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Performance of the Miniature Airborne GPS Receiver

by Tom Van Flandern and Thomas B. Bahder

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Performance of the Miniature Airborne GPS Receiver

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Abstract

At a fixed, well-surveyed location, position determinations from a MAGR (Miniaturized Airborne Global Positioning System Receiver) averaged over a six-week period were correct to within 0.5 m. However, the standard deviation of an individual position determination was 56 m. Almost 20 percent of the individual position determinations had errors exceeding 20 m. One in every 300 position determinations had an error exceeding 0.5 km. This anomalously large error distribution tail raises questions about the MAGR's suitability for some Army-critical functions, such as precision guidance.

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Introduction

From mid-October 1996 to mid-January 1997, a Rockwell Miniature Airborne GPS (Global Positioning System) Receiver (MAGR) was placed at a fixed, well-surveyed site: the NASA Goddard Space Flight Center (GSFC) Geophysical and Astronomical Observatory (GGAO) in Greenbelt, MD. Useful data were recorded during the six-week period from early December 1996 to mid-January 1997. Continual position determinations were recorded at 1-s intervals at every opportunity during that period. We report here the results of a study of the accuracy of those position determinations. In general, results in field use would be expected to be poorer than those given here, because of receiver motion and a continually changing environment.

The site in question was surveyed on 24 May 1995, and placed on the WGS 84 geodetic system. The surveyed site coordinates (X_0, Y_0, Z_0) are shown in table 1.

Over the six-week test span, the MAGR made continuous estimates (X_i, Y_i, Z_i), $i = 1, \ldots, N$, of the site position in the same reference system at 1-s intervals during the periods when it was active. Because the volume of data at that fine time spacing was quite large, and because the individual position determinations were changing so little on that time scale, this study employed 30-s sampling of the total data set, except where otherwise noted. This left $N = 8573$ individual sampled position determinations on which to base our analysis. From those, we compiled a number of plots and statistics to illustrate the accuracy of these measures.

Table 1. WGS 84 surveyed coordinates of MAGR at GGAO.

Site coordinate	Surveyed value (m)
X_0	+1,130,774.372
Y_0	–4,831,255.014
Z_0	+3,994,200.505

Mean Position

First, we formed differences between the individual MAGR position determinations and the surveyed position, which we call "position errors":

$$\Delta X_i = X_i - X_0,\ \Delta Y_i = Y_i - Y_0,\ \Delta Z_i = Z_i - Z_0 .$$

Then we computed simple arithmetic means of the position errors:

$$\langle \Delta X_i \rangle = \frac{1}{N} \sum_{i=1}^{N} \Delta X_i,\ \langle \Delta Y_i \rangle = \frac{1}{N} \sum_{i=1}^{N} \Delta Y_i,\ \langle \Delta Z_i \rangle = \frac{1}{N} \sum_{i=1}^{N} \Delta Z_i .$$

The mean position errors and their standard deviations are shown in table 2. We note that the mean position errors are zero to within one standard deviation, indicating that the MAGR apparently had no serious long-term bias problems as great as 0.5 m. However, the standard deviations are surprisingly large for such a large value of N. We show the reason for this shortly when we examine the detailed behavior.

Table 2. Position errors of MAGR at GGAO.

Coordinate	MAGR – WGS 84 (m) (mean)		(st dev)
$\langle \Delta X_i \rangle$	+0.282	±	0.491
$\langle \Delta Y_i \rangle$	+0.264	±	0.342
$\langle \Delta Z_i \rangle$	−0.087	±	0.234

Individual Position Errors

For our first inspection of the individual position errors, we simply plotted ΔY_i against ΔX_i, as shown in figure 1. It was immediately evident that something serious was wrong, because errors exceeding 30 m ought to be rare for any authorized receiver capable of 10-m or better accuracy. Yet not only were 30-m position errors common, some errors even reached the 1-km level. Figure 2, which plots ΔZ_i against ΔY_i, shows that the third dimension has similar behavior, although with a somewhat less extreme range of ±400 m in ΔZ_i.

