A TIDGET/Inertial Missile Sensor Fusion System[1]

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ABSTRACT:

Many guided munitions systems could benefit from the use of GPS position information to augment existing inertial navigation systems. These applications however, are characterized by no pre-launch visibility of GPS satellites, short duration, and high launch dynamics, which preclude the use of conventional GPS receivers. This paper describes and innovative approach to GPS/INS data fusion for these demanding applications that optimally combines GPS and INS data from both the launch platform and smart munitions. The advantages of this system include no initialization of GPS sensor pre-launch, rapid signal acquisition even in high dynamic environments (Time To First Fix < 1 sec), improved Anti-Jamming performance when compared to even an ideal conventional receiver, and inherent differential operation.

1. INTRODUCTION

1.1 GPS FOR PRECISION WEAPON DELIVERY

Attack aircraft currently carry a suite of precision sensors such as Global Positioning System (GPS), Inertial Navigation System (INS), Forward Looking Infrared (FLIR) systems, and Synthetic Aperture Radar (SAR) that can be used to provide precision air-to-ground or air-to-air targeting. Smart weapons also carry a sensor suite including inexpensive IMUs and sometimes GPS equipment for precision weapon delivery. However, the size, weight, and cost of the missile electronics limit the functions that can be performed on-board. The ability to fuse data from on-board sensors and off-board assets can significantly improve the accuracy of the weapon delivery while reducing the cost of the weapon system.

NAVSYS has designed an innovative tracking system that optimally combines data from the aircraft and missile sensors, including GPS and INS data from both sources. This architecture has the following key advantages over previous GPS/INS missile guidance systems.

- Low cost GPS sensor used in place of a full receiver on the missile.
- No initialization needed of GPS sensor pre-launch.
- Rapid initial signal acquisition even in high dynamic maneuvers (TTFF <1 sec).
- Sensor fusion of aircraft and missile GPS/INS data performs rapid in-flight alignment of missile INS, reducing time needed for pre-launch initialization and alignment.
- Enhanced signal processing of GPS data on aircraft increases signal margin and anti-jamming (A/J) performance of missile GPS data.
- "Differential" missile-to-aircraft operation provides improved GPS precision for targeting using aircraft sensors.

The TIDGET/INS Missile (TIM) system concept, is

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illustrated in Figure 1.

The missile carries on-board an inexpensive, miniaturized GPS sensor, the TIDGET™. The TIDGET is used to periodically collect "snapshots" of the GPS data. This data is formatted into a message that also includes the missile INS position, velocity, and attitude data, which is transmitted back to the aircraft. The aircraft receives the data from the missile and passes it to the TIM tracking system for processing. The TIM tracking system combines the data from the aircraft GPS/INS systems with the TIDGET/INS data received from the missile, and processes this to compute an integrated GPS/INS solution for the relative location and velocity of the missile to the aircraft. This can be combined with FLIR and SAR data to accurately target the weapon system.

1.2 APPLICATIONS

Several applications can benefit from the use of a TIM tracking system to improve the guidance accuracy. This paper focuses on the use of the technology in an extended range air-to-air missile that operates as follows:

A target is acquired by the launch aircraft. The missile is then launched and uses its on-board INS to fly towards an aim point (expected future location of the target) supplied by the launch aircraft. Based on the target motion, the launch aircraft transmits updates of the aim point to the missile during flight. Once the missile reaches the aim point and the target can be acquired by the missile seeker, the mid-course guidance phase ends and the missile starts using its seeker for terminal guidance to the target. Note that if the missile INS provides inaccurate navigation information, the capability of the missile to reach the aim point will be severely degraded.

Although this paper considers an air-to-air application, the TIM system can be used in any guided missile or bomb that relies on an on-board INS for navigation/guidance.

1.3 TECHNICAL ISSUES

A block diagram of the NAVSYS TIM tracking system is shown in Figure 2. The key technical issues in the design of the TIM system are:

<u>TIDGET/INS Data Fusion</u>
A system that relies on an INS navigation information for guidance is subject to guidance errors due to the fact that the INS (if uncorrected) exhibits errors that grow with time. The magnitude of the INS errors depends on the size of initialization errors, as well as the instrument, i.e. accelerometer and gyro errors. In airborne applications where missiles are launched from wing mounts, a large source of INS error occurs due to incorrect attitude initialization (i.e. incorrect alignment), which results from wing twist etc [1]. Furthermore, if low cost Inertial Measurement Units (IMU's) are used, the accelerometers and gyros will exhibit large errors.

By fusing GPS and INS data, improvements in system accuracy are obtained because of:

- <u>Improved INS initialization:</u> by using the appropriate data fusion process, it is possible to significantly reduce the effects of incorrect INS initialization after processing only a few GPS measurements. This means that for example in a hostile jamming environment, only a small number of GPS measurements are required, whereupon autonomous operation using only the INS is possible.
- <u>Improved Navigation information:</u> if the GPS data is used to correct the INS at regular intervals throughout the missile flight, one obtains a system that exhibits the best characteristics of both GPS and inertial navigation systems, viz. the accuracy and stability of GPS, as well as the high bandwidth of an INS.

The key issues regarding TIDGET/INS data fusion are the tradeoffs related to: IMU quality and cost, and number and accuracy of TIDGET/GPS updates required.

Rapid Acquisition of GPS Signal

In many smart munitions applications, a munitions-mounted GPS receiver will not be able to receive GPS signals until launch. Furthermore, launches of smart munitions typically involve high accelerations. Both of these factors are detrimental to conventional GPS receiver operation and result in larger delays for GPS solutions to become available.

Anti-Jam Capability

The effectiveness of any munitions system is threatened by the use of enemy jammers. Although GPS signals are spread-spectrum, their low power levels and particular spread spectrum architecture make them susceptible to jamming.

