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INERTIAL SENSOR PERFORMANCE REQUIREMENTS FOR A LONG RANGE ARTILLERY ROCKET (U)

by

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TECHNICAL NOTE 93-13

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Ottawa

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J.S. Bird
Communications and Navigation Systems Section
Electronics Division

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ABSTRACT

With continuing advances in rocket propulsion systems for extended-range artillery, it is possible that operational ranges of 60 kilometers (up from the current 30 km) will be the norm within 20 years. However if the munitions are unguided, the dispersion errors at these long ranges, due to such factors as muzzle velocity errors and down-range weather conditions, make effective use of such rounds prohibitively expensive. This report investigates the performance required of inertial components that could be used for an onboard guidance system that would enable the rocket to determine its position to a sufficient level of accuracy. The high dynamics of the launch environment and the relatively short flight times make for unusual conditions for an inertial navigation system. It is shown that some components are of critical importance and must be of high performance (thus of more expense) while others are of much less importance and savings can be made when specifying the instruments for those functions.

RÉSUMÉ

Avec l'avancement continuel des systèmes de propulsion d'armement à longue portée, il est possible que des portées d'opération jusqu'à 60 kilomètres (le double de la valeur actuelle) soient la norme d'ici 20 ans. Toutefois si les munitions sont non-guidées, l'erreur de dispersion à ces grandes portées, dues à des facteurs tels que les erreurs de vélocité du canon et les conditions atmosphériques incertaines, fait que l'usage de ces munitions soit hors prix. Ce rapport fait enquête sur la performance requise des composantes inertielles qui pourraient être utilisées dans un système de guidance de bords qui devrait permettre à la fusée de déterminer sa position avec une précision adéquate. La haute dynamique de l'environnement de lancement et les durées de vol relativement courts font naître des conditions hors de l'ordinaire pour un système de navigation inertiel. Il est démontré que certaines composantes sont d'importance critique et doivent être de haute performance (donc plus dispendieuses) tandis que d'autres sont plus ou moins importantes et des économies peuvent être réalisées lors de la spécification des instruments pour ces fonctions.

EXECUTIVE SUMMARY

With continuing advances in rocket propulsion systems for extended-range artillery, it is possible that operational ranges of 60 kilometers (up from the current 30 km) will be the norm within 20 years. However if the munitions are unguided, the dispersion errors at these long ranges, due to such factors as muzzle velocity errors and down-range weather conditions, make effective use of such rounds prohibitively expensive. Thus a preliminary study was undertaken to examine the feasibility of placing sensible guidance systems aboard the munitions that would reduce the dispersion errors at 60 km to the same level they are at the current 30 km. A NATO Long Term Scientific Study (LTSS/39) on Inexpensive Guidance for Indirect Fire Munitions was initiated to look at several aspects of the problem in terms of the technology that would be available at a reasonable cost in the next 10 and 20 year time frames.

The problem partially addressed by this report is one of determining the in-flight position, velocity and attitude of a fast accelerating (30 g), high velocity (Mach 2 to 3), rapidly rolling (10 rev/s) rocket during its approximate 2 minute flight. This would allow the rocket to predict its impact point relative to the target location so that it can make the appropriate guidance corrections. There are many possible ways of doing this. For example, tracking from a ground radar, using the Global Positioning System (GPS) satellites, or using radio transponders are among the schemes that have been suggested. Other solutions make use of inertial components aboard the round. There are advantages and disadvantages to all such schemes, but the primary advantage of using an inertially based positioning system is that it makes the munition fully autonomous, requiring no ground support after launch and making it immune from electronic countermeasures.

This report investigates the performance requirements of the inertial components that would be required to enable the munition to determine its position to a sufficient level of accuracy. The high dynamics of the launch environment and the relatively short flight times make for unusual conditions for an inertial navigation system. It is shown that some components are of critical importance and must be of high performance (thus of more expense) while others are of much less importance and savings can be made when specifying the instruments for those functions.

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1.0 INTRODUCTION

1.1 BACKGROUND

With continuing advances in rocket propulsion systems for extended-range artillery, it is possible that operational ranges of 60 kilometers (up from the current 30 km) will be the norm within 20 years. However if the munitions are unguided, the dispersion errors at these long ranges, due to such factors as muzzle velocity errors and down-range weather conditions, make effective use of such rounds prohibitively expensive. Thus a preliminary study was undertaken to examine the feasibility of placing sensible guidance systems aboard the munitions that would reduce the dispersion errors at 60 km to the same level they are at the current 30 km. A NATO Long Term Scientific Study (LTSS/39) on Inexpensive Guidance for Indirect Fire Munitions was initiated to look at several aspects of the problem in terms of the technology that would be available at a reasonable cost in the next 10 and 20 year time frames.

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1.2 SCOPE OF THIS REPORT

After stating the overall performance requirements, the next section outlines some of the major complicating factors that are characteristic of the artillery problem that may constrain the type of instrumentation that can be considered. Some aspects of the problem are then mentioned that may be exploited to enable the choice of simpler and less expensive sensors. The third section consists of the results of some computer simulations of inertial systems, with their characteristic errors included, in a simulated rocket flight profile. These simulations are used to determine the minimum quality of individual components that will still satisfy the overall system requirements.