The computed standard deviation of a single ΔX_i value is 45 m; for a single ΔY_i value it is 32 m; and for a single ΔZ_i value it is 22 m. The mathematical reason for these unexpectedly large deviations is simply that a single error of 1000 m contributes more to the standard deviation than do 8000 "normal" observations with errors of order 10 m each. So we see that the error distribution is so far from a normal distribution that it cannot be accurately represented by a standard deviation. For the same reason, we do not attempt to compute other such customary error measures, such as "circular error probable" (CEP) [1] and its three-dimensional counterpart "spherical error probable" (SEP), inasmuch as they too would be misleading.

Figure 3 plots ΔX_i against time, showing the distribution of problem points over the six-week data span. Time is measured in hours from December 1, 1996, which is the beginning of a GPS week. It is blocked into 1-week groups over the 6-week span of data collection, beginning 40 hours into the first GPS week.

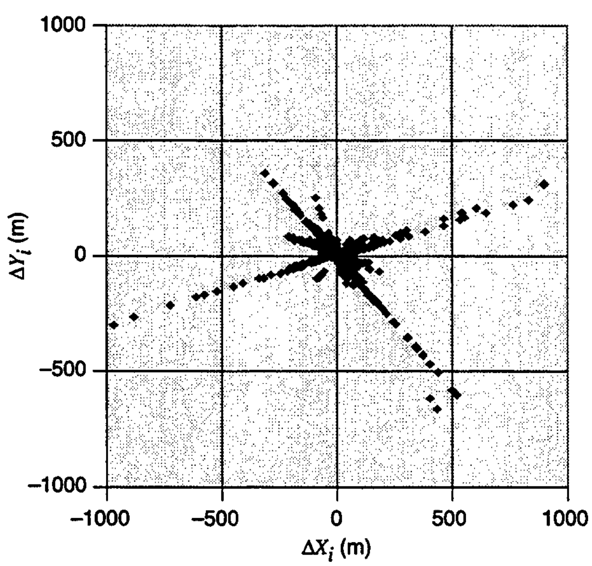


Figure 1. MAGR (X, Y) position errors.

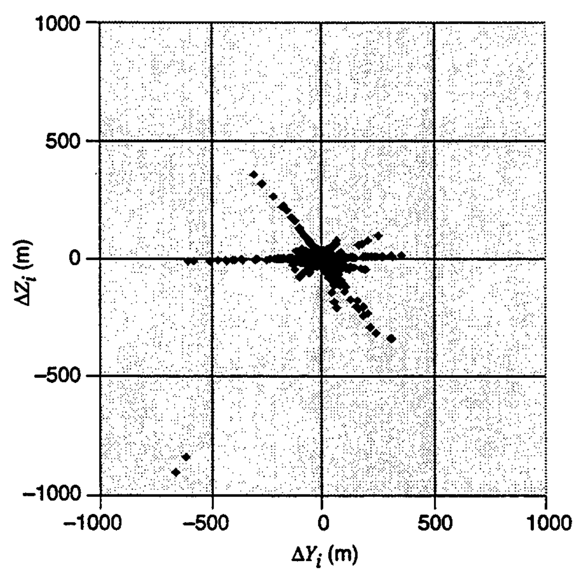


Figure 2. MAGR (Y, Z) position errors.

[1]J. L. Leva, M. U. de Haag, and E. D. Van Dyke, 1996. In *Understanding GPS: Principles and Applications*, E. D. Kaplan, ed., Artech House, Boston, p 281.

Figure 3. MAGR (*X*, *T*) position errors.

