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UCRL-51130 Vol. 2

**FINAL REPORT ON THE DEVELOPMENT
OF THE GEOGRAPHIC POSITION LOCATOR (GPL)**

**Volume 2
Executive Summary**

J. D. Salisbury

Nov. 2, 1972

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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NOTICE

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Preface

Navigation without external reference during a mission requires inertial navigation technology. If the mission length is more than a day or so, the position errors of the inertial navigator can become unacceptably large. However, if the mission includes stationary periods, the navigator's errors can be dramatically reduced by the effective use of these periods.

The idea of using the stationary periods to minimize inertial navigator errors has resulted in a concept called the Geographic Position Locator (GPL). A GPL is a completely automatic system with the following key functions:

- Sensing whether it is moving or stationary.
- Minimizing accumulated position errors during stationary periods.
- Comparing its computed position with stored position data and, as a result of this comparison, executing a prescribed action.

The GPL concept was investigated under the PASSPORT program. PASSPORT was conducted by the Lawrence Livermore Laboratory under the joint sponsorship of the U.S. Atomic Energy Commission's Division of Military Application and the Department of Defense's Advanced Research Projects Agency.

The objective of PASSPORT was to determine the feasibility of the GPL concept and to evaluate the capabilities of a GPL system using commercial-quality inertial components.

This objective was achieved. The excellent performance capabilities of the GPL error reduction techniques that resulted should make them attractive for use in any inertial navigation system that is occasionally stationary during a mission.

The GPL final report, UCRL-51130, consists of the following volumes:

1. Summary
2. Executive Summary
3. Non-Linear Aspects of System Performance
4. Error Reduction
5. Motion Sensing
6. Performance
7. Field Considerations
8. Technical Support
9. WISPIN—An Inertial Navigation System Simulation Program
10. DINSII—A Navigation Data Reduction Program
11. Data Reduction Kalman Filter—Subroutine
12. Data Reduction A3FIX—Subroutine
13. Vulnerability (SDI)

The GPL development project was primarily staffed by an average of about 10 persons at LLL. In alphabetical order, those persons who were on, or directly associated with, the Livermore staff engaged in this project and who made significant and original contributions to the success of the GPL program were:

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W. A. Niven

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R. M. Refowitz
A. Schiff
W. M. Stevens

Major offsite support was provided by contracts with the Charles Stark Draper Laboratory of the Massachusetts Institute of Technology (MIT), The Analytic Sciences Corporation (TASC), and EG&G Inc.

As with any project of this scope, the generous assistance of many other people, both within and without the Laboratory, was of great help and is gratefully acknowledged.

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Contents

Abstract	1
Introduction	1
GPL System Description	2
Hardware Considerations	3
MAP	3
Computer	4
Performance Improvement Concepts	5
System Errors	5
Error Reduction	8
Optimal Kalman Filter	8
Suboptimal Kalman Filter	10
Motion Sensing	10
Motion Characteristics	11
Motion Sensors	11
Transient	12
Azimuth	12
Careful	12
Performance	13
Navigation Performance of GPL-A	13
Optimal Filter Results	13
Analysis of Results	14
Performance with Frequent Stops	15
Oscillatory Error Removal	15
Comparison of the Suboptimal and Optimal Filters	16
Summary of Navigation Performance	16
Conclusions	17

VOLUME 2 - EXECUTIVE SUMMARY

Abstract

The Geographic Position Locator (GPL) is a small, self-contained unaided system for accurate, long-term, land-based inertial navigation. It uses the normal rest periods of land-based systems to reduce system errors and improve the subsequent navigational accuracy.

Operation can be fully automatic, with a motion-state sensor activating the error-reduction process during stationary periods. Stored map information for

automatic comparison with computed position, and selective response based on the comparison, also could be part of a fully-automated GPL system.

Possible use of the GPL with nuclear weapons was the primary motivation of our program. The techniques developed, however, apply to other navigation systems where the mission includes occasional stops and external references are unavailable.