Communications Link Bandwidth

The bandwidth of the downlink between the missile and the aircraft will determine the amount of GPS data available for processing. The amount of data available for processing will affect the navigation solution accuracy and availability, especially in jamming scenarios. Given a fixed, effective communications bandwidth, the trade-off is between the TIDGET sampling rate of the GPS signal structure, the quantization level of the TIDGET sampler (number of bits), the length of the TIDGET snapshots, and the frequency of the TIDGET snapshots (i.e. the number of TIDGET snapshots per unit time).

2. TIDGET OPERATION

The proposed system is based on the low cost TIDGET sensor developed by NAVSYS Corporation. The TIDGET sensor architecture is a compromise between a full GPS receiver and a GPS digital translator, which in this application provides the best features of both for missile tracking.

A conventional GPS receiver includes an RF subsystem, frequency synthesizer, digital signal processing (DSP) chip, and a microprocessor. The RF subsystem receives the L1 GPS signals and converts them to a convenient intermediate frequency (IF). The IF signals are filtered and digitized. Typically, a sample rate of at least 2 MHZ is used to digitize the GPS signals which are at 1.023 MHZ for the C/A code. A 20 MHZ sample rate is required to capture the full P/Y code bandwidth. A second down-converter and A/D sampler is used to capture the L2 bandwidth if required.

The digitized GPS signals are then processed in a semi-custom DSP chip to provide code and carrier demodulation. Samples of the demodulated signals are accumulated and processed in the microprocessor to provide pseudo-range (PR) and delta-range (DR) measurements. These measurements are then used to derive the position and velocity of the receiver. In a tracking system implementation, the receiver provides either the raw PR/DR measurements or a position and velocity fix as output from the microprocessor. This data is transmitted via a telemetry link to a ground station for further processing.

The trade-offs between the receiver-based implementation and the translator include cost, complexity, power, size, bandwidth, and performance. The receiver approach requires that each missile being tracked carry a complete GPS receiver that can process the GPS data for transmission to the ground station. A more efficient approach, which reduces the amount and complexity of the flight hardware, is to perform navigation processing on-board the aircraft, where size and weight constraints are less significant.

A GPS translator implements this idea by retransmitting the raw GPS data from the vehicle to a translator processing system. The front-end of the translator is identical to that of a conventional GPS receiver. The raw (unprocessed) GPS signals are then transmitted via a telemetry link to the ground-based translator processing system. Figure 3 shows the two basic sensor alternatives.

The advantage of the translator system over a receiver system is in the acquisition and tracking performance. Missile-borne GPS receivers have difficulty in rapidly acquiring and tracking satellite signals due to the high dynamics of the missile. Large swings in the frequency of the receiver's oscillator are introduced by the missile's high dynamics, especially during missile launch. These frequency swings create an extremely difficult acquisition and tracking problem for the receiver, since it has to search over a large Doppler range to find the satellite signals. This problem is compounded by the fact that the receiver may not be able to "see" GPS satellites prior to launch, since the missile is usually located beneath the wing of an aircraft. Even in a static environment, a receiver typically requires several minutes to acquire and track enough satellite signals to provide a navigation solution.

The major disadvantage of translators for this application is the larger telemetry bandwidth required. Existing GPS translator systems developed by the US Navy and by the tri-service Range Applications Joint Program Office (RAJPO) are based on analog translators and therefore require wide bandwidth telemetry systems (>2 MHZ) which are not suited for tactical applications.

The NAVSYS design uses a missile sensor that incorporates the size, weight, cost, and performance advantages of a digital translator while requiring only a low bandwidth telemetry link as does a GPS receiver. This system design is based on the patented TIDGET GPS sensor illustrated in Figure 4.

In addition to downconverting and digitizing the GPS signal, the TIDGET also includes a digital data buffer (DDB) to provide the capability to reduce the output data rate. This data rate reduction is achieved by buffering a "snapshot" of the digital GPS data. The selected interval of data is then transmitted to the aircraft with the INS data from the missile. The GPS snapshot and INS data are fused with the aircraft sensor data to derive the missile position, velocity, and attitude solution relative to the aircraft and target. The aircraft uses this information to send fire control data and INS calibration data to the missile across the telemetry link.

3 TIDGET PERFORMANCE

The TIDGET is a compromise between a full GPS receiver and a GPS digital translator and exhibits performance characteristics, i.e. signal to noise ration (SNR) values and A/J capability unique to its architecture.

3.1 TIDGET SNR DEGRADATIONS

The TIDGET sensor (see Figure 4) includes three main components: (I) the analog front-end where the RF GPS signal is bandpass filtered and downconverted through three stages of mixing; (ii) a presampler filter along with an A/D converter that quantizes the filtered analog signal to 2 bits (sign and magnitude) which then are provided to latches for sampling; (iii) and a component containing the DDB and other control functions required for the proper operation of the interfacing I/Os [1]. Each of these components degrades the receiver SNR by increasing the thermal noise in the received signal, reducing the effective signal strength, or introducing noise to the received signal.

Front End Degradation

The first component, where all the front-end functions are performed, usually reduces the SNR by increasing the effective thermal noise in the received signal. This component of the TIDGET sensor has been carefully designed so that this SNR degradation is no larger than 4 dB [1], which is similar to the majority of receivers and digital translators.

Presampler/Converter Degradation:
The SNR degradations introduced by the presampler/converter component in the TIDGET are usually not encountered in the same fashion on either full receivers or digital translators. These performance degradations are explained below.