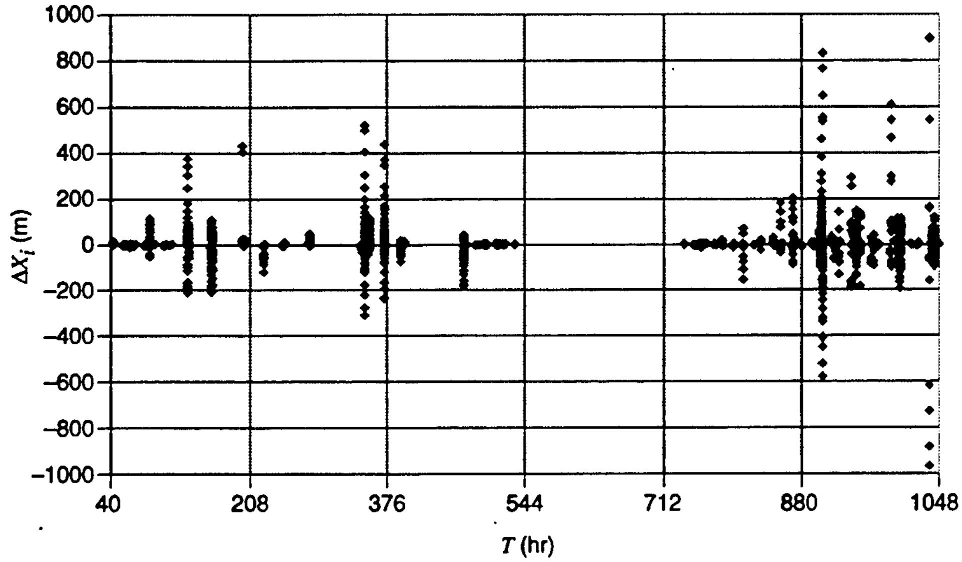


Figure 4 shows successively closer views of the center of the (ΔX_i, ΔY_i)-position error distribution, similar to figure 1, revealing more details for the smaller errors.

For further study, it is useful to compute the magnitude of the position error vector (ΔX_i, ΔY_i, ΔZ_i) at each observation:

$$\Delta R_i = \sqrt{\Delta X_i^2 + \Delta Y_i^2 + \Delta Z_i^2} \ .$$

Figure 5 is a histogram showing the distribution of ΔR_i in our 8573 sampled data points. Table 3 gives the statistics that actually describe the error distribution, and which were used to plot the histogram. For example, 1583 (18.46 percent) of the 8573 ΔR_i values lie in the range from 10 to 15 m.

Note that 56 percent of the measures lie within a nominal 10-m error sphere. This result is consistent with MAGR error descriptions in other reports, which have led to such conclusions as "The probability that the error lies within a 9.5-m sphere is 50 percent, and the MAGR therefore meets specifications." However, as the table shows, that statistic is highly misleading, since many more large errors exist than it would normally imply. Because the error distribution is not even approximately a normal distribution, no valid conclusions could be drawn about MAGR position errors in general from any single summary statistic. A histogram such as figure 5 would be needed for a proper assessment of reliability. However, if the customary error parameters had been supplemented with the standard deviation of an individual position error (56 m for our MAGR data), appropriate alarms would have been raised from the start.

Figure 4. MAGR (X, Y) position errors at successively closer views.

