Position-Velocity Aiding of a Mitel ORION Receiver for Sounding-Rocket Tracking

Oliver Montenbruck, *Deutsches Zentrum für Luft- und Raumfahrt* (*DLR), German Space Operations Center,*
82234 Wessling, Germany, oliver.montenbruck@dlr.de

Werner Enderle, *DLR, German Space Operations Center, 82230 Wessling, Germany*
Markus Schesny, *ComNav Systems, 86923 Finning, Germany*
Vincent Gabosch, *DLR*, *Institute of Communications and Navigation, 82230 Wessling, Germany*
Sascha. Ricken, Peter Turner, *DLR, German Space Operations Center, 82230 Wessling, Germany*

BIOGRAPHY

Oliver Montenbruck is head of the GPS Technology and Navigation Group at DLR's German Space Operations Center (GSOC). He received his Ph.D. from Munich's University of Technology in 1991. Since 1987 he's working at DLR/GSOC as a flight dynamics engineer, where he specialized in satellite orbit determination. His current field of work comprises the development of on-board navigation systems and spaceborne GPS applications. He's written various text books on computational astronomy and satellite orbits.

Werner Enderle received his Ph.D. in 1998 from the Technical University of Berlin. He works for DLR/GSOC since 1994 in the flight dynamics division, where he is specialized in attitude determination using GPS and spaceborne GPS applications. Currently he is joining the Galileo Support Team (GAST), which supports the European commission in the context of the design studies for the European Global Navigation Satellite System (Galileo). He was a co-investigator of the EQUATOR-S GPS experiment that first proved the possibility of main and sidelobe tracking of GPS satellites from geo synchronous altitudes and above.

Markus Schesny is a development engineer of ComNav Systems GmbH, Finning. On behalf of DLR/GSOC, he currently in charge of modifying the GPS Orion receiver hard- and software for sounding rocket and space applications.

Vincent Gabosch and *Sascha Ricken* have contributed to the present project during their diploma study. They have recently received their Bachelor degree.

Peter Turner is head of DLR's Mobile Rocket Base, which he joined in 1975. He is responsible for flight qualification and integration of the GPS receiver hardware in the current project.

ABSTRACT

The paper describes a simple and effective concept for aiding the signal acquisition of a GPS receiver in sounding rocket applications. A segmented, low-order polynomial representation of the nominal flight path is employed to provide the receiver with approximate position and velocity values of the host vehicle. These are used for an open-loop Doppler and visibility prediction, which in turn assists the channel allocation and code search. The proposed concept has been implemented in the 12-channel GPS Orion receiver, which employs Mitel's GP 2000 chipset and supports firmware modifications via the Architect developer kit. Using hardware-in-the-loop simulations in a GPS signal simulator testbed, the modified receiver's robustness against temporary signal losses has been demonstrated. While the unaided receiver is essentially unable to reacquire signals in case of intermitted signals, the position-velocity aiding allows a stable and reliable operation both during the boost and free-flight phase. Test flights on actual sounding rockets are currently planned for spring (Kiruna) and summer (Alcantara, VS30/Orion) of 2001.

INTRODUCTION

The Mobile Rocket Base (MORABA) of DLR's German Space Operations Center plans, prepares and implements scientific sounding rocket and balloon campaigns in the fields of aeronomy, magnetospheric research, astronomy and microgravity. Tracking services are currently performed using C-band radars (AN/MPS-36, RIR-774C), which are relocatable but comprise bulky equipment and result in costly ground operations. As an alternative, the development of a low cost, GPS based tracking system for sounding rockets has therefore been initiated at DLR.

Available experience with commercial-off-the-shelf (COTS) GPS receivers shows that various models can provide continuous tracking of sounding rockets under favorable conditions, provided that no hard-coded altitude or velocity limits are implemented. 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.