- Effect of Sampling Rate: In the presampler/converter, the downconverted GPS signal is filtered, sampled, and quantized by a 1 or 2 bit A/D converter. Aliasing is avoided by bandlimiting the signal through a filter prior to sampling. In a full receiver, the downconverted received signal will be passed through a pair of presampling filters that not only bandlimit the received signal, but also produce a pair of signals that when treated as a complex construct forms an analytical signal. In the TIDGET sensor, the downconverted received signal is only passed through a single presampling filter and then sampled not at the Nyquist frequency but at half the Nyquist frequency. The resulting sampled signal contains only the real or imaginary part of the analytical signal encountered in a full receiver. When correlated with either a P or C/A reference code, this results in an SNR degradation of approximately 3 dB due to the loss of signal power.
- Degradation Due to Quantization In the TIDGET the downconverted received signal, is further quantized by a 1 bit quantizer. The effects of this quantization in the effective SNR of the TIDGET output data can be seen by considering the output of a typical correlator when this quantized data is used. Assuming coherent detection of the carrier phase and independent noise samples, it can be shown (see [1]) that the performance degradation due to 1 bit quantization for weak signals is results in a 1.96 dB loss.

Thus the total SNR loss associated with a typical TIDGET sensor is 4.97 dB.

3.2 ACQUISITION PERFORMANCE

The TIDGET sensor data is only used to acquire and track the GPS code and carrier information in order to obtain PR and carrier-range (CR) measurements. The GPS signal structure also carries satellite ephemeris and time information modulated on the spread spectrum signal structure at a 50 bps rate. This data information is not used by the TIDGET, but is gathered at the reference receiver. Because of this, the best acquisition performance can be obtained if the data modulated on the GPS signal is removed before processing the TIDGET data. This process, called data aiding, significantly improves the acquisition and tracking performance of the TIDGET system.

The GPS signals must be acquired in both time (code phase) and Doppler frequency offsets (carrier phase) before the tracking operation can begin. This implies a search for the single synchronization in both time and frequency. The search problem is greatly simplified, however, if a-priori information about the Doppler frequency is obtained, which allows the use of coherent phase detection. This reduces the two-dimensional frequency-phase search to only a one-dimensional search over all possible code phases until synchronization is acquired. For the TIM system, the missile inertial information, along with the GPS receiver data, provide a-priori information to permit coherent detection. In order to improve performance even further the TIM system uses a sequential search method, since this allows the use of maximum likelihood detection methods. The higher performance obtained results more rapid acquisition in a noisy environment (see e.g. [1],[2])

3.3 TRACKING PERFORMANCE

As indicated earlier, using a-priori information about the carrier phase, obtained through data aiding between sensors, coherent carrier phase demodulation can be obtained and resolved before code phase acquisition and tracking. Once code phase synchronization is obtained, the code phase can be tracked by using a delay lock loop to obtain estimates of the code phase. Typically, receivers track the code phase by using delay lock loops which provide minimum mean square error estimates of the code phase. In order to obtain maximum performance the TIM system uses a Maximum Likelihood Estimator (MLE) in stead of a minimum mean square error method. The MLE method results in an improvement in measurement accuracy by at least a factor of 2, depending on the TIDGET snapshot length.

3.4 JAMMING PERFORMANCE

Four types of jammers present a typical threat to the TIM system: spoofing, narrowband or CW jammers, pulsating jammers, and broadband jammers.

Spoofing Jammers

Spoofing jammers are spread spectrum signals that emulate GPS signals by reproducing the GPS signal structure associated with C/A codes. The simplest method to defeat C/A code spoofing jammers, is to process the encrypted P code signals. In this regard, the TIDGET architecture is no different than conventional receivers. If spoofing jammers are a concern, P code signal processing can be used.

Narrowband or CW Jammers

Narrowband or CW jammers are high power signals that occupy narrow or small bandwidths that fall on or close to the GPS carrier frequencies. In an ideal receiver, these signals are spread during the correlation with the reference code. Thus their effects are mitigated by the spreading factor associated with the reference code. However in some cases this reduction in the SNR degradation introduced by the jammer may not be enough in many cases. In the TIDGET, the effects of this type of jammer also include the introduction of spurious responses at the limiter output of the A/D converter, as well as non-linear effects due to stuck faults of the quantization bit in the A/D converter.

The suggested approach to dealing with narrowband jammers is to treat the problem as a cancellation of the narrowband signal (the CW jammer) in the presence of broadband noise (the GPS signal). There are several methods that can be used to reduce the effective power of the narrowband signal before correlation with the reference code is performed (see e.g. [3]). These procedures can be applied equally well to TIDGET and conventional receivers.

Pulsating Jammers

Pulsating jammers are very high power signals of very short duration. These signals have a strong detrimental effect on the data detectors in ideal receivers [7], by acting as a noise source that introduces burst errors on the data stream. The smaller the duration of the jamming pulse, the more power it contains and the more bursty the effective channel behavior is. This type of jammer can be compensated either by introducing error correction capabilities in the transmitted GPS signal or by estimating the jammer state (present or not present) and ignoring the data when the jammer is present.

Fortunately, this problem does not severely affect the performance of the TIDGET sensor if the duration of the pulsating jammer is small compared to the length of the sensor data. Since this is the case for almost all practical cases, it can be presumed that such jammers do not affect significantly the TIDGET performance.

Broadband Jammers

Broadband jammers are signals of moderate power and broad bandwidth centered on or around the GPS carrier frequencies and behave like band-limited white Gaussian noise. The main effect of the this jammer is to degrade the effective SNR by effectively increasing the noise floor.

One defense against broadband jammer signals is to reduce their power by filtering the jammer spectrum in order to reduce its effective bandwidth. This band-limiting operation can be performed by the presampler filter in the TIDGET sensor.