Introduction

The Geographic Position Locator (GPL) was designed to provide long-term geographic positional information without access to external references. An inertial navigation system (INS) is a necessary but not sufficient requirement for such a mission. Even high quality, state-of-the-art inertial systems normally need external navigation aids to provide high accuracy for missions of extended duration. Without such aids a mission involving several days of continuous inertial navigation results in a position error of many nautical miles (nm). If the mission includes stationary periods, however, we can reduce the position error considerably even without external data. The information that it is not moving with respect to the earth can be used to great advantage by the system.

The GPL achieves improved accuracy by using the INS outputs as measurements

for reducing navigation errors whenever some other indicator establishes that the system is at rest. The GPL mission calls for occasional periods of motion interspersed with periods of rest over a time interval of many weeks. It is possible to detect these rest periods with a motion sensor that uses only data from the inertial measuring unit. The motion sensor provides a velocity reference to the GPL by indicating that the true velocity is zero. Under these circumstances the INS-indicated velocities (other than zero) are errors; they can then be used to estimate other system errors.

The development program's objective was to determine the feasibility of the GPL concepts, using a commercial-quality INS coupled to an additional computer. The major program effort aimed to develop a sensitive motion/rest discriminator, to explore the theoretical

means for position error minimization during rest periods, to simulate the error-reduction techniques, and finally to evaluate them in the experimental system (GPL-A) under various assumed field conditions.

Design requirements for the GPL also include ruggedness, small size, low power and ability to deal with hostile environments. A GPL with these characteristics could have application to nuclear weapons and many other potential uses.

GPL System Description

The Geographic Position Locator (GPL) has three fundamental requirements:

- It must be capable of exercising a positive area control.
- It must be highly insensitive to accidentally or intentionally imposed environments.
- Its physical and logistic characteristics must be consistent with its intended operational uses.

Functionally, GPL is composed of three major subsystems—Navigator, System Condition Evaluator (SYSCON), and Responder—plus an integral standby power supply. See Fig. 1 for a block diagram of the system. Function of the subsystems are briefly as follows:

Navigator: computes position, compares it with stored information (MAP), and provides an appropriate signal to the Responder. Position is computed by an inertial navigation system comprising an inertial measuring unit (IMU) and the computer (NAV./E. RED.). In addition to navigation, the computer also carries out error minimizing procedures when the

The GPL system is described briefly in the next section. Subsequent sections describe the performance improvement concepts, system errors, error reduction, motion sensing and the navigation performance of GPL-A. Each of these is discussed in depth in the other volumes of this report.

The concluding section summarizes the results of the GPL program and our recommendations for future use of the GPL techniques.

system is motionless as determined by the motion sensor (MOTION).

System Condition Evaluator (SYSCON): identifies when the GPL is malfunctioning or when environments outside the design range are encountered.

Responder: receives signals from the Navigator and SYSCON, and provides an appropriate response.

The primary power source (EXTERNAL POWER) normally remains connected throughout a mission. The internal source (STANDBY POWER) provides power during short interruptions of the main power. The power is conditioned and distributed as necessary.

Although shown as separate blocks, the MAP and MOTION functions can probably best be integrated into the computer along with the navigation and error-reduction functions.

The system of Fig. 1 illustrates the basic elements needed for a GPL in its use with nuclear weapons. As stated previously, the GPL error-reduction techniques could be very effectively used

Fig. 1. Geographic Position (GPL) system.

in normal land INS applications or any INS use involving occasional motionless periods. In such uses, moreover, most of the elements of Fig. 1 would probably be unnecessary. The only requirements would be an INS with a computer of sufficient additional memory capacity for the error-reduction and motion-sensing functions.

The motion sensor is not essential in the ordinary land navigation application, but it is recommended as a simple means of achieving automatic operation and of discriminating against very noisy environments; i.e., environments which might be detrimental to the error-reduction process even if the vehicle were not moving.