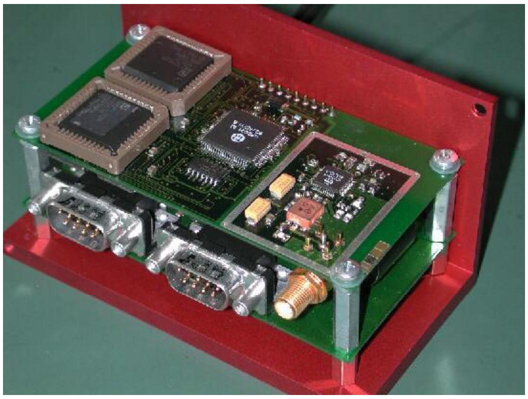

Fig. 1 The Mitel ORION receiver comprises a main receiver board (top) with RF front end, correlator, processor and memory as well as an interface board with power regulator, battery backup and serial interfaces (bottom). Physical dimensions are 95 x 50 x 30 mm^3.

The Orion receiver itself has been built by DLR based on Mitel design information [MIT99] and is described in the subsequent section along with the relevant software changes. Besides the receiver, the overall tracking system will comprise a single or dual antenna configuration for at least hemispherical visibility [END00] and a TM/TC interface for ground communications. Given the recent completion of the receiver modification and testing, two prototype flights are under preparation for the first and second quarter of 2001 to validate the tracking system under real flight conditions and assess its performance in comparison with ground based radar tracking.

RECEIVER DESIGN AND MODIFICATION

The GPS Orion has been developed by Mitel Semiconductor as a prototype of a highly-integrated GPS receiver and rebuilt by DLR based on Mitel design information [MIT99]. The receiver makes use of the GP2000 chipset, which comprises a GP2015 RF down-converter, a DW9255 SAW filter, a GP2021 correlator and a 32-bit ARM-60B microprocessor. Using a single active antenna and RF frontend, the receiver supports C/A code tracking of up to 12 channels on the L1 frequency. It is hardware and software compatible with the off-the-shelf GPS Architect Development System [MIT97], but designed to act as a stand-alone receiver. To this end, the main receiver board is supplemented by an interface board which comprises a power regulator, a backup battery for real-time clock operation and memory retention as well as a TTL-to-RS232 serial interface convertor (Fig. 1). The small size and the open-source policy makes the Orion receiver particularly interesting for the envisaged application on a sounding rocket. Here, most functions of the interface board are taken over by the on-board power system and data handling system, allowing a total receiver size of roughly 10 x 5 x 1 cm^3.

To cope with the highly dynamical environment, various modifications of the standard receiver software have been made and tested in a hardware-in-the-loop simulation using a GPS signal simulator. While initial tests showed that the unmodified receiver is able to track GPS signals up to constant accelerations of about 15g and provides continuous tracking throughout the boost and free-flight phase of a sample sounding rocket trajectory, it cannot properly reacquire the tracking signals in case of a temporary signal loss.

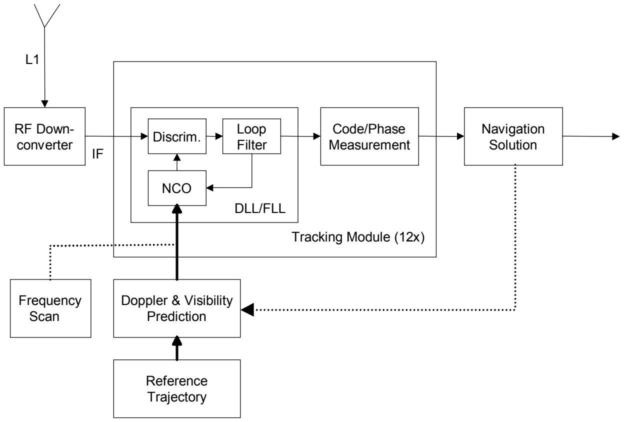

Fig. 2 Doppler and visibility prediction for code & frequency tracking on highly dynamical host vehicles. An open-loop prediction based on the nominal flight path (bold line) replaces the cold start frequency search and the feed back from the navigation solution of the receiver (dashed line).

