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FLUIDIC HEADING SYSTEM STUDY: SUMMARY REPORT, (U)
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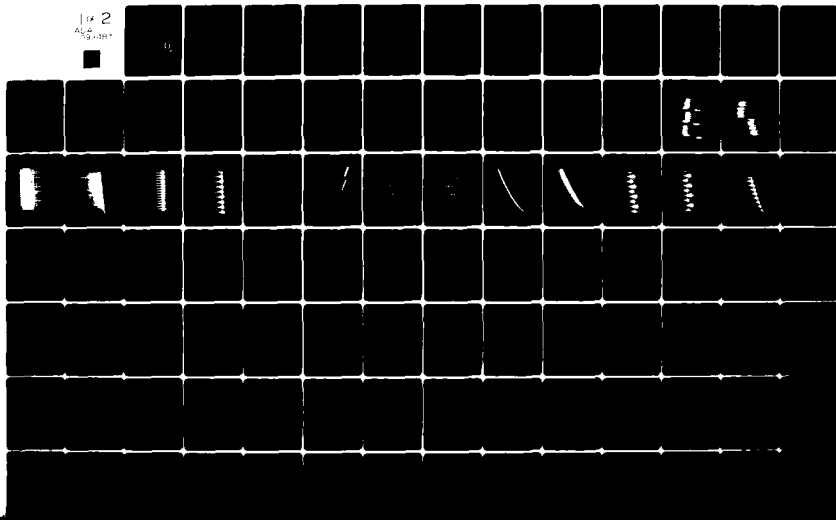
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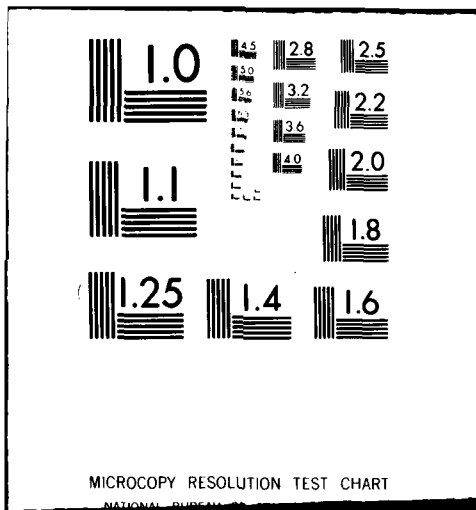
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Fluidic Heading System Study: Summary Report

By Abraham Finkel

Prepared by

The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20810

Under contract

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**U.S. Army Electronics Research
and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783**

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1. INTRODUCTION

1.1 Statement of Task

The purpose of this study was to investigate the feasibility of incorporating a fluidic angular rate sensor into a heading sensor system. The fluidic sensor may offer a cheap and rugged alternative to the rate gyro. A heading sensor of this type would find application in armored vehicles where a magnetic compass cannot be used. Goals for the system are low production cost ($< \$6,000$) and a drift rate of 0.8 deg per hour, although a higher drift rate may be acceptable in some applications.

1.2 Principal Conclusions and Recommendations

- (a) The fluidic sensor (including necessary fluidic amplifiers) demonstrates sensitivity of the required order of magnitude.
- (b) Drift characteristics under laboratory conditions are encouraging.
- (c) A key element (a transducer which converts pressure to an electrical signal with the necessary stringent requirements) is yet to be demonstrated and developed.
- (d) Many important environment characteristics are yet to be determined with precision.
- (e) Essential environmental tests should be applied to an integrated sensor-transducer package.
- (f) Certain effects such as the long-term equivalent drift under vibration are best measured by integration of the output. A high-quality continuously rebalanced integrator should be developed. An integrator of this type will likely be required to furnish angular incremental data to the computer.
- (g) Modern microprocessors can handle the computation burden. Thirty-two bit precision will be required with a sampling frequency of about 100 per second.
- (h) The main thrust of further effort should be directed toward the construction of an integrated sensor-transducer package before conducting precision environmental tests.

2. SYSTEM CONSIDERATIONS

2.1 Description

For a vehicle whose orientation is perfectly horizontal (no pitch or roll), a heading may be obtained by simply integrating the angular rate of the vehicle's vertical axis. Hence, for such a single axis system, a single angular rate sensor is sufficient. With pitch and roll present, large errors would result and it is necessary to measure angular rates about all three vehicle axes. The required computations are, of course, much more complex and are briefly outlined in Appendix A.

At some point, digitizing is required so that computation may proceed with the necessary accuracy. It would be possible to sample the angular rate sensors directly and enter rates into the computer. Noise and vibration are apt to make this approach unworkable unless strong filtering is employed, in which case vital rate information may be lost. Furthermore, a rate resolution equal to the desired drift rate of 0.8 deg/hr (0.0002 deg/s) is required. If the vehicle's maximum angular rate is 40 deg/s, an 18-bit analog-to-digital conversion is implied for each sample.

A more practical approach utilizes angle increments as the basic unit. Angle increments are obtained by integrating the rate sensor output and sampling the integrator output. Rapid sampling is still required to keep the increments small, since knowledge of varying velocity between samples will be lost. The computational algorithm assumes constant velocity between samples, although it is possible, with added complexity, to estimate acceleration and higher-order terms utilizing more than one sample interval. The integration which takes place prior to digital computation effectively filters noise and properly reacts to high-frequency motion, thus giving correct angle increments. A carefully constructed pulse-balanced integrator can circumvent the need for 18-bit readout while maintaining 18-bit sensitivity to any accumulated angular increments by virtue of the memory aspect of the integrator capacitor. The features of this type of circuit will be described at the end of this section.

A system would therefore take the form illustrated in Figure 1.

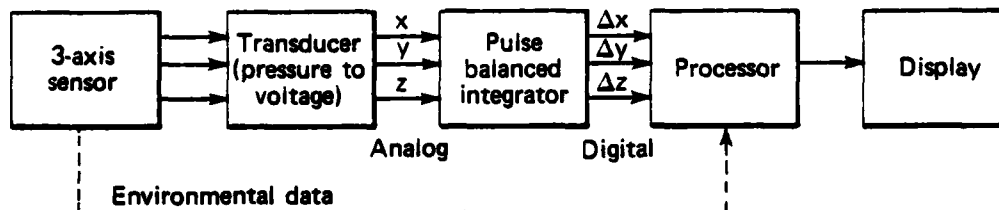


Figure 1 Heading sensor system block diagram.

The transducer need not be limited to a voltage output as shown. The integrator block would be modified to accommodate other types. In particular, if a pressure-to-frequency transducer were available, the integrator would simply be a counter. To the extent that the sensor-transducer combination cannot be sufficiently isolated from the environment, an additional data path to the computer is shown to allow for proper compensation. (Of course, transfer functions must be stable and known with precision.)

2.2 Operation

The operator will put the computer into one of two modes: ALIGN or NAVIGATE. In the align mode, start-up information must be fed into the computer so that it can calculate initial values for the elements of the attitude matrix and earth-rate components. Entry could be made via either a simple keyboard or a number of switches. The required input data are latitude and pitch, roll, and heading angles.

Latitude must be known so that the effect of earth rate may be properly accounted for. Pitch and roll angles may be read from gravity-sensitive devices (e.g., a gimballed platform with level indicators). Initial heading must be determined with reference to a known direction. Note that the computer will not properly calculate departure from an arbitrarily defined initial heading. The absolute heading must be known to enable calculation of earth rate effects. The gyrocompassing technique of determining initial alignment, conventionally used in inertial navigation systems, requires very accurate sensing of earth rate and does not appear to be within reach for the present fluidic sensors.

With the initial alignment procedure complete, the stationary vehicle should sense no motion with respect to the ground. Nonzero outputs are due to sensor bias, and an observation period is required to determine the magnitudes (and rate of change, if uniform). Bias (and bias rate) are thus known corrections to be applied during the NAVIGATE mode. Advantage could be taken of any subsequent vehicle stops to obtain updates on the sensor bias.

The computer is switched to NAVIGATE prior to the start of vehicle travel. Updating of the attitude matrix and display of heading then proceeds automatically.

2.3 Microprocessor

The computational requirements for one particular algorithm are outlined in Appendix A. Thirty-two bit precision is required, with updating at a rate of about 100/s. A 16-bit microprocessor is a logical choice with the possible use of a hardware multiplier if execution time must be improved. Variations from a basic configuration to provide various compensations will not have major impact on either cost or execution time (e.g., look-up tables to modify the transfer function). A significant simplification could be made if no compensation at all were required, for then power-of-two angular increments could be used as multipliers, resulting in simple shift operations. Some simplification of the algorithm may also be possible by changing the reference coordinate system, as described in Appendix B.

For high-volume production, development and programming costs need not be considered. The cost of a fully packaged microprocessor with the program contained in masked read-only memory (ROM) will probably lie in the \$1- to \$2-K range. As an example, a prewired and assembled Texas Instruments module (TM 990/101M) containing memory is available for \$500 to \$600 in production quantities. The microprocessor component alone (TMS 9900) is available for \$30. A full-temperature military version (SBP 9900AM) costs \$400.

2.4 Integrator

Considerable dynamic range must be exhibited at the output of the angular rate sensor. The sensor must be capable of responding to both the maximum angular rate (≈ 40 deg/s) and the allowable drift rate (≈ 0.0002 deg/s), a range equivalent to 18 bits. However, if integration precedes the computer, sampling of the integrator output requires only that the readout resolution be sufficient for accurate updating. Thus, if 10 ms

sampling is used, the maximum angular step is 0.4 deg, while a resolution of 0.04 deg may be sufficient provided that the remaining angle increment less than 0.04 deg is retained and added to the next increment. Despite the coarse angle readout, there is no accumulation of errors. These properties are exhibited by the pulse-rebalanced integrator shown in simple form in Figure 2.

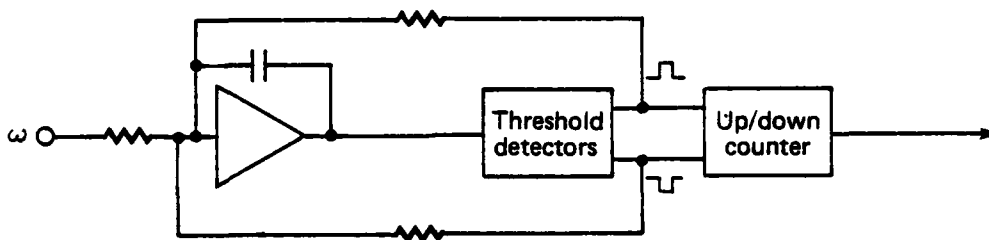


Figure 2 Pulse-rebalanced integrator.

The integrator output represents angle. When a positive or negative threshold equal to the least significant readout bit is reached, a precision pulse is generated to rebalance the integrator. The change of integrator output voltage due to the pulse must equal this resolution angle. The pulses drive a counter which is read out periodically by the processor.

While the readout need only consist of a few relatively coarse bits, the bias and drift at the integrator input must still satisfy the 18 bit requirement. This is readily achievable with good quality modern operational amplifiers and careful design. Changes of components or charge quantities result in scale factor errors. Scale factor stability of 0.1 to 1% is tolerable provided that such changes apply uniformly to all segments of the transfer function. Innovative circuit design will be required to guarantee equal scale factors for positive and negative inputs ($\approx 0.01\%$).

This circuit is in reality a voltage-to-frequency converter with the resulting pulses counted to develop angle increments and will be necessary to accommodate a pressure-to-voltage transducer. If a pressure-to-frequency transducer of sufficient accuracy is developed, then, of course, only a counter would be required.

2.5 System Limitations

The heading sensor system cannot calculate position unless linear velocity (or acceleration) is also measured. Hence, the change of attitude due to travel over the earth's curved surface must be neglected. •

Travel over level ground of 70 miles from the starting point results in an apparent tilt of 1 deg. Bias errors also develop, since the effect of earth rate is not properly compensated. In particular, a north-south travel of 70 miles from the equator will cause the vertical axis to sense an uncompensated rotation rate of 0.25 deg/hr.

For missions of up to three hours, therefore, these errors will have little impact on system accuracy.

3. COMPUTER STUDIES OF SENSOR REQUIREMENTS

3.1 Purpose

It is relatively easy to see the effects of sensor errors in a single-axis system. A scenario of angular motion is multiplied by the normalized transfer function of the sensor (output vs. angular rate). The product is integrated over time to obtain the angle output. This may be compared to the precise angular position which is given by the integral of the input angular motion. Hence, for example, a perfectly linear, stable transfer function with an unanticipated offset of 1 deg/hr will simply accumulate an angular error at the rate of 1 deg/hr, regardless of the input scenario. Nonlinear transfer functions produce additional errors which are scenario-dependent due to a rectification effect which is equivalent to adding additional bias or offset.

For the full 3-axis system, there will be additional errors due to cross-coupling. It was always felt that, given a system which is not allowed to produce errors greater than, say 3 deg (1 deg/hr for a 3 hr mission), the 3-axis effects would not be drastic and that the simple one-axis system could be the basis of rule-of-thumb requirements on the sensors. However, to demonstrate the correctness of the intuitive conclusions, a computer simulation was performed. This simulation allowed for sensor bias and scale factor errors only. "Bias" should be considered to be due to all contributory factors: unpredictable offset, the effect of motion scenario upon an asymmetrical or nonlinear transfer function, and the rectification effects of vibration (discussed further in Section 6).

The following requirements for a successful computer analysis are somewhat incompatible:

3.1.1 Long simulated (vehicle) time

If 3-hr missions are contemplated, the full 3 hr should be simulated. Heading error may grow nonlinearly, and it would be incorrect to extrapolate the results of a shorter run.

3.1.2 Reasonably short computer time

If a multitude of runs is to be made so that many factors may be varied, a short run time is essential.

3.1.3 Highly accurate attitude updating

Typical similar computer studies derive "system" errors rather than errors due solely to sensor deficiencies. Contributing to these system errors are also the approximation errors inherent in the attitude-updating procedure. Accuracy is obtained by high-frequency updating which, of course, requires long computer runs and, even then, roundoff errors may become a factor.

3.2 Approach

The foregoing incompatible requirements may be satisfied through a slight subterfuge. The underlying vehicle scenario is described in terms of sine waves (a convenient mathematical representation is needed to enter 3-hr worth of motion into the computer). These sinusoidal waveforms are then quantized at sampling intervals which are short enough to preserve the basic nature of the motion; i.e., many samples per cycle. It is this quantized motion, a series of angular steps, which then becomes the assumed angular motion applied to the vehicle. Computer updating need be performed only when the angular steps occur. The three principal sources of computation errors are either eliminated or minimized:

(1) There is no varying velocity between updates since there is no vehicle motion between steps.

(2) The solution of the matrix differential equation required by the updating procedure involves a matrix exponential. In the normal algorithm, one or more terms of the series approximation will be used. With a large-scale computer and the relatively infrequent updating required by the quantized motion, an exact closed-form solution may be used.

(3) Computer roundoff error is considerably reduced due to the reduced frequency of updating.

To further reduce the total number of updates, only angular steps exceeding a prescribed minimum are allowed. If, at a sampling instant, the angular step were less than the minimum, no step at all would be allowed. Thus, if the scenario includes long periods of little or no motion, fewer computations are made, thereby decreasing both the errors and computer time.

As described elsewhere, a nine-element direction cosine (or "C") matrix describes the vehicle attitude. In this computer program, two such C matrices are updated at each angular step. The reference matrix, CREF, describes the actual vehicle attitude. The computed matrix, CCMP, describes the attitude obtained based on erroneous data from the rate sensors. Since heading error is of primary interest, heading is calculated from each of the matrices with the difference tabulated as the heading error. Whenever an angular step is encountered, the following three C-matrix updates are performed:

- (1) CCMP is updated for any rotation sensed since the previous angular step. A sensor bias will, of course, result in a fictitious rotation. Also, since the matrix is misaligned, earth rotation is not properly compensated for so that the computer thinks there has been some net motion with respect to the ground.
- (2) CREF is updated for the angular step, involving one, two, or all three axes.
- (3) CCMP is similarly updated for the angular step. In this case, the angular steps reflect the erroneous scale factors assumed for the angular rate sensors.

The exact, closed-form solution of the matrix differential equation is shown in Appendix C, along with an equivalent formulation convenient for computation.

3.3 Program Inputs and Outputs

To allow flexibility of vehicle scenario, angular motion of each of the three axes is specified in terms of angular amplitude and period for each of four successive intervals. The time at the end of each interval may also be selected. Any number of iterations of the four time intervals may be chosen to simulate any total vehicle time. Additionally, in one version, a steering instability (or Z-axis fluctuation) was superimposed.

The program as written also allows selection of latitude, initial heading, sampling interval, minimum angular step, and printout interval.

Output quantities tabulated are time, heading, tilt, and heading error. Since pitch, roll, and yaw are independently specified, the resulting attitude is fully determined. As

further discussed in Appendix D, symmetrical motion about the vehicle axes can result in a considerable attitude "creep." The tilt readout shows whether this effect is getting out of hand, resulting in an unrealistic scenario although, in any event, the ability of the computer to follow with acceptable error is the concern of these studies.

The final two columns of the readout are labelled DETCREP and DETCCMP. These list at each time the value of the determinants of the respective matrices. For many of the C-matrix updating procedures, a prime concern is the development of "skewness" or lack of orthogonality as updating proceeds. A property of an orthogonal matrix is that the value of its determinant is unity. The printout of DETCREP and DETCCMP is one way of checking that the matrix is being updated properly. A listing for this program is given in Appendix E. A selected number of computer printouts is reproduced in Appendix F.

3.4 Tabulation of Results

A quick look at the results under various conditions may be obtained by examining the heading at the end of 3 hr. For a fair comparison, we wish to exclude that portion of the error which is simply the final heading excursion multiplied by the scale factor error. Thus, if at a heading of 100 deg a system with a 2% scale factor error shows a heading error of 2 deg (of comparable sign), then there has been no error accumulation. The latitude is 45 deg unless otherwise indicated.

3.4.1 Z-axis motion only: continuous half sine waves of 90 deg amplitude repeating every 10 minutes

- (a) Z sensor scale factor 1.02; 1 deg/hr bias
accumulated heading error after
3 hr = 2.08 deg
- (b) Z sensor bias error only of 1 deg/hr
heading error = 2.85 deg
- (c) Z sensor bias error only of 1 deg/hr;
latitude = 0 deg
heading error = 2.70 deg
- (d) Z sensor bias error of 1 deg/hr;
latitude = 90 deg
heading error = 3.00 deg

[shows that at 90 deg LAT, where the Z axis is aligned to the earth's spin axis, a misalignment due to Z-axis rotation does not pick up additional errors due to earth rate. Also, the computation is exact.]

- (e) Z sensor bias error of 1 deg/hr; sampling interval reduced from 1.0 to 0.5 s
heading error = 2.85 deg (same as (b))
- (f) All sensors with bias of 1 deg/hr and scale factors of 1.02
heading error = 1.06 deg
(change of ≈ 2 deg due to cross axis effects)
- (g) Reduced Z amplitude of 5 deg; 0.1 deg angle no sensor errors
heading error = 0
- (h) Reduced Z amplitude of 5 deg; 0.1 deg steps; Z sensor bias of 1 deg/hr
heading error = 2.85 deg (same as (b))
- (i) Reduced Z amplitude of 5 deg; 0.1 deg steps; all sensors with 1 deg/hr bias and scale factors of 1.02
heading error = 1.30 deg
- (j) Full Z amplitude; X, Y, Z scale factors 1.02; X, Y, Z biases of -1, -1, +1 deg/hr
heading error = 2.91 deg
(compare to (f); this choice of signs has increased error)

3.4.2 Full Scenario: Three Axes Motion

1st 100 s - X=10 deg amplitude, 10 s period
 Y=10 deg amplitude, 11 s period
 Z=90 deg amplitude, 1200 s period

next 100 s - no Y motion

next 100 s - no X motion

next 300 s - no X nor Y motion

(pattern repeats every 600 s)

1.0 s sampling

1.0 deg minimum angle step

- (a) Z sensor bias of 1 deg/hr
heading error = 2.83 deg
(almost identical to 3.4.1(b); no cross-axis effect with perfect X,Y sensors)
- (b) All sensors with 1 deg/hr bias
heading error = 1.84 deg
- (c) Bias errors (X, Y, Z) of -1, -1, +1 deg/hr
heading error = 3.71 deg
- (d) Scale factors of 1.02 on all sensors; no bias
heading error = -1.07 deg
- (e) Scale factors of 1.05 on all sensors; no bias
heading error = -2.73 deg
- (f) X, Y, Z scale factors of 0.95, 0.95, 1.05, no bias
heading error = -2.60 deg
- (g) Combined sensor errors: scale factor 1.02 and bias of 1 deg/hr on all sensors
heading error = 0.78 deg
(Note: (b) + (d) = 0.77 deg)
- (h) Combined sensor errors: 1.02 scale factor on all sensors; X, Y, Z bias of -1, -1, +1 deg/hr
heading error = 2.65 deg
- (i) Repeat of (g) with minimum step of 0.5 deg
heading error = 0.97 deg
- (j) Repeat of (g) with minimum step of 0.5 deg, 0.5 s sampling
heading error = 0.97 deg

3.4.3 Full scenario changed to eliminate simultaneous pitch and roll (X motion removed during 1st 100 s). Therefore, no Z axis coning motion. Sensor errors as in 3.4.2(g)

heading error = 0.47 deg

3.4.4 Full scenario changed to reflect higher frequencies as shown on charts of measured pitch and roll

A chart for one particular vehicle course shows high pitch and roll amplitudes of 10 deg and 5 deg, respectively. Those motions are in phase with a period of 2.5 s. A worst-case is simulated where this motion continues for the entire 3 hr. A single half-sine wave of yaw having 90 deg amplitude and a 200-s half-period is assumed every 600 s. In addition, a yaw fluctuation or steering wander is assumed to be continuously present with 3 deg amplitude and a 3 s period. The sampling interval is reduced to 0.3 s to accommodate these higher frequencies.

- (a) Z sensor bias of 1 deg/hr
heading error = 2.90 deg
(compare to 3.4.2(a) = 2.83 deg)
- (b) Z sensor scale factor 1.02
heading error = -1.48 deg
- (c) X, Y, Z bias errors of -1, -1, +1 deg/hr
heading error = 3.63 deg
(compare to 3.4.2(c) = 3.71 deg)
- (d) Combined sensors errors: scale factor 1.02 and bias of 1 deg/hr on all sensors
heading error = 2.35 deg
(compare to 3.4.2(g) = 0.78 deg)

3.4.5 Full scenario changed to include coning motion

Since in-phase motion does not produce the serious coning effects of quadrature motion, the roll (Y) period was changed to 2.6 s, thereby giving a continuously varying phase difference between X and Y. There is now considerably greater creep of the vehicle both in heading and tilt. (See discussion of this effect in Appendix D). While somewhat unrealistic, the heading sensor system should still be able to follow with reasonably small error.

- (a) Z sensor bias of 1 deg/hr
heading error = 2.89 deg
- (b) Scale factor 1.02, bias of 1 deg/hr on all sensors
heading error = 4.58 deg

(c) Repeat of (b) but with steering wander removed

heading error = 4.70 deg

3.4.6 Full scenario changed to test for highest frequency pitch and roll

Most of the measured vehicle motion shows pitch and roll motion of 3 deg amplitude, 1.5 s period. An additional program was run with continuous X axis and Y axis motion of 3 deg amplitude and periods of 1.5 and 1.6 s, respectively. Yaw motion remained as in 3.4.4. The sampling interval was further reduced to 0.2 s. With scale factors of 1.02 and biases of 1 deg/hr on all axes:

heading error = 1.80 deg

3.5 Conclusions

The data substantiated the tentative conclusion stated earlier; namely, that for systems with allowable errors of only a few degrees, the contributions of cross-axis effects will be minor. In none of the cases where scale factor errors were limited to 2% did the heading error after 3 hr exceed the simple single-axis calculation by more than 2 deg (single-axis heading error = Z-axis bias times 3 hr). A case of 5% scale factor errors (2e) did produce a heading error of 2.73 deg, but a 5% scale factor error may already be considered intolerable, since the heading will always be in error by 5% X angular excursion. Thus, anytime the vehicle has turned 180 deg, an error of 9 deg will be encountered.

The foregoing analyses included only two of many types of sensor errors: bias and scale factor. Some other types of sensor errors such as asymmetry and nonlinearity may be examined in terms of bias and scale factor (see Section 6). The effects of g-sensitivity could be entered into this program if a realistic profile of vehicle acceleration could be modeled.

4. COMPUTER STUDIES OF MICROPROCESSOR BASED ALGORITHMS

4.1 Purpose

The results of Section 3 indicate heading errors due to various combinations of sensor errors and scenarios, processed by near-perfect computations. This section addresses the corollary question: Assuming perfect sensors, will a practical microprocessor achieve the desired accuracy? The algorithm utilized requires periodic updating of the nine-element direction cosine matrix as described in Appendix A. Alternate computational techniques were not considered since feasibility rather than optimization was the objective.

4.2 Approach

4.2.1 Reference Program

As in Section 3, an appropriate scenario must be selected since errors will be scenario-dependent. Following somewhat the procedures used in that section, a basic 600 s time span was divided into intervals of 192 and 408 s. A yaw motion of a full half sine wave (amplitude = 1.5 radian and period = 384 s) is imposed during the first 192 s, followed by no yaw during the balance of the 600-s span. Throughout the 600-s span, sinusoidal pitch and roll motions of 0.06 radian amplitude are assumed. The pitch and roll periods are 1.5 and 1.6 s, respectively. As noted in Section 3, a choice of slightly different pitch and roll frequencies allows varying phase relationships.

A reference program, referred to in the program listing as the tank simulation program (TNKSIM), accepts the foregoing scenario and generates heading, tilt, and a record of angular increments to be sensed by the physical sensors, with earth rate accounted for. These angular increments are subsequently used as the inputs to the "test" program. Due to the lengthy time required, the program allows for follow-on runs to previous records by reading the last attitude matrix as a starting point. A succession of such runs provided a record of 30-min of vehicle travel.

Since maximum accuracy is an objective of the reference program, calculations proceed with full precision and with 2 ms updating. A second-order algorithm (see Appendix A) was utilized with parallel updating (wherein all values of the

present instant are obtained solely from values of the previous instant). Skewness of the attitude matrix was monitored by printing the value of its determinant. After 30 min, a departure from unity of 2×10^{-8} was obtained. A further test of the reference algorithm accuracy is described in Appendix G.

4.2.2 Test Program

In this program (TNKTST), the reference record is the source of sensor inputs. The program models the pulse-balanced integrator to develop periodic angular increments which are then used as the source of updating. A second-order algorithm identical to that used for the reference program is used, except that now computational limitations are intentionally inserted. For the two sets of runs completed, precision of 32 and 24 bits were selected. In both cases, a 10-ms update interval was used, coupled with an integrator threshold (least significant bit) of 0.06 deg. Heading and tilt are calculated and compared to the reference to obtain errors.

4.2.3 Plots of Outputs

Plots of heading, tilt, heading error, and tilt error were obtained by further sampling of the computed outputs. To plot 30 min of data requires a sampling frequency well below the frequency of the fine structure. Therefore, care must be exercised in interpreting fine structure of the plots (as well as the more frequently sampled data available in printouts). The low-frequency components are of much more significance.

Figures 3 through 11 were obtained with 32 bit computation. Heading (as obtained by the 32 bit processor) and heading error for the entire 30 min are shown in 3 and 4. Expanded plots of part of the error record are shown in 5 and 6. The effect of the 0.06 deg integrator threshold is clearly seen. Calculated tilt angle for the entire period is shown in 7. Tilt error for the entire period is shown in 8, with expanded plots in 9 and 10.

Figures 11 through 19 are similar to the previous plots, except for 24-bit computation. Figure 16 (as well as Figure 8) seems to show a discontinuity at 200 s. The expanded plot of 19 demonstrates that this is merely a quirk of insufficient resolution coupled with the piecewise construction of the scenario. The apparently missing 2-deg fluctuations are now made visible.

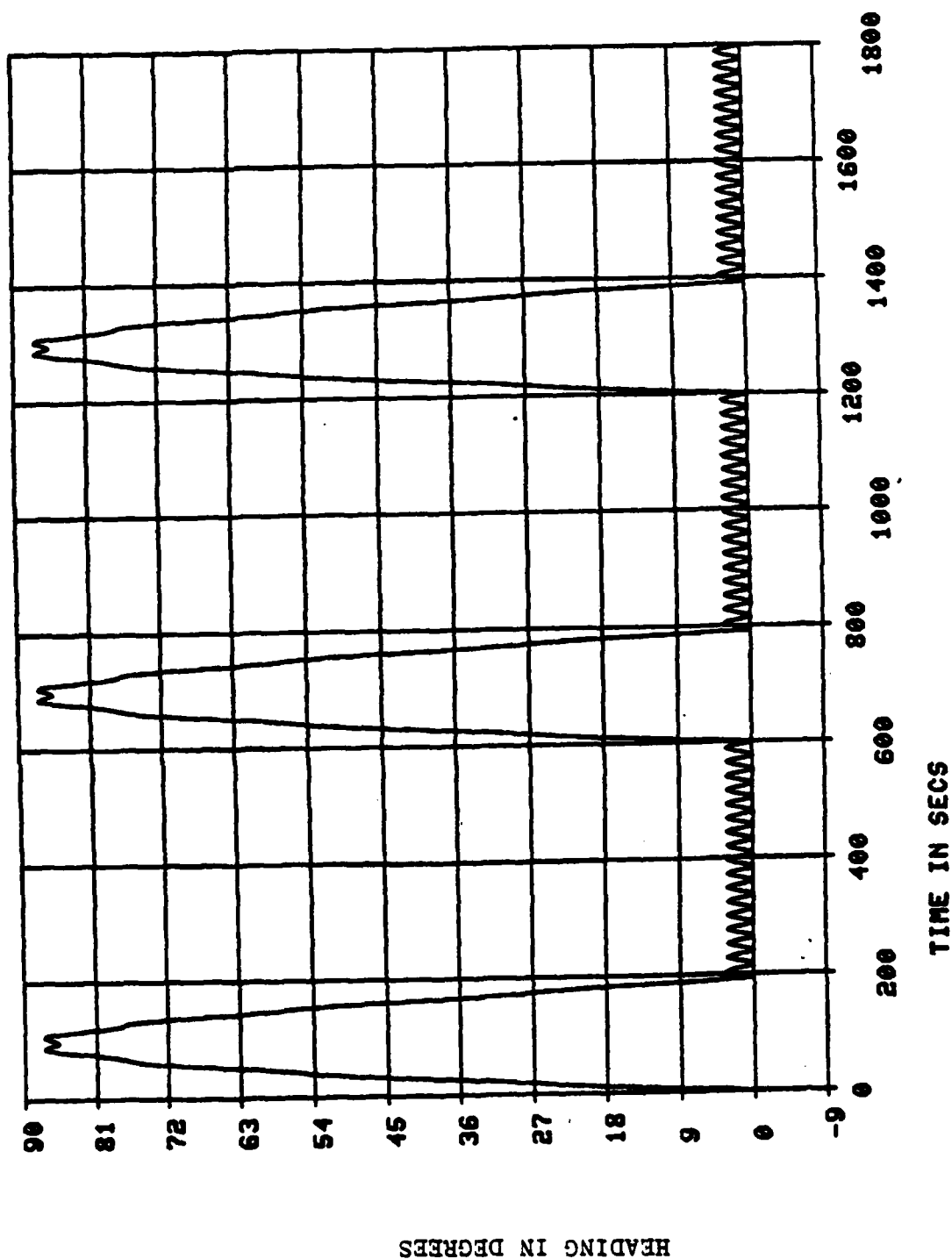


Figure 3. Heading obtained with 32 bit computation.