2.0 REQUIREMENTS AND ENVIRONMENT CONSIDERATIONS

2.1 SYSTEM PERFORMANCE REQUIREMENTS

The performance requirements in LTSS/39 were phrased in terms of matching the accuracy of current 30 km artillery at 60 km. There are 4 parameters to this: range *bias* (or mean) error, range *precision* (or standard deviation) error, cross-range bias, and finally cross-range precision. Rather than complicating matters unnecessarily by specifying all four parameters, which if linked to specific equipment would be classified, a simpler, but related, positioning requirement will suffice for the purposes of this note. These requirements are:

Position Error: 150m
Attitude (roll, pitch or heading) Error: 5 degrees

These requirements state that the inertial system must indicate its position to within 150 m of the true position throughout the duration of the flight, and that the attitude error components must not exceed 5 degrees. To be more precise, these parameters should have associated statistical significances (such as SEP for the position error, and 1σ for the angular errors).

2.2 COMPLICATING FACTORS

There are several aspects of the artillery rocket positioning problem that are usually not encountered in more benign platforms. These factors can affect the choice of certain sensors or systems that are routinely used to provide position, velocity and attitude and will require special consideration before such sensors can be used.

a. Initial acceleration: For an artillery rocket, this is in the 10 to 30 *g* range. The instrumentation must survive the launch forces, and the inertial components must measure through the launch acceleration for proper positioning computations. Thus, the forward pointing accelerometer of an inertial system must have a large dynamic range.

b. Initialization time: The time allowed for sensor initialization may only be a few seconds between loading and firing. This has particular implications for inertial components since there will be little time for initial alignment. Thus a transfer alignment from the launcher will probably be required.

c. Velocity: Velocity measurement is critical. In long range artillery, a dominant error source is launch velocity variation. Velocities will be on the order of 700 - 800 m/s.

d. Rocket roll: The rocket may be rolling very rapidly (on the order of 3600 deg/sec) in order to increase the predictability of aerodynamic forces. This has severe implications. Continuous roll causes trouble for inertial systems as it can rectify certain types of errors (such as gyro scale factor errors and accelerometer misalignments) into position errors.

The scale factor error of the roll gyro is particularly critical; for example, to maintain a roll angle error of less than 5 degrees after 100 seconds of 3600 deg/sec roll rate requires a scale factor error less than 15 PPM (0.0015%). This is within the range of good quality gyros today but beyond most inexpensive "missile grade" gyros. This roll, however, can also be beneficial in other respects, as discussed in *b* below.

e. Attitude measurement: Platform attitude (roll, pitch and heading) might be required at a high rate by guidance algorithms that steer the rocket. This implies that gyros will likely be required. (Although attitude could in principle be derived from the position deviation from the aerodynamic model prediction, but it may not be very accurate.) On the other hand, guidance systems that *displace*, rather than steer, the rocket may only require accurate roll angle information. The aerodynamic forces will keep pitch and heading errors small and the main displacement errors will be due to velocity variations and crosswinds. The roll angle determination must be accurate to within a few degrees at the time of the guidance algorithm displacements.

2.3 FEATURES TO EXPLOIT

There are some characteristics of the problem that could be taken advantage of to reduce the quality of the required components.

a. Initial conditions: The initial conditions are known very precisely. This is inherent in an artillery application. The initial launcher position will usually be known to within a few meters, and heading and elevation will be accurate to within a fraction of a milliradian. This data is available from in-service artillery positioning systems. Transfer of this information to the rocket should be relatively straightforward. However the initial roll angle may not be known to the launcher. Onboard accelerometers could be used to sense the direction of gravity or the rocket might be keyed to fit only one way in the launcher.

b. Rocket roll: The roll of the platform will partially cancel out many inertial sensor errors, especially lateral and vertical accelerometer biases and scale factor errors as well as azimuth and pitch gyro biases and scale factor errors. To see this, consider an accelerometer bias in the lateral accelerometer. When the accelerometer is pointing to the left, say, this bias will be doubly integrated by the strapdown algorithm and will create a position error to the left. However, the roll of the rocket will, in a fraction of a second, turn this accelerometer around to the right so the bias will be integrated into a position shift to the right, effectively cancelling out the error accumulated when it was pointing to the left. The overall effect is a small, bounded sinusoidal error. One caveat, here; this cancellation depends on the strapdown algorithm having the correct roll angle and this requires a very accurate roll gyro (see *d* above).

c. Short flight time: The short (2 minute) flight time will minimize the effects of gyro and accelerometer bias drifts on inertially-based position calculations. For example, even a poor quality 100 deg/hr gyro would cause an integrated angular error of only 3.3 degrees after 2 minutes.

d. Predictable trajectory: For the most part, the trajectory of the rocket is somewhat predictable because it is essentially ballistic after the initial thrust. It is the deviation from the nominal trajectory that is to be measured. This *a priori* information would be useful in the design of any predictor-corrector (*e.g.* Kalman) type filtering algorithms that require a model of the platform motion to update the proper state equations.

2.4 POSSIBLE SHORTCUTS

Full inertial positioning requires 3 gyroscopes and 3 accelerometers. Some of the components must be of higher quality than components normally used in attitude and heading reference systems (AHRS) for missiles, for example, because in addition to supplying attitude, the system must also act as a full *inertial navigation system* (INS) in order to provide projectile position and velocity. At the same time, however, some can be of lesser quality because of the cancellation of errors due to the rolling platform. Since there is some *a priori* knowledge of the trajectory, it is conceivable that a *partial* inertial sensor suite may still suffice. For example: if the pitch rate can be accurately modelled and varies little from round to round, the pitch gyro may not be necessary. Or it might be determined that the lateral velocity variations are insignificant compared to the effects of muzzle velocity variations. In such a case, the lateral accelerometers might be eliminated. Perhaps pitch and heading variations may be small in an aerodynamically stable projectile so the corresponding gyros could be eliminated. Also, there are instruments called "multisensors" that can measure both acceleration and angular rates. They may be quite inexpensive and may suffice for the other 2 axes. None of these situations has been investigated to any extent at present so it is still assumed that a full 3-axis navigation system would be used. It should just be noted that there may be specific characteristics of the artillery rocket problem that may be further exploited.