4 TIDGET/INS KALMAN FILTER

The TIM tracking system is designed to generate the real-time TIDGET/INS navigation solution for the missile. The data processing architecture is illustrated in Figure 5. The modules perform the following functions:

4.1 MISSILE INS

The strapdown navigation module propagates the missile position, velocity, and attitude solution from the $\Delta\theta$, ΔV data provided by the IMU. The INS navigation solution is periodically corrected from the INS error correction module so that it maintains the current best estimate of position and velocity. The output of the INS navigation solution is therefore the composite TIDGET/INS integrated solution (a "closed loop" filtering approach).

4.2 MISSILE TIDGET MODULE

The missile TIDGET periodically collects snapshots of raw GPS data suitable for PR and DR computations. This raw data is formatted into a message packet that also includes the missile INS position, velocity, and attitude data. These packets of TIDGET and missile data are transmitted to the aircraft

4.3 AIRCRAFT TIDGET RECEIVER

The aircraft TIDGET receiver demodulates and unpacks the transmitted TIDGET data, and passes it to the Kalman filter measurement residual module.

4.4 KALMAN FILTER MEASUREMENT RESIDUAL

The aircraft and missile data is fused in the measurement residual generated to update the Kalman filter. The residual observes the errors in the missile INS navigation solution. This algorithm has the following benefits.

GPS Error Cancellation By differencing the GPS measurements between the aircraft and missile, any common system errors in the satellite signal cancel. This "differential" technique removes the effect of satellite clock and position errors, resulting in a significantly improved accuracy of the missile-aircraft relative position.

Aircraft Truth Solution The aircraft is assumed to carry a GPS receiver and an INS. The aircraft GPS receiver and INS are used to computes a highly accurate navigation solution, even under high dynamic maneuvers.

Relative Missile Solution The missile navigation solution is computed from the truth reference provided by the aircraft (absolute accuracy ~16 meters) and the relative missile-aircraft solution (relative accuracy ~10 meters). This has the effect of providing a PPS quality position solution for the missile while only requiring C/A code and unencrypted (SPS) processing in the TIDGET processing system. This simplifies the system architecture by eliminating the need for any PPS-SM or encryption devices without compromising on the accuracy of the final solution.

The following equation is used to compute the PR residual. This observes the missile INS position error states and TIDGET clock bias.

$$\tilde{PR} = PR_M - \hat{PR}_M - PR_A + \hat{PR}_A$$

$$\hat{PR}_M = |P_M^{INS} - P_{SV}| + \hat{B}_U$$

$$\hat{PR}_A = |P_A - P_{SV}| + B_A$$

$$\tilde{PR} = 1_{SV}^T\, \delta P_M + \tilde{B}_U$$

where: PR_A = PR provided by the aircraft
PR_M = PR provided by the TIDGET sensor
PR_M^{INS} = Position provided by missile INS
P_A = Position provided by aircraft INS
P_{SV} = Satellite position
B_U = TIDGET clock bias
B_A = Aircraft GPS clock bias

A similar equation is used to derive the DR residual. The DR residual observes the missile INS velocity error states, the attitude errors in the INS, and the TIDGET clock frequency offset.

The measurement residuals are provided to the TIDGET/INS Kalman filter module where the state updates are computed.

4.5 TIDGET/INS KALMAN FILTER

The TIDGET/INS Kalman filter estimates errors in the missile INS outputs. Upon obtaining the measurement residuals, the Kalman filter state estimate and covariance are updated according to the standard Kalman filter equations (see [4]).

When the measurement update is completed, the Kalman filter propagates the filter states and covariances (see [4]) to the time just before the next measurements will be obtained from the TIDGET.

In order to account for the delays in the communication link between the aircraft and missile, the propagated state estimates are then used to compute corrections to the missile strapdown navigation algorithms applicable at the (future) time instant just before new TIDGET measurements are made. Once this is done, the Kalman filter state estimates are zeroed. The computed corrections are then transmitted to the missile so that they can be applied by the correction module at the appropriate time instant.

4.6 INS ERROR CORRECTION

The INS error correction module applies the corrections computed from the Kalman filter state estimates to the strapdown inertial navigation algorithms.

5. SIMULATION RESULTS

Simulation testing has demonstrated the TIM system's capability to achieve accurate navigation performance with a low cost IMU. For these simulations an IMU with performance characteristics similar to the Litton LN-200 (see [5]) was used.

The missile trajectory shown in Figure 6 was used in the simulations. Parameters such as launch velocity, axial acceleration etc were chosen to produce missile motion representative of an extended range air to air missile engagement (see e.g. [6]).

Although the TIDGET is capable of obtaining GPS data for all satellites in view data from only six satellites was used in the simulation. For the TIDGET system, GPS errors depend on the size of snapshot length. A PR error of 15/29 m (1-σ) and a velocity error of 0.1/0.87 m/sec (1-σ) were used to simulate the effect of receiver errors. These errors correspond to snapshot lengths of 20 ms and 5 ms, respectively.

The simulation model was run to determine the navigation accuracy that could be achieved for different TIDGET snapshot sizes and different TIDGET measurement update rates. The following measurement update rates were investigated.

Simulation A	Measurement updates at 1 sec intervals throughout the missile flight, starting 1 sec after launch.
Simulation B	Measurement updates at 5 sec intervals throughout the missile flight, starting 1 sec after launch.
Simulation C	Measurement updates at 20 sec intervals throughout the missile flight, starting 1 sec after launch.
Simulation D	Measurement updates at 1 sec intervals, starting 1 sec after launch, with the last update occurring 21 sec after launch.
Simulation E	Measurement updates at 5 sec intervals, starting 1 sec after launch, with the last update occurring 21 sec after launch.
Simulation F	Measurement updates at 10 sec intervals, starting 1 sec after launch, with the last update occurring 21 sec after launch.