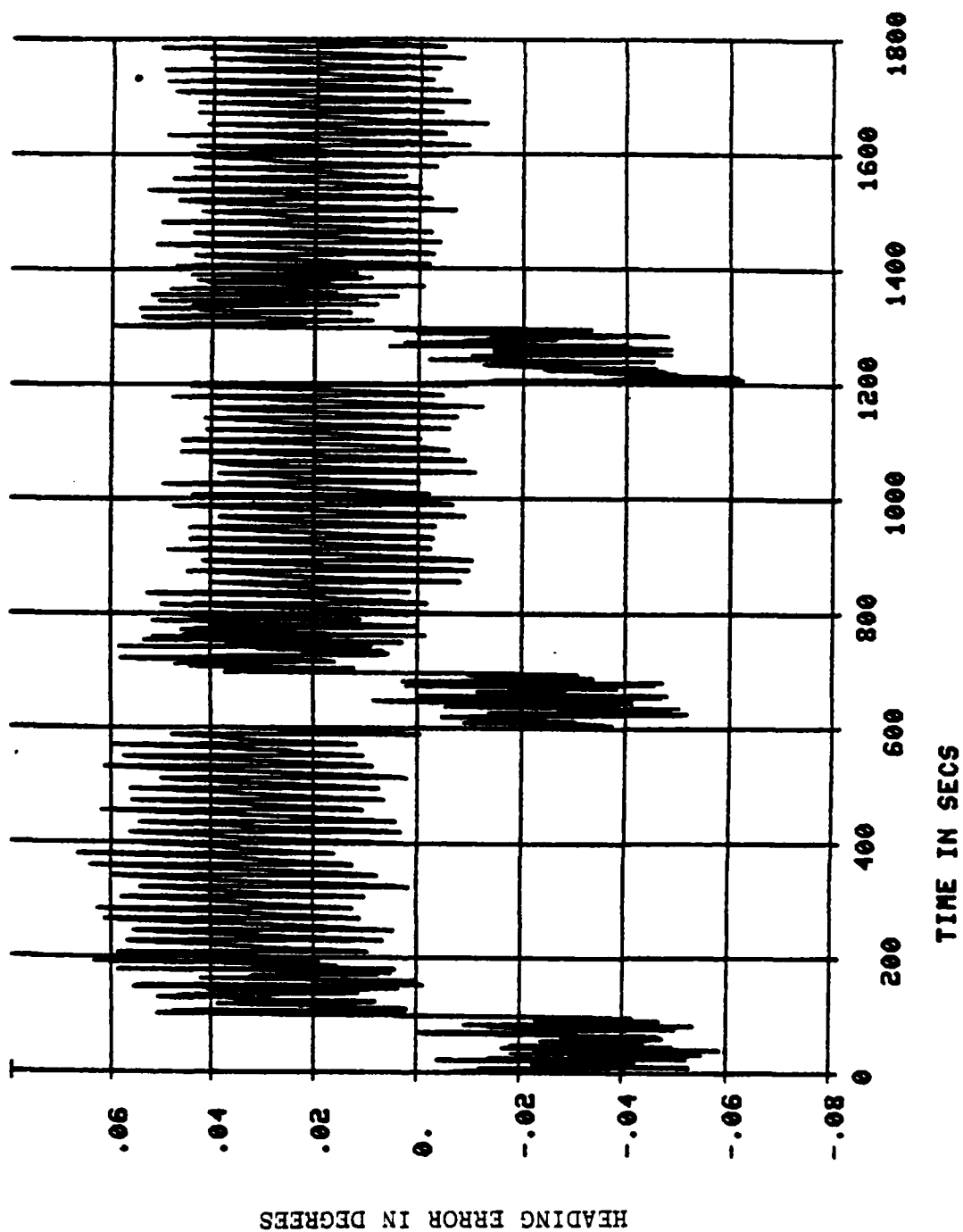


Figure 4. Heading error obtained with 32 bit computation.

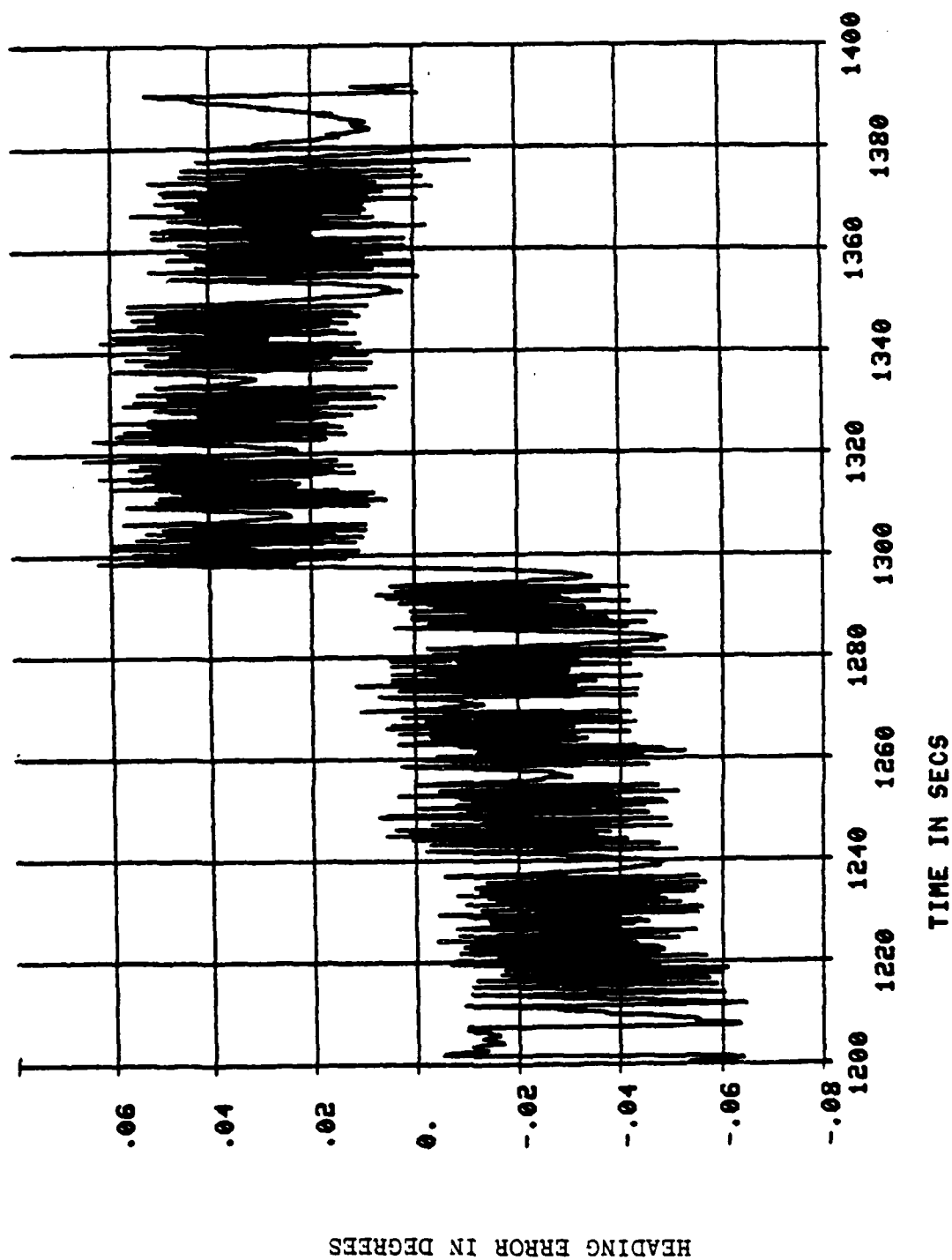


Figure 5. Heading error obtained with 32 bit computation (expanded time scale).

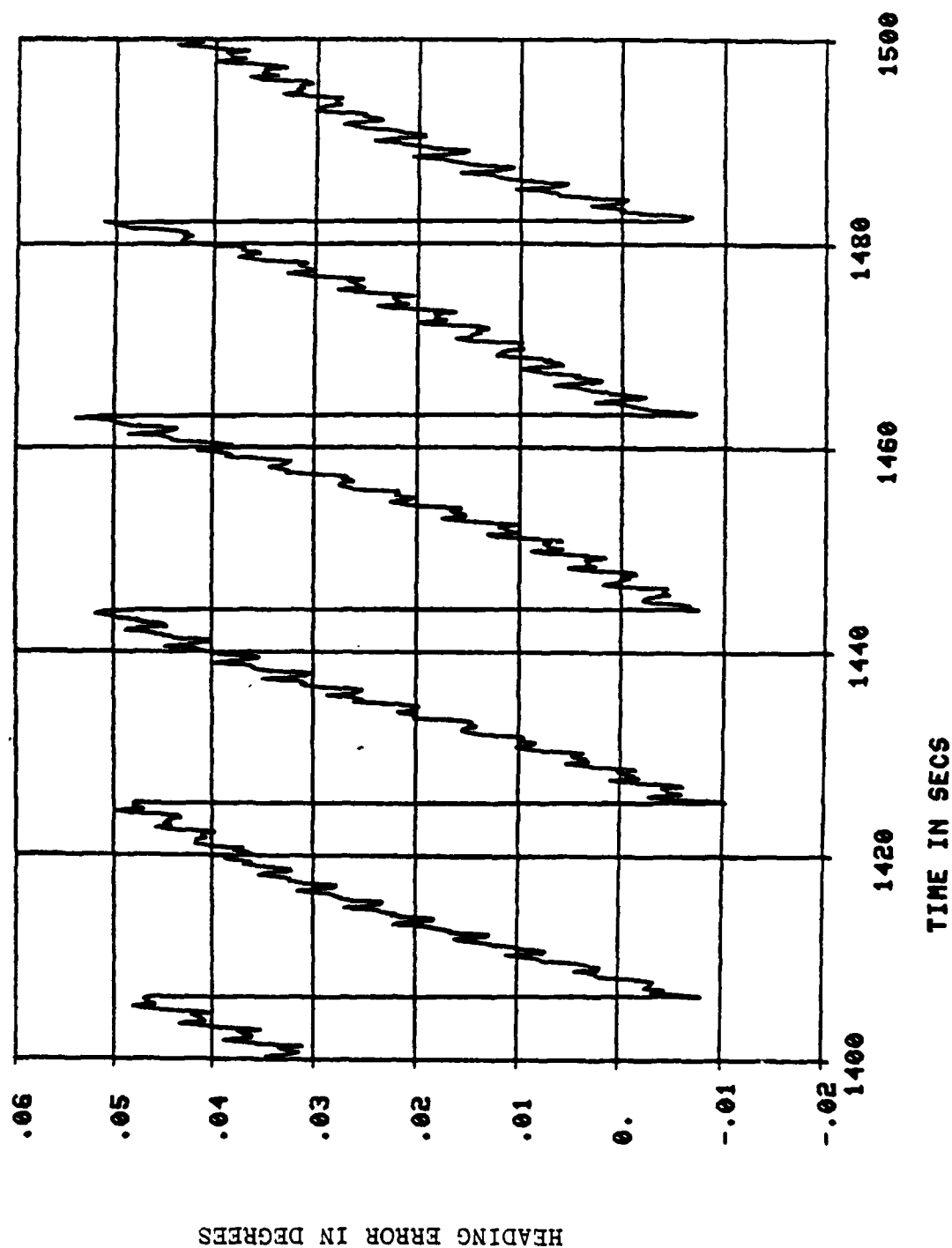


Figure 6. Heading error obtained with 32 bit computation (expanded time scale).

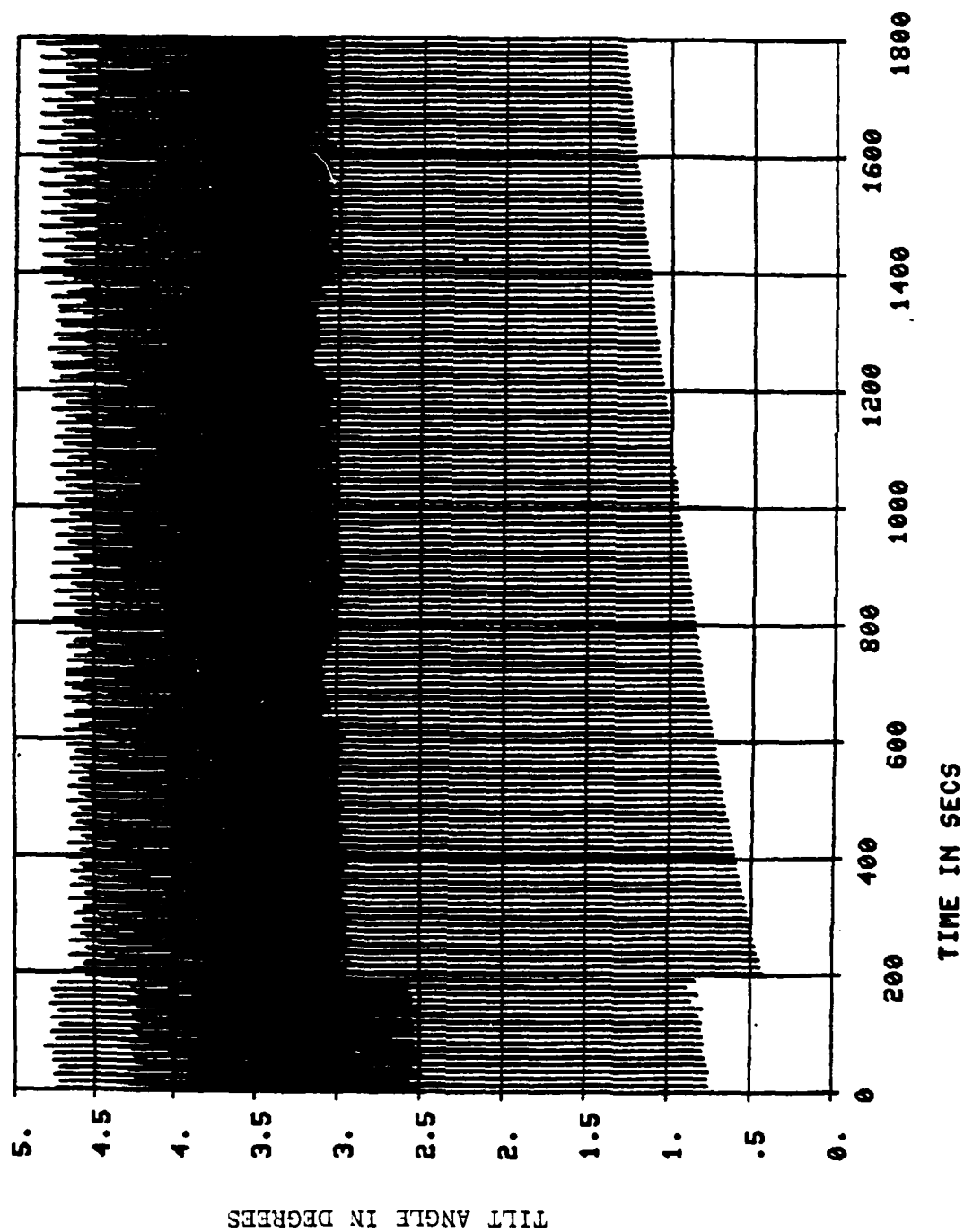


Figure 7. Tilt angle obtained with 32 bit computation.

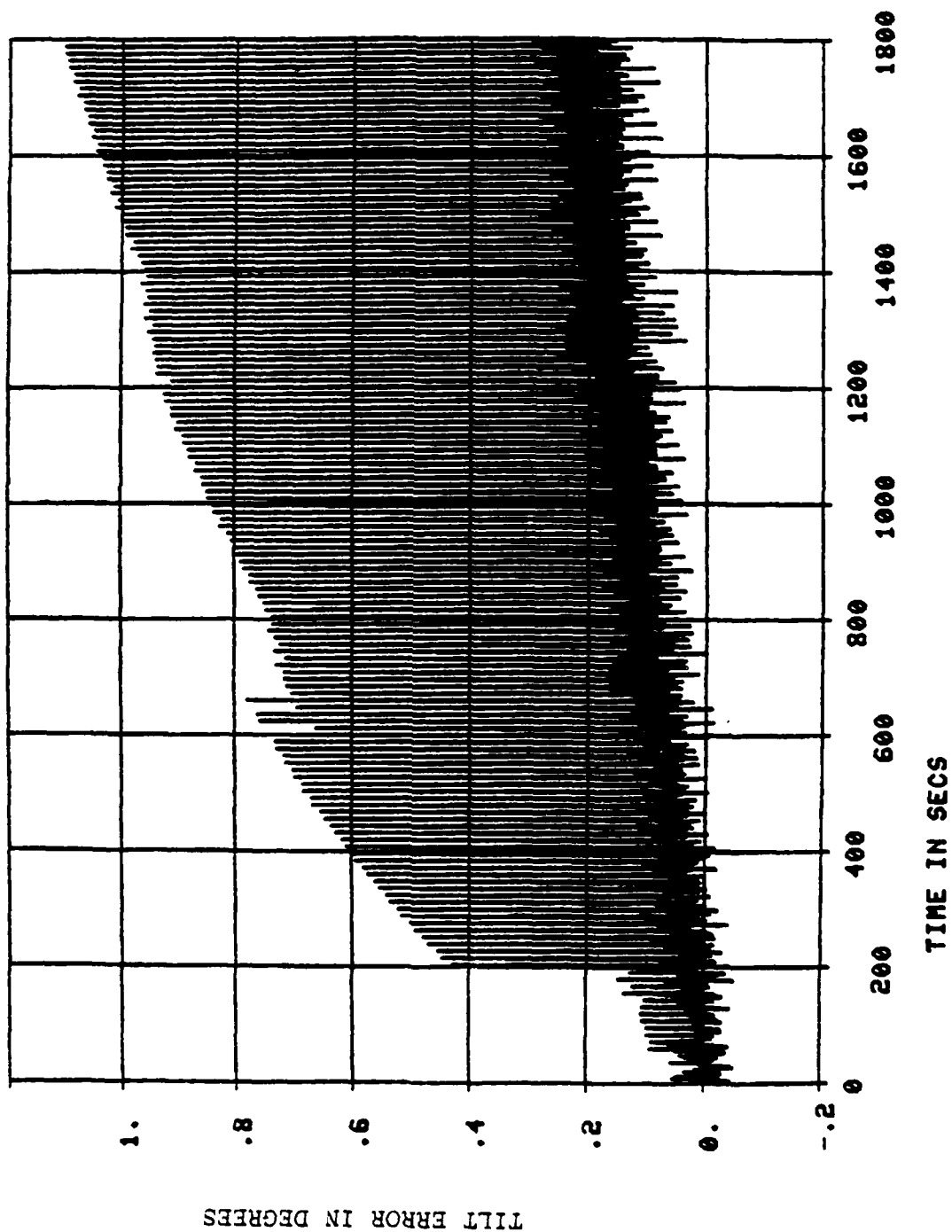


Figure 8. Tilt error obtained with 32 bit computation.

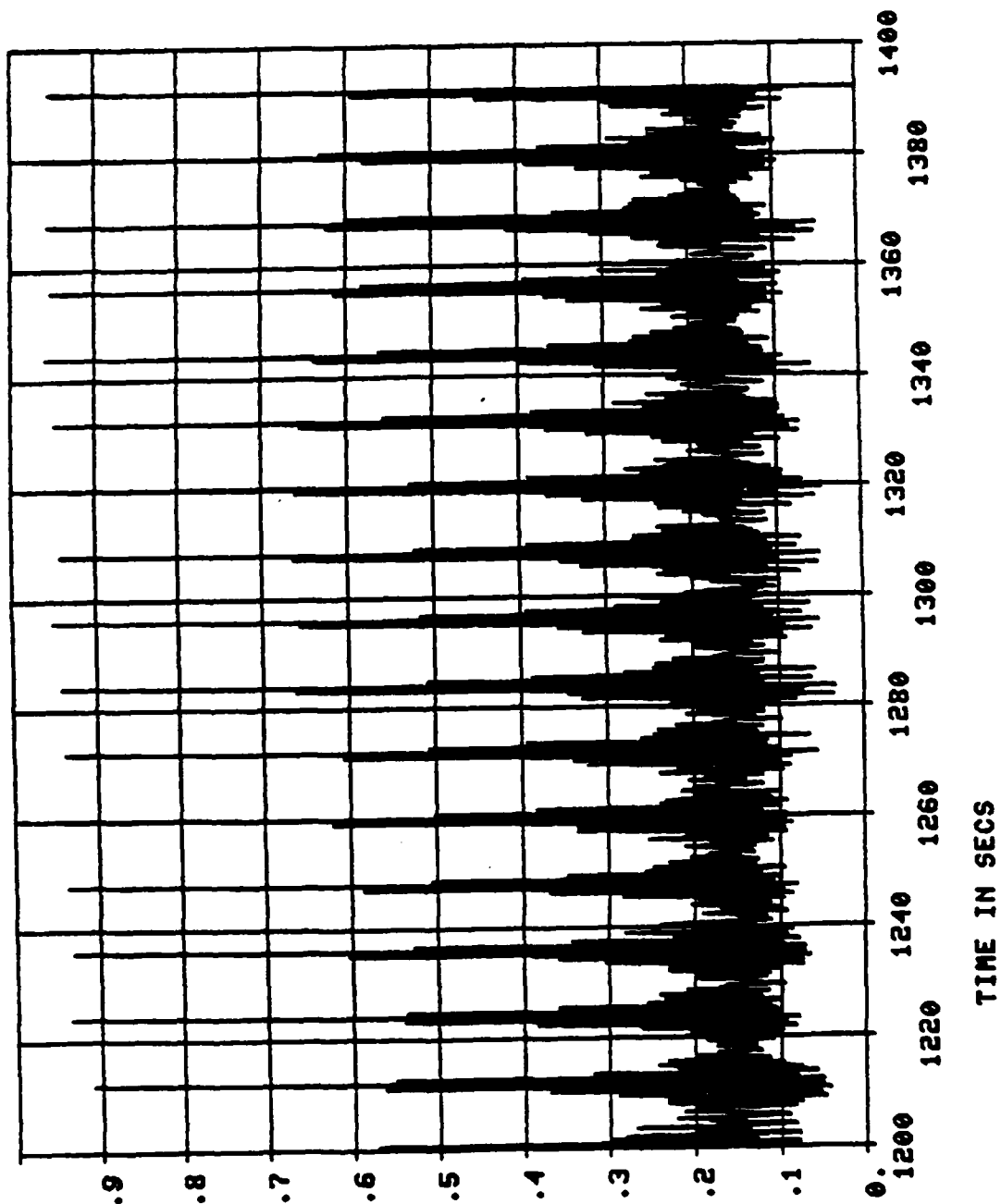


Figure 9. Tilt error obtained with 32 bit computation (expanded time scale).

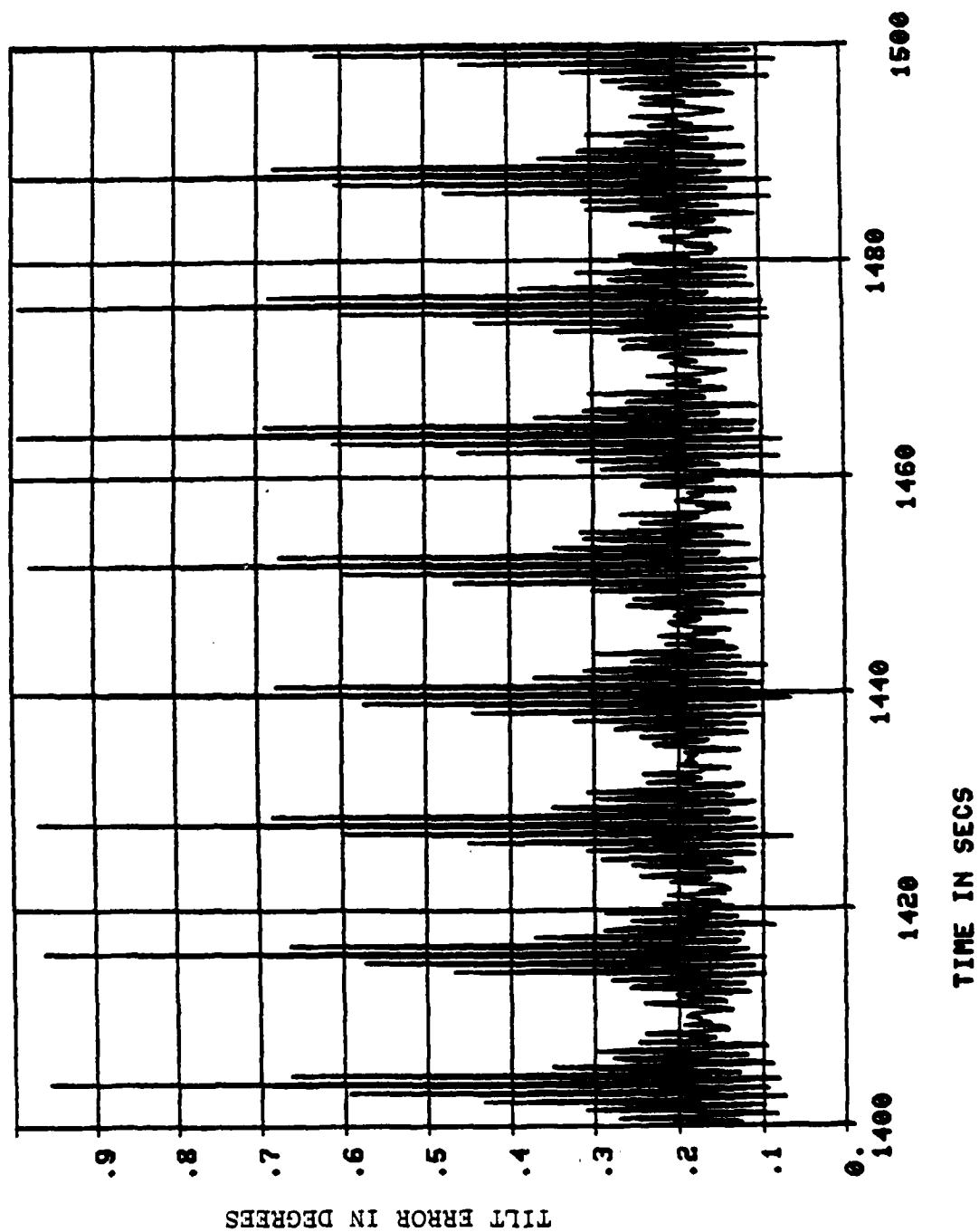


Figure 10. Tilt error obtained with 32 bit computation (expanded time scale).

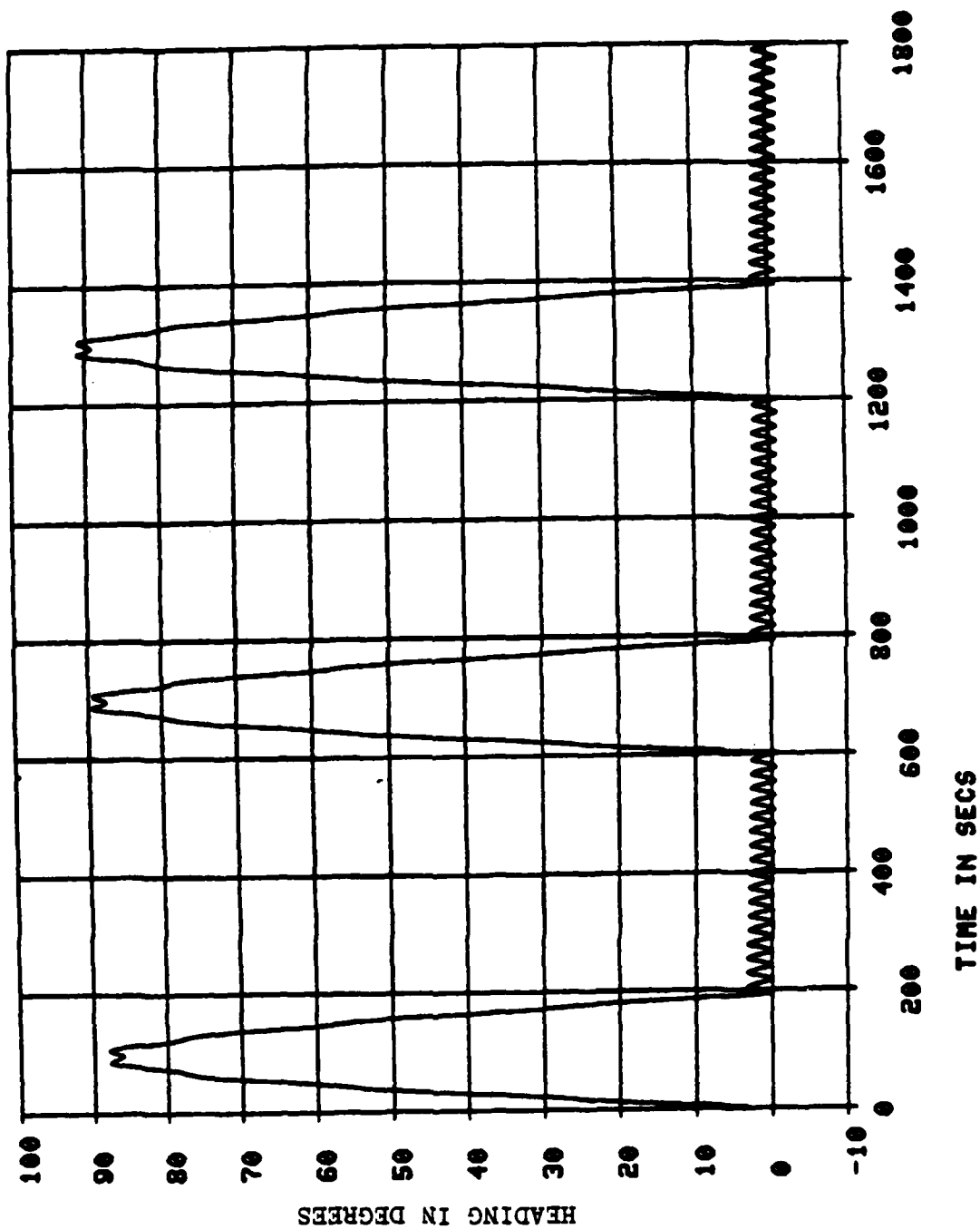


Figure 11. Heading obtained with 24 bit computation.