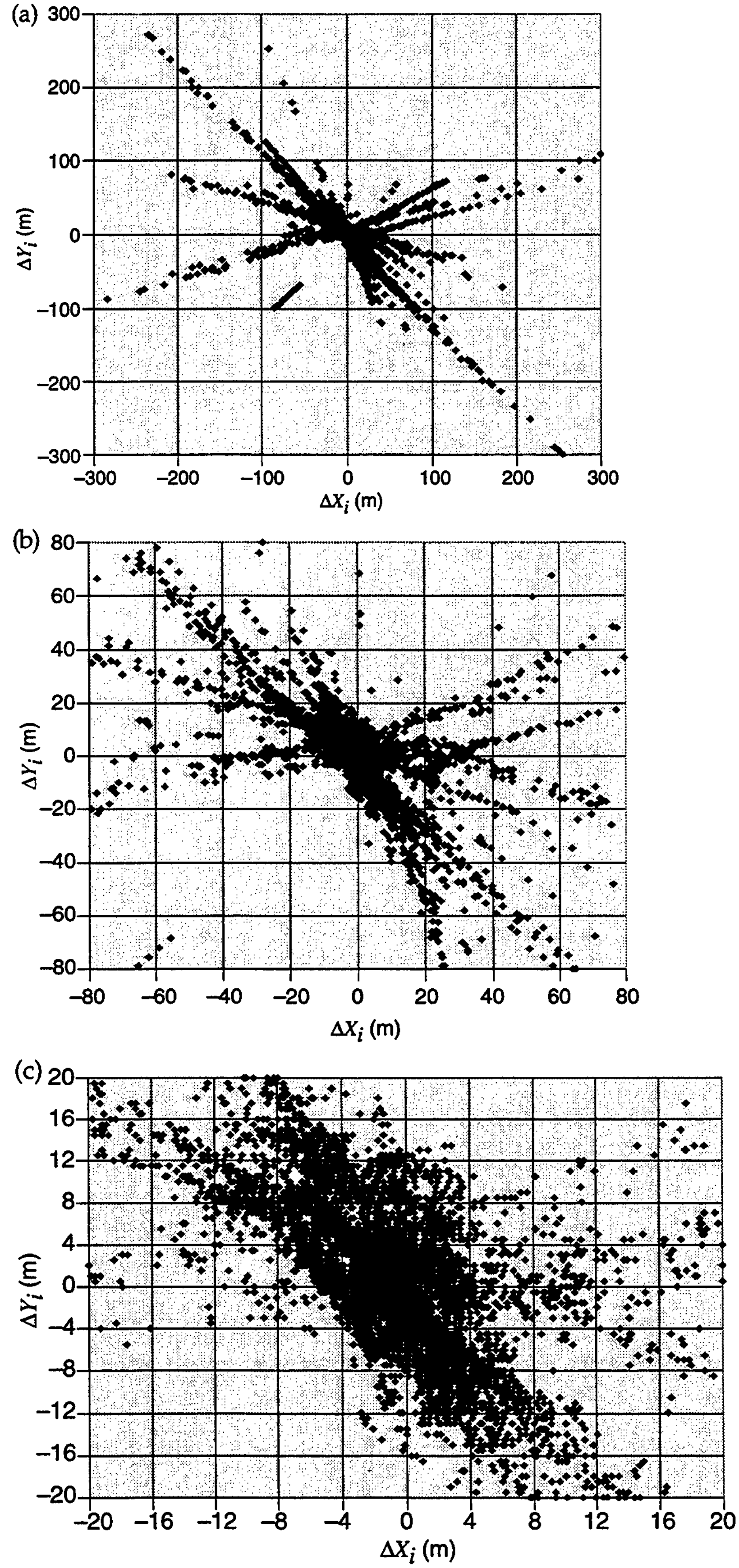


Figure 5. Histogram of position errors.

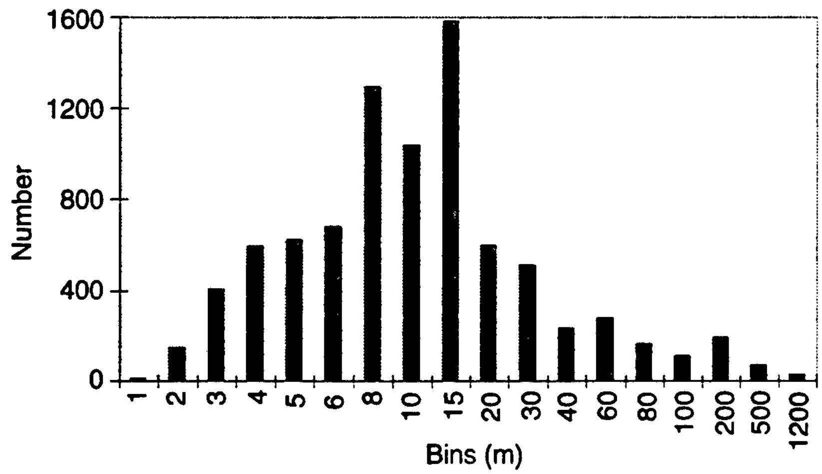


Table 3. Error distribution statistics.