For each of the update rates above simulations were repeated for 2 cases, one for a 20 ms TIDGET snapshot and the other for a 5 ms TIDGET snapshot. The results of the simulation tests are summarized in Table 1 and Table 2. Figure 7 shows typical results for a Monte Carlo run. Note that the estimated covariance for the heading error is larger than the actual errors, indicating that the estimates given in Tables 1 and 2 are conservative.

Tables 1 and 2 show that in most cases it is possible to significantly reduce INS initialization errors using only three GPS updates.

6. CONCLUSIONS

The TIM system, based on the TIDGET GPS architecture and aided with missile-based INS data, provides the capability to obtain accurate navigation information for guided munitions.

By using the unique characteristics of the TIDGET it is possible obtain the benefits of GPS while still meeting the demands for rapid GPS signal acquisition even in high dynamic environments (Time To First Fix < 1 sec), improved Anti-Jamming performance when compared to even an ideal conventional receiver, and inherent differential operation.

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Table 1: Simulation Results for 20 msec TIDGET Snapshots

Simulation	6 sec into flight		21 sec into flight		41 sec into flight		61 sec into flight		81 sec into flight	
	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)
No meas update	150	17.47	500	17.5	860	17.55	1230	17.6	1580	17.65
A	7	2	5	2	4	2	4	2	4	2
B	12	5	10	3	8	3	6	3	6	3
C	20	10	15	5	12	3	12	3	12	3
D	7	2	5	2	15	3	30	3	80	3
E	12	5	10	3	30	3	50	3	120	4
F	30	10	10	4	30	4	70	4	175	5

Table 2: Simulation Results for 5 msec TIDGET Snapshots

Simulation	6 sec into flight		21 sec into flight		41 sec into flight		61 sec into flight		81 sec into flight	
	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)	Pos Err (m)	Head Err (mrad)
A	10	4	10	3	10	3	10	3	10	3
B	15	5	13	4	13	3	13	3	13	3
C	30	10	30	6	30	4	30	4	30	4
D	11	4	8	3	30	3	60	3	130	4
E	18	5	14	4	40	4	100	4	180	4
F	14	10	14	5	40	5	90	5	190	5