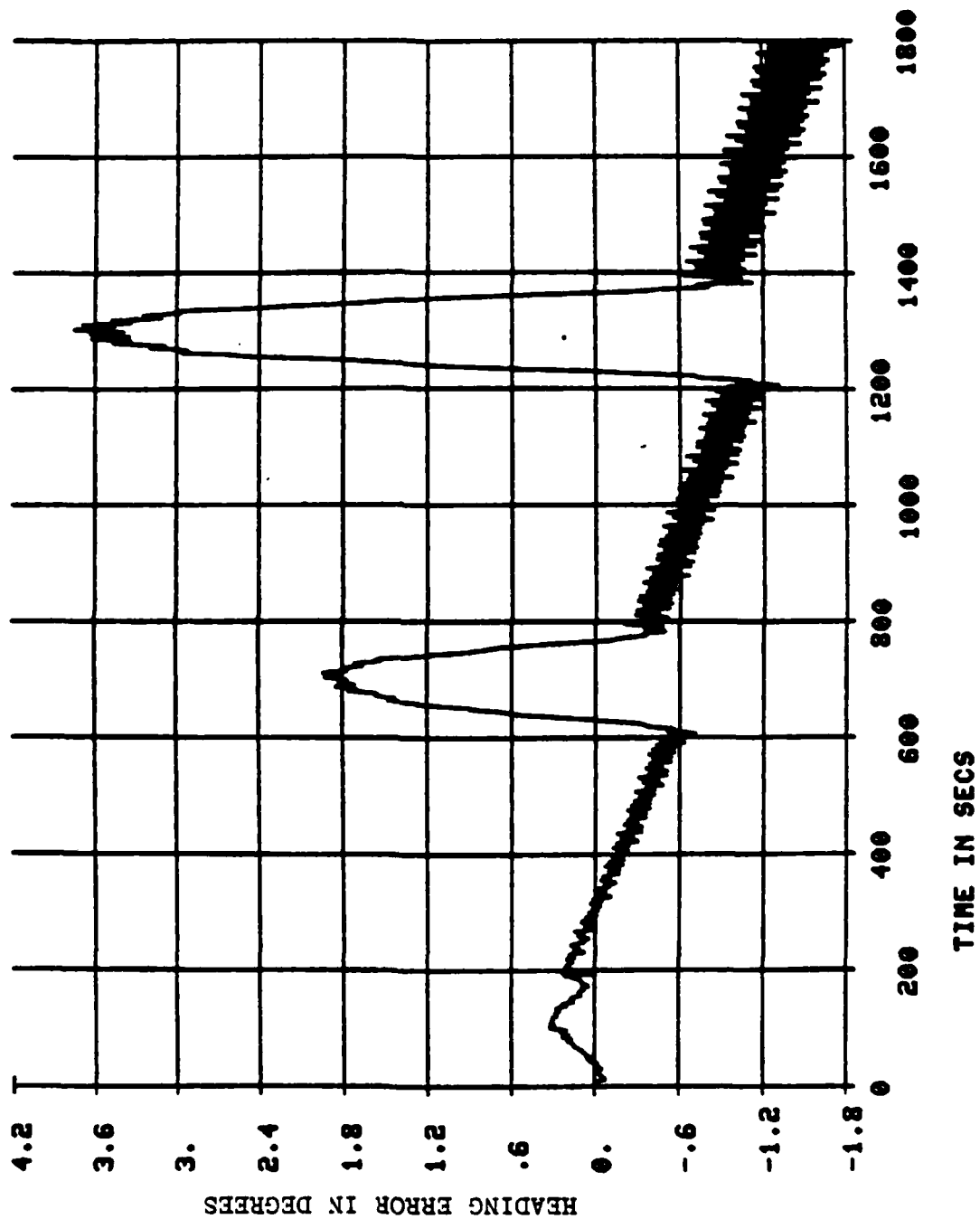


Figure 12. Heading error obtained with 24 bit computation.

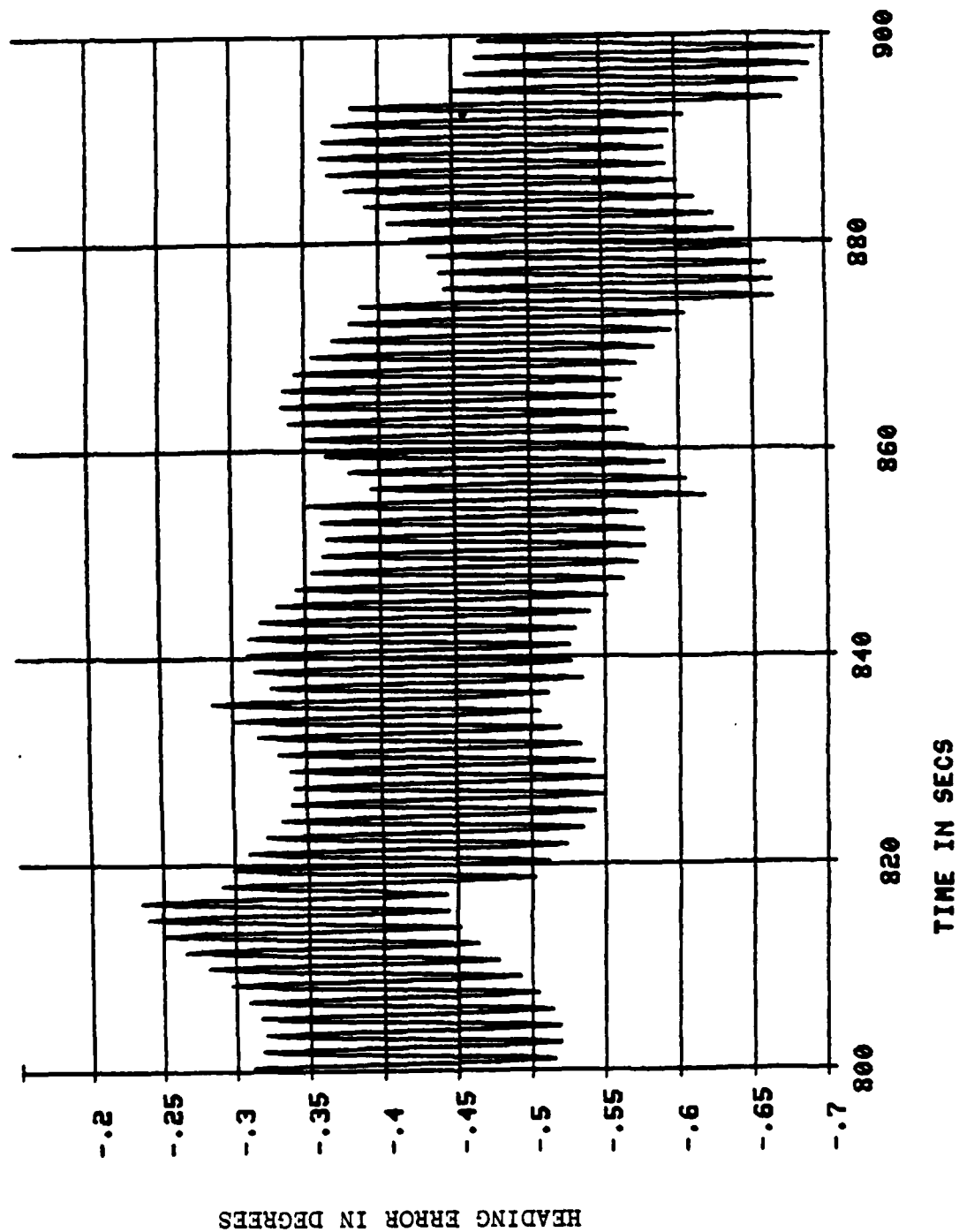


Figure 13. Heading error obtained with 24 bit computation (expanded time scale).

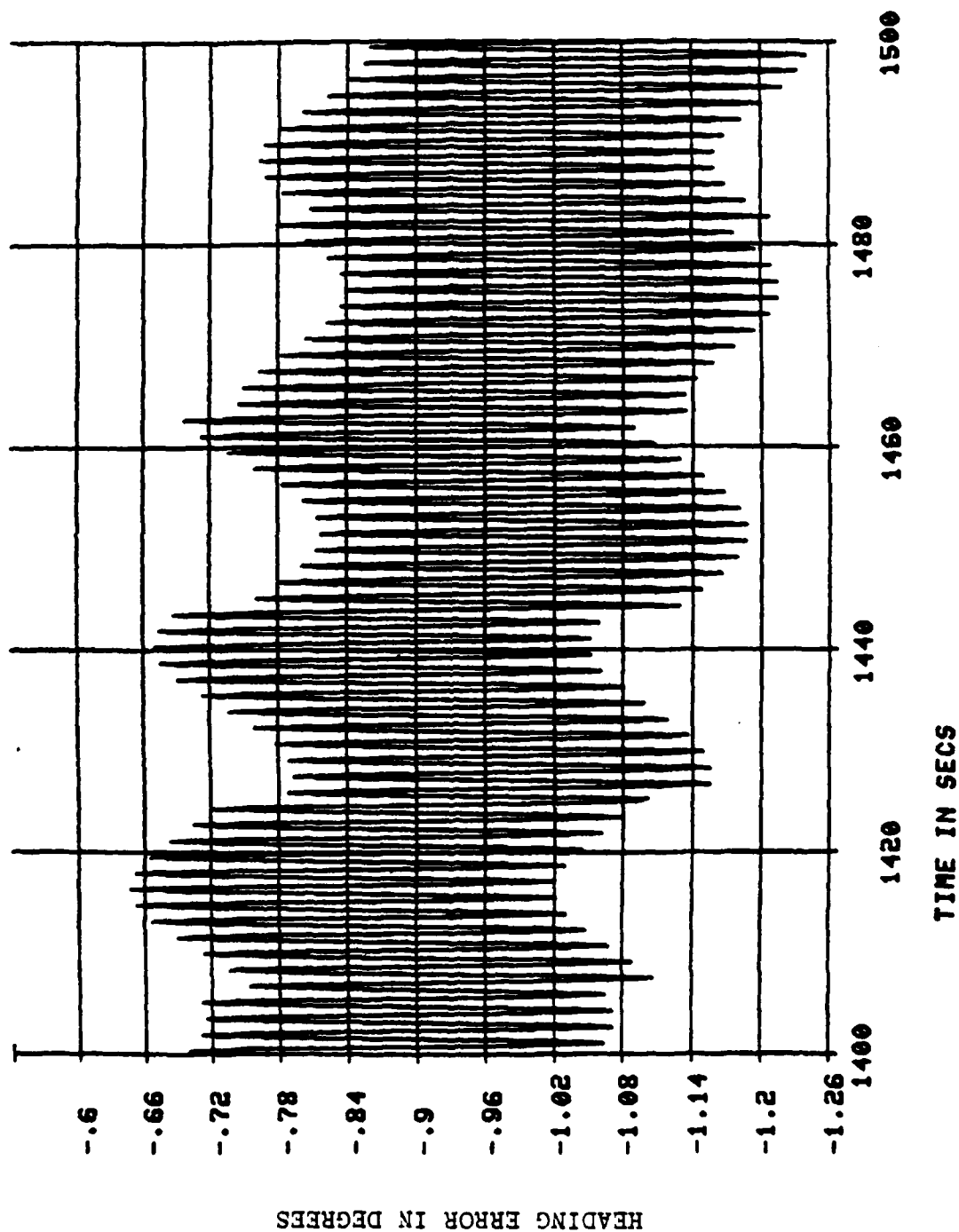


Figure 14. Heading error obtained with 24 bit computation (expanded time schedule)

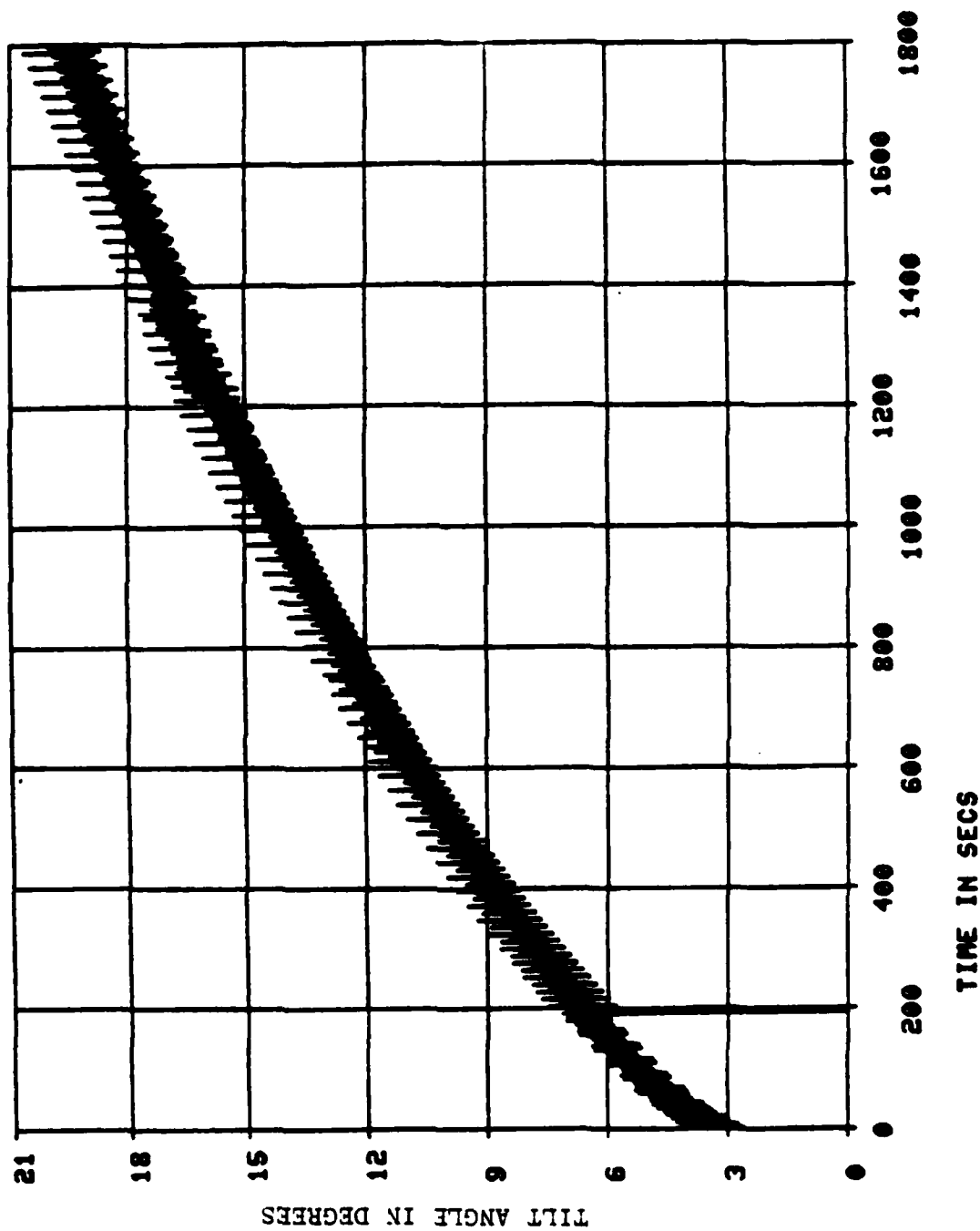


Figure 15. Tilt angle obtained with 24 bit computation.

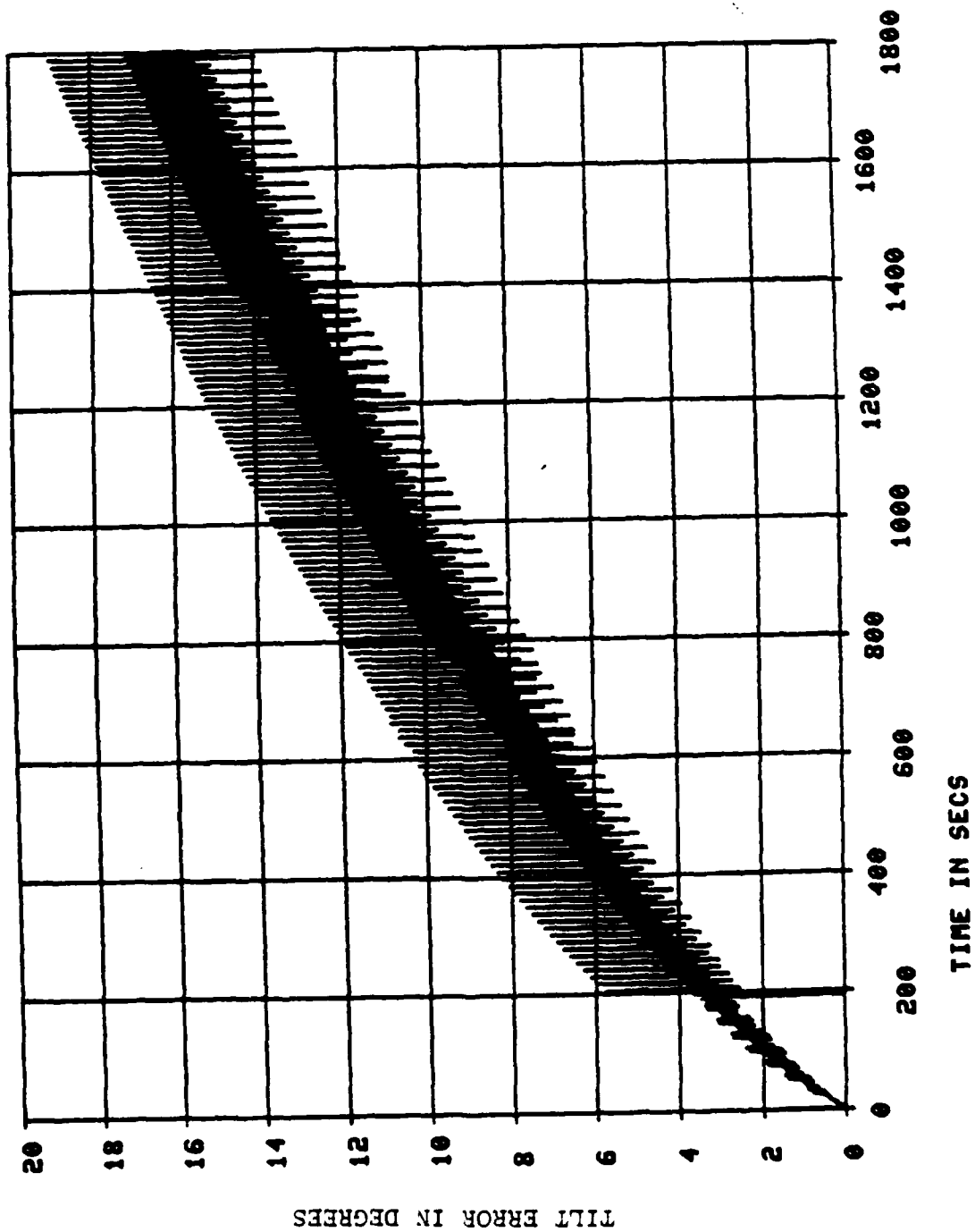


Figure 16. Tilt error obtained with 24 bit computation.

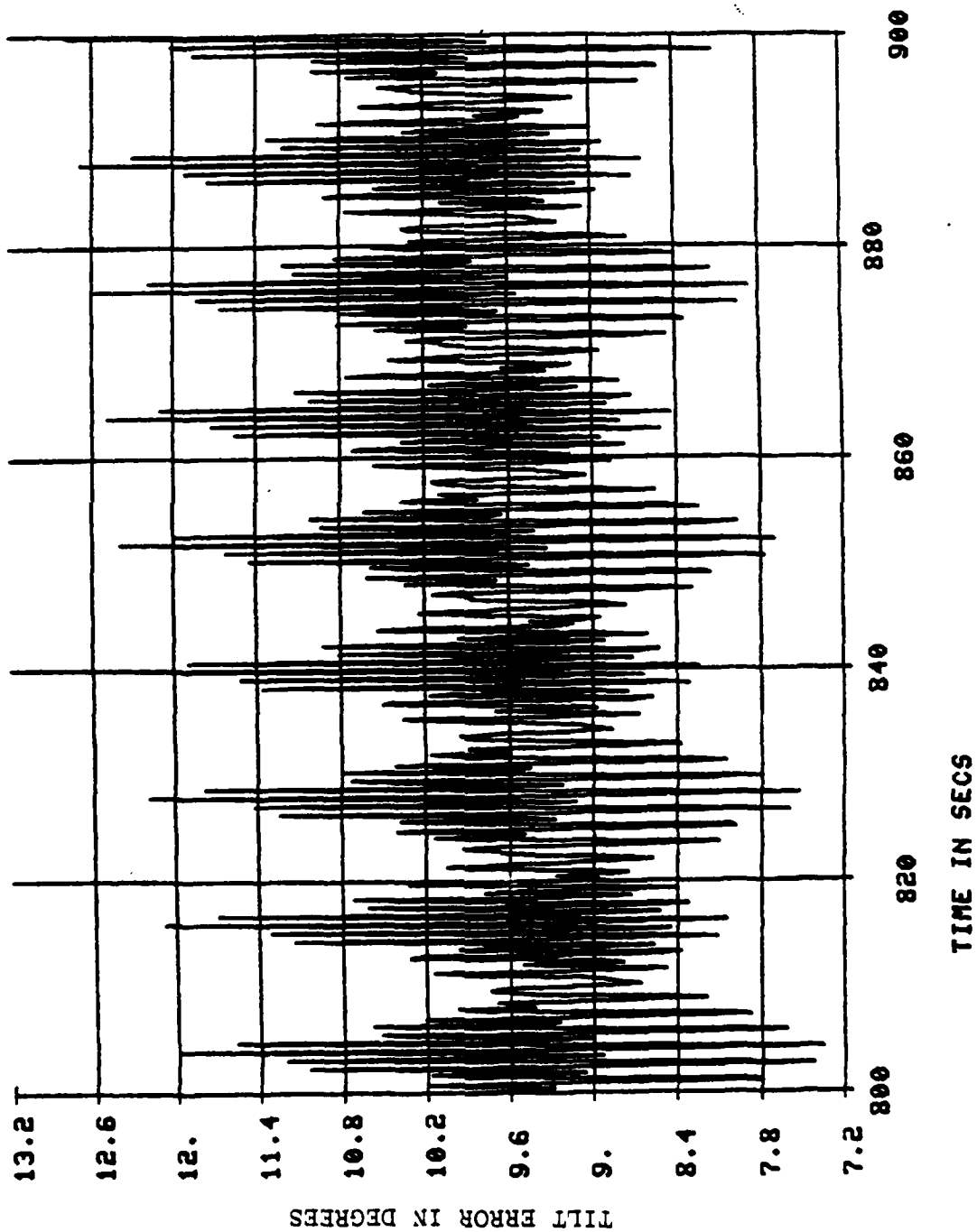


Figure 17. Tilt error obtained with 24 bit computation (expanded time scale).

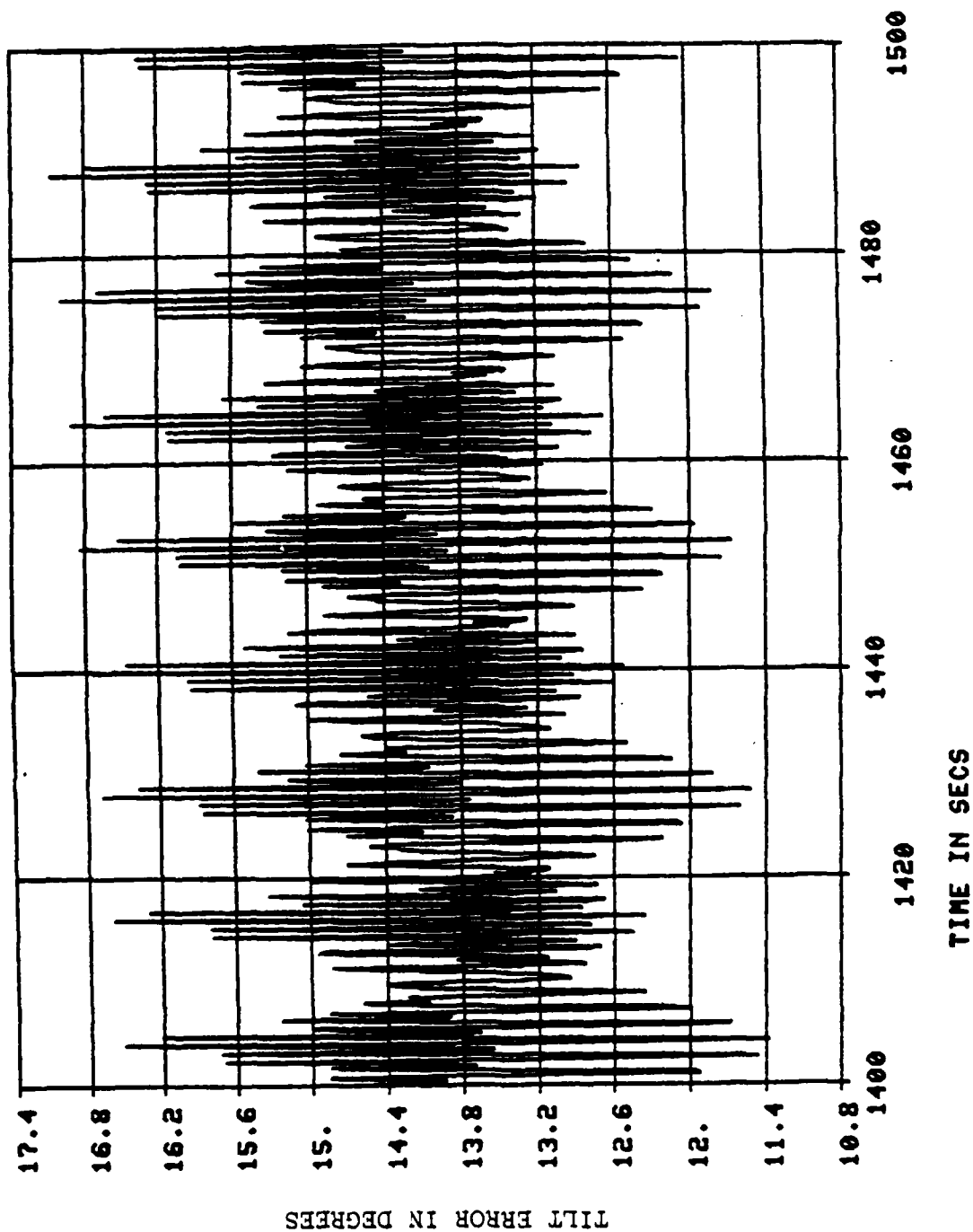


Figure 18. Tilt error obtained with 24 bit computation (expanded time scale).

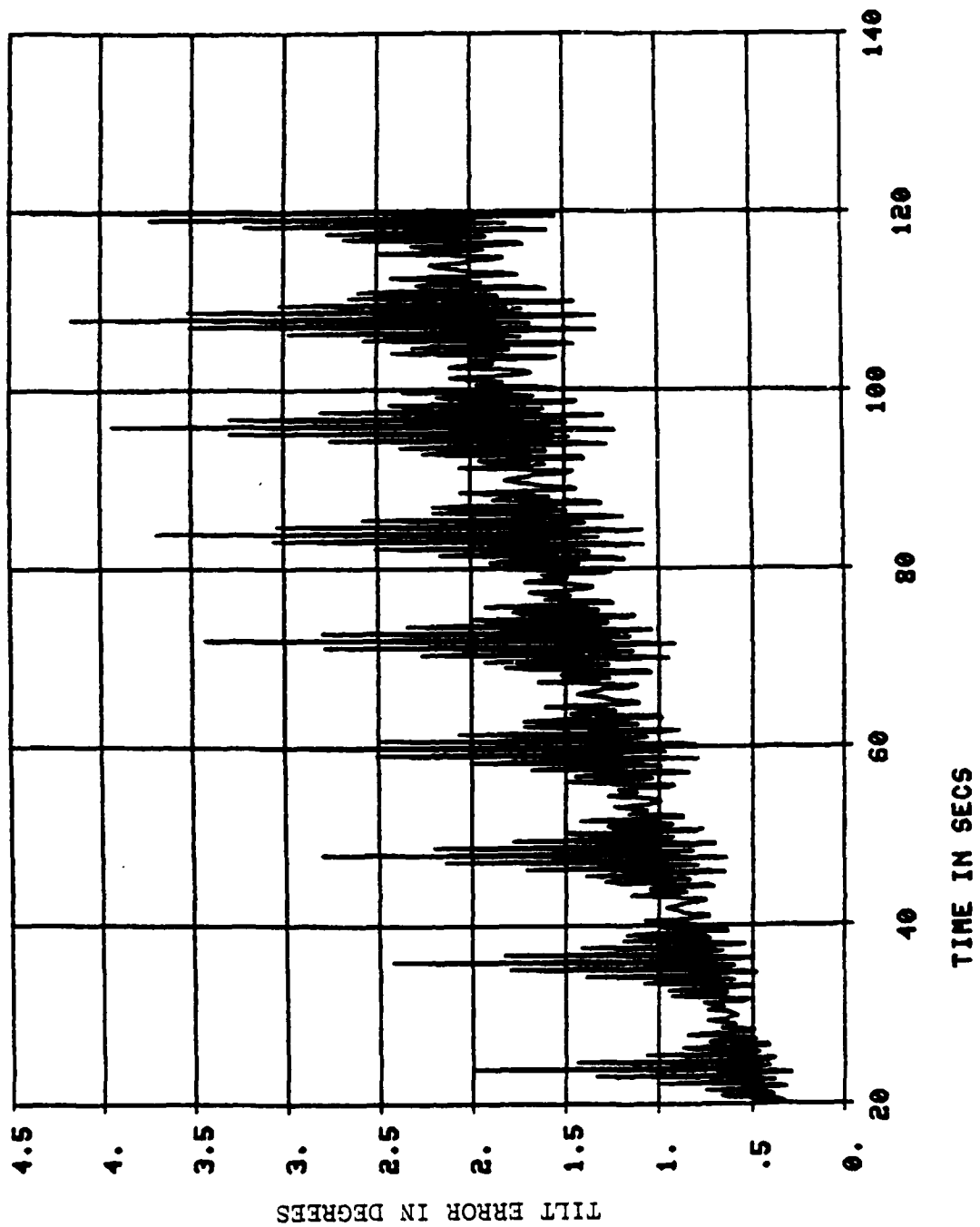


Figure 19. Tilt error obtained with 24 bit computation (expanded time scale).