HARDWARE CONSIDERATIONS

Some consideration was given to predicting the characteristics that might be the most important in future applications of a GPL system. Approximate specifications applying to the high-quality future GPL system model shown in Fig. 2 include:

Weight	20-50 pounds
Volume	1/5-1/2 cubic foot
Power	100-200 watts
Reliability	1000-5000 hours MTBF

A GPL of the size shown in Fig. 2 could be made now using commercial quality inertial and computer hardware together with suitable interface electronics. Its performance would be similar to what we have achieved in the GPI-A system. More accurate, small INS units, when they become available, could lead to even better performance.

Several commercial-quality inertial navigation systems of very small size have been under development by various industrial firms. Primary emphasis in their development was to reduce cost, size, power and mechanical complexity and increase reliability. All of this is expected to be achieved without greatly reducing position accuracy performance from what is now available in commercial INS's.

A trade-off between size and performance accuracy can probably be effected in the near future.

MAP

In the GPL system a means (MAP) must be provided for determining if the

Fig. 2. Model of a high-quality, small size GPL. Scale is in inches.

computed geographic position is within a prescribed geographic area. The problem of storing the area boundary with a given accuracy was studied with the objective of minimizing the storage requirement.

The MAP can best be stored in digital form in the memory of the GPL computer. In our study the MAP was undefined. It could range in complexity from a simple geometric shape to the irregular area of a large country with its boundary defined by natural features such as rivers, lakes and mountains. We covered the spectrum of possible area shapes by studying the worst case, an irregular area.

To give the reader some idea of computer storage requirements imposed by

MAP, India's boundaries can be stored to a useful accuracy for less than 1000 computer memory words. Probably most applications could be satisfied with only a fraction of this storage capacity.

"Field Considerations," Volume 7 of this report, contains our recommendations and a discussion of several methods we studied for MAP storage. Computation speed is not a problem. The problem amounts to approximating an irregular boundary with straight-line segments.

COMPUTER

The INS used in GPL-A had a computer with 4000 memory words. Our studies indicate that approximately 6000 words

(24 bits each) of storage will be needed for the GPL with a suboptimal Kalman Filter and 7000 words if the optimal Kalman Filter is used. This is the total

memory requirement including 1000 words for MAP storage. See Volume 7 for a more complete discussion of the computer requirements.

Performance Improvement Concepts

Making use of the stationary periods to minimize position errors was a key element of the GPL system. Many systems such as tanks, aircraft, and portable missiles, associated with mobility, actually are at rest with respect to the earth's surface most of the time. Relative to our problem, then, the question is how best to take advantage of these rest periods. What information is available when a system is stationary? How can this rest condition be sensed? Can the rest period be used without degrading performance if motion is unexpectedly resumed?

The first and most obvious step is to freeze the computed position when the system is stationary; properly done this action causes the accumulated error to be more nearly proportional only to the time the system is in motion rather than total elapsed time. This is only a step in the right direction, however.

It also seems obvious that the north and east indicated (computed) velocities

could be set to zero. But these velocity errors contain useful information, and there is a preferred way to reset them. For example, information can be extracted from the east velocity to give a partial estimate of longitude error. Simultaneously, we can reduce or eliminate other errors that would contribute to the future buildup of more position error. Thus, considerably more can be done than just to freeze the position and zero the velocity.

We have demonstrated in an INS that these performance improvement means can lead to greatly improved navigation. Their utility is limited by the characteristics of the system to which they are applied and the detailed interactions involved in their use. These factors are explored in the sections that follow. An estimate of the improvement to be expected in a particular application also requires, of course, a time-motion analysis of probable operational profiles.

System Errors

Many sources of error must be considered in the detailed analysis of an inertial navigation system. Most of these cause the INS to oscillate at its characteristic frequencies, with corresponding oscillations

in the errors of position and velocity. In general, the amplitudes of the oscillations grow with time, and they may become the dominant contribution to the total error in a short-term mission.

Fig. 3. Latitude error data from a continuous 72-hr test with unusually large 24-hr oscillation amplitude. The mean error is low, due to a low effective equatorial drift rate (0.0043 deg/hr).

However, oscillatory errors can be substantially reduced or removed when the system is at rest.