3.0 INS POSITIONING SIMULATIONS

3.1 METHODOLOGY

This section describes the simulation system that was used to generate the rocket motions and simulate the inertial navigation system. The results of the simulations are then presented. The simulations were conducted by trial and error: each error source was introduced one at a time and increased until the positioning error was a substantial fraction (1/10 to 1/5) of the overall performance requirement. Then when all error sources were activated simultaneously, the overall positioning performance (which is roughly the root sum square of the positioning errors caused by each sensor error individually) was seen to just meet the overall requirements. In this way, estimates for the maximum allowable values for each of the individual sensor error sources were obtained.

3.2 TRAJECTORY GENERATION DESCRIPTION

The programs used to generate the data were taken from software normally used to generate trajectories and sensor data for long-term land, sea and air navigation systems. The extremely high roll rates and initial accelerations of the rocket problem required running the programs at much higher iteration rates than normal to accurately calculate the correct angular and velocity increments from one sample to the next. The programs were not specifically optimized for any particular trajectory but are typically used to simulate vehicles with the dynamics of, say, a transport plane or a helicopter. For these applications, data generated at 50 Hz is sufficient. For a rocket rolling at 10 RPS, a 50 Hz iteration rate was not sufficient. By experiment, it was found that a rate of 600 Hz was required to enable these programs to accurately generate the rocket profile. If the algorithms were optimized to take advantage of this high, but steady roll rate, the iteration rate could be made substantially less.

The simulations are two-pass. First, the trajectory generator produces a truth data file containing the true position, velocity and attitude of the platform, along with platform body angular and velocity increments. Then the sensor simulator reads this truth data (for the platform increments) and other files that specify the errors to be added to the individual components and computes the output of the positioning algorithm based on these increments and errors. The simulation does not operate in closed loop, *i.e.*, the position as calculated by the sensor model is not fed back to the trajectory generator, so a full guidance scenario is not simulated. However, the position output of the sensor algorithms can be compared with the truth data from the trajectory generator and one can thus determine the sensitivity of the position errors to individual component errors.

The parameters in Table 3-1 below were supplied to the trajectory generator to calculate the truth data (bear in mind that this only approximates the rocket ballistics).

Table 3-1.. Trajectory Generation Simulation Parameters

Initial Conditions	Launch Segment (5 sec)
Initial latitude: 0 deg Initial longitude: 0 deg Initial altitude: 0 m Initial azimuth: 0 deg Initial pitch: 45 deg Initial roll: 0 deg Initial velocity: 0 m/s Initial ang. rates: 0 deg/s	Roll rate: 0 to 10 RPS in 5s Velocity: 0 to 700 m/s in 5s Thrust: 0 to 30 g in 2.5s, to 0 g at 5s **Ballistic Segment (the next 105 sec)** Vertical acceleration: -1g (freefall) Deceleration: -0.3 m/s^2 (to approx. drag) Azimuth rate: 0.003 deg/s (to approx drift) Pitch angle: 45 deg to -45 deg in 105s Range travelled: 64 km

There is a variety of coordinate nomenclature used in the following discussion. Table 3-2 below can be referred to when interpreting the results.

Table 3-2. Coordinate System Nomenclature

Axis	Accelerometer	Gyro	Position
x	forward	roll	range
y	lateral	pitch	cross-range
z	vertical	azimuth/yaw	altitude

Shown in the following figures is some output data from the trajectory generator for the "true" rocket flight path; the ground track in Fig. 3-1, (converted from lat-lon to meters based on an Earth radius of 6370 km) and the altitude profile in Fig. 3-2.

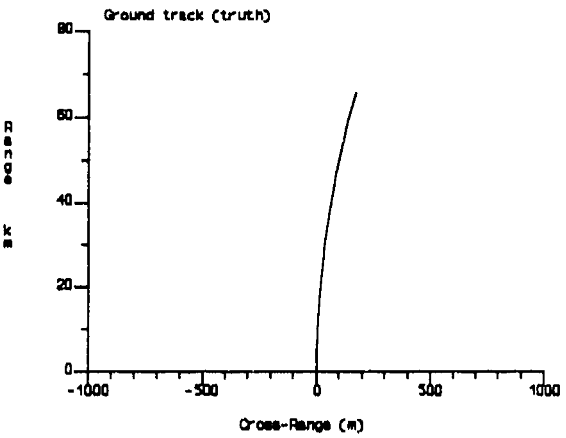

Fig. 3-1: True ground track

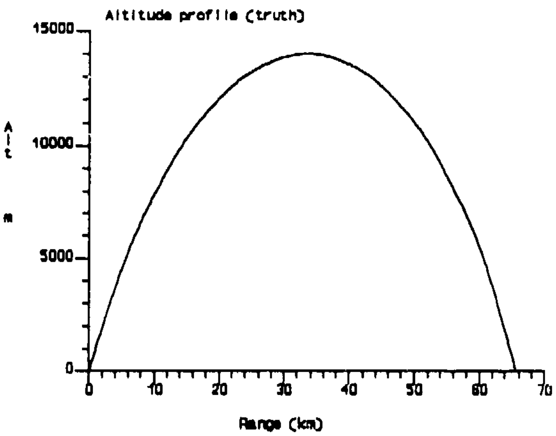

Fig. 3-2: True altitude profile

3.3 STRAPDOWN INERTIAL SIMULATIONS - ONE ERROR AT A TIME

The plots in Appendix A show the position errors versus time which result from individual inertial sensor errors. All other error sources were set to zero except for the one indicated in the title of the plot, which is set to a constant value. All 3 position errors (range, cross-range and altitude) are shown in units of meters. These are the errors that would be produced solely by the INS assuming a perfect rocket trajectory (*i.e.*, no wind errors, etc.).