A position-velocity aiding concept has therefore been developed, which makes use of a piece-wise polynomial approximation of the nominal flight path in Cartesian WGS84 coordinates. To minimize the computational workload of the ARM processor, second-order polynomials in position have been selected, which provide a first-order approximation of the sounding rocket velocity. Up to ten polynomials can be configured and stored via a suitably modified command interface, which is sufficient to provide a position accuracy of about 2 km and a velocity accuracy of roughly 100 m/s. Based on the polynomial approximation of the nominal trajectory, the reference position and velocity of the sounding rocket in the WGS84 reference frame are computed once per second. The result is then used to obtain the line-of-sight velocity and Doppler frequency shift for each visible satellite, which in turn serve as initial values for the steering of the delay and frequency locked loops. The position-velocity aiding thus assists the receiver in a fast acquisition or re-acquisition of the GPS signals and ensures near-continuous tracking throughout the boost and free-flight phase of the sounding rocket trajectory.

Further modifications comprise corrections to software limits for altitude and velocity, an extension of the Doppler computation to properly account for the receiver velocity and a replacement for the kinematic position and velocity determination. By default the least-squares estimation of the host vehicles state vector is carried out in spherical coordinates to support the implementation of an altitude hold-mode in case of lacking GPS satellite visibility. Since the frame rotation of the co-moving North-East-Up system is not properly accounted for in the original firmware, the velocity estimation exhibits a severe degradation in case of fast moving host vehicles. This is particularly notable for near-polar trajectories and high ground velocities. As a remedy, a traditional, Cartesian formulation has been implemented [HOF97], which does not support fixed-altitude operation but provides accurate navigation solutions (WGS84 position and velocity) even for ballistic trajectories and orbiting spacecraft.

TRAJECTORY APPROXIMATION

For the prediction of nominal Doppler data (and, to a less extent, visibility data) a suitable approximation of the sounding rocket trajectory must be made available to the receiver. Both the user's velocity and position must be known to compute the line-of-sight range-rate

$$\dot{\rho} = (\boldsymbol{v} - \boldsymbol{v}_{\mathrm{gps}})^T \frac{(\boldsymbol{r} - \boldsymbol{r}_{\mathrm{gps}})}{|\boldsymbol{r} - \boldsymbol{r}_{\mathrm{gps}}|} \tag{1}$$

and the carrier Doppler shift

$$\Delta f = f_{\mathrm{L1}} \frac{\dot{\rho}}{c} = 5.25\mathrm{Hz} \cdot \dot{\rho}[\mathrm{m/s}] \tag{2}$$

from known ephemerides of the GPS satellites. Given a typical deviation of 200-500 Hz between the nominal and actual reference oscillator frequency as well as a 500 Hz frequency search bin width, we require that the prediction of the nominal Doppler shift should typically be accurate to 250 Hz or about 50 m/s. Requiring a similar relative accuracy for the line of sight vector then yields a tolerable position uncertainty of about 50-100 km. To minimize the computational workload in each update step, we have selected a simple 2nd-order polynomial

$$\boldsymbol{r}(t) = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} + \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix}(t - t_0) + \begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix}(t - t_0)^2 \tag{3}$$

to approximate the sounding rocket trajectory over discrete time intervals in the WGS84 reference frame. Upon differentiation, one readily obtains an associated approximation of the instantaneous Earth-fixed velocity vector

$$\boldsymbol{v}(t) = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix} = \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} + 2\begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix}(t - t_0)\,, \tag{4}$$

which is linear in time. Accordingly, the individual time intervals should be chosen in such a way as to exhibit a near constant acceleration. For practical purposes a maximum of ten intervals turned out to be sufficient for the proper representation of a dual stage sounding rocket trajectory.