Figures 3 and 4 show the nature of the errors in latitude and longitude respectively. The data were taken from a 72-hr continuous run of the experimental GPL—an aircraft inertial navigation system,

modified for GPL experimental use, with a nominal position error growth rate of 1 nm/hr. This run was typical of those made to get long-term base performance data (without error reduction).

In this run unusually large 24-hr oscillations were generated, as shown in Fig. 3. The higher frequency modulation

is the Schuler (84-min) characteristic. The longitude error plot in Fig. 4 shows the oscillations as they appear in this error state.

Certain other errors, though non-oscillatory, are also of little concern because they are bounded. The latitude bias error is an example of this type. (The 82-min and 24-hr components of error oscillate about the bias value.) Note that

the latitude bias error in Fig. 3 is only 1 arc-min (1 nm) at 72 hr and that this would be the final error if the oscillations were correctly removed. This error is due to the equatorial drift rate (sum of gyro drift components that are parallel to the equator.)

There is another error source, in longitude, which is of prime concern because it is unbounded and increases faster

Fig. 4. Longitude error data from a continuous test of 72 hr. Note the Schuler (84-min) and 24-hr oscillations. The polar drift rate is derived from the test data and integrated to give the smooth curve shown here, which closely matches the mean longitude error.

than a linear function of time between rest periods. (By comparison, other errors are easier to control or make far less contribution.) This source is the drift rate of the "polar gyro," a hypothetical gyro whose drift is the sum of the components of gyro drifts that are parallel to earth's spin axis.

As an illustration, the polar drift rate was extracted from the test data and integrated to give a polar error angle plot (Fig. 4) which closely corresponds to the longitude bias error. Polar error angle remains after removal of the oscillatory error components.

In summary, if the oscillatory components of system error are properly

handled, the only remaining errors of significance are those due to the gyros. The latitude bias error, normally small, is due to the unknown drift rate of the equatorial gyro and the longitude error is due to the unknown drift angle which the polar gyro develops. Finally, a direction bias error, normally of small value, is produced by the unknown drift rate of the east gyro.

Computer simulations verify that the polar gyro drift rate is the primary error source. Analysis of experimental data also confirms this, as shown in Fig. 4. The following section on error reduction will explain how to reduce the effect of this error source.

Error Reduction

We have examined the nature of navigational errors and their relative importance to GPL. Some of the errors were oscillatory, usually with growing amplitude. Some were bounded. Most important to a long-term mission was the unbounded longitude error. We found that all these errors can be reduced and the oscillatory errors essentially removed during a rest period. However, the effectiveness of the rest period for error reduction depends in varying degrees on the length of time available, the technique used, and the time since the last rest period. Shorter navigation periods not only build up smaller errors, they also help the error-reduction technique make a greater percentage reduction of these errors.

Error reduction can be viewed, first, as a deterministic, directly calculable

problem and second, as a purely statistical problem. Damping is an example of deterministic error reduction. It was used as part of a simplified error-reduction technique. The statistical approach, epitomized by Kalman filtering, will be described in some detail since it was the most important aspect of the error-reduction methods.

Of the error-reduction methods we studied, the optimal Kalman filter and the suboptimal Kalman filter were judged to be the most important. These were implemented and tested in the experimental system (GPL-A).

OPTIMAL KALMAN FILTER

Kalman filtering is the most powerful of the various techniques available for estimating and reducing errors. The

Kalman filter requires more computer capability, however, than a simple deterministic method such as damping. But the small size of today's computers makes this a reasonable penalty in exchange for improved performance, rapid error estimation, and the ability to handle unobservable errors. (See volume 4, "Error Reduction" for more detail.)

A Kalman filter incorporates statistical information on measurement noise and system disturbances, e.g., random gyro drift rates, in the design. This additional information is the basis of the filter's improved error reduction performance.

The Kalman filter is optimal in the sense that it will minimize the difference between the INS errors and the error estimates at a maximum rate. This feature makes it possible to reduce errors substantially during very short rest periods.

