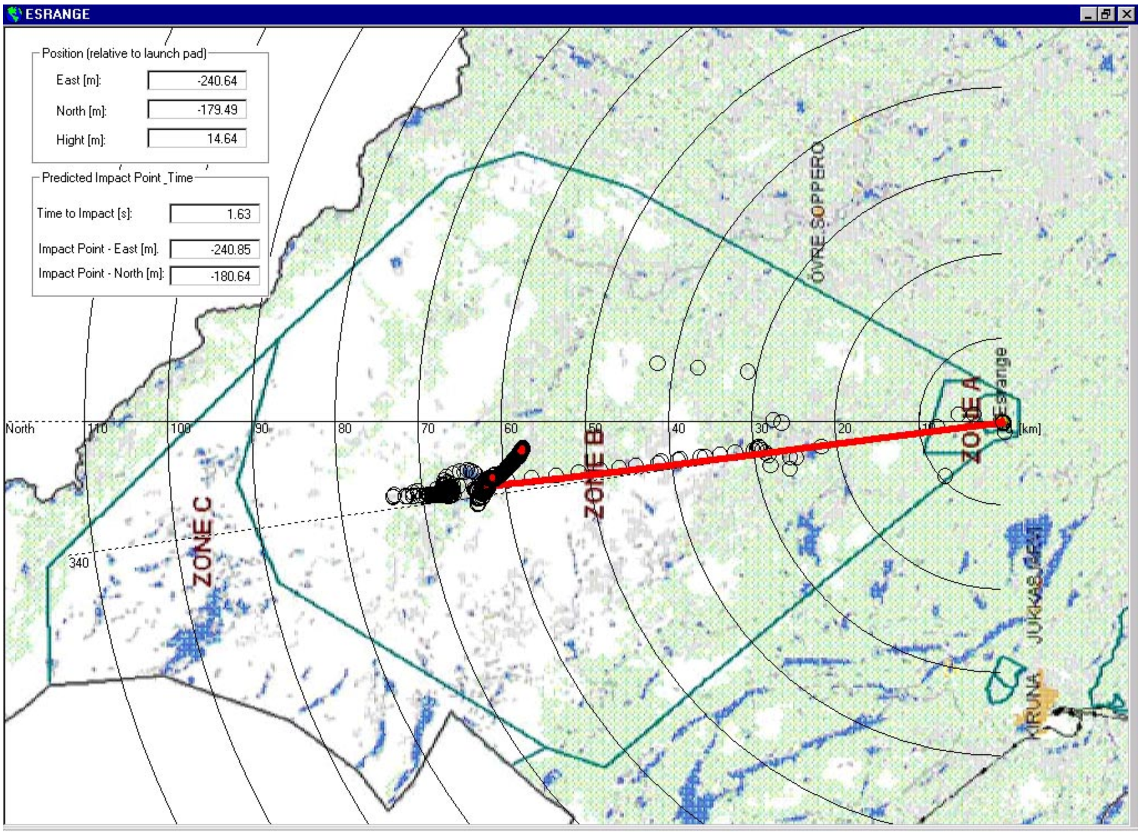

Fig. 3.1 Screenshot of the Instantaneous Impact Point (IIP) prediction display. Ground track (line) and IIP (circles) for the TestMaxus-4 flight.

During the initial phase of the ascent trajectory a notable scatter of the predicted IIP can be observed. This can be attributed to a degradation of the position-velocity vector obtained by the GPS receiver due to the above described impact of physical acceleration forces on the oscillator. The simplified (ballistic) model used in the present implementation of the IIP prediction is furthermore responsible for the fact that the IIP predicted briefly after burnout is about 10 km further away from the launch site than the value obtained briefly thereafter. Since the burnout takes place at an altitude of 24 km, the atmospheric drag reduced the ground speed by roughly 15 m/s during the subsequent ten seconds. As a result, the impact point distance is reduced by the above mentioned value. Corriolis forces have been neglected in the IIP prediction in view of the low altitude and flight time.

4 Summary and Conclusions

During the Test Maxus-4 Campaign a newly developed GPS based tracking system for sounding rockets, comprising a modified Orion GPS receiver and a switchable-multi-antenna- system, has first been flown during a real mission. The evaluation of the collected flight data has show that the system worked well during the entire flight. The receiver had typically 10 to 11 satellites in lock and has therefore been in 3-D navigation mode without any outages from 20 minutes before lift-off to telemetry loss near landing. Only during the boost phase and during the re-entry a loss of some satellites could be observed. This effect can be attributed to mechanical stress of the applied quartz oscillator during phases with high acceleration. A more detailed investigation of the oscillator behavior under high dynamics an some additional flight test with more suitable oscillator devices will be necessary in the future.