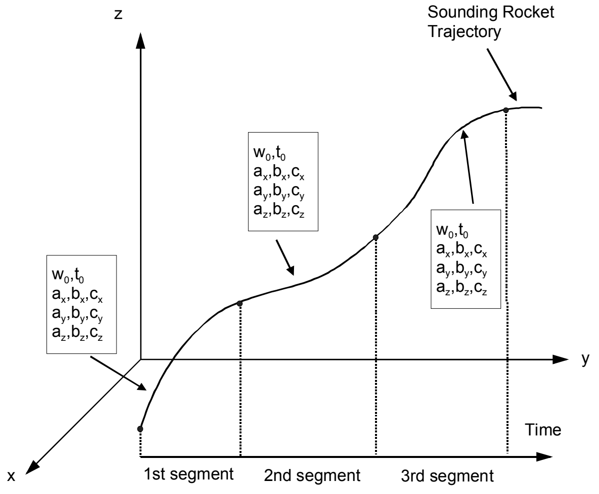

Fig. 3 Piecewise polynomial approximation of the reference trajectory of a sounding rocket. Each time interval is represented by its start epoch (GPS week and seconds) and three coefficients per axis.

SIMULATION SCENARIOS

To assess the performance of the proposed position velocity aiding, two different sounding rocket scenarios have been considered. The Brazilian VS40 is a dual stage rocket, which is launched from Alcantara Space Center and achieves a maximum altitude of 660 km at the assumed payload mass of 477 kg [WIL97]. The second scenario refers to a Texus launch from ESRANGE/Kiruna using a dual stage Goldfinch/Raven-11 rocket. Further details of both scenarios are given in Table 1.

Table 1 Sounding rocket scenarios considered in the simulations

Parameter	VS40	Texus
Launch epoch	1999/07/15 12:03 GPS Time (GPS week 1018, t_{ow} 302580s)	
Launch site	λ=-44.4° ϕ= -2.3°	λ=+67.9° ϕ=+21.1°
Boost duration (1st stage)	62 s	5 s
Boost duration (2nd stage)	71 s	36 s
Flight time	ca. 900 s	ca. 520 s
Max. altitude	660 km	250 km
Horizontal range	780 km	75 km
Max. velocity	3200 m/s	1950 m/s
Max. acceleration	6.4 g	8.6 g

In accord with the observed velocity profile, a total of eight intervals was selected to approximate the VS40 reference trajectory (cf. Table 2). Out of these, six segments are employed to match the 1st and 2nd boost phase as well as the intermediate coast arc. Two further segments provide a modeling of the ascending and descending part of the parabolic free flight trajectory up to the time of parachute deployment.

Table 2 Approximation of the VS40 trajectory using segmented 2nd-order polynomials

#	Start [s]	Duration [s]	Position error [km]	Velocity error [m/s]	Remarks
1	0	30	0.1	33	1st boost
2	30	15	0.1	81	1st boost
3	45	35	0.1	67	coast arc
4	80	20	0.1	34	2nd boost
5	100	17	0.0	32	2nd boost
6	117	28	0.0	40	2nd boost
7	145	345	1.1	41	ascent
8	490	390	2.2	70	descent

Within each interval, a least-squares fit of the WGS84 position values was performed to derive the coefficients of a second order polynomial (cf. Eqn. 3). As illustrated in Fig. 4, the overall approximation is accurate to roughly 2 km in position and 80 m in velocity, which is in fair accord with the assumed requirements. Despite the larger number of subintervals, the maximum velocity errors occur during the boost phase, where acceleration changes (yerks) are most pronounced. It is further noted that pronounced discontinuities are present at the interval boundaries, since the individual fit polynomials have been derived completely independent of each other. No attempt has been made, however, to perform a constrained least-squares fit, since the condition of a continuous and smooth interpolation is incompatible with second order polynomials. If desirable, a cubic spline interpolation could be employed to meet these conditions at the expense of a potentially larger coefficient set and a slightly larger processor load. As will be shown below, however, the chosen approach already provides a satisfactory receiver performance and no need to improve the trajectory approximation is currently foreseen.