It is possible with a Kalman filter to reduce some unobservable errors that deterministic methods cannot calculate. The filter algorithm computes the covariances between all the system errors. After the available measurements determine the observable errors, the filter uses the covariance to estimate statistically the unobservable errors. This is very important when applied to the error in longitude. The longitude error is the larger component of position error and cannot be directly calculated from velocity error measurements alone. A significant portion of the longitude error is correlated with the polar drift rate and the oscillations in the stable platform heading, however. Both of these errors can be determined from the velocity errors and can be used with the covar-

iances to make a "best guess" about the value of the longitude error.

As a control, we propagated the error covariance equations for the GPL navigator for 10 days without performing any error minimization. The resulting curves for RMS (root-mean-square) latitude and longitude errors appear in Fig. 5. The points were plotted at 24-hr intervals to exclude the 24-hr oscillations. Note the complete dominance of longitude error over latitude error.

Covariance simulations of optimal Kalman filter error reduction were conducted also over a 10-day interval but with one calibration period each day. The position error results are shown in Fig. 6. Comparison with the curves in Fig. 5 demonstrates the dramatic performance improvement possible with an optimal error reduction scheme; i.e., the errors were reduced by a factor of ten with calibration once daily.

Figure 6 exhibits the capability of the filter to reduce the RMS longitude error

Fig. 5. Long-term open loop position error performance.

Fig. 6. Long-term optimal Kalman filter baseline performance. The scallops are due to longitude error recovery.

each time calibration is performed. The partial error recovery is due to correlation of the longitude error (built up during the previous navigate mode) with the present value of polar gyro drift rate.

SUBOPTIMAL KALMAN FILTER

The suboptimal filter can operate on the data only after damping removes the oscillatory errors. Analysis reveals that the velocity signals in the damped navigation system are effectively equivalent to

direct measurements of the gyro drift rates. Thus, if heavy damping is applied to the navigation system, the original velocity measurements may be used as inputs to the reduced Kalman filter. (Ref. volume 4).

The filtering starts after damping settles the level and azimuth errors. The polar gyro drift estimate is fed back as a correction to the gyro drift rates of the system in such a way that the equatorial component of drift rate is unaffected.

In the optimal Kalman filter all significant system errors are modeled. Care must be taken to minimize the number of errors that are modeled or much more computer memory will be used than is necessary. This is because a large part of the required memory space increases as the square of this number.

The objective of the suboptimal filter was to reduce, as far as possible, the memory requirement. To achieve this end, the error-reduction technique uses damping for removing the system oscillations (oscillatory components of error). Position errors are then reset to their bias values, by deterministic means, and the greatly reduced Kalman filter is used only to estimate and reset part of the (unobservable) longitude error.

Motion Sensing

GPL techniques are based on the condition that the mission will include one or more periods of rest. Before these periods may be used to reduce the accumulated navigation errors, the system must first verify that it is at rest. (See Volume 5, "Motion Sensing" for more details.)

In the GPL, sensing of the motion state is complicated by ground rules that include deliberate attempts to deceive the motion-sensing feature. Simply stated, if the system can be moved without detection by the motion sensor, the primary mission of the GPL might be subverted.

If the threat of deceiving the motion sensor does not exist; for example, in normal land navigation, motion sensing signals could be supplied externally. This procedure is not recommended for three reasons, however: 1) we found it very simple to provide highly effective internal motion sensing. 2) The error-reduction process might be degraded by a rest period in a bad environment; i.e., an environment involving large amounts of vibration and/or shock. Correctly adjusted, an internal motion sensor would interpret this kind of rest period as motion and keep the GPL in the navigation mode, whereas the external means might not have this discrimination. 3) External connections invite potential problems. Furthermore, a navigation system that requires only a power source during its mission offers a maximum of convenience for installation and use.

An inertial navigation system provides a wealth of information about its own motion state. The GPL-A accelerometers, mounted on a stable platform, were sensitive to a few micro-g's. Pitch, roll and azimuth (heading) information could be resolved to less than 1 arc minute nominally, but the azimuth sensitivity was increased so that heading changes of as little as 4.5 arc seconds could be detected.