The plots are summarized in Table 3-3 (at t=110 sec = time of impact). Recall that the primary initial launch conditions were 30 g's of initial acceleration, a 5 second rocket motor burn time and a 10 RPS spin rate.

Table 3-3. Strapdown Positioning Errors due to Individual Sensor Errors
(30 g, 5s burn, 10 RPS)

Figure	Instrument Error	Magnitude	Range error (m)	Cross-range error (m)	Altitude error (m)
Fig. A-1	x accel bias	700 μg	30	0	15
Fig. A-2	y accel bias[1]	20,000 μg	5	15	-5
Fig. A-3	z accel bias[1]	20,000 μg	10	-8	-10
Fig. A-4	x accel scale factor	500 PPM	30	0	35
Fig. A-5	y or z accel scale fact.[1,2]	5000 PPM	10	0.1	-20
Fig. A-6	x accel misalignment	5 mrad	1	-25	-1
Fig. A-7	y accel misalignment	5 mrad	7	2	-7
Fig. A-8	z accel misalignment	5 mrad	2	-10	-2
Fig. A-9	x gyro bias drift	50 deg/hr	2	-35	-2
Fig. A-10	y gyro bias drift[1]	50 deg/hr	-10	7	10
Fig. A-11	z gyro bias drift[1]	50 deg/hr	5	15	-7
Fig. A-12	x gyro scale factor	5 PPM	2	-40	-2
Fig. A-13	y or z gyro scale fact.[1,2]	5000 PPM	-0.5	-0.2	15
Fig. A-14	x gyro g-sensitive drift	10 deg/hr/g	1	-30	-1
Fig. A-15	y or z gyro g-sens. drift[1]	50 deg/hr/g	2	-20	-2
Fig. A-16	gyro misalignments	0.25 mrad	15	20	-15
Fig. A-17	Init roll angle error	0.333 deg	1.5	-30	-1.5
Fig. A-18	Init pitch angle error	0.333 mrad	-20	-0.1	20
Fig. A-19	Init azimuth angle error	0.333 mrad	-0.3	20	0.3

Note 1: The rocket roll did not completely cancel out the effects of these error sources, as was suggested in 2.3 *b* above, because the rocket was spun up to 10 RPS over 5 seconds. During this transient period, the effects of the sensor errors are felt asymmetrically around the roll axis and error accumulation does occur. This accumulation is seen to lead to a small position error that grows with time.

Note 2: These results may be optimistic due to the lack of lateral dynamics in the simulations.

3.4 STRAPDOWN INERTIAL SIMULATIONS - ALL ERRORS INCLUDED

When all the error sources in Table 3-3 were turned on simultaneously, the plot shown in Fig. 3-3 resulted. Shown are the range, cross-range and altitude errors as well as the root-sum-square (RSS) which peaks at about 150 m, which satisfies the overall performance requirement.

Finally, the attitude (roll, pitch and heading) errors for the composite error case is shown in Fig. 3-4. The simulations suggest accumulated roll, pitch and heading errors of less than 5 degrees which also satisfies the requirements.

Based on these simulations, it is seen that the most stringent inertial sensor requirements are on the roll gyro and forward accelerometer because of the high roll rate and initial accelerations. The *y* and *z* accelerometer and gyro errors are almost completely removed by the continuous roll and less expensive sensors can be used on these axes. The critical requirements are listed in Table 3-4 (for 5s burn, 10 RPS, 30g launch).

Table 3-4. Critical Inertial Component Requirements (for 5s burn, 30g, 10 RPS)

Component Error	Requirement
Roll gyro scale factor error	Less than 5 PPM
Roll gyro bias uncertainty	Less than 50 deg/hr
Forward accel bias uncertainty	Less than 700 μg
Forward accel scale factor error	Less than 500 PPM
Gyro misalignments	Less than 1/3 mrad
Initial roll angle error	Less than 1/3 deg
Initial pitch and heading errors	Less than 1/3 mrad

The only requirement likely to drive the cost of a component above about a thousand (1993) dollars is the roll gyro scale factor of 5 PPM. This may require a navigation quality gyro on the order of $1000-$5000. Most of the other requirements should be met with middle or lesser quality components on the order of $500-$1000 per axis.

The requirements on the initial attitude errors should not cause many problems. The launcher will know its own attitude to within these limits and they can be relayed to the rocket just before launch. Maintaining an initial roll angle error of 1/3 degree should not be too difficult with good mechanical design.