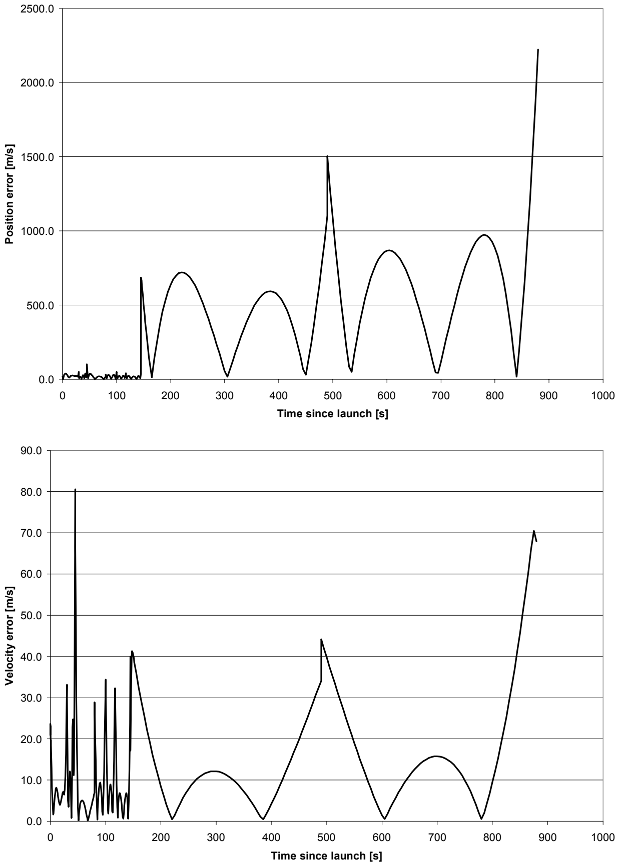

Fig. 4 Accuracy of the VS40 trajectory approximation using 2nd order position polynomials (*top*: position, *bottom*: velocity).

For the Texus trajectory, a segmented second-order polynomial approximation was likewise established, which yields a 70 m and 74 m/s error during the boost phase. A single polynomial only was employed to cover the full free flight phase up to parachute deployment at the expense of an increased velocity error of 210 m/s.

TEST PERFORMANCE

Using an STR2760 GPS signal simulator, different hardware-in-the-loop simulations were carried out to validate the proposed trajectory aiding concept for both the VS40 and the Texus scenario. Initial tests with an unmodified Orion receiver showed that the Delay Locked Loop (DLL) and Frequency Locked Loop (FLL) employed in the receiver are, in principle, able to follow

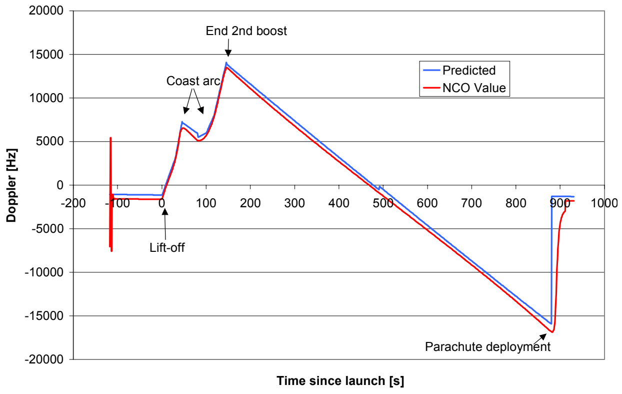

Fig. 5 Comparison of predicted Doppler shifts and measured NCO values for PRN 16 in the VS40 test scenario.

the dynamic range and range-rate variations from launch to landing, if a stable and continuous GPS signal is ensured. This permits a comparison of the Doppler shift as computed from the polynomial approximation of the reference trajectory with the frequency offset of the Numerically Controlled Oscillator (NCO). Representative results are illustrated in Figs. 5 and 6 for the VS40 scenario and GPS satellite PRN 16. The overall Doppler curve exhibits a pronounced zig-zag pattern, which reflects the thrusted (positive acceleration), free-flight (negative acceleration) and parachute phase (positive acceleration). On average, the difference between predicted and measured Doppler values amounts to roughly 500 Hz, which corresponds to a 0.33 ppm frequency offset of the employed quartz oscillator. Superimposed variations of up to 400 Hz (~80 m/s) reflect the accuracy of the polynomial trajectory approximation discussed above.