4.3 Conclusions

The choice of 10 ms, second-order updating with 32-bit precision is demonstrated to be quite adequate. No significant long-term trend in heading error can be detected. The more sensitive tilt error shows a gradual growth to 0.2 deg after 30 min. The sine wave pattern of heading excursions during periods of no yaw motion as seen in Figure 3 is a result of the coning phenomenon (see Appendix D). The direction and rate of change of heading continuously change as the pitch and roll phase relationship varies.

A reduction to 24 bits shows a significant deterioration. In addition to no longer accurately following the 90 deg yaw excursions, a steady error accumulation to 1.5 deg at 30 min is apparent. The tilt error is a full 16 deg at 30 min.

A further comparison may be made of the determinants for the two cases. For the 32-bit case, the determinant of the attitude matrix at the end of 30 min was 0.99935. For the 24-bit case, the determinant equalled 0.8529, a considerable departure from the ideal unity.

Ten minutes worth of data was also obtained from a test of 32-bit, first-order processing. While no serious heading errors had yet developed, the determinant at the end of 10 min was a horrendous 1.45. It is safe to conclude that 10 ms. first-order processing is unsatisfactory.

Computer program listings for Section 4 are given in Appendix H.

5. MEASUREMENTS OF SENSOR CHARACTERISTICS

In addition to the studies of a heading sensor system which would incorporate a fluidics angular rate sensor, a concurrent measurement effort was undertaken with joint participation of APL and HDL personnel. These measurements were aimed at key fluidics sensor characteristics.

The tests were performed under admittedly benign laboratory conditions, but demonstration of feasibility of the existing sensor design was the immediate objective. As noted elsewhere in this report, the successful development of a heading sensor with a 1 deg/hr drift requires extremely accurate measurement of angular rate inputs. Whether or not the angular rate sensor will meet these objectives must await the construction of a combined sensor-transducer package which can then be subjected to precision testing under a variety of environmental conditions.

Measurement of angular rate was made via three stages of fluidic amplification and a Barocel pressure transducer. Data were recorded on an X-Y plotter. Angular rates were obtained with a rate table. Standard laboratory air was used as the power source with different venting arrangements. (A single output port reduces the ambient noise effects.)

Pertinent data from one set of tests are reproduced as Figure 20. An operating point of 13 mm Hg was selected as being least sensitive to supply pressure fluctuations.

The transfer function of output pressure change versus angular rate was 0.05 mm Hg per deg/s. The response to angular rate excursions of ± 0.02 deg/s is shown on Plot 2 of Figure 20. Plot 3 shows a very discernible response to ± 0.002 deg/s. Thus, the equivalent of earth rate (0.004 deg/s) can be seen by the sensor. To achieve the desired goal of 0.8 deg/hr, a sensitivity of 0.0002 deg/s is required. Since it is expected that rate signals will drive an integrator, it is the long-time integral which must be sensitive to rates of 0.0002 deg/s. Hence, even if such signal levels at the X-Y plotter would appear to be submerged in noise, conclusions about sensitivity for this application are premature unless suitable instrumentation is employed.

Plot 4 shows one measurement of a second key characteristic; namely, offset drift. The offset appears to have changed by the equivalent of a rate change of 0.001 deg/s over 24 min or a drift rate of 9 deg/hr/hr. In a simple

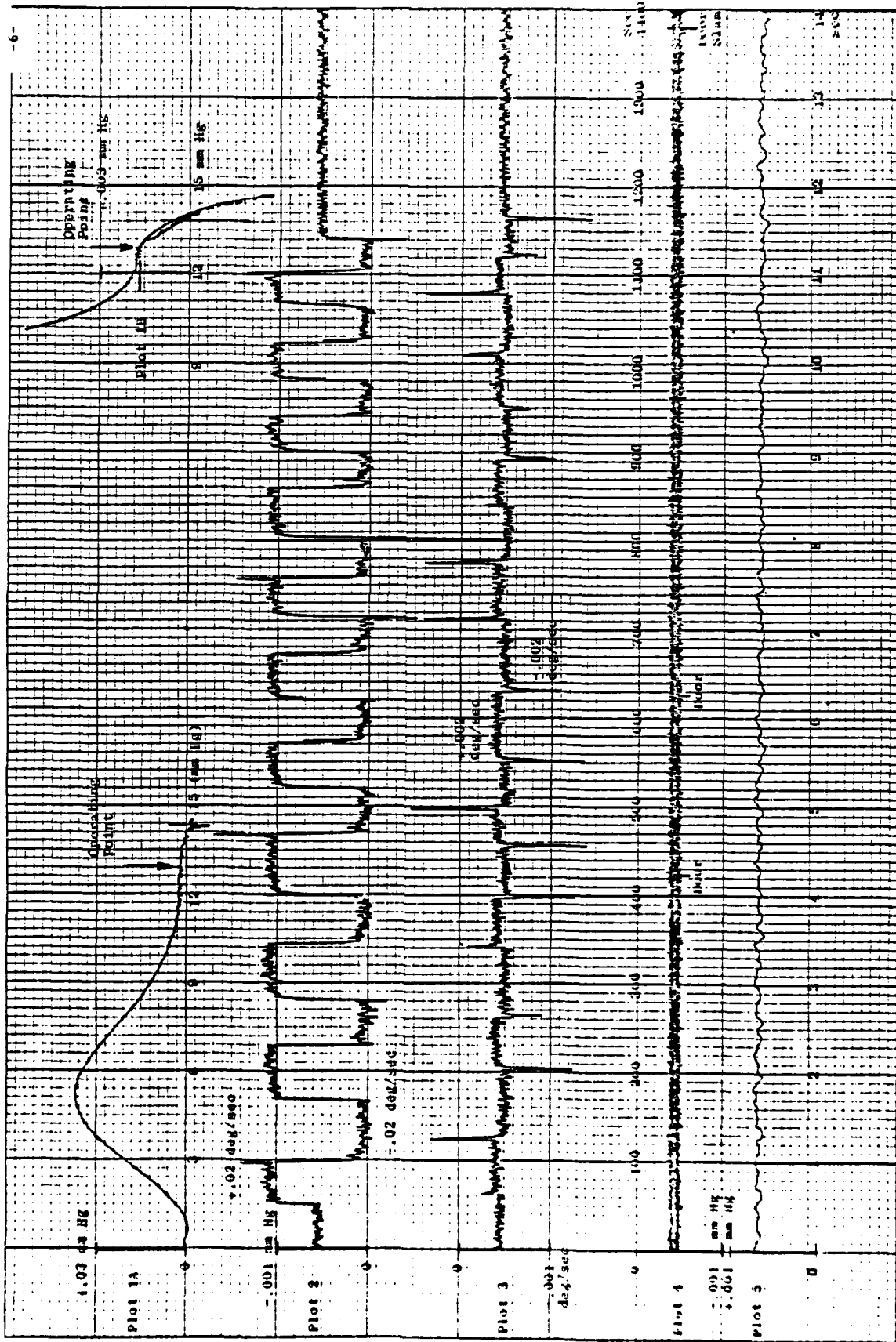


Figure 20. Sensor test results.

single-axis system, the angle is simply the integral of the rate. Hence, the error would be 4.5 deg after 1 hr and 40.5 deg after 3 hr. If, in a final system, constant drift rates are experienced and can be accurately determined during an alignment period, suitable compensation can be obtained within the processor. If offset changes cannot be predicted, their magnitudes would have to be further reduced.

It should be noted that an available sensor was used as the basis for these tests. A potential for improvement exists by optimizing the sensor design for the specific application at hand. (For example, the present high angular rate capability may be relaxed.)

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6. CONTRIBUTIONS TO SENSOR ERRORS

Results of the computer simulations given in Section 3 demonstrate that the limitations on rate sensor errors can be estimated by considering only a single-axis system. Hence, for a 1 deg/hr heading drift, the angular sensor should have an unpredictable (and hence uncompensated) bias of approximately the same magnitude or less. A general requirement may be stated as follows: the total effect of all sensor deficiencies should produce an output which, on the average, tracks the input angular rate with an error no greater than the desired heading drift. Many of the contributory factors will be scenario dependent. The "bias" of Section 3 should be recognized as the effective sum of many error sources.

6.1 Offset

Any unpredictable or unexpected shift of the null point is, of course, a bias in the sense of Section 3. This offset, in turn, may be the result of uncompensated temperature or pressure changes within the angular rate sensor or transducer.

6.2 Asymmetry

In Section 3, it was shown that scale factor errors of one percent or so would be tolerable. However, should there be a lack of symmetry of the transfer function, rectification of input motion results in a bias, as shown in Figure 21.

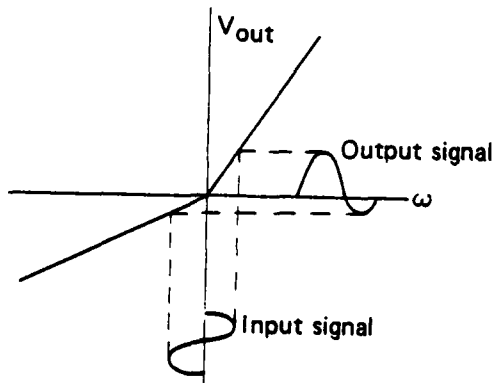


Figure 21 Nonsymmetrical transfer function.

If the input motion is sinusoidal with a 6 deg peak-to-peak amplitude, then 6 deg represents the integral of a half sine wave of the corresponding angular rate waveforms. If positive and negative scale factors differ by 1%, then a 0.06 deg error is generated every cycle. For motion with a 1.5 s period, the equivalent "bias" is 145 deg/hr. Therefore, considerably better matching of positive and negative characteristics (of the order of 0.02%) is required (after compensation).

6.3 Nonlinearity

A similar rectification effect can be produced from a nonlinear transfer function, even if symmetry is maintained, because of nonsymmetrical input motion.

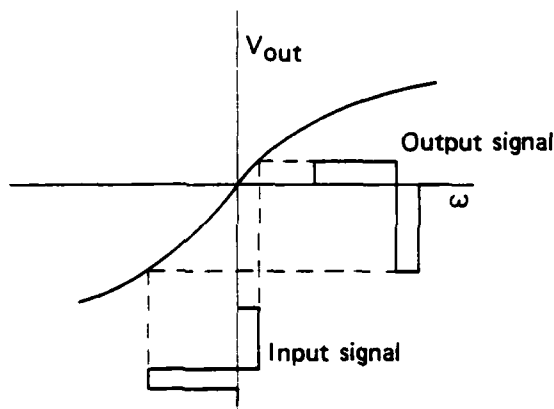


Figure 22 Nonlinear transfer function.

One can readily visualize a vehicle drifting slowly in yaw which is periodically corrected by the driver as illustrated in Figure 22. The drift is long and slow; the correction short and fast. For the vehicle to maintain its average direction, the integration of the input waveform must equal zero. But the integral of the output waveform delivers a "bias" to the computer by virtue of the unequal positive and negative scale factors. If a 5 deg drift were corrected every five seconds, a nonlinearity of 1% gives an angular error of 0.05 deg every five seconds or an equivalent "bias" of 36 deg/hr.

It will be noted that, insofar as certain characteristics such as non-linearity, hysteresis, g-sensitivity are concerned, the specification for an acceptable sensor is intimately related to the profile of vehicle motion. For the sensor to operate acceptably under all possible conditions, the angular rate error would have to be limited to the desired

drift rate independent of input motion. Hence, for a 1 deg/hr sensor (≈ 0.0002 deg/s), and a maximum rate of 40 deg/s, the nonlinearity must be limited to 0.0005% of full scale. Since maximum rate is not encountered frequently, such a requirement is much too stringent. (The maximum angular rate corresponding to the example of 3 deg, 2.5 Hz. motion is 12 deg/s). The simple examples given here to illustrate the effects of asymmetry and nonlinearity indicate that 0.01% would be more realistic.

6.4 Hysteresis

Any memory exhibited by the device can result in an effective bias, again depending on the vehicle scenario. Ideally, the output of the sensor as a function of past history should vary by less than the desired drift rate.

6.5 Cross-Axis Sensitivity

Obviously, the sensor should not produce outputs for angular motion about any but its designated input axis. To the extent that this effect can be measured and is repeatable, compensation can be introduced into the processor.

6.6 Sensitivity to Linear Acceleration

If the sensor is g-sensitive, errors due to gravity can be compensated for since the attitude is always known in the computer (not without penalty, however; such additional computations will take additional time). Without accelerometers as part of the system, there would be no way to compensate for errors due to vehicle acceleration. A detailed computer run of the type of Section 3 could be made for a vehicle scenario of three-axis acceleration.

6.7 Two-Axis Quadrature Vibration

If two axes of the vehicle undergo quadrature motion, the third axis will show an effective rotation which is not sensed by the third axis sensor. This is the coning effect which must be properly handled by the computational procedures. Now, should the two axes experience quadrature vibration which is not true vehicle motion, the computer will erroneously calculate a third-axis rotation which never takes place. This vibration must be slow enough to be seen at the sampling intervals (≈ 10 msec).

6.8 Rectification of Vibration

Another vibration effect occurs when vibrational motion is accompanied by vibrational tilt, resulting in a rectification effect.

The effects of vibration may be reduced via shock-mounting of an integrated 3-axis sensor package. The attitude of the package rather than the vehicle is tracked, allowing momentary insignificant vehicle heading errors with no error accumulation. Small angular differences between the sensor package and the vehicle would be of some concern if an attempt were made to combine a vehicle speedometer with the heading sensor to obtain position.

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V. F. Neradka
T. M. Rankin
J. G. Wall
L. L. Warnke

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APPENDIX A.--COMPUTATIONAL ALGORITHM

This section briefly outlines the computational algorithm needed to continuously track a vehicle heading. No attempt was made in this study to determine an optimum approach. Rather, the purpose of this phase of the study was to demonstrate feasibility. Accordingly, the popular direction-cosine matrix technique was used, neglecting other possibilities (such as the use of quaternions) described in the literature^{1, 2}. With such a feasibility demonstrated, development efforts could be concentrated upon the input sensor and transducer. Feasibility consists of demonstrating acceptably small errors when the algorithms are limited to the capabilities of a modern microprocessor. Any marginal speed problems can be safely neglected since it is a small matter to add a hardware multiplier.

The direction cosine matrix is a nine element matrix which fully describes the attitude of the vehicle with respect to the local (or navigation) frame. Each element is the cosine of the angle between a pair of axes.

		Vehicle Axes		
		X	Y	Z
NAV Axes	X'	C_{11}	C_{12}	C_{13}
	Y'	C_{21}	C_{22}	C_{23}
	Z'	C_{31}	C_{32}	C_{33}

X, Y, and Z are the longitudinal, transverse, and vertical axes of the vehicle. For a right-hand system, positive directions are taken as forward, right, and down. X', Y', Z' are the corresponding local frame axes and are chosen to coincide with north, east, and down*, respectively. Any vector

¹ J. C. Wilcox, "A New Algorithm for Strapped-Down Inertial Navigation," IEEE Transactions on Aerospace and Electronics Systems, Vol. AES-3, No. 5, September 1967, pp. 796-802.

² J. E. Bortz, "A New Mathematical Formulation for Strap-down Inertial Navigation," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-7, No. 1, January 1971, pp. 61-66.

*Toward the center of the earth.

in the vehicle frame may be transformed to a vector in the NAV frame by premultiplying by this direction cosine matrix (C_V^N).

So defined, the elements C_{11} and C_{21} give the north and east components, respectively, of the vehicle's longitudinal axis. Therefore, heading may be extracted from the C-matrix by computing the arc tangent of C_{21}/C_{11} . The more difficult task is the accurate updating of the C-matrix as angular increments over a sample period are developed from the angular rate sensors.

The rate of change of the C-matrix is given by

$$\dot{C} = CW, \quad (1)$$

where W is a matrix describing the angular rates of the vehicle's axes, \dot{x} , \dot{y} , \dot{z} :

$$W = \begin{pmatrix} 0 & -\dot{z} & \dot{y} \\ \dot{z} & 0 & -\dot{x} \\ -\dot{y} & \dot{x} & 0 \end{pmatrix}. \quad (2)$$

For constant velocity, the solution for C at any time t is

$$C(t) = C(0)e^{Wt}$$

or, in terms of samples every n^{th} instant,

$$C_{n+1} = C_n e^{W\Delta t}. \quad (3)$$

The matrix $W\Delta t$ is now a matrix of angular increments rather than angular rates.

The exponential term may be expressed as an infinite series, leading to

$$C_{n+1} = C_n \left[I + W\Delta t + \frac{(W\Delta t)^2}{2} + \dots \right] \quad (4)$$

where I is the identity matrix.

The microprocessor is thus required to update the most recent C -matrix after each sampling, with summation and matrix multiplication as indicated by equation (4). If only the terms I and $W\Delta t$ are used, the process is simple first-order updating.

Greater accuracy is obtained by including the term $\frac{(W\Delta t)^2}{2}$, referred to as second-order updating.

Prior to updating per equation (4), a correction must be applied to $W\Delta t$ to reflect the effect of earth rate. This is necessary since the angular rate sensors measure the vehicle's motion with respect to inertial space, whereas the C -matrix gives the vehicle's attitude with respect to the local frame which, in turn, is rotating. For the earth spin rate Ω and latitude L , the NAV (local) frame components are $\Omega \cos L$, 0 , and $-\Omega \sin L$. Premultiplying these components by the transpose of the C_V^N matrix then gives the earth rate effect as seen by the vehicle axes. Subtracting from the measured angular rates will give the net rates (or increments) with respect to the NAV frame.

Some 42 multiplications per sample are indicated for the foregoing procedures. Assuming 200 μsec per 32-bit multiplication, a 10 msec sampling period should allow sufficient time for computation. A hardware multiplier can always be used for faster execution, if necessary, at a small ($< \$200$) additional cost.

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APPENDIX B.--ALTERNATE ALGORITHMS

The computational procedure described in Appendix A is fairly conventional for "strap-down" inertial systems. When so desired, ground speed information may be combined with attitude to calculate position. If display of heading only is the ultimate objective, then computation of heading may be performed relatively inaccurately and infrequently. However, the underlying attitude matrix must be updated with precision. A tradeoff may be implemented wherein the chore of matrix updating is simplified at the expense of a more complex heading calculation.

The C-matrix is now chosen to describe the vehicle attitude with respect to inertial space, C_V^I . Updating of this matrix from the measured angular increments requires no prior correction for earth rate, thus eliminating the multiplication involving the transpose of C_V^N . Only when a heading calculation is to be performed is an additional coordinate rotation required.

In one version of this approach, the inertial axes are selected to coincide with the local navigation frame at the start of a mission, simplifying the initialization procedure. Accurate updating of the C_V^I matrix from the angular increment readouts proceeds every sampling instant. When at any time t it is desired to compute heading, it is first necessary to compute C_I^N (inertial-to-navigational) matrix at that time. The change of attitude of the navigational frame in inertial space over the time t may be visualized as a succession of three rotations:

- (1) rotation $+L$ deg about Y axis (pitch up)
- (2) rotate $+\Omega t$ about new X axis
- (3) rotate $-L$ deg about new Y axis (pitch down)

(L is latitude and Ω is the earth spin rate.)

The product of the corresponding rotation matrices gives the matrix C_I^N . The elements C_{11} , C_{21} , and C_{31} of the C_V^I matrix

form a vector describing the direction of the vehicle's longitudinal axis with respect to the inertial frame. When pre-multiplying by C_I^N , the components with respect to the navigational frame are obtained, from which heading may be calculated in the usual manner.

An even great simplification may be obtained at the cost of greater complexity in the initial alignment procedure. Earth-aligned inertial axes are chosen:

X - directed toward and perpendicular to the earth's axis.

Y - east

Z - parallel to negative spin axis

(X and Y lie in a plane parallel to the equatorial plane.)

Only two rotations are needed to transform from this inertial frame to the local NAV frame:

(1) rotate $-\Omega t$ about the Z axis

(2) rotate $(90 \text{ deg} - L)$ about the new Y axis

The calculation of heading proceeds as before.

These procedures have merit only if heading is to be calculated infrequently. If position navigation is required, continuous updating of heading may be needed to minimize errors, in which case the use of inertial frames would be of no benefit.

APPENDIX C.--"PRECISION" MATRIX UPDATING USED IN SECTION 3, BODY OF REPORT

The computer program described in Section 3 attempts to eliminate computational errors so that the heading errors obtained are due solely to angular rate sensor errors. One effect of the quantizing of input motion is to allow for a more time-consuming but highly precise updating.

Given the three angular increments between sampling instants, the microprocessor-based algorithm is described by equation (4), Appendix A:

$$C_{n+1} = C_n \left[I + W t + \frac{(W \Delta t)^2}{2} + \dots \right]$$

With a large-scale computer available, a closed-form solution may be utilized for the above infinite series:

$$C_{n+1} = C_n (\phi) ,$$

where the elements of ϕ are

$$\phi_{11} = \frac{x^2}{\beta^2} + \frac{\Delta y^2 + \Delta z^2}{\beta^2} \cos \beta$$

$$\phi_{12} = \frac{-\Delta z}{\beta} \sin \beta + \frac{\Delta x \Delta y}{\beta^2} (1 - \cos \beta)$$

$$\phi_{13} = \frac{\Delta y}{\beta} \sin \beta + \frac{\Delta x \Delta z}{\beta^2} (1 - \cos \beta)$$

$$\phi_{21} = \frac{\Delta z}{\beta} \sin \beta + \frac{\Delta x \Delta y}{\beta^2} (1 - \cos \beta)$$

$$\phi_{22} = \frac{\Delta y^2}{\beta^2} + \frac{\Delta z^2 + \Delta x^2}{\beta^2} \cos \beta$$

$$\phi_{23} = -\frac{\Delta x}{\beta} \sin \beta + \frac{\Delta y \Delta z}{\beta^2} (1 - \cos \beta)$$

$$\phi_{31} = \frac{-\Delta y}{\beta} + \frac{\Delta x \Delta z}{\beta^2} (1 - \cos \beta)$$

$$\phi_{32} = \frac{\Delta x}{\beta} \sin \beta + \frac{\Delta y \Delta z}{\beta^2} (1 - \cos \beta)$$

$$\phi_{33} = \frac{\Delta z^2}{\beta^2} + \frac{\Delta y^2 + \Delta x^2}{\beta^2} \cos \beta$$

$$\beta^2 = \Delta x^2 + \Delta y^2 + \Delta z^2 .$$

A more convenient, equivalent form is obtained for the computer updating via the following steps¹:

$$\beta^2 = \Delta x^2 + \Delta y^2 + \Delta z^2$$

$$\beta = \sqrt{\beta^2}$$

$$S = \frac{\sin \beta}{\beta}$$

$$Q = \frac{1 - \cos \beta}{\beta^2}$$

$$\phi_{11} = 1 - Q(\Delta y^2 + \Delta z^2)$$

$$\phi_{12} = Q \Delta x \Delta z - S \Delta z$$

$$\phi_{13} = Q \Delta x \Delta z + S \Delta y$$

¹ W. F. Ball, "Strapdown Analysis, Part 4, Gyro Modelling and Gyro Storage Error," Naval Ordnance Test Station Technical Note 404-38, 15 June 1966.

$$\phi_{21} = Q \Delta x \Delta y + S \Delta z$$

$$\phi_{22} = 1 - Q(\Delta x^2 + \Delta z^2)$$

$$\phi_{23} = Q \Delta x \Delta z - S \Delta x$$

$$\phi_{31} = Q \Delta x \Delta z - S \Delta y$$

$$\phi_{32} = Q \Delta y \Delta z + S \Delta x$$

$$\phi_{33} = 1 - Q(\Delta x^2 + \Delta y^2)$$

For each update to be performed, the ϕ matrix is developed from the three angular increments in a subroutine. The previous C-matrix is then multiplied by the ϕ matrix to obtain the updated C-matrix.

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APPENDIX D.--CONING MOTION AND ITS SIGNIFICANCE

This section discusses some aspects of coning motion with a view towards understanding its impact on attitude creep, computer simulation, and processing requirements.

The term "coning" derives from the fact that if two axes are subjected to sinusoidal motion of equal amplitude and frequency but 90 deg out of phase, the third axis describes a cone in space. In general, any combination of motion about two axes will result in changes of orientation about all three axes. The computer's function is to accurately track this changing attitude.

Sequential Pitch and Roll

Some insight may be obtained by examining the effect of sequential pitch and roll operations. For a rotation θ about any axis, the corresponding transformation matrix contains 1, $\cos \theta$, $\cos \theta$ in the main diagonal. $\sin \theta$ and $-\sin \theta$ appear once in symmetrical off-diagonal positions, with zero in the remaining positions. Rotation in the opposite direction ($-\theta$) results in the identical matrix except for a change of sign in the sine terms, equivalent to the transpose of the original matrix. Hence, if P is the rotation matrix for a pitch of θ and R is the rotation matrix for a roll of θ , the sequence of pitch $+\theta$, roll $+\theta$, roll $-\theta$, and pitch $-\theta$ is given by

$$P^T R^T R P = P^T I P = I \text{ (unity matrix) ,}$$

and we return to the starting position. This is motion where the Z axis retraces its path. If there is any misalignment in the C-matrix to begin with, its errors remain undisturbed.

If the Z axis does not retrace its path, such as in the sequence pitch $+\theta$, roll $+\theta$, pitch $-\theta$, roll $-\theta$, a net change in attitude occurs. (This should be intuitively obvious, since the positive and negative rotations are made about axes whose spatial orientation are different). The sequence of +pitch and +roll is given by

$$\begin{aligned}
 RP &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{pmatrix} \\
 &= \begin{pmatrix} \cos \theta & 0 & -\sin \theta \\ \sin^2 \theta & \cos \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & -\sin \theta & \cos^2 \theta \end{pmatrix}
 \end{aligned}$$

The sequence of -pitch and -roll is as above but with $-\theta$ substituted for $+\theta$. The resulting matrix is post multiplied by RP to obtain the final transformation matrix. When this is done, the following terms of interest result:

$$C_{11} = \cos^2 \theta + \sin^2 \theta \cos \theta$$

$$C_{12} = -\sin^2 \theta$$

$$C_{33} = 2 \sin^2 \theta \cos \theta + \cos^4 \theta$$

For $\theta = 5$ deg, a change of heading ($\tan^{-1} \frac{C_{12}}{C_{11}}$) of 0.435 deg is obtained. A very small change of tilt ($\cos^{-1} C_{33}$) of 0.027 deg also results. Note that, in this case, if the C-matrix is misaligned to begin with, the computer will calculate net motion about an axis whose orientation is in error (even with perfect calculation). Hence, errors can grow as a result.

The motion about the third axis is real motion, the result of stipulated motion about the other axes. Much of the literature assumes, as a condition, that there is no cumulative motion about the third axis. Coning is then interpreted as that compensating axis rotation (\dot{z} in this case) which would keep the heading constant.

Coning Theorem

A very useful theorem¹ states that if some motion brings an axis (say Z) back into coincidence with its starting position, a Z rotation will have been experienced equal to the solid angle swept out by the Z axis. This rotation in addition to any rotation due to the integral of $\dot{z}dt$. A simple demonstration is to allow a level vehicle to pitch up 90 deg, roll 90 deg, and pitch down 90 deg. The vehicle undergoes a heading change of 90 deg with no sensed Z axis rotation whatsoever. Applying the theorem, the Z axis returns to its original orientation after sweeping out $1/8$ of a sphere or $\frac{4\pi}{8}$ radians.

For the coning motion test of Appendix G, the Z axis sweeps out a cone of half angle 36.85 deg five times, while the heading rotates 360 deg. The solid angle per sweep is $2\pi(1 - \cos 36.85 \text{ deg}) = 0.4\pi$. A full rotation of 2π therefore requires five such conical sweeps.

For the 5 deg pitch and roll example of this section, a 5 deg x 5 deg square is swept out. If the slight misalignment of the Z axis after one cycle is neglected, the approximate solid angle is $\frac{25}{3283} \times \frac{180}{\pi} = 0.435 \text{ deg}$, in agreement with the previous calculation of heading change.

Significance for Computer Simulation

The "creep" of heading and tilt for the vehicle scenarios of Sections 3 and 4 may be understood as coning effects resulting from a stipulation of 3-axis motion. The input motion of Section 3 is due to irregular quantizing of the underlying sine wave inputs. This irregularity destroys the compensating effects of the scenarios of Section 4, leading to greater magnitudes of creep.

The received plots of pitch and roll for vehicle test runs show an in-phase relationship. Assuming that such a phase relationship is not universal and knowing that quadrature effects are more severe, some of the runs were changed to reflect pitch and roll inputs of slightly different frequencies. Hence, all phase relationships are experienced. The results indeed show greater perturbations for the latter inputs.

¹Goodman and Robinson, "Effects of Finite Rotations on Gyroscopic Devices," Journal of Applied Mechanics, June 1958, pp. 210-213.

The plots of heading for the simulations of Section 4 are based on pure sine wave inputs, again with slightly differing pitch and roll frequencies. The effect on heading is clearly seen during the periods of no yaw (e.g., 200 to 600 sec.). As the phase between pitch and roll changes steadily, the heading drift changes direction, producing the beat pattern seen.