Aside from the Orion system two additional GPS receiver, an Ashtech G12 HDMA receiver and a BAe (Canadian Marconi) Allstar receiver, have been flown on the same rocket as part of an experiment provided by the Goddard Space Flight Center. This allowed an in-depth verification and comparison of system performance and navigation accuracy between different GPS tracking concepts for sounding rockets. The postprocessing of raw pseudorange and Doppler measurements collected by the Orion GPS receiver during the flight shows that the real time navigation solution is seriously degraded by the default filtering applied in the Mitel firmware. Without the filter, that is only appropriate for slow moving objects, position accuracies of better than 10 m (3D) are obtained during quiescent parts of the trajectory in comparison with a reference trajectory measured by the Ashtech G12 receiver. This compares well with the overall uncertainty of the reference solution itself that results from prevailing limitations in the modeling of tropospheric and ionospheric corrections for a sounding rocket trajectory. Within the analysis, individual pseudorange measurements were, furthermore, shown to be accurate to the level of 1m, which compares well with other receivers for space applications [11]. During phases of high acceleration tracking errors were found to increase to a level of several 100 meters and meters per second, respectively, which may be also attributed to the behavior of the reference oscillator of the Orion receiver mentioned above. This conclusion is confirmed both by the absence of corresponding errors in signal simulator tests conducted earlier and the observed scatter of the oscillator frequency offset as derived from Doppler observations.

An experimental Instantaneous Impact Point (IIP) prediction based on the Orion GPS navigation solution has been carried out during the Test Maxus-4 campaign. The results have shown that the accuracy of a GPS based on-board IIP prediction is competitive to the performance of commonly used range safety equipment. During the Maxus-4 test flight the computation has been done in the ground software but for future missions the IIP algorithm will be implemented into the on-board GPS software as a major part of the provided GPS services.

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Annex A – Data Format Description

GPS data have been collected from about 30 minutes before lift-off up to the loss of telemetry communication prior to landing. The receiver provides two serial interfaces (DUART channel A and B), out of which only channel A was employed in the flight experiment. The channel was operated at a 19.2 kbit/s rate in both directions (commanding and telemetry). At this rate, a maximum of 1920 characters per second could be transmitted.

Ports	2
Data rates (baud)	Port A: 19200 kbit/s TX (monitoring) 19200 kbit/s RX (commanding)
Update rate	2 Hz
Data bits	8
Parity	No
Stop bits	1
Protocol	Port A: Winmon

The flight receiver utilizes the Mitel Winmon protocol with DLR specific messages contents. Each transmit or receiver sentence starts with the Start of Transmission (STX) character (ASCII 02h) and is terminated by a 2 character sentence checksum followed by an End of Transmission (ETX) character (ASCII 03h). The sentence checksum is the hexadecimal representation of the exclusive-or of all the characters in the sentence, excluding the <STX> and <ETX>. All data bytes contained in the data field of the message are printable 7 bit characters (ASCII 32-127).

Transmit (telemetry) sentences are identified by a 3 character header following the <STX> character. The first character of the header is an 'F' (ASCII 46h) followed by 2 numerical only characters that uniquely define the contents and format of the remaining data field.

STX	'F'	n	n	x	x	. . . .	x	x	h	h	ETX

n = numeric character.
x = sentence data fields.
h = hexadecimal checksum character.

Receive sentences (commands) are structured in a similar, but employ a two character header for identification.

Following the successful initialization of the receiver at the launch pad, the output messages tabulated below was generated.

Messages F00 to F08 were output for compatibility with the original WINMON real-time monitoring program. To avoid overflows in sounding rocket applications, sentences F00 to F04 can be generated in an extended version supporting a larger number of digits in relevant output fields.

Messages F40 to F48 have been defined by DLR and provide complementary information for real-time display and post mission analysis.