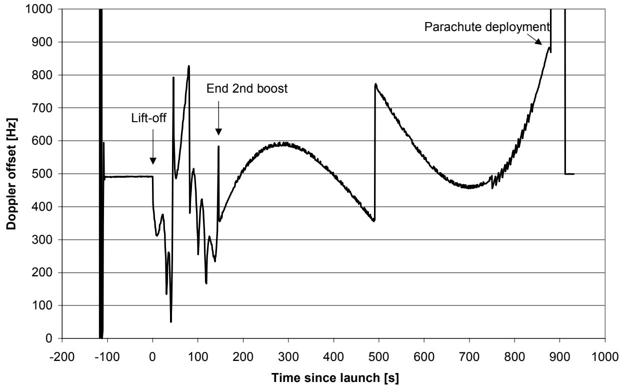

Fig. 6 Difference of predicted Doppler shifts and measured NCO values for PRN 16 in the VS40 test scenario.

In a subsequent test, the GPS signal was intentionally interrupted at well defined scenario times to compare the behavior of the aided receiver with the unaided version. For the VS40 scenario, a five second interrupt was performed during the first boost phase, when the line-of-sight acceleration was near its maximum for most satellites. The signal was interrupted once more for five seconds at the end of the second burn, which marks the start of the free flight phase and the turning point of the Doppler curve. Finally, the signal was interrupted for 60 s near maximum altitude (cf. Table 3).

Table 3 Reacquisition capability with and without trajectory aiding (times since launch for VS40 scenario)

#	Interrupt		Reacquisition		Remarks
	From	To	unaided	aided	
1	30s	35s	374s (nav)	38s (nav)	1st boost
2	145s	150s	n/a	151s (nav)	end 2nd boost
3	480	540s	559s (1sat) 631s (3sat) 650s (nav)	547s (3sat) 607s (nav)	max. altitude

While the unaided receiver takes a total of five minutes to produce a valid navigation solution after the first signal loss, the aided receiver is back on track within a few seconds after the end of both the first and second interrupt. At the time of the third interrupt, only five out of ten simulated GPS signals have a positive elevation above the mathematical horizon, which makes them trackable by a zenith looking antenna. Here both the unaided receiver and the aided receiver take much longer to regain four satellites for a full navigation solution. Despite a valid Doppler prediction, even the aided receiver is only able to acquire three GPS satellites right after the end of the signal loss. Thereafter, it takes about one minute to obtain pseudo-ranges for the remaining two satellites and establish a valid position estimate. The situation is even worse, however, for the unaided receiver, which takes approximately two minutes to resume full tracking operations.

Table 4 Reacquisition capability with and without trajectory aiding (times since launch for Texus scenario)

#	Interrupt		Reacquisition		Remarks
	From	To	unaided	aided	
1	20s	30s	92s (1sat) 162 (3sat) 175s (nav)	32s (nav)	2nd boost
2	76s	105s	n/a	106s (nav)	ascent
3	181	240s	258s (nav)	245s (nav)	max. altitude

A similar performance improvement is obtained for the Texus scenario, in which the signal was intentionally interrupted three times for 10 s, 30 s, and 60 s, respectively. In all cases, a valid navigation was provided by the aided receiver within a few seconds after return of the signal. The unaided receiver, in contrast, failed to reacquire four-satellite tracking for 2.5 mins after loosing the signal in the boost phase.

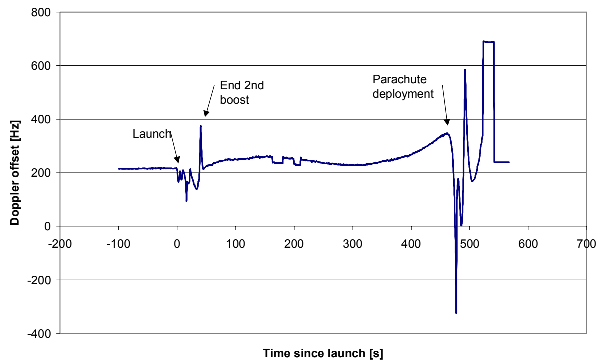

Fig. 7 Difference of predicted Doppler shifts and measured NCO values for PRN 7 in the Texus test scenario.