MOTION CHARACTERISTICS

Two types of motion can be ascribed to the GPL problem. "Gross motion" is characteristic of normal activity. We define "careful motion" as that intended to delude the GPL by moving it gently enough to avoid triggering the motion sensor. Gross motion, although simple to detect,

must be detected rapidly to prevent degradation of the error-reduction activity.

Interaction between the motion sensor and the optimal error-reduction technique is much less critical. This is because the INS is in navigate mode at all times. The navigation function remains unchanged during error-reduction. The motion-sensor function, in this case, is to determine whether or not to send to the error-reduction filter the INS measurements of heading and velocity. Furthermore, the filter does not require continuous measurements. In the GPL-A experiments, measurements were used once per minute for error-reduction. Thus, it was necessary only to ascertain that the velocity and heading indications were uncorrupted by motion during the previous one-minute period in order to use them as measurements—a less demanding requirement than that of the sub-optimal filter.

For either filter, the more difficult task of the motion sensor is to detect very careful motion.

MOTION SENSORS

Three types of motion sensors were developed in the GPL program as follows:

1. TRANSIENT—fast response, medium sensitivity
2. AZIMUTH—slower response, more sensitivity
3. CAREFUL—very slow response, high sensitivity

The nominal characteristics of these motion sensors are given in Fig. 7. For uniformity and ease of comparison the sensitivity of all motion sensor types is given in acceleration units (g) even though

Fig. 7. Motion sensor characteristics.*

*Note that, for ease of comparison, sensitivity is given in acceleration (g) units, even though the azimuth type responds only to change of heading. This is permissible because motion invariably causes heading changes

the azimuth type responds only to heading (angular) changes. This is a useful way to characterize the azimuth type and it is based on our observation that motion, even with great care, is practically impossible without a consequent change of heading. Azimuth was used as this was the most sensitive axis of the GPL-A system.

Transient

When motion starts, velocity changes. This is the basis of the Transient motion sensor operation. Velocity is continually monitored for changes. If the velocity change exceeds a given amount during a given period of time, this is interpreted as motion. Conversely, if the change of velocity is less than the preset amount during the time-period "window," this is interpreted as rest. The values of velocity-change and time-period that were used in GPL-A were adjustable.

When going from motion to rest it is desirable to test the rest condition for

several time periods. If no violation of the rest condition occurs during this longer time period, the GPL changes to the error-reduction mode. This procedure prevents frequent and possibly undesirable changes to and from the rest mode during short stops or from anomalous transient behavior of the system velocity indications.

Azimuth

The Azimuth motion sensor works on the same basis as the transient type except that it uses change of heading instead of change of velocity.

Careful

A somewhat more complex formulation was used in the Careful motion sensor design, based upon two hypotheses: (1) there are spectral differences between the background (ambient) vibration and that due to vehicle motion, (2) these differences can be detected by filtering the accelerometer outputs over long enough times to distinguish them and make a decision about the motion state.

This motion sensor was not tested in the GPL-A system because of its greater implementation requirements and because of the excellent performance of the Transient and Azimuth motion sensors. On the basis of our tests, these sensors adequately covered the entire motion spectrum. The Careful motion sensor is described here for completeness, in case an application should arise that could not be satisfied by the Transient and Azimuth motion sensors. It should be noted, however, that the Careful motion sensor's performance capability is based on theoretical work and not actual tests.

PERFORMANCE

The Transient and Azimuth motion sensors were integrated into the GPL-A system along with the suboptimal error reduction technique. Its interaction with the motion sensor is much more complex and demanding than the optimal error-reduction technique. Successful motion sensor performance with the suboptimal technique, therefore, would more than prove its ability to perform adequately with the optimal technique. Time was not available to test motion sensors with both filters.

Tests were performed:

1. With the gentlest starts we could provide.
2. With simulated normal field operation.

3. With the most severe starts and stops the test vehicle could do.

The GPL-A system was completely automatic—making all decisions about its motion state and controlling whether the GPL-A was in the navigate or error-reduction modes. All three parts of the tests were successfully accomplished with many starts and stops. Sudden motion, no matter how severe, was adequately handled and caused no degradation in performance of the suboptimal filter.