MsgID	**Chars.**	**Format**	**Description**
F00	**125/131**		**Navigation Data (Mitel)**
F03	**763/799**		**Channel Status (Mitel)**
F04	**458/490**		**Satellite Summary**
F05	**39**		**Processing Status**
F08	**26**		**Operating Parameters**
F40	**104**		**Navigation Data**
	1	x	<STX>
	3	xxx	Message Id (=F40)
	4	xxxx	GPS week
	12	xxxxxx.xxxxx	GPS seconds of week [s] (of navigation solution)
	2	xx	GPS-UTC [s]
	12	sxxxxxxxx.xx	x (WGS84) [m]
	12	sxxxxxxxx.xx	y (WGS84) [m]
	12	sxxxxxxxx.xx	z (WGS84) [m]
	12	sxxxxx.xxxxx	vx (WGS84) [m]
	12	sxxxxx.xxxxx	vy (WGS84) [m]
	12	sxxxxx.xxxxx	vz (WGS84) [m]
	1	x	Navigation status (0=no-Nav,2=3D-Nav)
	2	xx	Number of tracked satellites
	4	xx.x	PDOP
	2	xx	Checksum
	1	x	<ETX>
F41	**337**		**Pseudorange and range-rate**
	1	x	<STX>
	3	xxx	Message Id (=F41)
	4	xxxx	GPS week
	12	xxxxxx.xxxxx	GPS seconds of week [s] (GPS time of observ. using current clock model)
	2	xx	GPS-UTC [s]
	12	xxxxxx.xxxxx	TIC time [s]
			Repeated for each of 12 channels
	2	xx	PRN
	13	sxxxxxxxxx.xx	Pseudorange [m]
	9	sxxxxx.xx	Range-rate [m/s]
	1	x	Validity flag
	2	xx	Checksum
	1	x	<ETX>

F43	**253**		**Channel Status**
	1	x	<STX>
	3	xxx	Message Id (=F43)
	4	xxxx	GPS week
	8	xxxxxx.x	GPS seconds of week [s] (at message generation time)
	2	xx	GPS-UTC [s]
	4	xxxx	Almanac week
	6	xxxxxx	Time of applicability [s]
	2	xx	PRN of last almanac frame
	1	x	Track mode (1=HighElev,2=SatSel,3=ColdStart)
	1	x	Navigation status (0=no-Nav,2=3D-Nav)
	2	xx	Number of tracked satellites
			Repeated for each of 12 channels
	2	xx	PRN
	6	sxxxxx	Satellite Doppler (predicted) [Hz]
	6	sxxxxx	NCO [Hz]
	1	x	Subframe
	1	x	Lock indicator (c/C/B/F)
	2	xx	Signal-noise ratio (>0, [db])
	2	xx	Checksum
	1	x	<ETX>

F44	**71**		**Clock Data**
	1	x	<STX>
	3	xxx	Message Id (=F44)
	4	xxxx	GPS week
	12	xxxxxx.xxxxx	GPS seconds of week [s] (at message generation time)
	2	xx	GPS-UTC [s]
	8	xxxxxxxx	TIC count
	8	xxxxxxxx	Real Time Clock count [s]
	4	xxxx	Extrapolated boot time (GPS week)
	12	xxxxxx.xxxxx	Extrapolated boot time (GPS seconds of week) [s]
	6	sx.xxx	Clock drift [µs/s]
	8	xxxxxxxx	Time of applicability of clock model (TIC)
	2	xx	Checksum
	1	x	<ETX>

F48	**46**		**Configuration and status parameters**
	1	x	<STX>
	3	xxx	Message Id (=F48)
	4	xxxx	GPS week
	6	xxxxxx	GPS seconds of week [s] (at output)
	2	xx	GPS-UTC [s]
	4	xxxx	Almanac week
	5	sxxxx	Doppler offset [Hz]
	1	x	Mode (0=default,1=rocket,2=orbit)
	1	x	Output format (0=default,1=extended)
	1	x	Reserved
	2	xx	Spare CPU capacity [%]
	3	sxx	Elevation mask [deg]
	2	xx	PDOP mask
	8	xxxxxxxx	Launch time (tic count)
	2	xx	Checksum
	1	x	<ETX>

The navigation data message (F40) was output twice per second, while the remaining message was only once per 2 secs generated to limit the overall data volume generated by the receiver.

t	Msg Id	Bytes	Description
0.0s	F00	125/131	Navigation Data (Mitel)
	F04	458/490	Channel Status (Mitel)
	F05	39	Satellite Summary
	F08	26	Processing Status
	F40	104	Navigation Data
	F41	337	Pseudorange and range-rate
	F44	71	Clock Data
0.5s	F40	104	Navigation Data
1.0s	F00	125/131	Navigation Data (Mitel)
	F03	763/799	Channel Status (Mitel)
	F40	104	Navigation Data
	F43	253	Channel Status
	F48	46	Configuration and status parameters
1.5s	F40	104	Navigation Data
	…		