In general, the Texus scenario is easier to handle for both receiver versions than the VS40 test case. This is partly due to a larger number of simulated GPS satellites within the antenna visibility cone. More importantly, however, the northern latitude of the launch site implies that most satellites appear at low elevations, which reduces the line-of-sight range-rate and acceleration, as well as the Doppler prediction error. This is e.g. apparent in Fig. 7, which shows the offset of the predicted and NCO measured Doppler shift for the extreme case of PRN 7. Despite an overall error in the velocity approximation of 210 m/s during the parabolic free-flight phase, the Doppler offset differs by at most 150 Hz (≅ 50 m/s) from the steady state value. Larger errors occur only after parachute deployment, which results in extreme accelerations and is not modeled by a suitable number of trajectory polynomials.

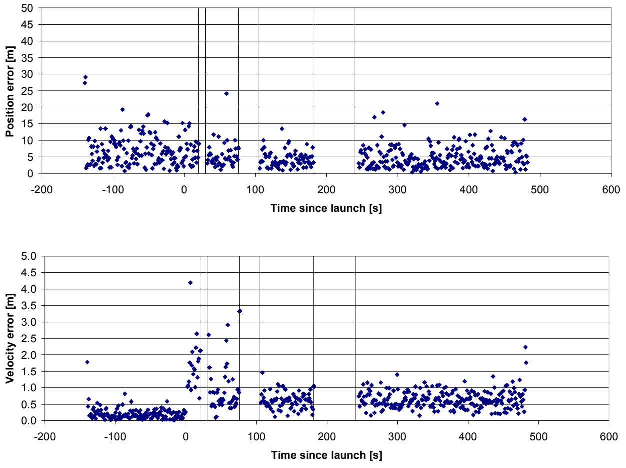

Fig. 8 Accuracy of navigation solutions (*top*: position; *bottom*: velocity) obtained by the modified GPS Orion receiver in a simulated Texus scenario. Vertical bars indicate times of intentional signal interrupts.

To conclude with, Fig. 8 shows the achieved tracking accuracy for the case of the Texus scenario. In accord with current practice, no Selective Availability (SA) was applied in the simulation. Total position errors are generally found to be less than ten meters, while the velocity is typically accurate to better than 1 m/s. Again, it is evident that the aided receiver resumes tracking rapidly after the each signal loss.

SUMMARY AND OUTLOOK

A simple concept for aiding the signal acquisition of GPS receivers in highly dynamical sounding rocket applications has been proposed and implemented in a Mitel GPS Orion receiver. Aside from a description of the trajectory approximation and receiver software modifications, the results of hardware-in-the-loop simulations are presented, which have been obtained with a GPS signal simulator for representative dual stage sounding rocket scenarios. It is shown that the position-velocity aiding increases the robustness of the tracking process and ensures a rapid reacquisition of signals after intentional interruption. Initial flight tests are planned for the first half of 2001. In addition to sounding rocket applications, preliminary tests indicate that the proposed aiding concept is likewise applicable for satellite applications when used with a simple analytic orbit model.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Kayser-Threde GmbH, Munich, which has kindly provided access to the GSS STR2760 signal simulator used in the hardware-in-the-loop simulations.

REFERENCES

[END00] Enderle W., Arbinger Ch., Milani P.G.; Junqueira C.; *A simple and low cost two-antennas concept for the tracking of a sounding rocket trajectory using GPS*; ION-GPS-2000, D1-A4, Salt Lake City, Sept. 19-22 (2000).

[HOF97] Hofmann-Wellenhof B., Lichtenegger H., Collins J.; *Global Positioning System Theory and Applications*; Springer-Verlag, Wien, New York, 4th ed. (1997).

[MIT99] *GP2000 GPS Receiver Hardware Design*; Mitel Semiconductor; AN4855 Issue 1.4, Feb. 1999.

[MIT97*] GPS Architect 12 Channel GPS Development System*; Mitel Semiconductor; DS4605 Issue 2.5; March 1997.

[WIL97] Willemse B. B.; *Information on the VS40 sounding rocket*; Technical University Delft http://dutlls1.lr.tudelft.nl/oshelp/projects/r1/vs40.html; April 1997