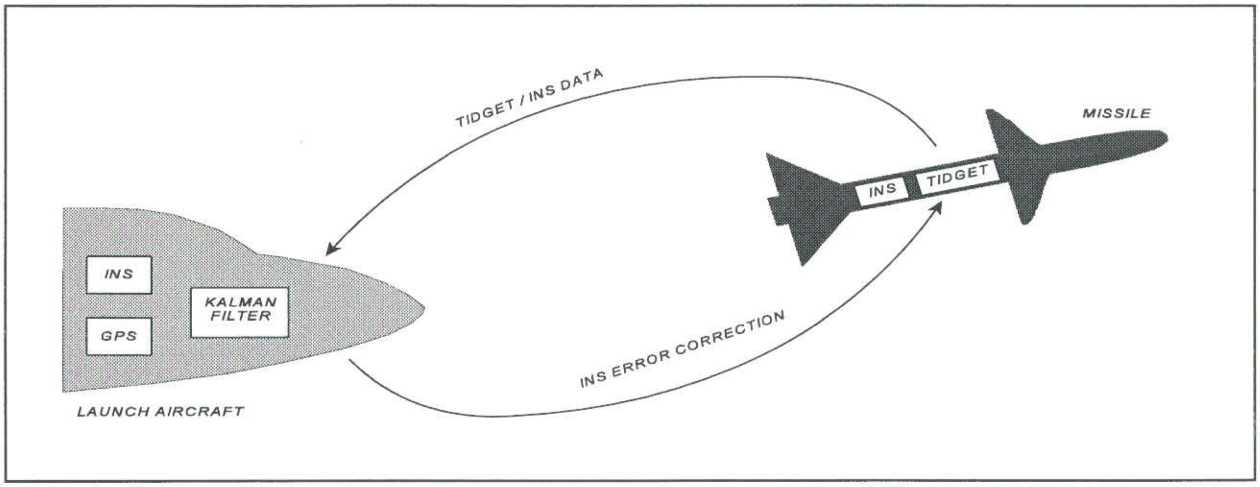

Figure 1: TIM System Concept

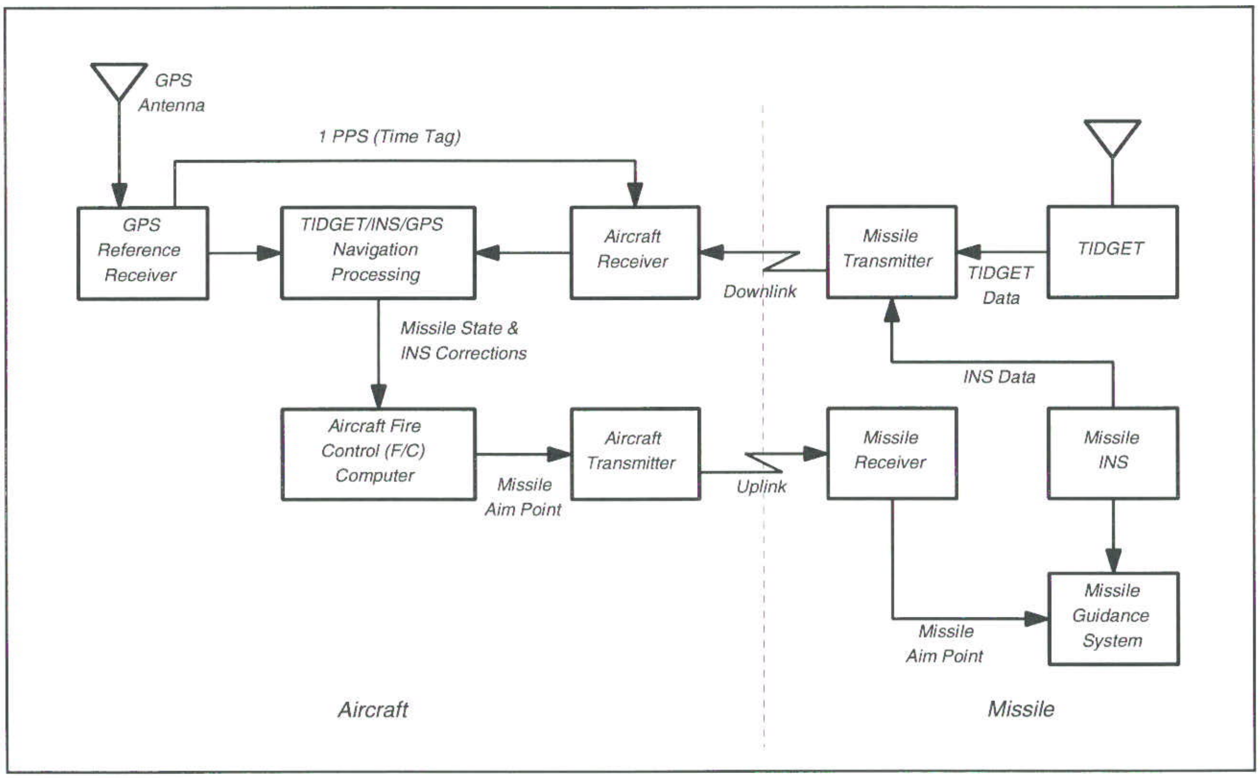

Figure 2: TIDGET/INS Missile (TIM) System Block Diagram

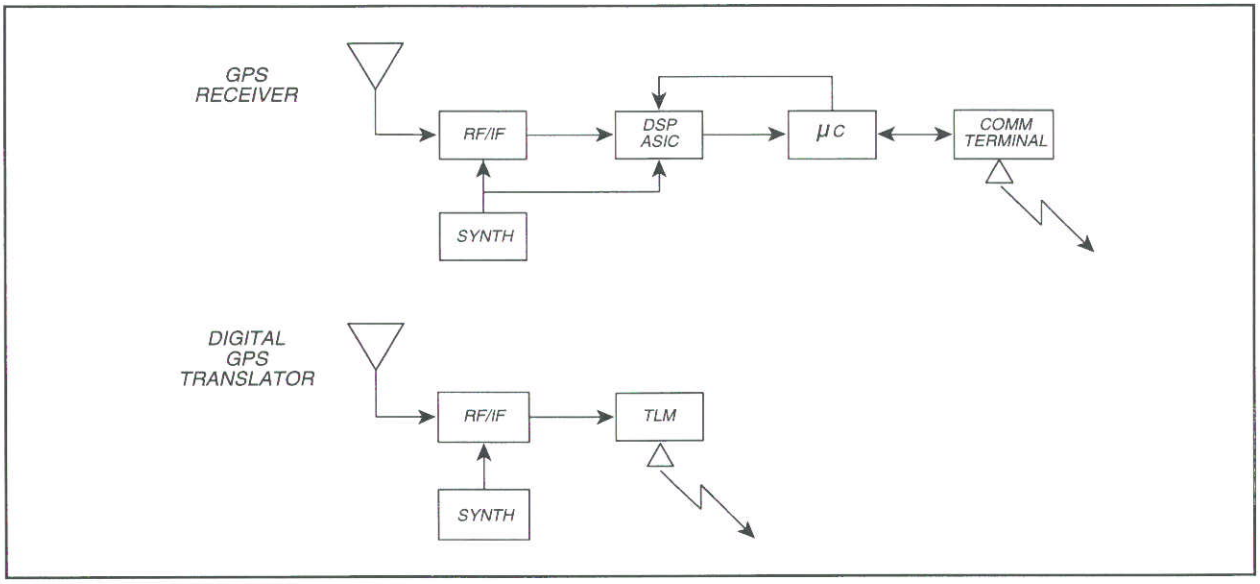