Despite their tolerance to a reasonable operating level of background vibration, the motion sensors detected our best efforts to produce careful motion. The tests consisted of carefully pushing the test vehicle on a smooth surface. In all cases the sensors detected motion in less than 6 inches of travel.

Navigation Performance of GPL-A

OPTIMAL FILTER RESULTS

We ran a wide variety of tests on the GPL-A experimental system to evaluate the optimal Kalman filter error-reduction technique. A brief summary of those tests is presented here. For more complete and detailed analyses, see Volume 6, "Performance."

The data discussed here are from eight experiments, representing about 350 hr of testing. These runs exhibited a broad spectrum of performance because of the variety of test conditions and the random nature of the navigation system error sources. Certain observations can be made, however. The implementation

of a full Kalman filter as an on-line error-reduction scheme is definitely feasible and has been achieved in the GPL-A. Once the system computer program was debugged, the optimal filter technique operated reliably and with few surprises. A few initially strange results occurred because of inertial instrument imperfections that had been unobserved because of their subtle nature.

The performance of the optimal filter generally exceeded our expectations. On the average, the optimal filter brought about a six-fold position error reduction relative to the errors of the INS alone despite the generally excellent performance of the INS. Of course, better-than-normal performance

of the navigator makes the error reduction appear to be less effective. In all tests, however, filter performance exceeded that of the INS, reducing errors by factors of 3 to 20 for individual tests.

Analysis of Results

The position error history of one of the eight evaluation tests is presented in Fig. 8. It is given in terms of the root-sum-square of the latitude and longitude errors (radial error). The upper curve is the INS radial error. The lower curve is the filter radial error, i.e. the error that would remain if the INS position error were corrected by the filter estimates. The times in the navigate mode

Fig. 8. Run 743 radial errors.

Fig. 9. Mean radial errors for the INS and the optimal filter.

(NAV) and the calibrate mode (CAL) are indicated on the figure.

In an attempt to quantify the performance of the runs, we averaged the errors for both INS and filter for each run and called this average the "mean radial error." The averaged performance for each test, as well as for all tests combined, is given in Fig. 9. The optimal filter estimation errors covered a wide range: 0.2 nm to 2 nm. The mean-radial-error growth-rate estimated for the optimal filter is about 0.36 nm/day; this is about 1/6 the mean-radial-error growth-rate in the tests for the uncorrected INS.

Performance with Frequent Stops

The preceding data demonstrates acceptable performance under adverse conditions; e.g. operation in the NAV mode for 22 hr and in the CAL mode for 2 hr each day. As a matter of interest we investigated the GPL's navigation capability under more favorable conditions, involving navigate periods of only 30 min. The NAV/CAL ratio is estimated at between 60 and 100, allowing less than 1/2 min for calibrations.

Figure 10 shows the precision navigation capability of the GPL-A using the optimal filter under these conditions. Actual performance of the filter was even better than indicated, since most of the variations were due to experimental limitations.

Oscillatory Error Removal

The previous analyses include the effects of the INS oscillatory error components and the ability of the filter to estimate and compensate for them. Because of the unusual requirements for GPL-type

error removal, however, the treatment by the filter of the oscillatory part of the errors seems worthy of separate comment.

In the usual case, removal of the INS oscillations is a trivial operation. This is because it is done at a known location and damping can be used without regard to its effects on position. When position error is unknown, however, removing oscillations is no longer trivial. Failure to determine both magnitude and phase of the oscillations brings in an unknown amount of position error bias from the damping action. The determination is complicated by the long periods of the oscillations. Despite this complication a full filter such as the optimal filter can, in a few minutes of measurement, form a very accurate estimate of the oscillatory content of the errors and remove or compensate for them.

Fig. 10. GPL-A performance using frequent brief stops.

The Kalman filter therefore is a superior way to achieve "damping." The oscillations may be removed by direct feedback correction to the INS or by propagating these error estimates and using them to correct the INS output.