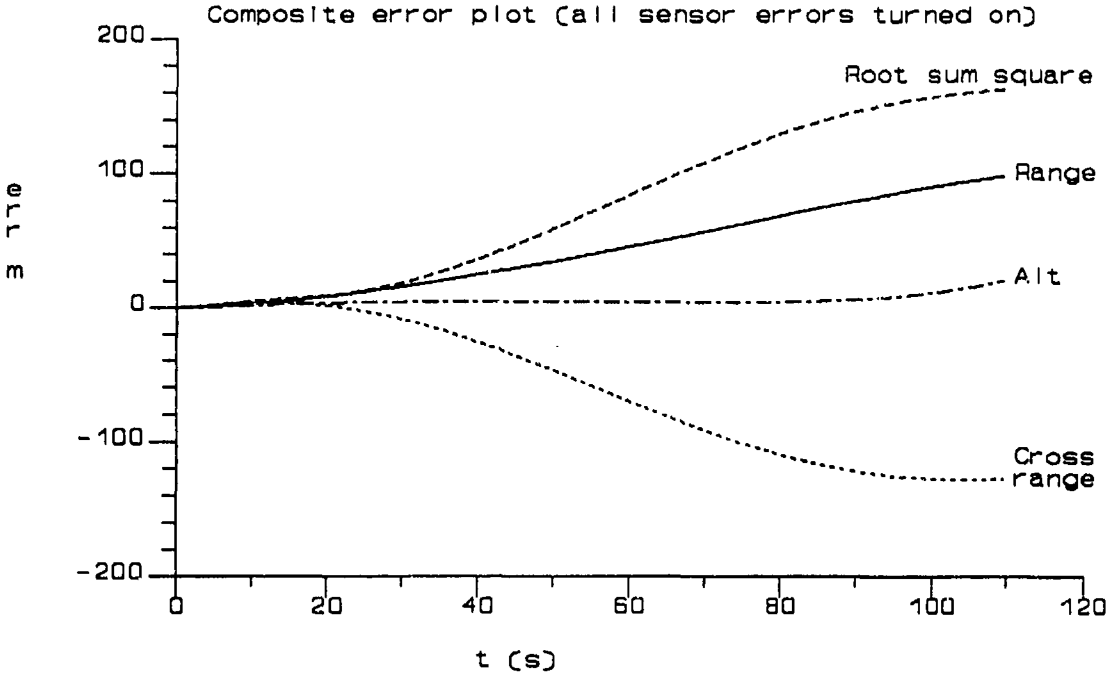

Fig. 3-3: Position errors due to all inertial sensor errors on simultaneously

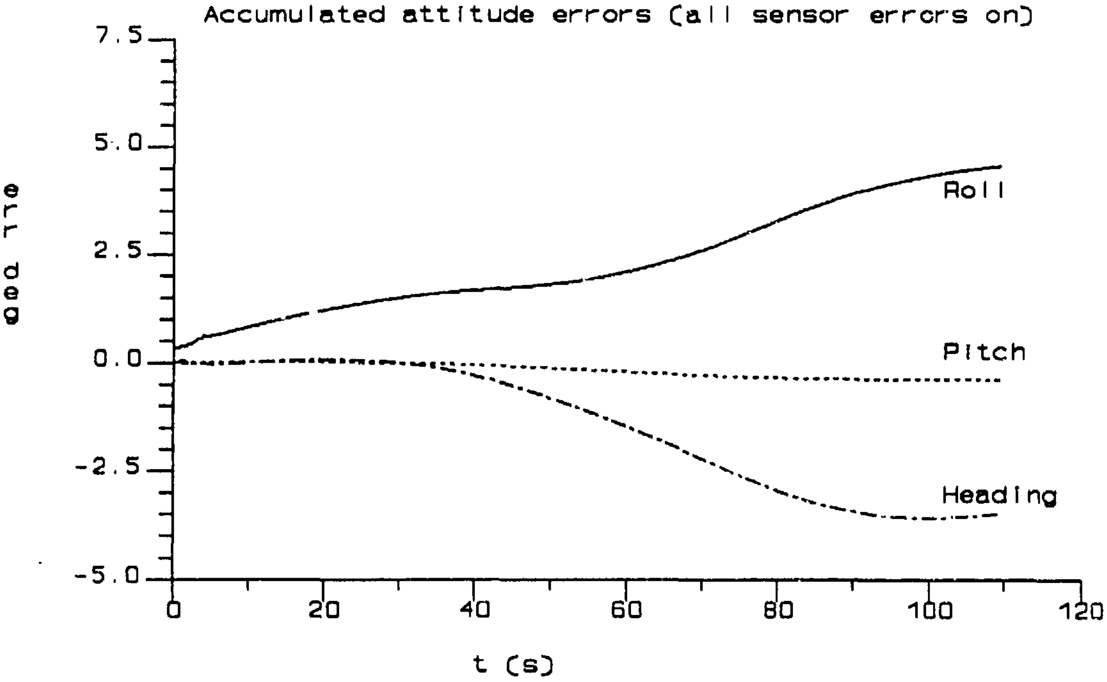

Fig. 3-4: Accumulated attitude errors when all inertial sensor errors are turned on.

4.0 SUMMARY

In this brief note on some positioning sensors that would meet the requirements of the long range indirect fire munitions, one candidate was explored in some depth; positioning by on-board inertial components. Simulation results were presented which showed that readily available inertial components could satisfy the performance requirements. In particular, Table 3-4 is useful in helping to define the required quality of each of the inertial sensors.