Figure 3: GPS Receiver and Translator Architecture

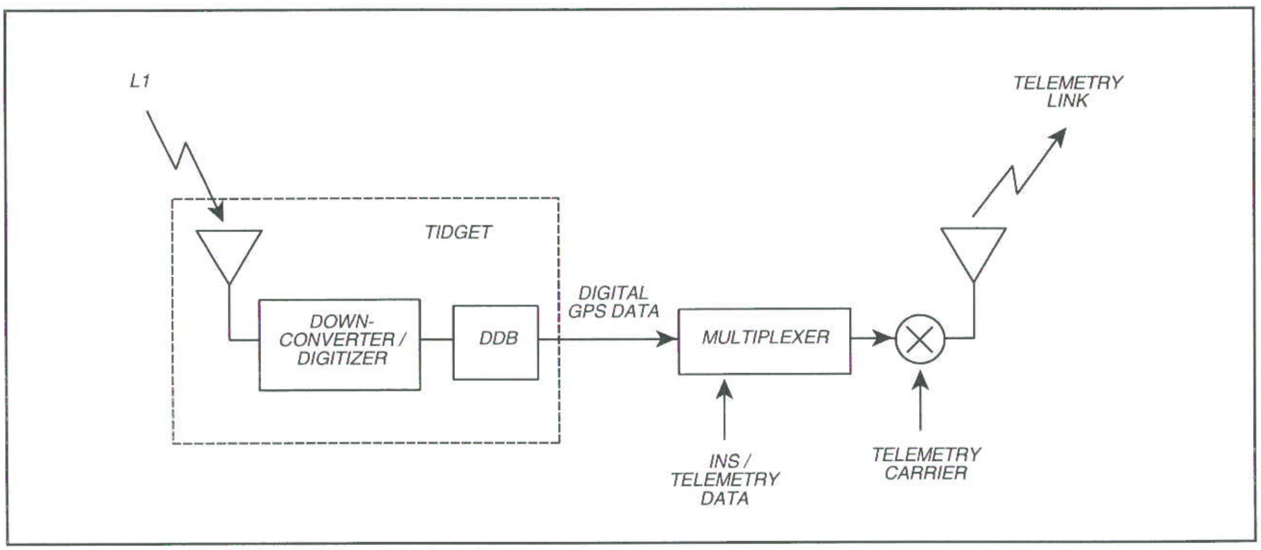

Figure 4: Missile TIDGET Sensor Architecture

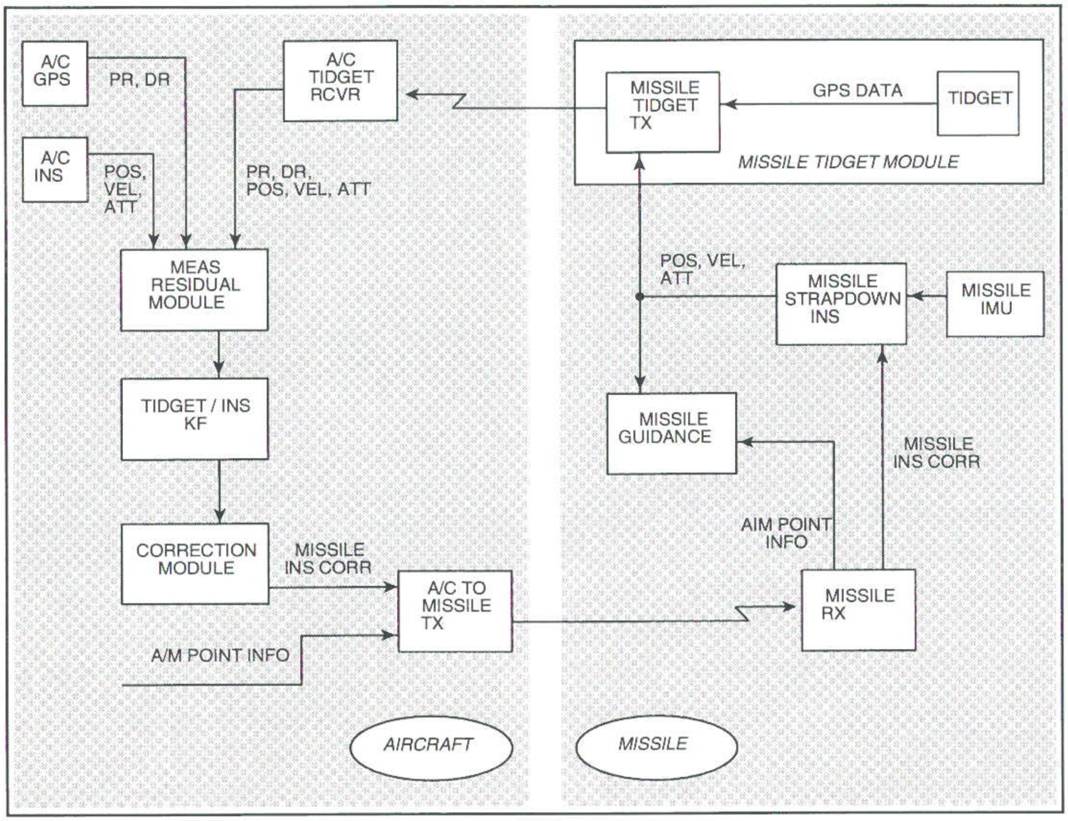

Figure 5: TIM Tracking Software Architecture

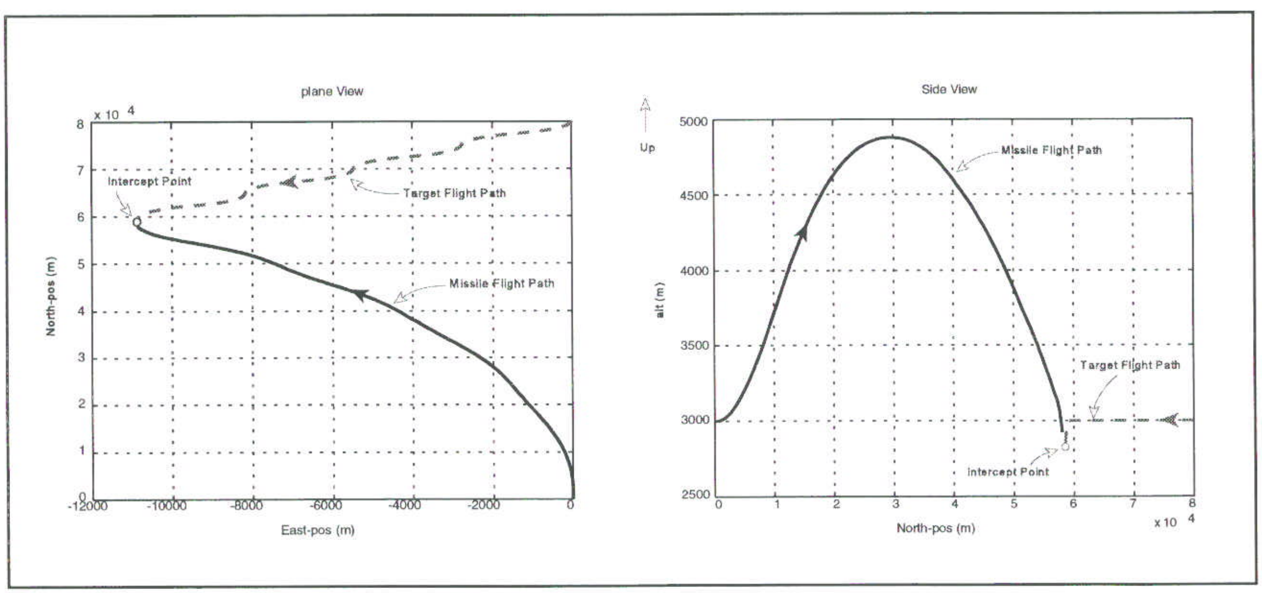