It must be emphasized that the foregoing effects describe real motion which must result if the 3-axis inputs are as specified. What is principally of concern is the ability of the system's output to properly define the attitude.

Significance for Sampling Interval

It has previously been mentioned that the computation algorithm is a "constant velocity" algorithm. To the extent that velocity is not constant between updates, some error will be introduced. It naturally follows that the maximum acceptable sampling interval is dependent on vehicle angular acceleration. If it is assumed that continuous coning motion due to pitch and roll represents a severe test, a simple intuitive estimation of drift may be made with the aid of the coning theorem.

Assume a worst case of quadrature motion. For equal amplitude pitch and roll, the Z-axis describes a cone, as shown in Figure D-1. The period of this sweep equals the pitch roll period. The half-cone angle equals the pitch and roll amplitude.

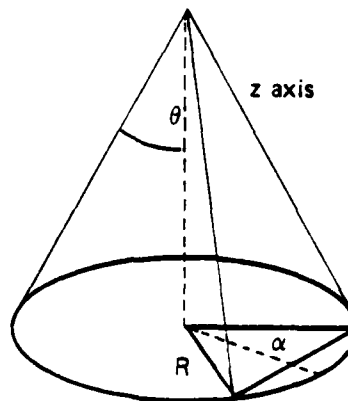


Figure D-1 Conical motion of Z-axis.

For small angles, there is little error in considering the spherical area intercepted by the cone to be a plane. The solid angle swept out per cycle is then proportional to the area of the plane circle (πR^2). The processor, however, assumes that the Z axis describes segments of the circle according to the sampling interval. It is assumed that the angular rate sensors are not sampled. Their outputs are continuously fed into integrators and it is the integrators which are periodically sampled. Hence, the angular position read at each sample is correct but the constant velocity algorithm assumes that the new position was attained via constant angular rate of the X and Y axes. The vehicle is thus thought to have rotated about a fixed axis in the X-Y plane. With no additional computation errors, a vehicle rotation about the Z axis will be calculated proportional to the area represented by the sum of the segments of the circle rather than the circle itself.

The area per segment is

$$A = R \sin \alpha \cdot R \cos \alpha = \frac{R^2}{2} \sin 2\alpha .$$

For N segments per circle,

$$\alpha = \frac{2\pi}{2N}$$

and the total area of N segments is

$$NA = \frac{NR^2}{2} \sin \frac{2\pi}{N} \approx \frac{NR^2}{2} \left[\frac{2\pi}{N} - 1/6 \left(\frac{2\pi}{N} \right)^3 \right] .$$

The second term within the brackets represents the departure from the area of the circle. The fractional error is

$$\text{Fractional error} = \left(\frac{2\pi}{N} \right)^3 \times 1/6 \times \frac{N}{2\pi} = 1/6 \left(\frac{2\pi}{N} \right)^2$$

Now, according to the coning theorem, the Z-axis rotation equals the solid angle swept out by the Z axis $\approx \pi\theta^2$ per cycle. The processor error is then

$$\epsilon = \pi\theta^2 \times 1/6 \frac{2\pi}{N}^2 = 2/3 \pi^3 \frac{\theta^2}{N^2} \text{ per cycle}$$

If T_p = pitch and roll period and T_s = sampling period:

$$N = \frac{T_p}{T_s}$$

$$\text{error rate} = 2/3 \pi^3 \frac{\theta^2 T_s^2}{T_p^2} \times \frac{1}{T_p} \text{ radians/sec.}$$

In terms of θ degrees and error rate in degrees/hour,

$$\text{error rate} = 1290 \frac{\theta^2}{T_p^3} T_s^2 \text{ deg/hr.}$$

Measured data indicate pitch and roll amplitudes of 3 deg with a period of 1.5 seconds. Then

$$\text{error rate} = 3400 T_s^2 \text{ deg/hr.}$$

A sampling interval of 0.1 s is clearly insufficient. At 0.01 s, the error is reduced to 0.34 deg per hour. The input motion is, of course, exceptionally severe since a constant 90 deg phase relationship between pitch and roll is assumed.

APPENDIX E.--PROGRAM LISTING FOR SECTION 3, BODY OF REPORT

The results of Section 3 were obtained with the following computer program, LNDNAV. The listing shows a particular choice of input parameters which, of course, are changed to accommodate the various vehicle scenarios. The notation AMP(3,2) refers to the Z-axis amplitude during the second interval. FREQ(1,4) is the period of the X-axis motion during the fourth interval. T1, T2, T3, and T4 give the time at the end of each interval.

In the listing shown, some of the constants were preselected even though the ability of the operator to insert these constants in response to computer prompting is preserved.

07/11/60 15:57:58 AF SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTRAN IV (REV - 0 / 7 8 S E P 6 0)

LNDRAY

```

1  PROGRAM LNDRAY
2  REAL*8 CREF,CCMP,PHI,DIAT,DHDS,CSHU,STNHU,P1,PX,MY,PZ,DELT,T
3  REAL*8 EDUT,FHM,CMPR,UELR,DELX,DELY,DELT,DELM,DELYM,DELTZ,STEP
4  REAL*8 P1,A,B
5  DIMENSION CREF(3,3),CCMP (3,3),A(3),B(3),AMP(5,4),
6  IFW(3,4),F(3),EKN(3),UELR(3),CMPR(3),PHI(5,3)
7
8  C
9  C
10 C
11 SELECT CONSTANTS
12 AMP(1,1)=0.0
13 AMP(1,2)=10.0
14 AMP(1,3)=0.0
15 AMP(1,4)=0.0
16 AMP(2,1)=10.0
17 AMP(2,2)=0.0
18 AMP(2,3)=10.0
19 AMP(2,4)=0.0
20 DU 500 J=1,4
21 FREF(1,J)=10.0
22 FREF(2,J)=11.0
23 AMP(3,1)=90.0
24 500 FREF(3,J)=1200.0
25 T1=100.0
26 T2=200.0
27 T3=300.0
28 T4=600.0
29 DLAT=45.
30 DHDS=0.
31 2 FORMAT (3F4.2)
32 13 FORMAT (D6.2)
33 WRITE (5,15)
34 15 FORMAT (' ENTER QUANTIZING INTERVAL IN TENTHS OF SECONDS '//)
35 READ (5,16) INT
36 16 FORMAT(I3)
37 WRITE (5,17)
38 17 FORMAT (' ENTER NUMBER OF ITERATIONS OF SCENARIO '//)
39 READ (5,18) LIMIT
40 WRITE (5,18)
41 18 FORMAT (' ENTER PRINT INTERVAL IN SECONDS '//)
42 READ (5,19) N
43 WRITE (5,19)
44 19 FORMAT (' ENTER X,Y,Z SENSOR SCALE FACTORS '//)
45 READ (5,20) A(1), A(2), A(3)
46 WRITE (5,20)
47 20 FORMAT (' ENTER X,Y,Z SENSOR BIAS IN DEGREES PER HOUR '//)
48 READ (5,21) B(1), B(2), B(3)
49 WRITE (5,21)
50 21 FORMAT (' ENTER MINIMUM ANGLE STEP IN DEGREES '//)
51 READ(5,13)STEP
52 C
53 C
54 C
55 PRINT OUT CONDITIONS
56 WRITE (7,30) (AMP (1,J),J=1,4)
57 30 FORMAT ('IX AMPLITUDES = ' 4F9.5)

```

03/11/80 15:57:58 AF SYSTEMS REAL-TIME MONITOR-7.0
SEL EXE CENDED FORT RAN IV (REV - 0 / 1 6 S E P 0 0)

L00NAV

```

25 WRITE (7,31) (FREQ(1,J), J=1,4)
26 FORMAT (' X PERIODS = ', 4F9.5)
27 WRITE (7,32) (AMP (2,J), J=1,4)
28 FORMAT (' Y AMPLITUDES = ', 4F9.5)
29 WRITE (7,33) (FREQ (2,J), J=1,4)
30 FORMAT (' Y PERIODS = ', 4F9.5)
31 WRITE (7,34) (AMP (3,J), J=1,4)
32 FORMAT (' Z AMPLITUDES = ', 4F9.5)
33 WRITE (7,35) (FREQ (3,J), J=1,4)
34 FORMAT (' Z PERIODS = ', 4F9.5)
35 WRITE (7,36) 11,12,13,14
36 FORMAT (' TIME AT END OF EACH INTERVAL IN SECONDS = ', 4F9.0)
37 WRITE (7,37) INT
38 FORMAT (' QUANTIZING INTERVAL IN TERMS OF SECONDS = ', 14)
39 WRITE (7,38) STEP
40 FORMAT (' MINIMUM ANGLE STEP = ', 14)
41 WRITE (7,39) UMUG
42 FORMAT (' INITIAL HEADING = ', 14)
43 WRITE (7,40) ULAT
44 FORMAT (' LATITUDE = ', 14)
45 WRITE (7,41) A(1), A(2), A(3)
46 FORMAT (' SENSOR X,Y,Z SCALE FACTORS = ', 3F9.3)
47 WRITE (7,42) B(1), B(2), B(3)
48 FORMAT (' SENSOR X,Y,Z BIAS IN DEGREES PER HOUR = ', 3F9.3)
49 WRITE (7,43)
50 FORMAT (' TIME (MINUTES)', 5X, 'HEADING', 5X,
51 'TILT', 5X, 'FERR', 8X, 'DETCR', 8X, 'DETCMP', 11)
52
53 C
54 C CALCULATE EARTHNAE OF NAV FRAME (EN)
55 C
56 PI=3.1415926536 D+0
57 PLAT=ULAT*PI/180.0 D+0
58 F0=PI/43200.0 D+0
59 EN(1)=UCOS (ULAT)*EDUT
60 EN(2)=0.0 D+0
61 EN(3)=-USIN(ULAT)*EDUT
62
63 C
64 C INITIALIZE DETECTION COSINE MATRICES
65 C
66 D006=UMUG*PI/180.0 D+0
67 C0S00=DCOS(D006)
68 S000=DSIN(D006)
69 CMF=0.0 D+0
70 CMF(1,1)=C0S00
71 CMF(1,2)=-S000
72 CMF(2,1)=S000
73 CMF(2,2)=C0S00
74 CMF(3,3)=1.0 D+0
75 CUMF=0.0 D+0
76 CUMF(1,1)=C0S00
77 CUMF(1,2)=-S000
78 CUMF(2,1)=S000
79 CUMF(2,2)=C0S00
80
81
82
83
84
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03/11/60 15:57:58 AF SYSTEMS REAL-TIME MONITOR-1.0
SEL EXTCNUEU FORTMAN IV (K E V - U / / D S E P U B)

L0DWAY

```

109      CCMPI(3,3)= 1.0 U+0
110      C
111      C CONVERT INPUT AMPLITUDES TO RADIAN
112      C
113      DO 50 J=1,3
114      DO 50 K=1,4
115      AMP(J,K)=AMP(J,K)* PI/180.0
116      STEP=STEP*PI/180.0
117      C
118      C CONVERT INPUT PERIODS TO RADIAN FREQUENCIES
119      C
120      DO 60 J=1,3
121      DO 60 K=1,4
122      FREQ(J,K)=2*PI/FREQ(J,K)
123      C
124      C
125      C INITIALIZE PRINT INTERNAL COUNTER IN TERMS OF SECONDS
126      C
127      C
128      C BEGIN MAIN PROGRAM
129      C
130      C
131      PA=0.0D+0
132      PY=0.0D+0
133      PZ=0.0D+0
134      MAX=14*10.0
135      NE=0
136      DO 210 ITER=1,LIMIT
137      DO 200 NT=INT,MAX,INT
138      T=NT
139      T=0.1*T
140      IF (T.LT.11) GO TO 110
141      IF (T.LT.12) GO TO 120
142      IF (T.LT.13) GO TO 130
143      DO 105 J=1,3
144      DO 100 K=1,4
145      F(J)=AMP(J,4)*SIN(FREQ(J,4)*T)
146      GO TO 140
147      DO 111 J=1,3
148      F(J)=AMP(J,1)*SIN(FREQ(J,1)*T)
149      GO TO 140
150      DO 121 J=1,3
151      F(J)=AMP(J,2)*SIN(FREQ(J,2)*T)
152      GO TO 140
153      DO 131 J=1,3
154      F(J)=AMP(J,3)*SIN(FREQ(J,3)*T)
155      DO 141 NT=NTPRINT-INT
156      M=NT+1
157      DELT=MAX(NT/10.0D+0
158      DELX=F(1)-PX
159      DELY=F(2)-PY
160      DELZ=F(3)-PZ
161      IF (ABS(DELX).LT.STEP) DELX=0.0D+0
162      IF (ABS(DELY).LT.STEP) DELY=0.0D+0
163      IF (ABS(DELZ).LT.STEP) DELZ=0.0D+0

```

```

03/11/68 15:57:58 AF SYSTEMS REAL-TIME MONITOR-1.0
SEL EATENDED FORTRAN IV (REV - U / 7 8 S E P 0 6)
LUNAV
103 IF (DELX + UFLY + DELZ .EQ.0. ) GO TO 160
104 PX=PX + DELX
105 PY=PY + DELY
106 PZ=PZ + DELZ
107
108 C REGIN MATRIX UPDATE ROUTINE
109 C
110 C COMPUTE ANGLE INCREMENTS BETWEEN STEPS AS SEEN BY COMPUTER
111 C
112 DO 151 J=1,3
113 CMPR(J)=H(J)*PI/648000.0D+0
114 DO 150 K=1,3
115 CMPR(J)=CMPR(J)+(A(J)*CREF(K,J)-CCMP(K,J))*ERN(K)
116
117 150 CONTINUE
118 DELR(J)=CMPR(J)*DELX
119 151 CONTINUE
120 C
121 C UPDATE CCMP WITH PHI MATRIX
122 C
123 CALL MAT(DELX(1),DELX(2),DELX(3),PHI)
124 CALL UPDAIE (CCMP,PHI)
125 C
126 C UPDATE CREF WITH ANGLE STEP
127 C
128 CALL MAT(DELX,DELY,DELZ,PHI)
129 CALL UPDAIE (CREF,PHI)
130 C
131 C UPDATE CCMP WITH MEASURED ANGLE STEP
132 C
133 DELX=DELX(1)*DELX
134 DELY=DELX(2)*DELY
135 DELZ=DELX(3)*DELZ
136 CALL MAT(DELX,DELY,DELZ,PHI)
137 CALL UPDAIE(CCMP,PHI)
138 C
139 C END OF MATRIX UPDATE ROUTINE
140 C
141 M=0
142 160 IF (NPRINT .GT. 0) GO TO 200
143 TIME=TIME+TIME-1)*MAX
144 TIME=TIME/600.0
145 SHDGE=DATA2(CREF(2,1),CREF(1,1))*180.0/PI
146 CREF(3,3)=CREF(3,3)
147 STILL=COS(CREF(3,3))*180.0/PI
148 FRUR=DATA2(CCMP(2,1),CCMP(1,1))*180.0/PI+SHDGE
149 DELX=DELX(1,1)*CREF(2,2)+CREF(3,3)-CREF(2,3)*
150 1CREF(3,2)-CREF(1,2)*CREF(2,1)+CREF(3,1)*CREF(2,2)
151 2-CREF(2,3)*CREF(3,1)+CREF(1,3)*CREF(2,1)+CREF(3,2)
152 3-CREF(2,2)*CREF(3,1)
153 DELX=CCMP(1,1)*(CCMP(2,2)+CCMP(3,3)-CCMP(2,3)*
154 1CCMP(3,2))-CCMP(1,2)*(CCMP(2,1)+CCMP(3,3)
155 2-CCMP(2,3)+CCMP(3,1))+CCMP(1,3)*CCMP(2,1)+CCMP(3,2)
156 3-CCMP(2,2)+CCMP(3,1)
157 WRITE (7,170) TIME,M,SHDGE,STILL,ERRON,DELR,DETC
158

```

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```

03/11/80  15:57:58  AF      SYSTEMS REAL-TIME MONITOR-1.0
SEL EXTENDUEU FORTRAN IV (REV - 0 / 1 8 S E P 0 8)

LN0NAV
217
218
219
220
221
222

170 FORMAT (9X,F6.2,F6.2,F10.2,F15.8)
400 FORMAT (3F15.8)
200 PRINT=
210 CONTINUE
      END

```

03/11/60 15:57:58 AF SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTRAN IV (REV - U / 7 0 5 E P 0 0)

MAT

```

1  SUBROUTINE MAT (X,Y,Z,C)
2  IMPLICIT REAL*8(A-Z)
3  DIMENSION C(3,3)
4  XSO=Y*X
5  YSO=Y*Y
6  ZSO=Z*Z
7  RSO=XSO+YSO+ZSO
8  S=1.0U+0
9  Q=0.0U+0
10 IF (RSO .EQ. 0) GO TO 350
11 BETA=OSQRT(RSO)
12 S=USIN(DELTA)/BETA
13 R=(1-OCOS(BETA))/BSQ
14 350 C(1,1)=1.0 U+0-W*(YSO+ZSO)
15 C(1,2)=Q*X*Y-S*Z
16 C(1,3)=Q*X*Z+S*Y
17 C(2,1)=Q*X*Y+S*Z
18 C(2,2)=1.0 U+0-W*(XSO+ZSO)
19 C(2,3)=Q*Y*Z-S*X
20 C(3,1)=Q*X*Z-S*Y
21 C(3,2)=Q*Y*Z+S*X
22 C(3,3)=1.0 U+0-W*(XSO+YSO)
23 RETURN
24 END

```

```

03/11/80 15:57:58 AF SYSTEMS REAL-TIME MONITOR-1.0
SEL EXTENDED FORTRAN IV (MEV-U / 105 E P U O)

UPDATE
1 SURROUTINE UPDATE (C,PHI)
2 REAL *A C,PHI,TEMP
3 DIMENSION C(3,3),PHI(5,5),TEMP(5,5)
4 DO 300 J=1,5
5 DO 300 K=1,5
6 TEMP(J,K)=0.0 D+0
7 DO 300 L=1,5
8 DO 300 M=1,5
9 DO 300 N=1,5
10 TEMP(J,K)=TEMP(J,K)+C(J,L)*PHI(L,M)
11 DO 300 K=1,5
12 C(J,K)=TEMP(J,K)
13 RETURN
END

```

APPENDIX F.--PRINTOUTS FOR SECTION 3

Printouts for a number of cases discussed in Section 3 are shown. These correspond to cases 3.4.2e, 3.4.2g, 3.4.3, 3.4.4(d), 3.4.5(b), and 3.4.6 of that section.

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X AMPLITUDES = 10.00000 10.00000 0.00000 0.00000 0.00000
Y AMPLITUDES = 10.00000 10.00000 10.00000 10.00000 10.00000
Z AMPLITUDES = 11.00000 11.00000 11.00000 11.00000 11.00000
TIME AT END OF EACH INTERVAL IN SECONDS = 100. 200. 300. 600.
QUANTIZING INTERVAL IN TENTHS OF SECONDS = 10
MINIMUM ANGLE STEP = 1.00000
INITIAL HEADING = 0.
LATITUDES = 45.
SENSOR X,Y,Z SCALE FACTORS = 1.050 1.050 1.050
SENSOR X,Y,Z BIAS IN DEGREES PER HOUR = 0.000 0.000 0.000

TIME (MINUTES)	HEADING	TILT	ERROR	DETREF	DETCOMP
1.00	44.13	2.79	3.02	0.99999994	0.99999994
2.00	53.79	0.16	2.60	0.99999994	0.99999994
3.00	73.00	0.14	3.62	0.99999994	0.99999994
4.00	65.73	9.85	4.21	0.99999994	0.99999994
5.00	69.46	0.10	4.41	0.99999994	0.99999994
6.00	66.73	0.10	4.24	0.99999994	0.99999994
7.00	73.53	0.10	3.57	0.99999994	0.99999994
8.00	53.07	0.10	2.54	0.99999994	0.99999994
9.00	27.98	0.10	1.28	0.99999994	0.99999994
10.00	0.17	0.10	-0.12	0.99999994	0.99999994
11.00	44.30	2.76	2.90	0.99999994	0.99999994
12.00	53.90	0.26	2.56	0.99999994	0.99999994
13.00	73.17	0.29	3.49	0.99999994	0.99999994
14.00	65.91	9.79	4.07	0.99999994	0.99999994
15.00	90.03	0.20	4.28	0.99999994	0.99999994
16.00	66.90	0.20	4.12	0.99999994	0.99999994
17.00	73.71	0.20	3.45	0.99999994	0.99999994
18.00	53.25	0.20	2.41	0.99999994	0.99999994
19.00	28.16	0.20	1.15	0.99999994	0.99999994
20.00	0.35	0.20	-0.23	0.99999994	0.99999994
21.00	44.47	2.78	2.78	0.99999994	0.99999994
22.00	54.14	0.36	2.43	0.99999994	0.99999994
23.00	73.34	0.39	3.36	0.99999994	0.99999994
24.00	66.10	9.74	3.93	0.99999994	0.99999994
25.00	90.20	0.31	4.15	0.99999994	0.99999994
26.00	67.07	0.31	3.94	0.99999994	0.99999994
27.00	73.98	0.31	3.32	0.99999994	0.99999994
28.00	53.42	0.31	2.24	0.99999994	0.99999994
29.00	28.33	0.31	1.02	0.99999994	0.99999994
30.00	0.52	0.31	-0.30	0.99999994	0.99999994
31.00	44.63	2.77	2.40	0.99999994	0.99999994
32.00	54.31	0.46	2.30	0.99999994	0.99999994
33.00	73.51	0.50	3.24	0.99999994	0.99999994
34.00	66.29	9.69	3.79	0.99999994	0.99999994
35.00	90.37	0.41	4.02	0.99999994	0.99999994
36.00	67.25	0.41	3.86	0.99999994	0.99999994
37.00	74.05	0.41	3.19	0.99999994	0.99999994
38.00	53.59	0.41	2.15	0.99999994	0.99999994
39.00	28.50	0.41	0.89	0.99999994	0.99999994
40.00	0.69	0.41	-0.51	0.99999994	0.99999994
41.00	44.80	2.77	2.53	0.99999994	0.99999994

42.00	50.00	0.56	2.17	0.99999994	0.99999994
43.00	73.69	0.60	3.10	0.99999994	0.99999994
44.00	86.00	9.63	3.64	0.99999994	0.99999994
45.00	90.55	0.51	3.84	0.99999994	0.99999994
46.00	87.42	0.51	3.73	0.99999994	0.99999994
47.00	74.22	0.51	3.06	0.99999994	0.99999994
48.00	53.76	0.51	2.02	0.99999994	0.99999994
49.00	28.66	0.51	0.76	0.99999994	0.99999994
50.00	0.86	0.51	-0.65	0.99999994	0.99999994
51.00	44.97	2.78	2.40	0.99999994	0.99999994
52.00	54.66	0.67	2.03	0.99999994	0.99999994
53.00	73.86	0.70	2.97	0.99999994	0.99999994
54.00	86.66	9.56	3.49	0.99999994	0.99999994
55.00	90.72	0.61	3.76	0.99999994	0.99999994
56.00	87.59	0.61	3.59	0.99999994	0.99999994
57.00	74.40	0.61	2.92	0.99999994	0.99999994
58.00	53.94	0.61	1.89	0.99999994	0.99999994
59.00	28.85	0.61	0.62	0.99999994	0.99999994
60.00	1.04	0.61	-0.78	0.99999994	0.99999994
61.00	45.14	2.79	2.27	0.99999994	0.99999994
62.00	54.83	0.77	1.90	0.99999994	0.99999994
63.00	74.03	0.80	2.83	0.99999994	0.99999994
64.00	86.85	9.53	3.35	0.99999994	0.99999994
65.00	90.84	0.72	3.62	0.99999994	0.99999994
66.00	87.76	0.72	3.45	0.99999994	0.99999994
67.00	74.57	0.72	2.78	0.99999994	0.99999994
68.00	54.11	0.72	1.75	0.99999994	0.99999994
69.00	29.02	0.72	0.48	0.99999994	0.99999994
70.00	1.21	0.72	-0.92	0.99999994	0.99999994
71.00	45.30	2.80	2.13	0.99999994	0.99999994
72.00	55.00	0.87	1.76	0.99999994	0.99999994
73.00	74.20	0.90	2.69	0.99999994	0.99999994
74.00	87.03	9.46	3.19	0.99999994	0.99999994
75.00	91.06	0.82	3.48	0.99999994	0.99999994
76.00	87.94	0.82	3.32	0.99999994	0.99999994
77.00	74.74	0.82	2.64	0.99999994	0.99999994
78.00	54.26	0.82	1.61	0.99999994	0.99999994
79.00	29.20	0.82	0.34	0.99999994	0.99999994
80.00	1.36	0.82	-1.00	0.99999994	0.99999994
81.00	45.47	2.82	2.00	0.99999994	0.99999994
82.00	55.17	0.97	1.62	0.99999994	0.99999994
83.00	74.37	1.01	2.55	0.99999994	0.99999994
84.00	87.22	9.43	3.04	0.99999994	0.99999994
85.00	91.23	0.92	3.34	0.99999994	0.99999994
86.00	88.11	0.92	3.17	0.99999994	0.99999994
87.00	74.91	0.92	2.50	0.99999994	0.99999994
88.00	54.95	0.92	1.46	0.99999994	0.99999994
89.00	29.37	0.92	0.20	0.99999994	0.99999994
90.00	1.50	0.92	-1.21	0.99999994	0.99999994
91.00	45.64	2.84	1.86	0.99999994	0.99999994
92.00	55.35	1.07	1.47	0.99999994	0.99999994
93.00	74.55	1.11	2.41	0.99999994	0.99999994
94.00	87.41	9.36	2.89	0.99999994	0.99999994
95.00	91.31	1.02	3.20	0.99999994	0.99999994
96.00	88.28	1.02	3.03	0.99999994	0.99999994
97.00	75.06	1.02	2.36	0.99999994	0.99999994
98.00	54.63	1.02	1.32	0.99999994	0.99999994
99.00	29.54	1.02	0.05	0.99999994	0.99999994
100.00	1.73	1.02	-1.35	0.99999994	0.99999994

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101.00	45.41	2.87	1.72	0.99999994	0.99999994
102.00	55.52	1.18	1.33	0.99999994	0.99999994
103.00	74.72	1.21	2.27	0.99999994	0.99999994
104.00	87.59	9.33	2.73	0.99999994	0.99999994
105.00	91.50	1.12	3.05	0.99999994	0.99999994
106.00	88.45	1.12	2.89	0.99999994	0.99999994
107.00	75.20	1.12	2.21	0.99999994	0.99999994
108.00	54.80	1.12	1.17	0.99999994	0.99999994
109.00	29.71	1.12	-0.10	0.99999994	0.99999994
110.00	1.90	1.12	-1.57	0.99999994	0.99999994
111.00	45.93	2.90	1.57	0.99999994	0.99999994
112.00	55.69	1.20	1.18	0.99999994	0.99999994
113.00	74.89	1.31	2.12	0.99999994	0.99999994
114.00	87.70	9.20	2.50	0.99999994	0.99999994
115.00	91.75	1.23	2.90	0.99999994	0.99999994
116.00	88.62	1.23	2.74	0.99999994	0.99999994
117.00	75.43	1.23	2.06	0.99999994	0.99999994
118.00	54.97	1.23	1.03	0.99999994	0.99999994
119.00	29.84	1.23	-0.25	0.99999994	0.99999994
120.00	2.00	1.23	-1.65	0.99999994	0.99999994
121.00	46.14	2.93	1.43	0.99999994	0.99999994
122.00	55.80	1.30	1.03	0.99999994	0.99999994
123.00	75.00	1.41	1.97	0.99999994	0.99999994
124.00	87.91	9.23	2.42	0.99999994	0.99999994
125.00	91.92	1.33	2.76	0.99999994	0.99999994
126.00	88.79	1.33	2.59	0.99999994	0.99999994
127.00	75.60	1.33	1.92	0.99999994	0.99999994
128.00	55.14	1.33	0.80	0.99999994	0.99999994
129.00	30.00	1.33	-0.00	0.99999994	0.99999994
130.00	2.25	1.33	-1.40	0.99999994	0.99999994
131.00	46.31	2.96	1.28	0.99999994	0.99999994
132.00	56.04	1.40	0.80	0.99999994	0.99999994
133.00	75.23	1.52	1.82	0.99999994	0.99999994
134.00	88.15	9.18	2.20	0.99999994	0.99999994
135.00	92.09	1.43	2.61	0.99999994	0.99999994
136.00	84.91	1.43	2.44	0.99999994	0.99999994
137.00	75.77	1.43	1.76	0.99999994	0.99999994
138.00	55.32	1.43	0.72	0.99999994	0.99999994
139.00	30.24	1.43	-0.55	0.99999994	0.99999994
140.00	2.15	1.43	-1.95	0.99999994	0.99999994
141.00	46.40	3.00	1.13	0.99999994	0.99999994
142.00	56.21	1.58	0.73	0.99999994	0.99999994
143.00	75.41	1.62	1.67	0.99999994	0.99999994
144.00	88.34	9.14	2.10	0.99999994	0.99999994
145.00	92.20	1.53	2.45	0.99999994	0.99999994
146.00	89.14	1.53	2.29	0.99999994	0.99999994
147.00	75.04	1.53	1.61	0.99999994	0.99999994
148.00	55.49	1.53	0.57	0.99999994	0.99999994
149.00	30.41	1.53	-0.70	0.99999994	0.99999994
150.00	2.60	1.53	-2.11	0.99999994	0.99999994
151.00	46.65	3.05	0.98	0.99999994	0.99999994
152.00	56.36	1.69	0.58	0.99999994	0.99999994
153.00	75.50	1.72	1.51	0.99999994	0.99999994
154.00	88.52	9.09	1.94	0.99999994	0.99999994
155.00	92.74	1.63	2.30	0.99999994	0.99999994
156.00	89.31	1.63	2.13	0.99999994	0.99999994
157.00	76.12	1.63	1.40	0.99999994	0.99999994
158.00	55.60	1.63	0.42	0.99999994	0.99999994
159.00	30.50	1.63	-0.66	0.99999994	0.99999994