APPENDIX A. POSITION ERROR PLOTS FOR INDIVIDUAL INERTIAL ERRORS

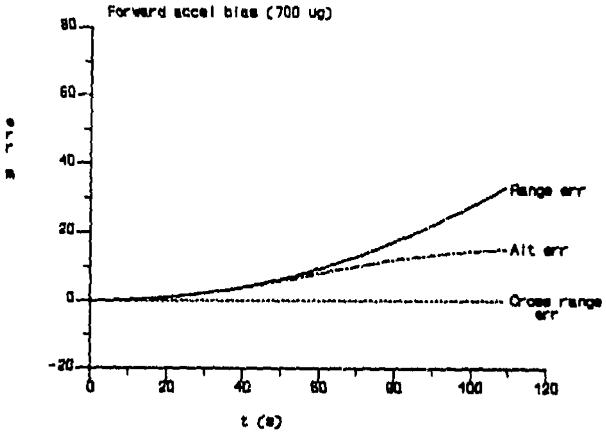

Fig. A-1

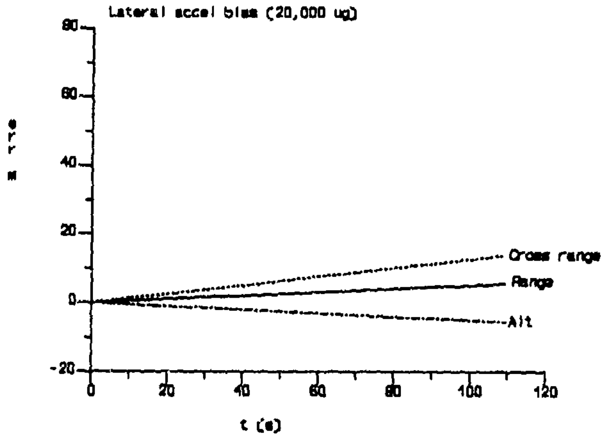

Fig. A-2

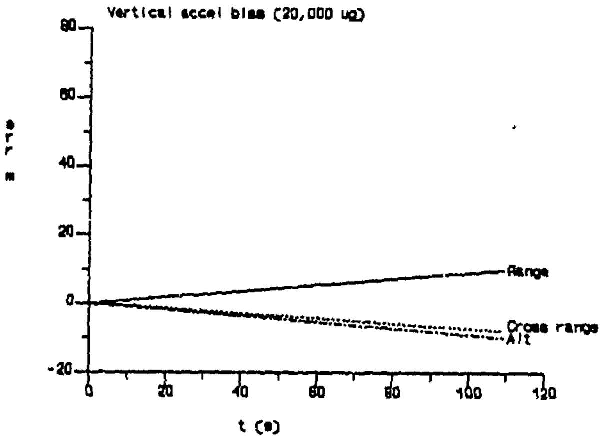

Fig. A-3

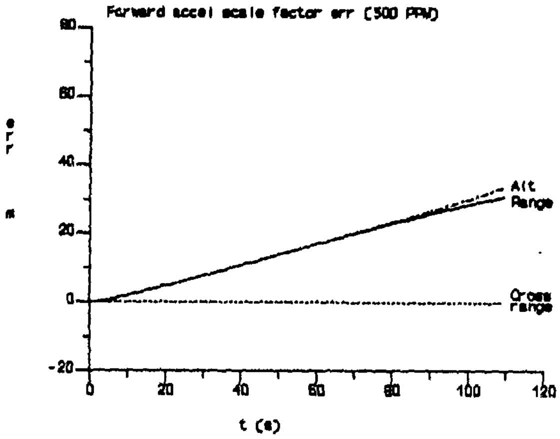

Fig. A-4

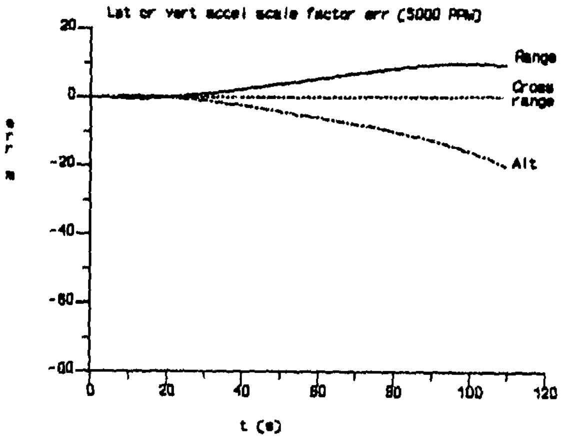

Fig. A-5

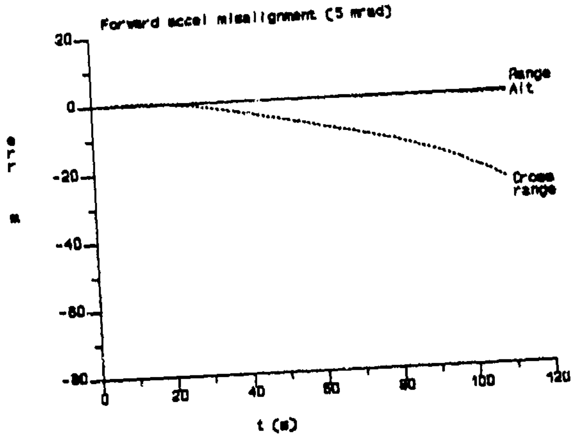

Fig. A-6

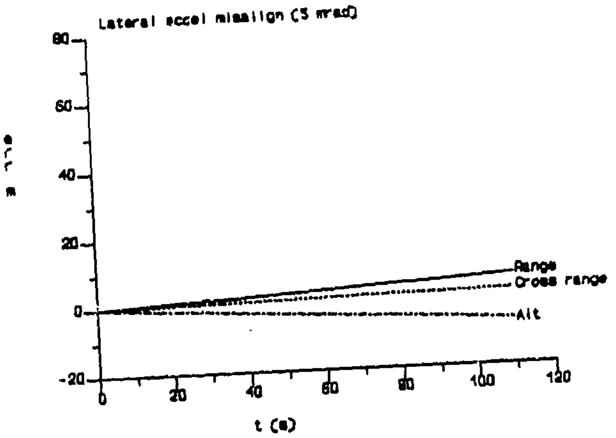

Fig. A-7

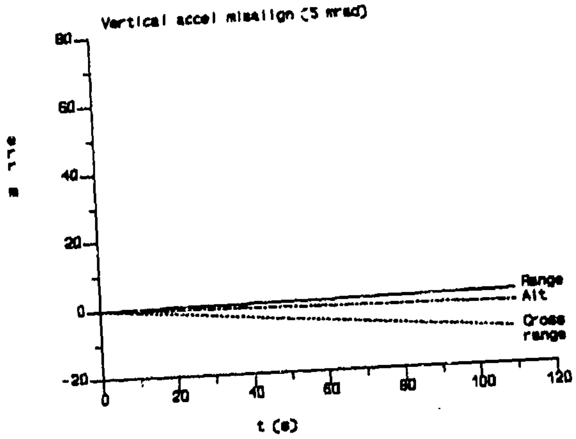

Fig. A-8

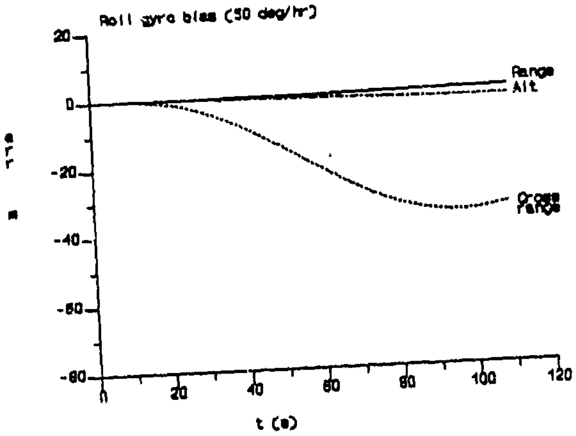

Fig. A-9

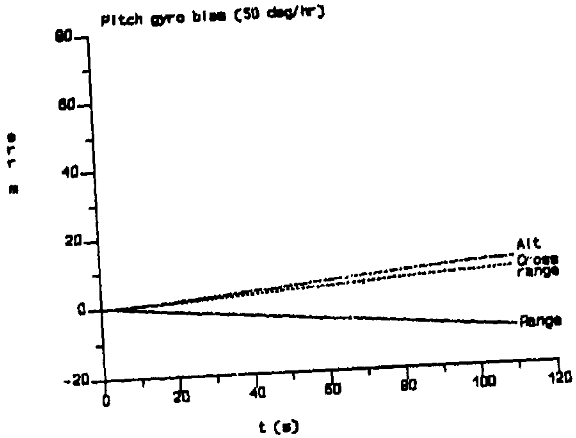

Fig. A-10

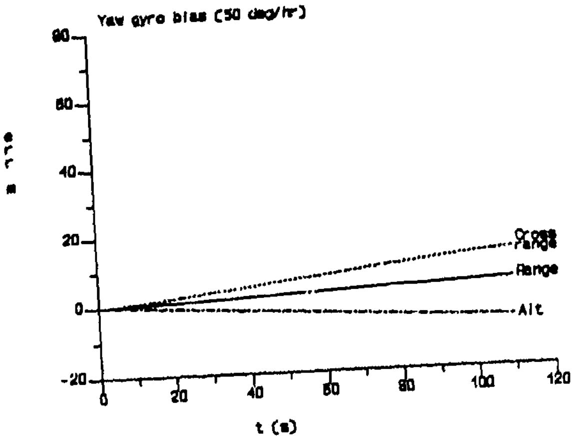

Fig. A-11

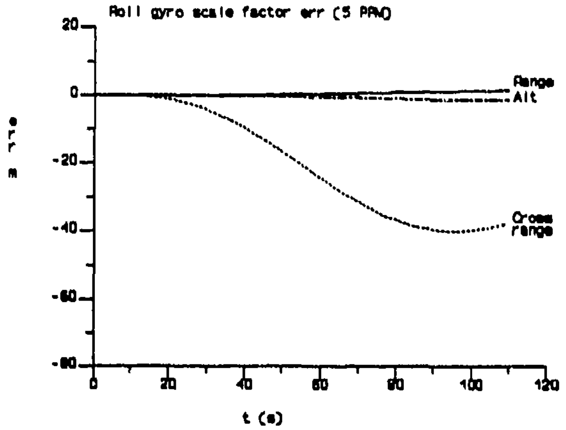

Fig. A-12

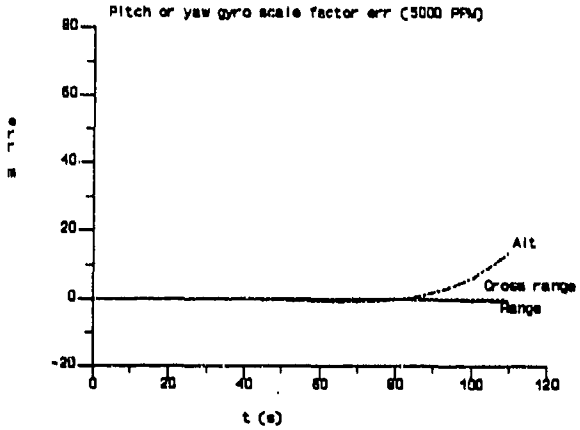