Figure 6: Simulated Missile Trajectory

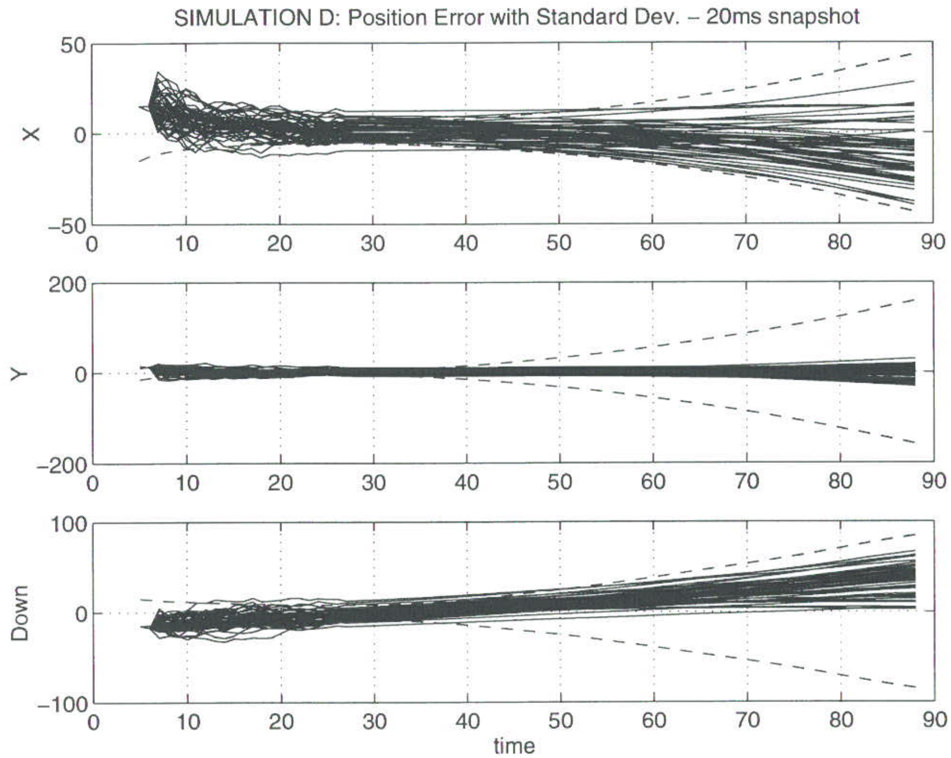

Figure 7: Results from Monte-Carlo Simulation

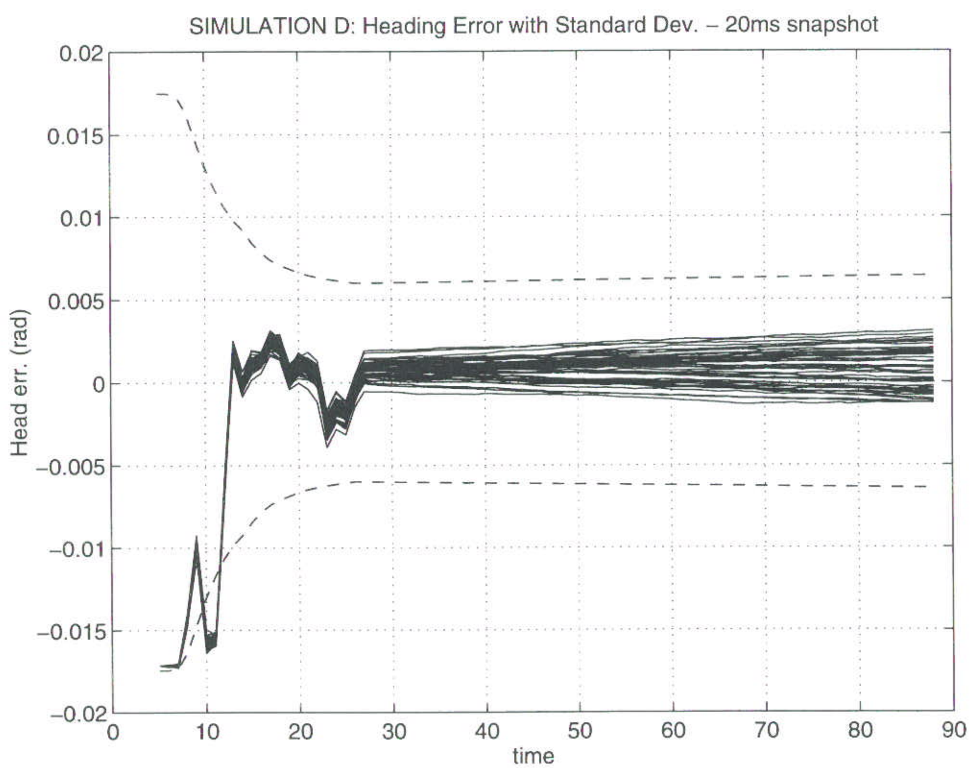

Figure 8: Results from Monte-Carlo Simulation