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160.00	2.71	1.63	-2.27	0.99999994	0.99999994
161.00	46.82	3.09	0.83	0.99999994	0.99999994
162.00	56.55	1.79	0.42	0.99999994	0.99999994
163.00	75.75	1.82	1.36	0.99999994	0.99999994
164.00	88.71	9.04	1.70	0.99999994	0.99999994
165.00	92.61	1.74	2.15	0.99999994	0.99999994
166.00	89.48	1.74	1.98	0.99999994	0.99999994
167.00	76.29	1.74	1.30	0.99999994	0.99999994
168.00	55.83	1.74	0.20	0.99999994	0.99999994
169.00	30.76	1.74	-1.02	0.99999994	0.99999994
170.00	2.95	1.74	-2.42	0.99999994	0.99999994
171.00	46.98	3.14	0.67	0.99999994	0.99999994
172.00	56.73	1.89	0.26	0.99999994	0.99999994
173.00	75.92	1.92	1.20	0.99999994	0.99999994
174.00	88.89	9.00	1.62	0.99999994	0.99999994
175.00	92.70	1.84	1.99	0.99999994	0.99999994
176.00	89.65	1.84	1.82	0.99999994	0.99999994
177.00	76.48	1.84	1.15	0.99999994	0.99999994
178.00	56.01	1.84	0.10	0.99999994	0.99999994
179.00	30.93	1.84	-1.18	0.99999994	0.99999994
180.00	3.12	1.84	-2.58	0.99999994	0.99999994

X AMPLITUDES = 10.0000 10.0000 0.0000 0.0000 0.0000
X PERIODS = 10.0000 10.0000 10.0000 10.0000 10.0000
Y AMPLITUDES = 10.0000 0.0000 10.0000 0.0000 0.0000
Y PERIODS = 11.0000 11.0000 11.0000 11.0000 11.0000
Z AMPLITUDES = 90.0000 90.0000 90.0000 90.0000 90.0000
Z PERIODS = 1200.00 1200.00 1200.00 1200.00 1200.00
TIME AT END OF EACH INTERVAL IN SECONDS = 100. 200. 300. 000.
QUANTIZING INTERVAL IN TENTHS OF SECONDS = 10
MINIMUM ANGLE STEP = 1.0000
INITIAL HEADING = 0.
LATITUDE = 45.
SENSOR X,Y,Z SCALE FACTORS = 1.020 1.020 1.020
SENSOR X,Y,Z BIAS IN DEGREES PER HOUR = 1.000 1.000 1.000

TIME (MINUTES)	HEADING	TILT	ERROR	DETREF	DEICMP
1.00	44.13	2.74	1.22	0.9999994	0.9999994
2.00	53.79	0.10	1.11	0.9999994	0.9999994
3.00	73.00	0.14	1.50	0.9999994	0.9999994
4.00	85.73	9.45	1.74	0.9999994	0.9999994
5.00	89.90	0.10	1.85	0.9999994	0.9999994
6.00	86.73	0.10	1.79	0.9999994	0.9999994
7.00	73.53	0.10	1.54	0.9999994	0.9999994
8.00	53.07	0.10	1.15	0.9999994	0.9999994
9.00	27.98	0.10	0.60	0.9999994	0.9999994
10.00	0.17	0.10	0.11	0.9999994	0.9999994
11.00	40.30	2.76	1.34	0.9999994	0.9999994
12.00	53.96	0.26	1.22	0.9999994	0.9999994
13.00	73.17	0.24	1.51	0.9999994	0.9999994
14.00	85.91	9.74	1.81	0.9999994	0.9999994
15.00	90.03	0.20	1.96	0.9999994	0.9999994
16.00	86.90	0.20	1.90	0.9999994	0.9999994
17.00	73.71	0.20	1.65	0.9999994	0.9999994
18.00	53.25	0.20	1.26	0.9999994	0.9999994
19.00	24.10	0.20	0.77	0.9999994	0.9999994
20.00	0.35	0.20	0.22	0.9999994	0.9999994
21.00	40.47	2.76	1.05	0.9999994	0.9999994
22.00	54.14	0.36	1.32	0.9999994	0.9999994
23.00	73.34	0.39	1.71	0.9999994	0.9999994
24.00	86.10	9.74	1.87	0.9999994	0.9999994
25.00	90.20	0.31	2.06	0.9999994	0.9999994
26.00	87.07	0.31	2.01	0.9999994	0.9999994
27.00	73.80	0.31	1.76	0.9999994	0.9999994
28.00	53.42	0.31	1.36	0.9999994	0.9999994
29.00	24.53	0.31	0.87	0.9999994	0.9999994
30.00	0.52	0.31	0.32	0.9999994	0.9999994
31.00	40.63	2.77	1.56	0.9999994	0.9999994
32.00	54.31	0.46	1.42	0.9999994	0.9999994
33.00	73.51	0.50	1.81	0.9999994	0.9999994
34.00	86.24	9.44	1.92	0.9999994	0.9999994
35.00	90.31	0.41	2.16	0.9999994	0.9999994
36.00	87.25	0.41	2.10	0.9999994	0.9999994
37.00	74.05	0.41	1.85	0.9999994	0.9999994
38.00	53.59	0.41	1.45	0.9999994	0.9999994
39.00	28.50	0.41	0.96	0.9999994	0.9999994
40.00	0.64	0.41	0.01	0.9999994	0.9999994
41.00	40.80	2.77	1.65	0.9999994	0.9999994

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42.00	50.00	0.50	1.51	0.499999994	0.999999994
43.00	73.69	0.60	1.90	0.500000006	0.999999994
44.00	66.08	9.63	1.97	0.499999994	0.999999994
45.00	90.52	0.51	2.25	0.500000006	0.999999994
46.00	67.42	0.51	2.19	0.499999994	0.999999994
47.00	74.22	0.51	1.94	0.500000006	0.999999994
48.00	53.70	0.51	1.54	0.499999994	0.999999994
49.00	28.68	0.51	1.04	0.500000006	0.999999994
50.00	0.80	0.51	0.09	0.499999994	0.999999994
51.00	44.97	2.70	1.75	0.500000006	0.999999994
52.00	54.66	0.67	1.60	0.499999994	0.999999994
53.00	73.86	0.70	1.99	0.500000006	0.999999994
54.00	86.66	9.58	2.01	0.499999994	0.999999994
55.00	90.72	0.61	2.33	0.500000006	0.999999994
56.00	87.59	0.61	2.28	0.499999994	0.999999994
57.00	74.40	0.61	2.02	0.500000006	0.999999994
58.00	53.94	0.61	1.62	0.499999994	0.999999994
59.00	28.85	0.61	1.12	0.500000006	0.999999994
60.00	1.04	0.61	0.57	0.499999994	0.999999994
61.00	45.14	2.79	1.83	0.500000006	0.999999994
62.00	54.83	0.77	1.67	0.499999994	0.999999994
63.00	74.03	0.80	2.07	0.500000006	0.999999994
64.00	86.85	9.53	2.05	0.499999994	0.999999994
65.00	90.89	0.72	2.41	0.500000006	0.999999994
66.00	87.70	0.72	2.35	0.499999994	0.999999994
67.00	74.57	0.72	2.10	0.500000006	0.999999994
68.00	54.11	0.72	1.69	0.499999994	0.999999994
69.00	29.02	0.72	1.19	0.500000006	0.999999994
70.00	1.21	0.72	0.63	0.499999994	0.999999994
71.00	45.30	2.80	1.90	0.500000006	0.999999994
72.00	55.00	0.87	1.74	0.499999994	0.999999994
73.00	74.20	0.90	2.14	0.500000006	0.999999994
74.00	87.03	9.40	2.07	0.499999994	0.999999994
75.00	91.06	0.82	2.48	0.500000006	0.999999994
76.00	87.94	0.82	2.42	0.499999994	0.999999994
77.00	74.74	0.82	2.16	0.500000006	0.999999994
78.00	54.20	0.82	1.70	0.499999994	0.999999994
79.00	29.20	0.82	1.25	0.500000006	0.999999994
80.00	1.30	0.82	0.69	0.499999994	0.999999994
81.00	45.47	2.82	1.97	0.500000006	0.999999994
82.00	55.17	0.97	1.81	0.499999994	0.999999994
83.00	74.37	1.01	2.20	0.500000006	0.999999994
84.00	87.22	9.43	2.09	0.499999994	0.999999994
85.00	91.23	0.92	2.54	0.500000006	0.999999994
86.00	88.11	0.92	2.40	0.499999994	0.999999994
87.00	74.91	0.92	2.22	0.500000006	0.999999994
88.00	54.05	0.92	1.81	0.499999994	0.999999994
89.00	29.37	0.92	1.30	0.500000006	0.999999994
90.00	1.50	0.92	0.74	0.499999994	0.999999994
91.00	45.64	2.84	2.03	0.500000006	0.999999994
92.00	55.35	1.07	1.80	0.499999994	0.999999994
93.00	74.55	1.11	2.25	0.500000006	0.999999994
94.00	87.41	9.38	2.11	0.499999994	0.999999994
95.00	91.41	1.02	2.59	0.500000006	0.999999994
96.00	88.20	1.02	2.54	0.499999994	0.999999994
97.00	75.08	1.02	2.28	0.500000006	0.999999994
98.00	54.63	1.02	1.80	0.499999994	0.999999994
99.00	29.54	1.02	1.35	0.500000006	0.999999994
100.00	1.73	1.02	0.79	0.499999994	0.999999994

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101.00	45.91	2.87	2.03	0.99999994	0.99999994
102.00	55.52	1.10	1.91	0.99999994	0.99999994
103.00	74.72	1.21	2.30	0.99999994	0.99999994
104.00	87.59	9.33	2.11	0.99999994	0.99999994
105.00	91.58	1.12	2.64	0.99999994	0.99999994
106.00	88.45	1.12	2.58	0.99999994	0.99999994
107.00	75.26	1.12	2.32	0.99999994	0.99999994
108.00	54.80	1.12	1.91	0.99999994	0.99999994
109.00	29.71	1.12	1.33	0.99999994	0.99999994
110.00	1.90	1.12	0.82	0.99999994	0.99999994
111.00	45.98	2.90	2.13	0.99999994	0.99999994
112.00	55.69	1.28	1.95	0.99999994	0.99999994
113.00	74.49	1.31	2.35	0.99999994	0.99999994
114.00	87.78	9.28	2.11	0.99999994	0.99999994
115.00	91.75	1.23	2.68	0.99999994	0.99999994
116.00	88.62	1.23	2.63	0.99999994	0.99999994
117.00	75.43	1.23	2.36	0.99999994	0.99999994
118.00	54.97	1.23	1.94	0.99999994	0.99999994
119.00	29.89	1.23	1.42	0.99999994	0.99999994
120.00	2.08	1.23	0.85	0.99999994	0.99999994
121.00	46.14	2.93	2.17	0.99999994	0.99999994
122.00	55.86	1.38	1.98	0.99999994	0.99999994
123.00	75.06	1.41	2.38	0.99999994	0.99999994
124.00	87.97	9.23	2.11	0.99999994	0.99999994
125.00	91.92	1.33	2.72	0.99999994	0.99999994
126.00	88.79	1.33	2.66	0.99999994	0.99999994
127.00	75.60	1.33	2.40	0.99999994	0.99999994
128.00	55.14	1.33	1.97	0.99999994	0.99999994
129.00	30.06	1.33	1.49	0.99999994	0.99999994
130.00	2.25	1.33	0.86	0.99999994	0.99999994
131.00	46.31	2.90	2.20	0.99999994	0.99999994
132.00	56.04	1.48	2.01	0.99999994	0.99999994
133.00	75.23	1.52	2.41	0.99999994	0.99999994
134.00	88.15	9.18	2.10	0.99999994	0.99999994
135.00	92.09	1.43	2.75	0.99999994	0.99999994
136.00	88.97	1.43	2.69	0.99999994	0.99999994
137.00	75.77	1.43	2.42	0.99999994	0.99999994
138.00	55.32	1.43	1.99	0.99999994	0.99999994
139.00	30.24	1.43	1.45	0.99999994	0.99999994
140.00	2.43	1.43	0.89	0.99999994	0.99999994
141.00	46.48	3.00	2.22	0.99999994	0.99999994
142.00	56.21	1.56	2.03	0.99999994	0.99999994
143.00	75.41	1.62	2.43	0.99999994	0.99999994
144.00	88.34	9.13	2.08	0.99999994	0.99999994
145.00	92.26	1.53	2.77	0.99999994	0.99999994
146.00	89.14	1.53	2.71	0.99999994	0.99999994
147.00	75.94	1.53	2.44	0.99999994	0.99999994
148.00	55.49	1.53	2.01	0.99999994	0.99999994
149.00	30.41	1.53	1.46	0.99999994	0.99999994
150.00	2.60	1.53	0.88	0.99999994	0.99999994
151.00	46.65	3.05	2.23	0.99999994	0.99999994
152.00	56.38	1.69	2.04	0.99999994	0.99999994
153.00	75.58	1.72	2.45	0.99999994	0.99999994
154.00	88.52	9.09	2.03	0.99999994	0.99999994
155.00	92.44	1.63	2.70	0.99999994	0.99999994
156.00	89.31	1.63	2.72	0.99999994	0.99999994
157.00	76.12	1.63	2.46	0.99999994	0.99999994
158.00	55.68	1.63	2.02	0.99999994	0.99999994
159.00	30.58	1.63	1.46	0.99999994	0.99999994

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160.00	2.71	1.63	0.81	0.99999994
161.00	46.82	3.09	2.24	0.99999994
162.00	56.55	1.79	2.04	0.99999994
163.00	75.75	1.82	2.40	0.99999994
164.00	88.71	9.04	2.03	0.99999994
165.00	92.61	1.74	2.79	0.99999994
166.00	89.48	1.74	2.73	0.99999994
167.00	76.29	1.74	2.40	0.99999994
168.00	55.83	1.74	2.02	0.99999994
169.00	30.76	1.74	1.45	0.99999994
170.00	2.95	1.74	0.80	0.99999994
171.00	46.98	3.14	2.24	0.99999994
172.00	56.73	1.89	2.04	0.99999994
173.00	75.92	1.92	2.40	0.99999994
174.00	88.89	9.00	1.99	0.99999994
175.00	92.78	1.84	2.80	0.99999994
176.00	69.65	1.84	2.74	0.99999994
177.00	76.40	1.84	2.40	0.99999994
178.00	56.01	1.84	2.01	0.99999994
179.00	30.93	1.84	1.44	0.99999994
180.00	3.12	1.84	0.84	0.99999994

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X AMPLITUDES = 0.0000 10.0000 0.0000 0.0000 0.0000
Y PERIODS = 10.0000 10.0000 10.0000 10.0000 10.0000
Y AMPLITUDES = 10.0000 0.0000 10.0000 0.0000 0.0000
Z PERIODS = 11.0000 11.0000 11.0000 11.0000 11.0000
Z AMPLITUDES = 90.0000 90.0000 90.0000 90.0000 90.0000
2 PERIODS = 1200.00 1200.00 1200.00 1200.00 1200.00
TIME AT END OF EACH INTERVAL IN SECONDS = 100. 200. 300. 600.
QUANTIZING INTERVAL IN TENS OF SECONDS = 10
MINIMUM ANGLE STEP = 1.0000
INITIAL HEADING = 45.
LATITUDE = 45.
SENSOR X,Y,Z SCALE FACTORS = 1.020 1.020 1.020
SENSOR X,Y,Z BIAS IN DEGREES PER HOUR = 1.000 1.000 1.000

TIME (MINUTES)	HEADING	TILT	ERROR	DETREF	VEICOMP
1.00	27.62	2.78	0.56	0.9999994	0.9999994
2.00	52.52	0.16	1.06	0.9999994	0.9999994
3.00	71.73	0.19	1.45	0.9999994	0.9999994
4.00	84.46	9.88	1.69	0.9999994	0.9999994
5.00	88.59	0.09	1.80	0.9999994	0.9999994
6.00	85.46	0.09	1.75	0.9999994	0.9999994
7.00	72.27	0.09	1.50	0.9999994	0.9999994
8.00	51.81	0.09	1.10	0.9999994	0.9999994
9.00	26.72	0.09	0.61	0.9999994	0.9999994
10.00	-1.09	0.09	0.07	0.9999994	0.9999994
11.00	26.52	2.72	0.63	0.9999994	0.9999994
12.00	51.45	0.25	1.15	0.9999994	0.9999994
13.00	70.63	0.28	1.52	0.9999994	0.9999994
14.00	83.36	9.85	1.72	0.9999994	0.9999994
15.00	87.49	0.19	1.87	0.9999994	0.9999994
16.00	84.37	0.19	1.82	0.9999994	0.9999994
17.00	71.17	0.19	1.56	0.9999994	0.9999994
18.00	50.71	0.19	1.17	0.9999994	0.9999994
19.00	25.62	0.19	0.60	0.9999994	0.9999994
20.00	-2.19	0.19	0.15	0.9999994	0.9999994
21.00	25.02	2.66	0.70	0.9999994	0.9999994
22.00	50.53	0.34	1.19	0.9999994	0.9999994
23.00	69.54	0.37	1.50	0.9999994	0.9999994
24.00	82.30	9.83	1.74	0.9999994	0.9999994
25.00	85.40	0.28	1.93	0.9999994	0.9999994
26.00	83.27	0.28	1.87	0.9999994	0.9999994
27.00	70.08	0.28	1.62	0.9999994	0.9999994
28.00	49.62	0.28	1.22	0.9999994	0.9999994
29.00	24.53	0.28	0.73	0.9999994	0.9999994
30.00	-3.28	0.28	0.19	0.9999994	0.9999994
31.00	24.52	2.60	0.70	0.9999994	0.9999994
32.00	49.24	0.43	1.24	0.9999994	0.9999994
33.00	64.44	0.47	1.63	0.9999994	0.9999994
34.00	81.22	9.81	1.75	0.9999994	0.9999994
35.00	85.30	0.37	1.98	0.9999994	0.9999994
36.00	82.18	0.37	1.93	0.9999994	0.9999994
37.00	64.98	0.37	1.67	0.9999994	0.9999994
38.00	44.52	0.37	1.27	0.9999994	0.9999994
39.00	23.43	0.37	0.78	0.9999994	0.9999994
40.00	-4.38	0.37	0.23	0.9999994	0.9999994
41.00	23.23	2.54	0.81	0.9999994	0.9999994

42.00	48.14	0.53	1.29	0.9999994	0.9999994
43.00	67.35	0.56	1.68	0.9999994	0.9999994
44.00	80.14	0.79	1.70	0.9999994	0.9999994
45.00	84.21	0.47	2.03	0.9999994	0.9999994
46.00	81.08	0.47	1.97	0.9999994	0.9999994
47.00	67.89	0.47	1.72	0.9999994	0.9999994
48.00	47.43	0.47	1.32	0.9999994	0.9999994
49.00	22.34	0.47	0.82	0.9999994	0.9999994
50.00	-5.47	0.47	0.27	0.9999994	0.9999994
51.00	22.13	2.48	0.25	0.9999994	0.9999994
52.00	47.05	0.62	1.33	0.9999994	0.9999994
53.00	66.25	0.65	1.72	0.9999994	0.9999994
54.00	79.06	9.77	1.76	0.9999994	0.9999994
55.00	63.11	0.50	2.06	0.9999994	0.9999994
56.00	79.99	0.56	2.01	0.9999994	0.9999994
57.00	66.79	0.56	1.75	0.9999994	0.9999994
58.00	46.33	0.56	1.35	0.9999994	0.9999994
59.00	21.24	0.56	0.86	0.9999994	0.9999994
60.00	-6.57	0.56	0.30	0.9999994	0.9999994
61.00	21.03	2.42	0.88	0.9999994	0.9999994
62.00	45.95	0.71	1.36	0.9999994	0.9999994
63.00	65.10	0.74	1.75	0.9999994	0.9999994
64.00	77.90	9.70	1.75	0.9999994	0.9999994
65.00	82.02	0.65	2.09	0.9999994	0.9999994
66.00	78.99	0.65	2.04	0.9999994	0.9999994
67.00	65.70	0.65	1.76	0.9999994	0.9999994
68.00	45.24	0.65	1.36	0.9999994	0.9999994
69.00	20.15	0.65	0.86	0.9999994	0.9999994
70.00	-7.60	0.65	0.35	0.9999994	0.9999994
71.00	19.93	2.36	0.90	0.9999994	0.9999994
72.00	44.80	0.81	1.39	0.9999994	0.9999994
73.00	64.00	0.84	1.76	0.9999994	0.9999994
74.00	76.90	9.75	1.75	0.9999994	0.9999994
75.00	80.92	0.75	2.12	0.9999994	0.9999994
76.00	77.79	0.75	2.00	0.9999994	0.9999994
77.00	64.60	0.75	1.81	0.9999994	0.9999994
78.00	44.14	0.75	1.40	0.9999994	0.9999994
79.00	19.05	0.75	0.90	0.9999994	0.9999994
80.00	-9.70	0.75	0.34	0.9999994	0.9999994
81.00	18.83	2.30	0.82	0.9999994	0.9999994
82.00	43.77	0.90	1.41	0.9999994	0.9999994
83.00	62.97	0.93	1.80	0.9999994	0.9999994
84.00	75.82	9.74	1.72	0.9999994	0.9999994
85.00	79.83	0.84	2.14	0.9999994	0.9999994
86.00	66.70	0.84	2.00	0.9999994	0.9999994
87.00	63.51	0.84	1.82	0.9999994	0.9999994
88.00	43.05	0.84	1.41	0.9999994	0.9999994
89.00	17.90	0.84	0.91	0.9999994	0.9999994
90.00	-9.95	0.84	0.35	0.9999994	0.9999994
91.00	17.74	2.24	0.93	0.9999994	0.9999994
92.00	42.67	0.99	1.42	0.9999994	0.9999994
93.00	61.87	1.02	1.81	0.9999994	0.9999994
94.00	74.74	9.74	1.89	0.9999994	0.9999994
95.00	78.73	0.93	2.15	0.9999994	0.9999994
96.00	75.60	0.93	2.09	0.9999994	0.9999994
97.00	62.41	0.93	1.83	0.9999994	0.9999994
98.00	41.95	0.93	1.42	0.9999994	0.9999994
99.00	16.86	0.93	0.91	0.9999994	0.9999994
100.00	-10.95	0.93	0.35	0.9999994	0.9999994

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101.00	15.64	2.19	0.93	0.99999994
102.00	41.59	1.09	1.42	0.99999994
103.00	60.76	1.12	1.41	0.99999994
104.00	73.61	9.74	1.60	0.99999994
105.00	77.64	1.03	2.15	0.99999994
106.00	74.51	1.03	2.09	0.99999994
107.00	61.42	1.03	1.83	0.99999994
108.00	40.86	1.03	1.42	0.99999994
109.00	15.77	1.03	0.90	0.99999994
110.00	-12.04	1.03	0.34	0.99999994
111.00	15.54	2.13	0.92	0.99999994
112.00	40.46	1.18	1.41	0.99999994
113.00	59.66	1.21	1.81	0.99999994
114.00	72.59	9.74	1.62	0.99999994
115.00	76.54	1.12	2.15	0.99999994
116.00	73.41	1.12	2.09	0.99999994
117.00	60.22	1.12	1.82	0.99999994
118.00	39.76	1.12	1.41	0.99999994
119.00	14.68	1.12	0.89	0.99999994
120.00	-13.14	1.12	0.33	0.99999994
121.00	14.44	2.06	0.90	0.99999994
122.00	59.39	1.27	1.40	0.99999994
123.00	58.59	1.30	1.80	0.99999994
124.00	71.51	9.74	1.58	0.99999994
125.00	75.44	1.21	2.13	0.99999994
126.00	72.32	1.21	2.06	0.99999994
127.00	59.13	1.21	1.81	0.99999994
128.00	33.67	1.21	1.39	0.99999994
129.00	13.59	1.21	0.87	0.99999994
130.00	-14.23	1.21	0.31	0.99999994
131.00	13.35	2.03	0.87	0.99999994
132.00	58.29	1.37	1.36	0.99999994
133.00	57.49	1.40	1.76	0.99999994
134.00	70.43	9.75	1.53	0.99999994
135.00	74.35	1.30	2.12	0.99999994
136.00	71.22	1.30	2.06	0.99999994
137.00	58.03	1.30	1.79	0.99999994
138.00	37.57	1.30	1.36	0.99999994
139.00	12.49	1.30	0.84	0.99999994
140.00	-15.33	1.30	0.27	0.99999994
141.00	12.25	1.96	0.84	0.99999994
142.00	57.20	1.46	1.35	0.99999994
143.00	56.40	1.49	1.75	0.99999994
144.00	69.35	9.75	1.88	0.99999994
145.00	73.25	1.40	2.09	0.99999994
146.00	70.13	1.40	2.03	0.99999994
147.00	56.93	1.40	1.76	0.99999994
148.00	36.40	1.40	1.33	0.99999994
149.00	11.39	1.40	0.80	0.99999994
150.00	-16.42	1.40	0.24	0.99999994
151.00	11.15	1.93	0.79	0.99999994
152.00	56.10	1.55	1.31	0.99999994
153.00	55.30	1.56	1.72	0.99999994
154.00	68.27	9.76	1.82	0.99999994
155.00	72.16	1.49	2.06	0.99999994
156.00	69.03	1.49	2.00	0.99999994
157.00	55.84	1.49	1.73	0.99999994
158.00	35.39	1.49	1.29	0.99999994
159.00	10.30	1.49	0.75	0.99999994

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160.00	-17.52	1.49	0.19	0.99999994	0.99999994
161.00	10.06	1.86	0.74	0.99999994	0.99999994
162.00	35.01	1.64	1.77	0.99999994	0.99999994
163.00	50.21	1.67	1.66	0.99999994	0.99999994
164.00	67.19	9.76	1.75	0.99999994	0.99999994
165.00	71.06	1.56	2.02	0.99999994	0.99999994
166.00	67.94	1.56	1.86	0.99999994	0.99999994
167.00	54.74	1.56	1.68	0.99999994	0.99999994
168.00	34.24	1.58	1.24	0.99999994	0.99999994
169.00	9.21	1.56	0.70	0.99999994	0.99999994
170.00	-18.61	1.56	0.14	0.99999994	0.99999994
171.00	8.96	1.84	0.66	0.99999994	0.99999994
172.00	33.92	1.74	1.22	0.99999994	0.99999994
173.00	53.11	1.76	1.63	0.99999994	0.99999994
174.00	66.11	9.80	1.28	0.99999994	0.99999994
175.00	69.97	1.67	1.98	0.99999994	0.99999994
176.00	66.84	1.67	1.91	0.99999994	0.99999994
177.00	53.65	1.67	1.63	0.99999994	0.99999994
178.00	33.20	1.67	1.18	0.99999994	0.99999994
179.00	8.11	1.67	0.64	0.99999994	0.99999994
180.00	-19.71	1.67	0.06	0.99999994	0.99999994

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42.00	44.27	0.34	2.54	0.49999994	0.99999994
43.00	37.24	1.53	1.46	0.99999994	0.99999994
44.00	9.90	2.11	0.93	0.99999994	0.99999994
45.00	10.12	2.16	0.95	0.99999994	0.99999994
46.00	10.34	2.22	0.97	0.99999994	0.99999994
47.00	10.57	2.26	0.99	0.99999994	0.99999994
48.00	10.79	2.33	1.01	0.99999994	0.99999994
49.00	11.02	2.39	1.03	0.99999994	0.99999994
50.00	11.24	2.45	1.05	0.99999994	0.99999994
51.00	83.65	1.08	2.47	0.99999994	0.99999994
52.00	46.52	0.76	2.72	0.99999994	0.99999994
53.00	59.49	2.02	1.66	0.99999994	0.99999994
54.00	12.15	2.60	1.13	0.99999994	0.99999994
55.00	12.37	2.65	1.15	0.99999994	0.99999994
56.00	12.60	2.71	1.17	0.99999994	0.99999994
57.00	12.82	2.77	1.19	0.99999994	0.99999994
58.00	13.05	2.82	1.21	0.99999994	0.99999994
59.00	13.27	2.88	1.23	0.99999994	0.99999994
60.00	13.50	2.94	1.25	0.99999994	0.99999994
61.00	65.90	1.48	2.65	0.99999994	0.99999994
62.00	48.77	1.26	2.89	0.99999994	0.99999994
63.00	41.75	2.50	1.80	0.99999994	0.99999994
64.00	14.40	3.09	1.32	0.99999994	0.99999994
65.00	14.62	3.14	1.34	0.99999994	0.99999994
66.00	14.85	3.20	1.36	0.99999994	0.99999994
67.00	15.07	3.26	1.38	0.99999994	0.99999994
68.00	15.30	3.31	1.40	0.99999994	0.99999994
69.00	15.52	3.37	1.42	0.99999994	0.99999994
70.00	15.75	3.43	1.44	0.99999994	0.99999994
71.00	88.10	1.91	2.82	0.99999994	0.99999994
72.00	101.02	1.74	3.05	0.99999994	0.99999994
73.00	44.01	2.99	2.05	0.99999994	0.99999994
74.00	16.65	3.58	1.51	0.99999994	0.99999994
75.00	16.88	3.63	1.53	0.99999994	0.99999994
76.00	17.10	3.69	1.55	0.99999994	0.99999994
77.00	17.33	3.75	1.56	0.99999994	0.99999994
78.00	17.55	3.80	1.58	0.99999994	0.99999994
79.00	17.78	3.86	1.60	0.99999994	0.99999994
80.00	18.00	3.91	1.62	0.99999994	0.99999994
81.00	90.42	2.36	2.98	0.99999994	0.99999994
82.00	103.27	2.22	3.20	0.99999994	0.99999994
83.00	46.28	3.47	2.25	0.99999994	0.99999994
84.00	18.91	4.07	1.69	0.99999994	0.99999994
85.00	19.13	4.12	1.71	0.99999994	0.99999994
86.00	19.36	4.18	1.72	0.99999994	0.99999994
87.00	19.58	4.23	1.74	0.99999994	0.99999994
88.00	19.81	4.29	1.76	0.99999994	0.99999994
89.00	20.04	4.34	1.78	0.99999994	0.99999994
90.00	20.26	4.40	1.80	0.99999994	0.99999994
91.00	42.67	2.82	3.13	0.99999994	0.99999994
92.00	105.52	2.71	3.34	0.99999994	0.99999994
93.00	48.54	3.90	2.41	0.99999994	0.99999994
94.00	21.17	4.50	1.80	0.99999994	0.99999994
95.00	21.39	4.61	1.80	0.99999994	0.99999994
96.00	21.62	4.67	1.80	0.99999994	0.99999994
97.00	21.84	4.72	1.92	0.99999994	0.99999994
98.00	22.07	4.77	1.93	0.99999994	0.99999994
99.00	22.30	4.83	1.95	0.99999994	0.99999994
100.00	22.52	4.88	1.97	0.99999994	0.99999994