COMPARISON OF THE SUBOPTIMAL AND OPTIMAL FILTERS

The suboptimal Kalman filter was tested in a manner similar to that of the optimal filter. As well as we could determine, the ratios of performance improvement were approximately the same (overall ratio of INS mean error to filter mean error). However, the INS errors appeared to be about two times larger during the tests of the suboptimal filter.

Intuitively we expected better performance from the INS part of GPL-A by using frequent resets, a requirement for the suboptimal filter. The indications are just the opposite. There is evidence to suggest that part of the advantage of using a suboptimal error-reduction technique may be lost because of its use of resets and damping; that is, the well-settled INS appears to have a greater rate of error-growth than the system with oscillatory errors already established, especially the higher frequency components. (For more detail see Volume 3, "Non-linear Aspects of System Performance.")

In the suboptimal filter the oscillatory errors must be removed by damping prior to the estimation process. The damping

process uses 12 to 20 min of the first part of the error-reduction mode. During this time no data is available to the filter for estimating polar gyro drift rate and longitude error. Thus short stops are relatively ineffective for error reduction using the suboptimal technique. The optimal filter, on the other hand, can use measurements for error estimation at the start of the error-reduction mode. Just a few measurements can provide a dramatic decrease in the estimation errors.

SUMMARY OF NAVIGATION PERFORMANCE

Our experience with GPL-A shows that the optimal filter is a very effective error-reduction technique. It can use motionless periods of only a few minutes duration. It appears to be most effective in the open-loop mode with infrequent or no resets depending upon the mission time duration or the magnitude of its estimation errors. A slight drawback is its greater computer memory requirement, but this is only a 10-20% increase over the suboptimal filter.

Under somewhat restrictive conditions, involving relatively long and infrequent rest periods, the suboptimal filter can achieve performance comparable to that of the optimal filter. The suboptimal filter's main drawbacks are its inability to use short rest periods or to operate open-loop, and its more complex interaction with the motion sensor.

Conclusions

The GPL concept of using the stationary periods of otherwise mobile equipment for self calibration offers a major opportunity for navigator performance improvement. Compared to continuous navigation, computer simulations predicted that the RMS position errors could be reduced tenfold in a 10-day mission even if suitable stationary periods occurred as infrequently as once a day. Performance evaluation of GPL-A tests tended to confirm this prediction, although for experimental reasons we made no test runs that long.

Our studies and experiments revealed a number of attributes which may have broad utility. For example, we attained a significant amount of longitude error recovery. Even under conditions of unknown position error and navigate periods of several hours, the optimal Kalman filter can achieve oscillatory-error recovery using calibration periods as short as 5 min.

As predicted, the suboptimal Kalman filter scheme was able to approach the performance of a fully optimal Kalman filter. For the general GPL application, however, the suboptimal filter may not prove to be significantly less demanding of computer needs (only 10-20% less) than the optimal filter. Furthermore, the suboptimal filter's "simplifying" aspects actually introduce additional complexity in system operation and in the motion sensor interaction. The damping sequence discards Schuler error information and prevents the use of short calibration

periods. Also, there are fairly definite indications that, for the GPL-A at least, the INS does not perform as well (by about a factor of two in average position error) under the closed-loop or reset mode of operation required in this scheme, as it did open-loop.

While we cannot generalize that all of these comparisons would apply equally to GPL's using other INS's, our observation is that a GPL with the optimal Kalman filter more than justifies its requirement for additional computer memory. We recommend, therefore, that the optimal filter be used in future GPL systems or for improving performance in any INS applications involving stationary periods.

We developed three motion sensors and implemented and tested two of them in GPL-A. We determined from the tests that the motion sensors could be set for adequate sensitivity to careful motion and still tolerate normal levels of background vibration. Also, we verified that they could detect our most careful attempts to move the test vehicle and still change modes from calibrate to navigate under severe acceleration without detriment to the navigation accuracy.

Finally, the GPL concepts have been validated in theory and test. They offer markedly improved performance from any inertial navigator which comes to rest occasionally, without expensive instrument changes or external aids. The techniques should be useful for a wide range of applications.

NOTICE

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