Fig. A-13

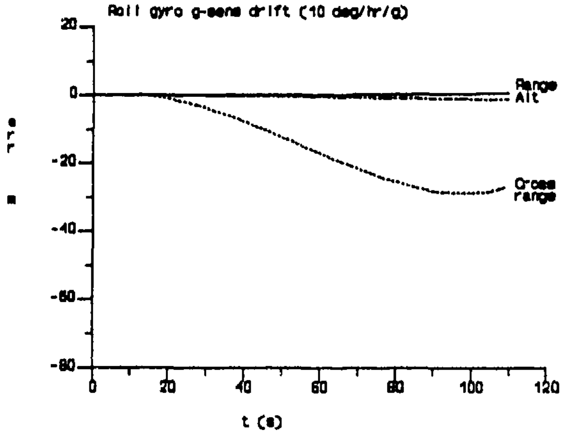

Fig. A-14

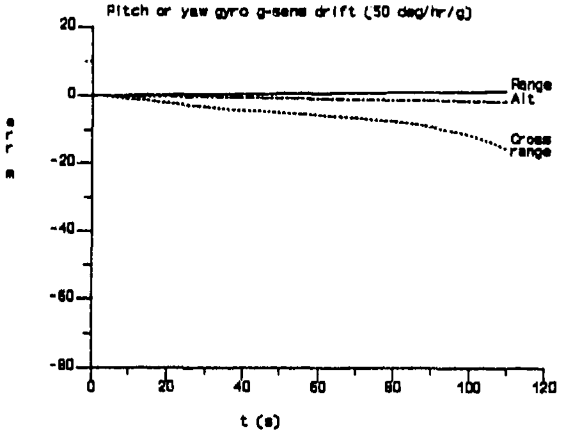

Fig. A-15

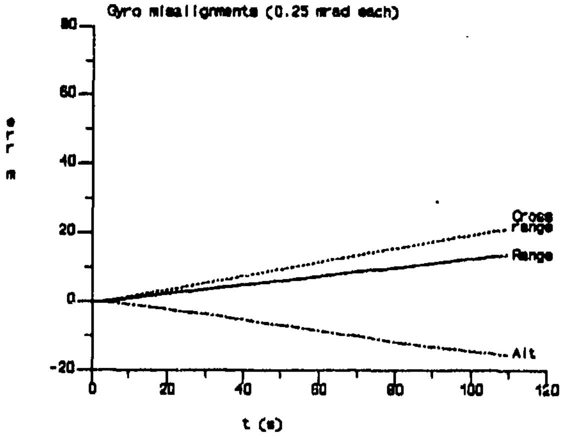

Fig. A-16

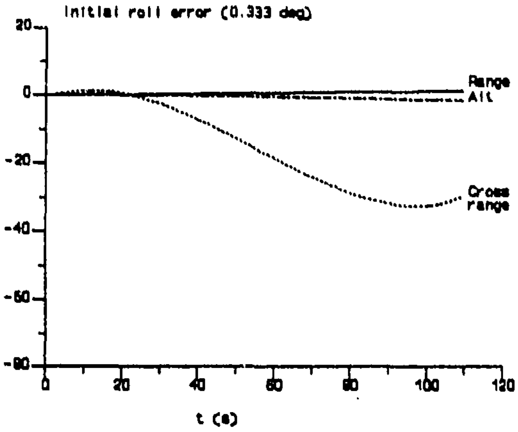

Fig. A-17

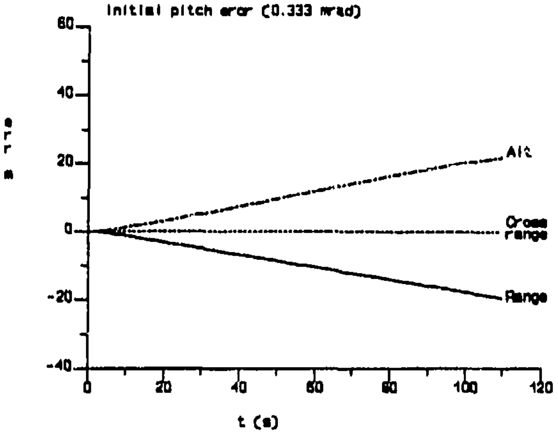

Fig. A-18

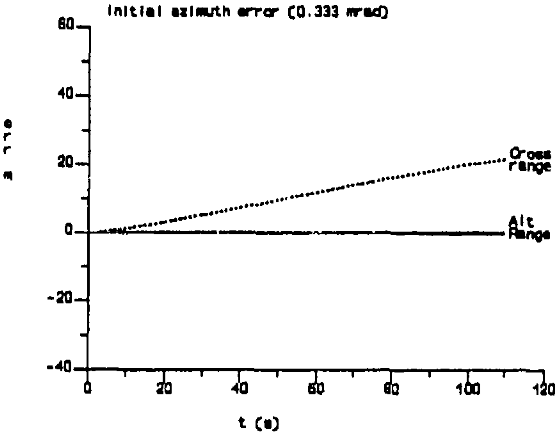

Fig. A-19

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With continuing advances in rocket propulsion systems for extended-range artillery, it is possible that operational ranges of 60 kilometers (up from the current 30 km) will be the norm within 20 years. However if the munitions are unguided, the dispersion errors at these long ranges, due to such factors as muzzle velocity errors and down-range weather conditions, make effective use of such rounds prohibitively expensive. This report investigates the performance required of inertial components that could be used for an onboard guidance system that would enable the rocket to determine its position to a sufficient level of accuracy. The high dynamics of the launch environment and the relatively short flight times make for unusual conditions for an inertial navigation system. It is shown that some components are of critical importance and must be of high performance (thus of more expense) while others are of much less importance and savings can be made when specifying the instruments for those functions.

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