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101.00	94.93	3.20	3.21	0.99999994	0.99999994
102.00	107.76	3.19	3.40	0.99999994	0.99999994
103.00	50.81	4.44	2.50	0.99999994	0.99999994
104.00	24.43	5.04	2.03	0.99999994	0.99999994
105.00	24.65	5.09	2.05	0.99999994	0.99999994
106.00	23.86	5.15	2.07	0.99999994	0.99999994
107.00	24.10	5.20	2.08	0.99999994	0.99999994
108.00	24.33	5.25	2.10	0.99999994	0.99999994
109.00	24.56	5.31	2.12	0.99999994	0.99999994
110.00	24.78	5.36	2.13	0.99999994	0.99999994
111.00	97.19	3.74	3.40	0.99999994	0.99999994
112.00	110.01	3.67	3.58	0.99999994	0.99999994
113.00	53.08	4.92	2.75	0.99999994	0.99999994
114.00	25.69	5.52	2.20	0.99999994	0.99999994
115.00	25.92	5.63	2.21	0.99999994	0.99999994
116.00	26.14	5.63	2.23	0.99999994	0.99999994
117.00	26.37	5.68	2.25	0.99999994	0.99999994
118.00	26.60	5.74	2.26	0.99999994	0.99999994
119.00	26.82	5.79	2.28	0.99999994	0.99999994
120.00	27.05	5.84	2.29	0.99999994	0.99999994
121.00	99.05	4.21	3.51	0.99999994	0.99999994
122.00	112.26	4.15	3.67	0.99999994	0.99999994
123.00	55.36	5.40	2.91	0.99999994	0.99999994
124.00	27.98	6.01	2.36	0.99999994	0.99999994
125.00	28.18	6.11	2.37	0.99999994	0.99999994
126.00	28.41	6.16	2.40	0.99999994	0.99999994
127.00	28.64	6.21	2.42	0.99999994	0.99999994
128.00	28.87	6.27	2.44	0.99999994	0.99999994
129.00	29.09	6.32	2.45	0.99999994	0.99999994
130.00	29.32	6.37	3.61	0.99999994	0.99999994
131.00	101.70	4.67	3.76	0.99999994	0.99999994
132.00	114.50	4.63	3.07	0.99999994	0.99999994
133.00	57.64	5.87	2.51	0.99999994	0.99999994
134.00	30.23	6.49	2.53	0.99999994	0.99999994
135.00	30.45	6.54	2.54	0.99999994	0.99999994
136.00	30.68	6.59	2.56	0.99999994	0.99999994
137.00	30.91	6.64	2.57	0.99999994	0.99999994
138.00	31.14	6.69	2.59	0.99999994	0.99999994
139.00	31.36	6.74	2.60	0.99999994	0.99999994
140.00	31.59	6.79	3.70	0.99999994	0.99999994
141.00	103.96	5.14	3.83	0.99999994	0.99999994
142.00	116.74	5.11	3.21	0.99999994	0.99999994
143.00	59.92	6.35	2.66	0.99999994	0.99999994
144.00	32.50	6.96	2.67	0.99999994	0.99999994
145.00	32.73	7.01	2.69	0.99999994	0.99999994
146.00	32.96	7.07	2.70	0.99999994	0.99999994
147.00	33.18	7.11	2.72	0.99999994	0.99999994
148.00	33.41	7.16	2.73	0.99999994	0.99999994
149.00	33.64	7.22	2.75	0.99999994	0.99999994
150.00	33.87	7.27	3.78	0.99999994	0.99999994
151.00	106.21	5.60	3.49	0.99999994	0.99999994
152.00	118.96	5.59	3.35	0.99999994	0.99999994
153.00	62.20	6.82	2.80	0.99999994	0.99999994
154.00	34.76	7.44	2.82	0.99999994	0.99999994
155.00	35.01	7.49	2.83	0.99999994	0.99999994
156.00	35.24	7.54	2.85	0.99999994	0.99999994
157.00	35.46	7.59	2.86	0.99999994	0.99999994
158.00	35.64	7.63	2.88	0.99999994	0.99999994
159.00	35.92	7.69	2.89	0.99999994	0.99999994

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160.00	56.15	7.74	2.89	0.99999994	0.99999994
161.00	108.47	6.06	3.84	0.99999994	0.99999994
162.00	121.22	6.06	3.93	0.99999994	0.99999994
163.00	64.89	7.24	3.86	0.99999994	0.99999994
164.00	37.06	7.91	2.94	0.99999994	0.99999994
165.00	37.29	7.96	2.96	0.99999994	0.99999994
166.00	37.52	8.01	2.97	0.99999994	0.99999994
167.00	37.75	8.05	2.99	0.99999994	0.99999994
168.00	37.98	8.10	3.00	0.99999994	0.99999994
169.00	38.21	8.15	3.02	0.99999994	0.99999994
170.00	38.43	8.20	3.03	0.99999994	0.99999994
171.00	110.72	6.52	3.89	0.99999994	0.99999994
172.00	123.46	6.53	3.96	0.99999994	0.99999994
173.00	66.76	7.75	3.61	0.99999994	0.99999994
174.00	39.35	8.38	3.68	0.99999994	0.99999994
175.00	39.58	8.42	3.09	0.99999994	0.99999994
176.00	39.91	8.48	3.11	0.99999994	0.99999994
177.00	40.03	8.52	3.12	0.99999994	0.99999994
178.00	40.26	8.57	3.14	0.99999994	0.99999994
179.00	40.49	8.62	3.15	0.99999994	0.99999994
180.00	40.72	8.66	3.16	0.99999994	0.99999994

X AMPLITUDES = 10.0000 10.0000 10.0000 10.0000 10.0000
X PERIODS = 2.5000 2.5000 2.5000 2.5000 2.5000
Y AMPLITUDES = 5.0000 5.0000 5.0000 5.0000 5.0000
Y PERIODS = 2.6000 2.6000 2.6000 2.6000 2.6000
Z AMPLITUDES = 90.0000 90.0000 90.0000 90.0000 90.0000
Z PERIODS = 400.00 400.00 400.00 400.00 400.00
TIME AT END OF EACH INTERVAL IN SECONDS = 100. 3
QUANTIZING INTERVAL IN TENTHS OF SECONDS =
MINIMUM ANGLE STEP = 1.0000
INITIAL HEADING = 0.
LATITUDES 45.
SENSOR X,Y,Z SCALE FACTORS = 1.020 1.020 1.020
SENSOR X,Y,Z BIAS IN DEGREES PER HOUR = 1.000 1.000 1.000

TIME (MINUTES)	HEADING	TILT	ERRON	DETREF	DEICMP
1.00	73.11	2.46	1.47	0.9999994	0.9999994
2.00	68.82	4.26	1.85	0.9999994	0.9999994
3.00	36.30	3.93	0.93	0.9999994	0.9999994
4.00	13.65	4.19	0.61	0.9999994	0.9999994
5.00	17.85	3.69	0.79	0.9999994	0.9999994
6.00	20.10	1.50	0.89	0.9999994	0.9999994
7.00	20.25	2.37	0.91	0.9999994	0.9999994
8.00	18.00	4.16	0.83	0.9999994	0.9999994
9.00	14.08	5.38	0.68	0.9999994	0.9999994
10.00	9.18	4.70	0.89	0.9999994	0.9999994
11.00	82.61	2.36	1.99	0.9999994	0.9999994
12.00	48.30	3.75	2.37	0.9999994	0.9999994
13.00	45.83	3.03	1.06	0.9999994	0.9999994
14.00	23.20	3.85	1.14	0.9999994	0.9999994
15.00	27.39	3.36	1.32	0.9999994	0.9999994
16.00	29.61	2.16	1.01	0.9999994	0.9999994
17.00	29.73	3.40	1.01	0.9999994	0.9999994
18.00	27.45	5.14	1.32	0.9999994	0.9999994
19.00	23.51	6.20	1.17	0.9999994	0.9999994
20.00	18.62	5.54	0.99	0.9999994	0.9999994
21.00	92.11	2.40	2.50	0.9999994	0.9999994
22.00	107.70	3.65	2.89	0.9999994	0.9999994
23.00	55.35	2.14	1.98	0.9999994	0.9999994
24.00	32.74	3.59	1.68	0.9999994	0.9999994
25.00	36.91	3.20	1.84	0.9999994	0.9999994
26.00	39.11	2.93	1.91	0.9999994	0.9999994
27.00	39.20	4.43	1.91	0.9999994	0.9999994
28.00	36.90	6.17	1.81	0.9999994	0.9999994
29.00	32.94	7.25	1.65	0.9999994	0.9999994
30.00	28.05	6.50	1.06	0.9999994	0.9999994
31.00	101.61	2.98	3.00	0.9999994	0.9999994
32.00	117.26	3.99	3.39	0.9999994	0.9999994
33.00	00.85	1.31	2.89	0.9999994	0.9999994
34.00	42.20	3.45	2.17	0.9999994	0.9999994
35.00	46.43	3.17	2.34	0.9999994	0.9999994
36.00	48.60	3.73	2.01	0.9999994	0.9999994
37.00	48.60	5.03	2.39	0.9999994	0.9999994
38.00	46.30	7.20	2.28	0.9999994	0.9999994
39.00	42.38	8.27	2.12	0.9999994	0.9999994
40.00	37.49	7.52	1.95	0.9999994	0.9999994
41.00	111.13	3.84	3.49	0.9999994	0.9999994

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42.00	126.74	4.60	3.89	0.99999994	0.99999994
43.00	74.36	0.83	2.90	0.99999990	0.99999994
44.00	51.71	3.45	2.67	0.99999994	0.99999994
45.00	55.93	3.31	2.83	0.99999994	0.99999994
46.00	58.09	4.54	2.80	0.99999994	0.99999994
47.00	58.16	6.00	2.80	0.99999994	0.99999994
48.00	55.83	8.22	2.74	0.99999994	0.99999994
49.00	51.84	9.30	2.57	0.99999994	0.99999994
50.00	44.94	4.55	2.00	0.99999994	0.99999994
51.00	120.65	4.83	3.98	0.99999994	0.99999994
52.00	136.24	5.57	4.36	0.99999994	0.99999994
53.00	83.86	1.22	3.45	0.99999994	0.99999994
54.00	61.28	3.58	3.15	0.99999994	0.99999994
55.00	65.44	3.59	3.31	0.99999994	0.99999994
56.00	67.59	5.33	3.35	0.99999994	0.99999994
57.00	67.66	7.32	3.31	0.99999994	0.99999994
58.00	65.32	9.20	3.16	0.99999994	0.99999994
59.00	61.32	10.32	3.00	0.99999994	0.99999994
60.00	56.41	9.57	2.84	0.99999994	0.99999994
61.00	130.19	5.86	4.40	0.99999994	0.99999994
62.00	145.74	6.53	4.87	0.99999994	0.99999994
63.00	93.38	2.03	3.92	0.99999994	0.99999994
64.00	70.76	3.83	3.62	0.99999994	0.99999994
65.00	74.94	3.98	3.77	0.99999994	0.99999994
66.00	77.11	6.10	3.79	0.99999994	0.99999994
67.00	77.18	8.20	3.74	0.99999994	0.99999994
68.00	74.84	10.13	3.60	0.99999994	0.99999994
69.00	70.92	11.29	3.42	0.99999994	0.99999994
70.00	65.90	10.55	3.26	0.99999994	0.99999994
71.00	139.74	6.89	4.53	0.99999994	0.99999994
72.00	155.24	7.58	5.35	0.99999994	0.99999994
73.00	102.90	2.92	4.37	0.99999994	0.99999994
74.00	80.29	4.18	4.07	0.99999994	0.99999994
75.00	84.46	4.43	4.22	0.99999994	0.99999994
76.00	86.64	6.83	4.23	0.99999994	0.99999994
77.00	86.72	9.02	4.16	0.99999994	0.99999994
78.00	84.39	11.01	4.01	0.99999994	0.99999994
79.00	80.36	12.21	3.82	0.99999994	0.99999994
80.00	75.42	11.44	3.67	0.99999994	0.99999994
81.00	149.30	7.90	5.41	0.99999994	0.99999994
82.00	164.74	8.61	5.83	0.99999994	0.99999994
83.00	112.45	3.82	4.82	0.99999994	0.99999994
84.00	89.81	4.58	4.50	0.99999994	0.99999994
85.00	93.94	4.92	4.65	0.99999994	0.99999994
86.00	96.14	7.51	4.65	0.99999994	0.99999994
87.00	96.30	9.78	4.50	0.99999994	0.99999994
88.00	93.97	11.82	4.82	0.99999994	0.99999994
89.00	89.94	13.06	4.72	0.99999994	0.99999994
90.00	84.97	12.37	4.00	0.99999994	0.99999994
91.00	159.80	8.87	5.89	0.99999994	0.99999994
92.00	174.24	9.62	-353.70	0.99999994	0.99999994
93.00	122.01	4.70	5.26	0.99999994	0.99999994
94.00	99.35	5.02	4.93	0.99999994	0.99999994
95.00	103.53	5.42	5.08	0.99999994	0.99999994
96.00	105.70	8.16	5.07	0.99999994	0.99999994
97.00	105.90	10.47	4.99	0.99999994	0.99999994
98.00	103.59	12.55	4.81	0.99999994	0.99999994
99.00	99.50	13.84	4.60	0.99999994	0.99999994
100.00	94.57	13.17	4.44	0.99999994	0.99999994

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101.00	108.42	9.79	6.37	0.99999994	0.99999994
102.00	-116.26	10.59	6.71	0.99999994	0.99999994
103.00	131.58	5.56	5.71	0.99999994	0.99999994
104.00	108.90	5.48	5.35	0.99999994	0.99999994
105.00	113.10	5.93	5.50	0.99999994	0.99999994
106.00	115.39	8.74	5.40	0.99999994	0.99999994
107.00	115.54	11.09	5.40	0.99999994	0.99999994
108.00	113.25	13.21	5.21	0.99999994	0.99999994
109.00	109.22	14.53	4.99	0.99999994	0.99999994
110.00	108.21	13.90	4.82	0.99999994	0.99999994
111.00	117.98	10.65	-353.15	0.99999994	0.99999994
112.00	-166.77	11.51	7.23	0.99999994	0.99999994
113.00	141.17	6.38	6.16	0.99999994	0.99999994
114.00	118.48	5.95	5.77	0.99999994	0.99999994
115.00	122.69	6.42	5.92	0.99999994	0.99999994
116.00	125.02	9.27	5.90	0.99999994	0.99999994
117.00	125.22	11.63	5.81	0.99999994	0.99999994
118.00	122.95	13.73	5.62	0.99999994	0.99999994
119.00	118.93	15.14	5.39	0.99999994	0.99999994
120.00	113.89	14.53	5.21	0.99999994	0.99999994
121.00	-172.48	11.45	7.32	0.99999994	0.99999994
122.00	-157.29	12.36	7.68	0.99999994	0.99999994
123.00	150.77	7.16	6.81	0.99999994	0.99999994
124.00	124.08	6.40	6.19	0.99999994	0.99999994
125.00	132.30	6.90	6.35	0.99999994	0.99999994
126.00	134.68	9.74	6.34	0.99999994	0.99999994
127.00	134.92	12.10	6.25	0.99999994	0.99999994
128.00	132.68	14.25	6.05	0.99999994	0.99999994
129.00	128.67	15.65	5.80	0.99999994	0.99999994
130.00	123.61	15.08	5.60	0.99999994	0.99999994
131.00	-182.95	12.16	7.79	0.99999994	0.99999994
132.00	-147.91	13.14	8.11	0.99999994	0.99999994
133.00	160.37	7.89	7.08	0.99999994	0.99999994
134.00	137.69	6.83	6.62	0.99999994	0.99999994
135.00	141.93	7.34	6.79	0.99999994	0.99999994
136.00	144.36	10.14	6.78	0.99999994	0.99999994
137.00	144.63	12.47	6.70	0.99999994	0.99999994
138.00	142.44	14.63	6.50	0.99999994	0.99999994
139.00	138.45	16.06	6.24	0.99999994	0.99999994
140.00	133.36	15.53	6.02	0.99999994	0.99999994
141.00	-153.43	12.80	8.25	0.99999994	0.99999994
142.00	-138.34	13.84	8.52	0.99999994	0.99999994
143.00	169.97	8.57	7.55	0.99999994	0.99999994
144.00	147.32	7.24	7.06	0.99999994	0.99999994
145.00	151.56	7.75	7.24	0.99999994	0.99999994
146.00	154.04	10.47	7.25	0.99999994	0.99999994
147.00	154.36	12.77	7.17	0.99999994	0.99999994
148.00	152.21	14.92	6.98	0.99999994	0.99999994
149.00	148.24	16.36	6.71	0.99999994	0.99999994
150.00	143.14	15.88	6.47	0.99999994	0.99999994
151.00	-143.92	13.36	8.69	0.99999994	0.99999994
152.00	-128.46	14.45	8.02	0.99999994	0.99999994
153.00	179.56	9.19	-351.97	0.99999994	0.99999994
154.00	156.95	7.62	7.52	0.99999994	0.99999994
155.00	161.20	8.11	7.71	0.99999994	0.99999994
156.00	163.73	10.73	7.74	0.99999994	0.99999994
157.00	164.10	12.97	7.68	0.99999994	0.99999994
158.00	161.97	15.10	7.08	0.99999994	0.99999994
159.00	158.05	16.56	7.21	0.99999994	0.99999994

160.00	152.94	16.12	6.86	0.9999994
161.00	-139.42	13.82	9.11	0.9999994
162.00	-119.37	14.97	9.29	0.9999994
163.00	-170.87	9.74	8.51	0.9999994
164.00	166.56	7.95	8.00	0.9999994
165.00	170.83	8.43	8.19	0.9999994
166.00	173.41	10.91	-351.76	0.9999994
167.00	173.82	13.08	-351.80	0.9999994
168.00	171.75	15.18	8.02	0.9999994
169.00	167.85	16.65	7.75	0.9999994
170.00	162.74	16.26	7.48	0.9999994
171.00	-124.92	14.19	9.51	0.9999994
172.00	-109.87	15.39	9.64	0.9999994
173.00	-161.31	10.23	8.99	0.9999994
174.00	176.20	8.25	-351.51	0.9999994
175.00	-179.54	8.70	8.69	0.9999994
176.00	-176.92	11.02	8.76	0.9999994
177.00	-176.48	13.10	8.74	0.9999994
178.00	-176.50	15.15	8.58	0.9999994
179.00	177.64	16.64	-351.64	0.9999994
180.00	172.53	16.29	-351.97	0.9999994

X AMPLITUDES = 1.00000 1.00000 1.00000 1.00000 1.00000 4.00000
X PERIODS = 1.50000 1.50000 1.50000 1.50000 1.50000 1.50000
Y AMPLITUDES = 3.00000 3.00000 3.00000 3.00000 3.00000 3.00000
Y PERIODS = 1.60000 1.60000 1.60000 1.60000 1.60000 1.60000
Z AMPLITUDES = 90.00000 90.00000 90.00000 90.00000 90.00000 90.00000
Z PERIODS = 400.00 400.00 400.00 400.00 400.00 400.00
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QUANTIZING INTERVAL IN TENS OF SECONDS = 100.2 200. 300. 400.
MINIMUM ANGLE STEP = 0.50000
INITIAL HEADING = 0.
LATITUDE = 45.
SENSOR X,Y,Z SCALE FACTORS = 1.020 1.020 1.020
SENSOR X,Y,Z BIAS IN DEGREES PER HOUR = 1.000 1.000 1.000

TIME (MINUTES)	HEADING	TILT	ERROR	DETREF	DETCCP
1.00	74.48	0.57	1.55	0.99999994	0.99999994
2.00	85.48	0.54	1.73	0.99999994	0.99999994
3.00	29.95	1.28	0.65	0.99999994	0.99999994
4.00	-0.01	1.17	0.65	0.99999994	0.99999994
5.00	2.17	0.98	0.15	0.99999994	0.99999994
6.00	-0.01	0.73	0.68	0.99999994	0.99999994
7.00	2.16	0.89	0.18	0.99999994	0.99999994
8.00	-0.01	0.86	0.10	0.99999994	0.99999994
9.00	2.16	1.31	0.20	0.99999994	0.99999994
10.00	-0.02	1.02	0.13	0.99999994	0.99999994
11.00	74.87	1.14	1.67	0.99999994	0.99999994
12.00	85.46	1.38	1.85	0.99999994	0.99999994
13.00	29.94	1.48	0.81	0.99999994	0.99999994
14.00	-0.00	1.43	0.18	0.99999994	0.99999994
15.00	2.16	1.74	0.28	0.99999994	0.99999994
16.00	-0.01	1.73	0.20	0.99999994	0.99999994
17.00	2.15	2.16	0.30	0.99999994	0.99999994
18.00	-0.03	2.23	0.23	0.99999994	0.99999994
19.00	2.13	2.71	0.42	0.99999994	0.99999994
20.00	-0.06	2.84	0.25	0.99999994	0.99999994
21.00	74.86	2.55	1.78	0.99999994	0.99999994
22.00	85.46	2.71	1.96	0.99999994	0.99999994
23.00	29.91	2.56	0.93	0.99999994	0.99999994
24.00	-0.01	2.59	0.31	0.99999994	0.99999994
25.00	2.15	3.02	0.81	0.99999994	0.99999994
26.00	-0.04	3.08	0.33	0.99999994	0.99999994
27.00	2.12	3.54	0.42	0.99999994	0.99999994
28.00	-0.07	3.64	0.35	0.99999994	0.99999994
29.00	2.08	4.12	0.44	0.99999994	0.99999994
30.00	-0.11	4.25	0.31	0.99999994	0.99999994
31.00	74.85	3.95	1.88	0.99999994	0.99999994
32.00	85.47	4.11	2.07	0.99999994	0.99999994
33.00	29.87	3.98	1.03	0.99999994	0.99999994
34.00	-0.03	3.94	0.43	0.99999994	0.99999994
35.00	2.12	4.36	0.53	0.99999994	0.99999994
36.00	-0.07	4.07	0.45	0.99999994	0.99999994
37.00	2.07	4.54	0.50	0.99999994	0.99999994
38.00	-0.12	5.05	0.47	0.99999994	0.99999994
39.00	2.03	5.54	0.56	0.99999994	0.99999994
40.00	-0.17	5.67	0.48	0.99999994	0.99999994
41.00	74.85	5.36	1.97	0.99999994	0.99999994

42.00	85.49	5.52	2.10	0.90099994	0.90099994	0.90099994
43.00	29.81	5.25	1.15	0.90099994	0.90099994	0.90099994
44.00	-0.06	5.41	0.55	0.90099994	0.90099994	0.90099994
45.00	2.07	5.17	0.66	0.90099994	0.90099994	0.90099994
46.00	-0.12	5.87	0.57	0.90099994	0.90099994	0.90099994
47.00	2.02	6.35	0.66	0.90099994	0.90099994	0.90099994
48.00	-0.18	6.47	0.58	0.90099994	0.90099994	0.90099994
49.00	1.96	6.96	0.67	0.90099994	0.90099994	0.90099994
50.00	-0.24	7.09	0.59	0.90099994	0.90099994	0.90099994
51.00	74.86	6.78	2.04	0.90099994	0.90099994	0.90099994
52.00	85.52	6.93	2.24	0.90099994	0.90099994	0.90099994
53.00	29.74	6.60	1.22	0.90099994	0.90099994	0.90099994
54.00	-0.11	6.70	0.67	0.90099994	0.90099994	0.90099994
55.00	2.02	7.17	0.76	0.90099994	0.90099994	0.90099994
56.00	-0.18	7.28	0.68	0.90099994	0.90099994	0.90099994
57.00	1.95	7.76	0.77	0.90099994	0.90099994	0.90099994
58.00	-0.25	7.88	0.69	0.90099994	0.90099994	0.90099994
59.00	1.87	8.38	0.78	0.90099994	0.90099994	0.90099994
60.00	-0.32	8.51	0.70	0.90099994	0.90099994	0.90099994
61.00	74.86	8.19	2.11	0.90099994	0.90099994	0.90099994
62.00	85.57	8.35	2.31	0.90099994	0.90099994	0.90099994
63.00	29.64	8.04	1.29	0.90099994	0.90099994	0.90099994
64.00	-0.17	8.10	0.76	0.90099994	0.90099994	0.90099994
65.00	1.95	8.58	0.87	0.90099994	0.90099994	0.90099994
66.00	-0.25	8.69	0.79	0.90099994	0.90099994	0.90099994
67.00	1.86	9.18	0.87	0.90099994	0.90099994	0.90099994
68.00	-0.33	9.30	0.80	0.90099994	0.90099994	0.90099994
69.00	1.77	9.79	0.86	0.90099994	0.90099994	0.90099994
70.00	-0.42	9.93	0.81	0.90099994	0.90099994	0.90099994
71.00	74.86	9.61	2.16	0.90099994	0.90099994	0.90099994
72.00	85.62	9.76	2.36	0.90099994	0.90099994	0.90099994
73.00	29.53	9.45	1.36	0.90099994	0.90099994	0.90099994
74.00	-0.24	9.51	0.89	0.90099994	0.90099994	0.90099994
75.00	1.86	9.99	0.97	0.90099994	0.90099994	0.90099994
76.00	-0.33	10.11	0.90	0.90099994	0.90099994	0.90099994
77.00	1.76	10.59	0.98	0.90099994	0.90099994	0.90099994
78.00	-0.43	10.72	0.90	0.90099994	0.90099994	0.90099994
79.00	1.66	11.21	0.98	0.90099994	0.90099994	0.90099994
80.00	-0.53	11.34	0.91	0.90099994	0.90099994	0.90099994
81.00	74.89	11.02	2.19	0.90099994	0.90099994	0.90099994
82.00	85.68	11.18	2.41	0.90099994	0.90099994	0.90099994
83.00	29.41	10.85	1.42	0.90099994	0.90099994	0.90099994
84.00	-0.32	10.92	1.00	0.90099994	0.90099994	0.90099994
85.00	1.76	11.40	1.07	0.90099994	0.90099994	0.90099994
86.00	-0.43	11.52	1.00	0.90099994	0.90099994	0.90099994
87.00	1.65	12.01	1.07	0.90099994	0.90099994	0.90099994
88.00	-0.54	12.14	1.00	0.90099994	0.90099994	0.90099994
89.00	1.54	12.63	1.68	0.90099994	0.90099994	0.90099994
90.00	-0.65	12.76	1.01	0.90099994	0.90099994	0.90099994
91.00	74.92	12.44	2.21	0.90099994	0.90099994	0.90099994
92.00	85.76	12.59	2.44	0.90099994	0.90099994	0.90099994
93.00	29.26	12.27	1.47	0.90099994	0.90099994	0.90099994
94.00	-0.42	12.31	1.10	0.90099994	0.90099994	0.90099994
95.00	1.65	12.82	1.17	0.90099994	0.90099994	0.90099994
96.00	-0.54	12.94	1.10	0.90099994	0.90099994	0.90099994
97.00	1.53	13.43	1.17	0.90099994	0.90099994	0.90099994
98.00	-0.66	13.55	1.10	0.90099994	0.90099994	0.90099994
99.00	1.40	14.05	1.17	0.90099994	0.90099994	0.90099994
100.00	-0.79	14.18	1.10	0.90099994	0.90099994	0.90099994

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101.00	74.94	13.46	2.22	0.99999994	0.99999994
102.00	85.84	14.01	2.06	0.99999994	0.99999994
103.00	29.10	13.64	1.51	0.99999994	0.99999994
104.00	-0.53	13.75	1.20	0.99999994	0.99999994
105.00	1.53	14.23	1.24	0.99999994	0.99999994
106.00	-0.66	14.36	1.20	0.99999994	0.99999994
107.00	1.34	14.84	1.26	0.99999994	0.99999994
108.00	-0.80	14.97	1.20	0.99999994	0.99999994
109.00	1.25	15.46	1.26	0.99999994	0.99999994
110.00	-0.94	15.00	1.20	0.99999994	0.99999994
111.00	74.98	15.27	2.21	0.99999994	0.99999994
112.00	85.94	15.43	2.06	0.99999994	0.99999994
113.00	28.92	15.09	1.54	0.99999994	0.99999994
114.00	-0.65	15.16	1.29	0.99999994	0.99999994
115.00	1.39	15.65	1.35	0.99999994	0.99999994
116.00	-0.79	15.77	1.29	0.99999994	0.99999994
117.00	1.24	16.26	1.35	0.99999994	0.99999994
118.00	-0.94	16.39	1.29	0.99999994	0.99999994
119.00	1.09	16.88	1.34	0.99999994	0.99999994
120.00	-1.10	17.02	1.28	0.99999994	0.99999994
121.00	75.02	16.69	2.12	0.99999994	0.99999994
122.00	86.03	16.45	2.45	0.99999994	0.99999994
123.00	28.72	16.51	1.56	0.99999994	0.99999994
124.00	-0.78	16.58	1.36	0.99999994	0.99999994
125.00	1.24	17.06	1.44	0.99999994	0.99999994
126.00	-0.94	17.19	1.38	0.99999994	0.99999994
127.00	1.08	17.68	1.43	0.99999994	0.99999994
128.00	-1.10	17.81	1.37	0.99999994	0.99999994
129.00	0.91	18.30	1.42	0.99999994	0.99999994
130.00	-1.27	18.44	1.37	0.99999994	0.99999994
131.00	75.06	18.11	2.14	0.99999994	0.99999994
132.00	86.17	18.26	2.42	0.99999994	0.99999994
133.00	28.50	17.92	1.57	0.99999994	0.99999994
134.00	-0.93	17.94	1.37	0.99999994	0.99999994
135.00	1.08	18.41	1.52	0.99999994	0.99999994
136.00	-1.10	18.51	1.46	0.99999994	0.99999994
137.00	0.90	19.09	1.51	0.99999994	0.99999994
138.00	-1.27	19.22	1.46	0.99999994	0.99999994
139.00	0.72	19.72	1.50	0.99999994	0.99999994
140.00	-1.45	19.85	1.45	0.99999994	0.99999994
141.00	75.11	19.53	2.09	0.99999994	0.99999994
142.00	86.31	19.68	2.34	0.99999994	0.99999994
143.00	28.26	19.34	1.57	0.99999994	0.99999994
144.00	-1.09	19.41	1.35	0.99999994	0.99999994
145.00	0.90	19.90	1.59	0.99999994	0.99999994
146.00	-1.27	20.02	1.54	0.99999994	0.99999994
147.00	0.71	20.51	1.54	0.99999994	0.99999994
148.00	-1.46	20.64	1.54	0.99999994	0.99999994
149.00	0.52	21.14	1.54	0.99999994	0.99999994
150.00	-1.65	21.27	1.53	0.99999994	0.99999994
151.00	75.16	20.95	2.02	0.99999994	0.99999994
152.00	86.45	21.10	2.33	0.99999994	0.99999994
153.00	28.00	20.75	1.57	0.99999994	0.99999994
154.00	-1.26	20.82	1.63	0.99999994	0.99999994
155.00	0.71	21.31	1.67	0.99999994	0.99999994
156.00	-1.45	21.44	1.62	0.99999994	0.99999994
157.00	0.51	21.93	1.66	0.99999994	0.99999994
158.00	-1.65	22.06	1.61	0.99999994	0.99999994
159.00	0.30	22.55	1.65	0.99999994	0.99999994

160.00	-1.86	22.69	1.61	0.99999994	0.99999994
161.00	75.22	22.36	1.93	0.99999994	0.99999994
162.00	86.62	22.52	2.26	0.99999994	0.99999994
163.00	27.72	22.17	1.54	0.99999994	0.99999994
164.00	-1.44	22.24	1.71	0.99999994	0.99999994
165.00	0.50	22.73	1.74	0.99999994	0.99999994
166.00	-1.65	22.86	1.70	0.99999994	0.99999994
167.00	0.29	23.35	1.73	0.99999994	0.99999994
168.00	-1.86	23.48	1.69	0.99999994	0.99999994
169.00	0.07	23.97	1.72	0.99999994	0.99999994
170.00	-2.08	24.11	1.68	0.99999994	0.99999994
171.00	75.24	23.78	1.82	0.99999994	0.99999994
172.00	86.79	23.93	2.17	0.99999994	0.99999994
173.00	27.43	23.58	1.54	0.99999994	0.99999994
174.00	-1.63	23.66	1.76	0.99999994	0.99999994
175.00	0.29	24.15	1.81	0.99999994	0.99999994
176.00	-1.86	24.27	1.77	0.99999994	0.99999994
177.00	0.06	24.76	1.79	0.99999994	0.99999994
178.00	-2.08	24.90	1.76	0.99999994	0.99999994
179.00	-0.18	25.39	1.78	0.99999994	0.99999994
180.00	-2.32	25.53	1.75	0.99999994	0.99999994

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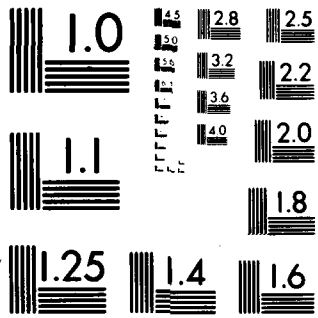
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APPENDIX G.--CHECK ON ACCURACY OF REFERENCE ALGORITHM

In the study of computation algorithms (Section 4), the "error" is simply the difference between a particular algorithm's output and that of the "reference" algorithm. A nagging question remains as to the sufficiency of the reference algorithm. A precise mathematical solution for any but extremely simple input motion is beyond reach.

One source of confidence is, of course, the small errors between the reference and the best of the test algorithms.

An additional check on the reference algorithm was made utilizing the mathematical formulation of attitude as a result of coning motion. This formulation is found in the literature¹. Coning motion is the result of quadrature motion on two of the axes, a motion which presents a most difficult test of computation adequacy.

For X and Y axis motion given by

$$\dot{x} = A \sin Bt$$

$$\dot{y} = A \cos Bt$$

$$R^2 = A^2 + B^2$$

the C-matrix components C_{11} and C_{21} at any time t may be expressed as

$$C_{11} = \frac{1}{2R} [(B+R) \cos (B-R)t - (B-R) \cos (B+R)t]$$

$$C_{21} = \frac{A^2}{R^2} \sin Bt + \frac{B}{2R^2} [(B-R) \sin (B+R)t + (B+R) \sin (B-R)t]$$

A suitable choice of A and B which makes the arithmetic simple, while giving a severe but practical test is $A = 0.15\pi$ and $B = 0.2\pi$. Then C_{11} and C_{12} reduce to

$$C_{11} = 0.9 \cos 0.05 \pi t + 0.2 \cos 0.45 \pi t$$

¹ A.A. Sutherland, Jr. and P. O. Bongiovanni, "Data Smoothing for Enhancement of Strapdown Inertial System Accuracy: Interpolative-Predictive Algorithms," Analytic Sciences Corp. Report TR-155-1, 31 August 1969.

$$C_{21} = 0.36 \sin 0.2 \pi t - 0.08 \sin 0.45 \pi t \\ - 0.72 \sin 0.05 \pi t$$

The period of this motion is 40 s. At $t = 10$ s, $C_{11} = 0$ for a heading of 90 deg, while at $t = 20$, $C_{21} = 0$ and the heading is 180 deg.

This motion was used to test the "reference" algorithm and confirmed precise agreement with the theoretical results.

NOTE

Since the program was written in terms of angle rather than rate, the rates \dot{x} and \dot{y} must be integrated to obtain the proper input.

$$x = -\frac{A}{B} \cos Bt + \frac{A}{B} .$$

$$y = \frac{A}{B} \sin Bt .$$

The constant of integration $\frac{A}{B}$ must be added to x so that $x(0) = 0$, since the expressions for the C-matrix elements assume initial alignment (identify matrix) at the start. It is, in fact, this initial alignment which makes the equations complex, since coning takes place about an axis offset from the vertical.

As a matter of interest, the tilt angle θ of the Z axis is given by

$$\cos \theta = C_{33} = 1 - \frac{A^2}{R^2} (1 - \cos Rt) \\ = 0.64 + 0.36 \cos 0.25 \pi t$$

This describes conical motion with $\theta_{\max} = 74$ deg and a period of 8 s. Hence, five complete cones are swept out by the Z axis during the 40 seconds it takes for the heading to make one complete revolution.

APPENDIX H.--PROGRAM LISTING FOR SECTION 4

The results of Section 4 were obtained with the following computer programs:

- a) TNKSIM calculates the reference heading and tilt angles and develops the record of angle increments which would be measured by the vehicle-mounted sensors. Earth rotation is accounted for in these outputs.
- b) TNKTST models the anticipated microprocessor-based system, including a pulse-balanced integrator as the analog-to-digital device.

UN125120 FORTRAN SYSTEMS REAL-TIME MONITOR-7.6
SEL EXTENDED FORTRAN IV (REV - 6 / 7 8 S E P 6 8)

INRSIM

```

1      PROGRAM INRSIM
2      IMPLICIT REAL*8(A-H,O-Z)
3      REAL*8 SUOUT,SHUX,SCVH
4      DIMENSION AMP(3),FREQ(3),CVN(3,3),CVNP(3,3),PPNV(3),ERATE(3),
5      1 HNR(20),PAV(3),UPNV(3),UPNV(3,3),ERIN(3),DOUT(5,250),
6      2 SUOUT(2500),SHUX(40),CVHS(9)
7      DIMENSION DPNV(3,3),DPNVI(3)
8      DIMENSION CVNP(3),CVNC(3),CVNP(6)
9      DIMENSION DPNV(3),DFREQ(3),KX(3)
10     EQUIVALENCE (SHUX(1),HNR(1)),(DOUT(1,1),SUOUT(1))
11     EQUIVALENCE (CVNP(1),CVNP(1)),(CVNC(1),CVNP(4)),(CVN(1,1),
12     1 EQUIVALENCE CVHS(1))
13     PI=3.1415926536D+0
14     KTY=5
15     TSMI=0
16     WRITE(KTY,600)
17     FORMAT(' ENTER 1 TO CONTINUE PREVIOUS RUN, 0 TO START NEW RUN')
18     READ(KTY,201)KA
19     IF(KA.EQ.0)GO TO 103
20
21     C FIND END OF PREVIOUS DATA AND SET C MARKIX
22     C
23     605     HEAD(21)SHUX
24     TSMI=HNR(12)
25     WRITE(KTY,601)HNR(12)
26     FORMAT(' PRESENT RUNNING TIME = ',F7.0,2X,'SECONDS')
27     1     ENTER 1 TO START SIMULATION, 0 TO SEARCH FURTHER')
28     READ(KTY,201)KA
29     HEAD(21)CVHS
30     HEAD(21,END=602)SUOUT
31     GO TO 603
32     602     READ(21)CVNS
33     READ(21,END=604)SUOUT
34     IF(KA.EQ.0)GO TO 605
35     PAUSE A
36
37     C ENTER CONSTANTS FOR INPUT MOTION
38     C
39     103     WRITE(KTY,1)
40     1     FORMAT(' ENTER X AMPLITUDE,PERIOD,PHASE: 1=SIN,0=COS')
41     READ(KTY,2)AMP(1),FREQ(1),KX(1)
42     2     FORMAT(2D20.12,11)
43     WRITE(KTY,3)
44     3     FORMAT(' ENTER Y AMPLITUDE,PERIOD,PHASE: 1=SIN,0=COS')
45     READ(KTY,4)AMP(2),FREQ(2),KX(2)
46     4     FORMAT(2D20.12,11)
47     WRITE(KTY,5)
48     5     FORMAT(' ENTER Z AMPLITUDE,PERIOD,PHASE: 1=SIN,0=COS')
49     READ(KTY,6)AMP(3),FREQ(3),KX(3)
50     6     FORMAT(2D20.12,11)
51     WRITE(KTY,7)
52     7     FORMAT(' ENTER SAMPLING INTERVAL IN SECONDS')
53     READ(KTY,8)DTSMI
54     8     FORMAT(D20.12)

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0025120 FORTMAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTMAN IV (REV - 0 / 7 0 S E P 0 N)

INRSIM

```

55 WRITE(KIV,9)
56
57 9 FORMAT(' ENTER LATITUDE IN DEGREES')
58 READ(KIV,9)LAT
59
60 91 FORMAT(I2)
61 IF(KV.EQ.6)GO TO 104
62 WRITE(KIV,105)TSIM
63
64 105 FORMAT(' PRESENT RUNNING TIME = ',F9.1,1X,' SECONDS'
65 1 ' ENTER CONTINUE RUNNING TIME IN SECONDS')
66 GO TO 107
67
68 104 WRITE(KIV,92)
69 92 FORMAT(' ENTER RUNNING TIME IN SECONDS')
70 READ(KIV,93)THAX
71
72 93 FORMAT(I20,12)
73 WRITE(KIV,94)
74
75 94 FORMAT(' ENTER PRINT TIME INTERVAL IN SECONDS')
76 READ(KIV,71)DPTIME
77
78 71 FORMAT(I20,12)
79 WRITE(KIV,200)
80
81 200 FORMAT(' ENTER 1 TO INPUT VEHICLE AXIS MOTION')
82 READ(KIV,201)AV
83
84 201 FORMAT(I1)
85 PTIME=DPTIME*TSIM
86 LPCW=25
87
88 96 FORMAT(1X,'LAT',3X,'SAMPLE',10X,'AMPLITUDE',10X,
89 1 ' PERIOD',13X,'PHASE(=COS,1=SIM)',10X,'MOTION(1=V,0=N)')
90
91 95 FORMAT(14,F9.3,315,20X,11//)
92
93 97 FORMAT(5X,'TIME',7X,'C11',6X,'C12',8X,'C13',8X,
94 1 'C21',8X,'C22',8X,'C23',8X,'C31',8X,'C32',8X,
95 2 'C33',8X,'HEADING',4X,'TILT')
96
97 C
98 C INITIALIZE C MATRIX
99 C
100 DO 106 K=1,3
101 DAMP(K)=AMP(K)
102 IF(KM.L4.1)GO TO 102
103 DO 10 K=1,3
104 DO 10 J=1,3
105 IF(K.EQ.J)GO TO 101
106 CVM(J,K)=0.0D+0
107 GO TO 10
108
109 101 CVM(J,K)=1.0D+0
110
111 10 CONTINUE
112 C
113 C INITIALIZE ANGULAR INPUT MOTION AND EARTH ROTATION MATRIX
114 C
115 C
116 EDUT=PI/43200.0D+0
117 TSIM=TSIM*1
118 DO 11 K=1,3
119 IF(KM.L4.1)GO TO 112
120 PPMV(K)=0.0
121 GO TO 11
122
123 112 PPMV(K)=DAMP(K)
124
125 11 CONTINUE
126 SLATELAT=PI/180.0D+0
127
128 0059.000
129 0060.000
130 0061.000
131 0062.000
132 0063.000
133 0064.000
134 0065.000
135 0066.000
136 0067.000
137 0068.000
138 0069.000
139 0070.000
140 0071.000
141 0072.000
142 0073.000
143 0074.000
144 0075.000
145 0076.000
146 0077.000
147 0078.000
148 0079.000
149 0080.000
150 0081.000
151 0082.000
152 0083.000
153 0084.000
154 0085.000
155 0086.000
156 0087.000
157 0088.000
158 0089.000
159 0090.000
160 0091.000
161 0092.000
162 0093.000
163 0094.000
164 0095.000
165 0096.000
166 0097.000
167 0098.000
168 0099.000
169 0100.000
170 0101.000
171 0102.000
172 0103.000
173 0104.000
174 0105.000
175 0106.000
176 0107.000
177 0108.000
178 0109.000
179 0110.000
180 0111.000
181 0112.000

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04125120 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXIEMDED FORTRAN IV (REV - 0 / 7 0 S E P 0 K)

TMSIM

```

109      EKATE(1)=OCOS(SLAT)*EDOT
110      EKATE(2)=0.0D+0
111      EKATE(3)=PSI*(SLAT)*EDOT
112      HOP(1)=TSIM
113      DO 111 K=1,3
114      HOP(1,K)=ADP(K)
115      HOP(4,K)=FREQ(K)
116      OFREQ(4)=2.0D+0*PI/FREQ(K)
117      HOP(14,K)=KX(K)
118      HOP(16)=KV
119      HOP(7,K)=EKATE(K)
120      HOP(14)=END
121      HOP(11)=SLAT
122      HOP(12)=TMAX
123      WRITE(21)SHOR
124      DOUT(4,1)=0.0D+0
125      WRITE(21)CVMS
126
127      C      TOP OF PROCESSING LOOP
128      C      OBTAIN INCREMENTS OF INPUT ANGLES
129      C
130      C      DO 15 K=1,250
131      TSIM=TSIM+DTSIM
132      DO 16 K=1,3
133      IMETA=OFREQ(K)*(TSIM-TSIM1)
134      IF(KX(K).EQ.0)GO TO 122
135      PNV(K)=DAMP(K)*DSIN(THETA)
136      GO TO 120
137      PNV(K)=SHARP(K)*UCOS(THETA)
138      UPNV(K)=PNV(K)-PPNV(K)
139      PPNV(K)=PPNV(K)
140      IF(KV.EQ.0)GO TO 164
141      DO 165 K=1,3
142      DPNV(K)=OPNV(K)
143      GO TO 166
144      C      ROTATE INTO VEHICLE AXIS
145      C
146      DO 163 J=1,3
147      UPNV(J)=0.0D+0
148      DO 163 K=1,3
149      DPNV(J)=OPNV(J)+CVA(K,J)*OPNV(K)
150
151      C      DETERMINE INCREMENT MATRIX AND MUTATE C MATRIX
152      C
153      UPNV=0.0D+0
154      UPNV(2,1)=OPNV(3)
155      DPNV(1,2)=OPNV(3)
156      DPNV(1,3)=OPNV(2)
157      DPNV(3,1)=OPNV(2)
158      UPNV(3,2)=OPNV(1)
159      UPNV(2,3)=OPNV(1)
160      DO 161 J=1,3
161      DO 161 K=1,3
162      DPNVMS(J,K)=0.0D+0

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TXN314

111

04125120 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTRAN IV (REV-0/78 SEP 04)

TAKSIM

```

217 LPCN=LPCNT+1
218 CONTINUE
219 WRITE(21)SOUT
220 IF((1514*001).LT.TMAX)GO TO 119
221 WRITE(7,152)
222 ENDFILE 21
223 WRITE(21)CVMS
224 ENDFILE 21
225 WRITE(KTY,81)
226 FORTM11 ENTER 1 TO CONTINUE RUN, 0 TO EXIT(//)
227 READ(KTY,201)AB
228 IF(KB.EQ.0)GO TO 20
229 ISIM=1MAX
230 GO TO 103
231 READ 21
232 END

```

04120140 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTRAN IV (REV - 0 / 7 8 S E P 0 4)

TAKTST

```

1  PROGRAM TAKTST
2  IMPLICIT INTEGER(A-C,E-Z)
3  IMPLICIT REAL*8(G)
4  REAL*4 SHDR,SILO,SUOHDR,SUOHU,SCVR,SHDR
5  DIMENSION SHDR(40),UMDR(20),ERATE(3),UMDR(20),SHDR(40),
6  DIMENSION SHDR(3,3),SILO(2500),LIND(5,250),UPIV(3),UPPIV(3),
7  PIV(3),PIMI(3),PNVI(3),PNVC(3,3),CVNU(3,3),UMDU(4,500),
8  SOUNU(4000),UCVR(3,3),UCVNS(9),UCVNS(3,3),CVNS(9),
9  SHDR(40),UMDR(20)
10 DIMENSION UCVR(3),UCVNC(3),UCVNP(6),PMVN(3,3)
11 DIMENSION PIMI(3),CINI(3),PMVNS(3,3)
12 EQUIVALENCE (UCVNP(1),UCVNP(1)),(UCVNC(1),UCVNP(4))
13 EQUIVALENCE (UMDU(1,1),SOUNU(1)),(SILO(1),LIND(1,1)),
14 (SHDR(1),UMDR(1)),(UMDR(1),SHDR(1)),
15 (UCVNS(1),UCVNS(1,1)),(CVN(1,1),CVNS(1)),
16 (SHDR(1),UMDR(1))
17 DATA ONE/240000000/
18 DPI=1.4159265360+0
19 KTY=5
20
21 C
22 C
23 C
24 105 READ(21)SHDR
25 WRITE(NTV,1)UMDR(1)
26 1 FORMAT(' INPUT SAMPLING TIME = ',F10.4,2X,'SECONDS' )
27 WRITE(NTV,2)UMDR(12)
28 2 FORMAT(' RUMMING TIME = ',F10.4,2X,'SECONDS' )
29 WRITE(NTV,/)
30 7 FORMAT(' ENTER INTEGRATOR THRESHOLD N : VALUE=2*(-N) RAD.'//)
31 READ (NTV,2)BIT
32 2 FORMAT(12)
33 WRITE(NTV,83)
34 83 FORMAT(' ENTER RUNNING TIME IN SECONDS'//)
35 READ(NTV,84)NTRUN
36 84 FORMAT(D20.12)
37 WRITE(NTV,8)
38 8 FORMAT(' ENTER PAINT TIME INTERVAL IN SECONDS'//)
39 READ(NTV,81)DPTIME
40 81 FORMAT(D20.12)
41 WRITE(NTV,11)
42 11 FORMAT(' ENTER PLOT TIME INTERVAL IN SECONDS'//)
43 READ(NTV,11)DPLTME
44 WRITE(NTV,9)
45 9 FORMAT(' ENTER NO. OF BITS FOR PROCESSING'//)
46 READ(NTV,2)NBIT
47 46 FORMAT(11-1)
48 85 85 BIT=32-NBIT
49 WRITE(NTV,85)
50 85 FORMAT(' ENTER 1 FOR 2ND ORDER UPDATING OF C MATRIX'//)
51 READ(NTV,2)AU
52 C
53 C
54 SET SCALE FACTORS AND COMPUTE EARTH RATE MATRIX
55 DEDOT=UPI/43200.00+0
56
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04120140 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL A I E N D E D F O R T R A N I V (W E V - U / 7 8 S E P 0 0)

INRTSI

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55  DRATE=1.00*0/(2*PI*KBIT)
56  DANG=DRATE
57  DCSC=1.00*0/(2*PI*(KBIT-1))
58  QTIME=1.00*0/(2*PI*KBIT)
59  ERATE(1)=(QDOUT*DCOS(DHNR(11)))/DRATE
60  ERATE(2)=0
61  ERATE(3)=-((QDOUT*DSIN(DHNR(11)))/DRATE
62  C
63  C
64  C
65  PIVC=0
66  DHNR(12)=0*PI*E
67  DHNR(13)=BIT
68  DHNR(14)=0*PI*H
69  DHNR(15)=0*PI*H
70  DO 10 J=1,11
71  DHNR(J)=DHNR(J)
72  DO 102 K=1,3
73  DHNR(15+K)=DHNR(14+K)
74  DHNR(11)=KBIT
75  DHNR(19)=DHNR(18)
76  DTIME=0
77  DINTO=0
78  K=DHNR(19)
79  DHNR(20)=DHNR(19)
80  IF(K=0.0)GO TO 103
81  READ(22,END=110)DHNR
82  READ(22)DCVNS
83  READ(22,END=110)SDOUD
84  GO TO 112
85  READ(22)CVNS
86  READ(22)DINTD
87  READ(22)DTIME
88  WRITE(KTY,117)DTIME
89  FORMAT(' PRESENT RUNNING TIME =',F9.1,X,'SECONDS')
90  I = ENTER 1 TO START TEST PROGRAM, 0 TO SEARCH MORE')
91  READ(KTY,2) KCON
92  READ(22,END=115)SDOUD
93  IF(KCON=0.0)GO TO 111
94  WRITE(22)SDOUD
95  DLAT=DHNR(11)*180.00*0/DPI
96  C
97  C
98  C
99  INITIALIZE C MATRIX
100 READ(21)DCVNS
101 WRITE(22)DCVNS
102 IF(KB=0.1) GO TO 116
103 DO 20 J=1,3
104 DO 20 K=1,3
105 IF(J=0.0)GO TO 201
106 CVM(J,K)=0
107 GO TO 20
108 CVM(J,K)=2*PI*(KBIT-1)
201 CVM(J,K)=2*PI*(KBIT-1)
20 CONTINUE

```

04124100 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTRAN IV (REV - U / 7 8 S E P 0 8)

INRTST

```

109      DOUD=0.0D+0
110      DPIV=0.0D+0
111      WK1=(1.0D-2+1.0D-5)/DHDR(1)
112      TPAX=DPLTME/(1.0D-2)
113      PTAX=DPLTME/DPLTME
114      DMRES=1.0D+0/12.0D+0*(BIT)
115      PSCLAE=2.0D+0*(BIT-1-BIT)
116      DTHRES=DTHRES*180.D+0/DPI
117      TTIME=0
118      PTIME=0
119      TIME1=0
120      TIME=1.0D-2/DTIME
121      CINT=0
122      LPCNT=25
123      N=1
124
125      C TOP OF MAIN PROCESSING LOOP
126      C
127      24 READ(21,END=101)SIND
128      IF(UTIME.GE.DTRUN)GO TO 101
129      N=1
130      NMK=0
131      NMK=NMK+NMK
132      IF(NMK.GT.251)GO TO 24
133      DTIME=DTIME+DHDR(1)
134      TIME1=TIME1+1
135      DO 500 J=1,3
136      DINTD(J)=DINTD(J)+DIND(J,N)
137      IF(N.GE.NMK) GO TO 594
138      N=N+1
139      GO TO 593
140
141      594 DO 591 J=1,3
142      CINT(J)=DINTD(J)/DTHRES
143      DINTD(J)=DINTD(J)-CINT(J)*DTHRES
144      CONTINUE
145      DO 505 J=1,3
146      PIVI(J)=CINT(J)*PSCALE
147      CINT(J)=0
148
149      505 C
150      C
151      C CALCULATE EARTH RATE INCREMENTS AND SUBTRACT FROM INPUT
152      C
153      TIME1=TIME1+DHDR(1)/DTIME
154      DO 22 J=1,3
155      ERIN(J)=0
156      DO 221 K=1,3
157      CALL MUL32(CVNA(K,J),ERATE(K),TEMP,SUIT)
158      ERIN(J)=ERIN(J)+TEMP*2
159      CALL MUL32(ERIN(J),TIME1,PIVI(J),SBIT)
160      PIVI(J)=PIVI(J)-PIVI(J)
161      TIME1=0
162
163      C
164      C SET DELTA PHV MATRIX AND UPDATE C MATRIX
165      C
166      PIVC=0

```

```

103 PNVC(1,2)=PNVI(3)
104 PNVC(1,3)=PNVI(2)
105 PNVC(2,1)=PNVI(3)
106 PNVC(2,2)=PNVI(1)
107 PNVC(3,1)=PNVI(2)
108 PNVC(3,2)=PNVI(1)
109
110 C
111 C
112 C
113 C
114 C
115 C
116 C
117 C
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216 C

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04124140 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDEO FORTRAN IV (REV - 0 / 7 8 S E P 0 8)

TN181

```

217      PTIME=PTIME+1
218      IF (PTIME.LE.PTMAX) GO TO 524
219      PTIME=0
220      IF (LPCMT.LT.25) GO TO 566
221      LPCMT=0
222      WRITE(7,580)
223      FORMAT(11)
224      WRITE(7,581)
225      FORMAT(4X,'OITS',3X,'SAMPLE',10X,'AMPLITUDE',
226      1 10X,'PERIOD',13X,'PHASE(1=SIG,0=COS)',5X,'UNITION(1=V,0=W)',
227      2 6X,'THRESHOLD')
228      WRITE(7,582)
229      1 DHOR(15),UTIMESU
230      FORMAT(4X,14
231      1 7F9.3,2X,3F5.0,11X,F5.0,11X,F10.6,/)
232      WRITE(7,583)
233      FORMAT(5X,'LINE',7X,'C11',7X,'C12',7X,'C13',7X,'C21',
234      1 7X,'C22',7X,'C23',7X,'C31',7X,'C32',7X,'C33',5X,
235      2 'HEADING',3X,'ERROR',5X,'TILT')
236      DO 587 J=1,3
237      DO 587 K=1,3
238      DCVNC(J,K)=CVN(J,K)*DCSC
239      WRITE(7,584)UTIME,((DCVN(J,K),K=1,3),J=1,3),(DUUD(L,M),L=1,3)
240      FORMAT(1X,F9.3,9F10.5,F11.4,2F9.4)
241      DO 520 J=1,3
242      UT=0
243      DO 521 K=1,3
244      UT=UT+DCVN(J,K)*2
245      DCVRN(J)=DSUM(UT)
246      DO 522 K=1,3
247      UT=0
248      DO 523 J=1,3
249      UT=UT+DCVN(J,K)*2
250      DCVNC(K)=DSUM(UT)
251      DCVND=DCVN(1,1)*DCVN(2,2)+DCVN(3,3)+
252      2 DCVN(1,3)+DCVN(2,1)+DCVN(3,2)+
253      3 DCVN(1,2)+DCVN(2,3)+DCVN(3,1)-
254      4 DCVN(1,3)+DCVN(2,2)+DCVN(3,1)-
255      5 DCVN(1,2)+DCVN(2,1)+DCVN(3,3)-
256      DCVN(1,1)+DCVN(2,3)+DCVN(3,2)
257      WRITE(7,585)DCVND,(DCVNP(J),J=1,6)
258      FORMAT(5X,7F15.6)
259      LPCMT=LPCMT+1
260      C CHECK FOR OUTPUT RECORD
261      C
262      524      MEN+1
263      IF (M.LE.500) GO TO 501
264      MEN=1
265      WRITE(22)SOUND
266      IF (UTIME.GE.UTRUM) GO TO 104
267      DUUD=0
268      MEN+1
269      GO TO 25
270      101 WRITE(22)SOUND
271
0206.000
0207.000
0208.000
0209.000
0210.000
0211.000
0212.000
0213.000
0214.000
0215.000
0216.000
0217.000
0218.000
0219.000
0220.000
0221.000
0222.000
0223.000
0224.000
0225.000
0226.000
0227.000
0228.000
0229.000
0230.000
0231.000
0232.000
0233.000
0234.000
0235.000
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0237.000
0238.000
0239.000
0240.000
0241.000
0242.000
0243.000
0244.000
0245.000
0246.000
0247.000
0248.000
0249.000
0250.000
0251.000
0252.000
0253.000
0254.000
0255.000
0256.000
0257.000

```

```

04124140   FORTMAN      SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTMAN IV (F E V - 0 / 7 8 S E P 0 8 )
TNK1ST
271          104   ENDFILE 22
272          WRITE(22)CVMS
273          WRITE(22)U1-110
274          WRITE(22)U1TIME
275          ENDFILE 22
276          WRITE(XTY,150)
277          150   FORMAT(' ENTER 1 TO REWIND INPUT TAPE, 0 TO LEAVE AS IS')
278          HEAD(XTY,2)XRA
279          IF (XRA-EN.1)GO TO 152
280          READ(21)UCVMS
281          READ(21,END=151)SIND
282          REWIND 21
283          152   ENDFILE 21
284          REWIND 22
285          READ(22)SOUNDH
286          DGMOR(15)=DUTHUN
287          REWIND 22
288          WRITE(22)SUOMOR
289          CONTINUE
290          CALL EXIT
291          END
0258.000
0259.000
0259.100
0259.200
0260.000
0261.100
0261.200
0261.300
0261.400
0261.500
0261.600
0262.000
0262.010
0262.020
0262.030
0262.040
0262.050
0262.060
0262.100
0263.000
0264.000

```

04120840 FORTRAN SYSTEMS REAL-TIME MONITOR-7.0
SEL EXTENDED FORTRAN IV (REV - 0 / 7 0 SEP 0 6)

MUL32

1	SUBROUTINE MUL32(I,J,K,L)	0265.000
2	11=1	0266.000
3	12=J	0267.000
4	13=L	0267.100
5	IMLINE	0268.000
6	LW 7,11	0269.000
7	LK 5,12	0270.000
8	LMM 3,13	0270.100
9	MPI 5,6	0271.000
10	SLD 6,1	0272.000
11	010 5,1400	0272.100
12	STA 6,13	0273.000
13	ENDI	0274.000
14	K=13	0275.000
15	RETURN	0276.000
16	END	0277.000

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