Range bins (m)	Number of position errors in bin	Percentage of total errors
0–1	11	0.13
1–2	49	1.74
2–3	406	4.73
3–4	594	6.93
4–5	625	7.29
5–6	679	7.92
6–8	1293	15.08
8–10	1040	12.13
10–15	1583	18.46
15–20	599	6.98
20–30	512	5.97
30–40	235	2.74
40–60	278	3.24
60–80	166	1.94
80–100	111	1.29
100–200	193	2.25
200–500	70	0.82
500–1200	29	0.34

Anomalies

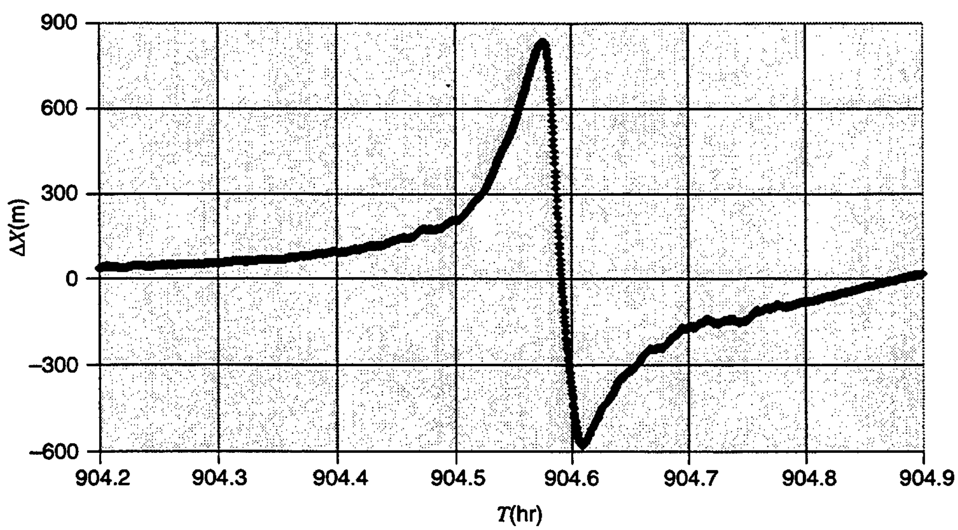
Figure 6 shows high time-resolution detail for one of the largest position error excursions. ΔX_i is plotted against time in hours over a 39-minute span. Points are at 1-s intervals (rather than the usual 30-s sampling), and individual blocks are six minutes wide. (The structure of other anomalies is usually similar.) Although the anomaly is slow to build and slow to terminate, the sudden jump in the middle takes place in just two minutes. During that interval, our stationary site at GSFC would register a velocity approaching 80 km/hr if MAGR position determinations were taken literally.

We define the fraction of individual position errors within a sphere of radius R as $n(R)$, where $0 \le n(R) \le 1$, $R^2 = X^2 + Y^2 + Z^2$, and $\delta(X)$ is the Dirac delta function:

$$n(R) = \frac{1}{N} \int_0^R 4\pi R^2 \, dR \sum_{i=1}^{N} \delta\left(X - \Delta X_i\right) \delta\left(Y - \Delta Y_i\right) \delta\left(Z - \Delta Z_i\right) .$$

The value of R that yields $n(R) = 0.5$ is the traditional SEP performance parameter. Figure 7 shows a plot of 100 $n(R)$, the percentage of individual position errors ΔR_i within a sphere of radius R, versus $\text{Log}_{10} R$. The logarithm of radius in meters was used so that errors over such a large range can be seen in one plot. The ordinate is just the percentage of individual position errors for which $\Delta R_i < R$. As an example, the plot shows that 90 percent of the individual position errors have $\text{Log}_{10} \Delta R_i <$ 1.6, which corresponds to errors less than 40 m; 10 percent of the errors are above 40 m.

Figure 6. MAGR (X, T) position errors at high time resolution.



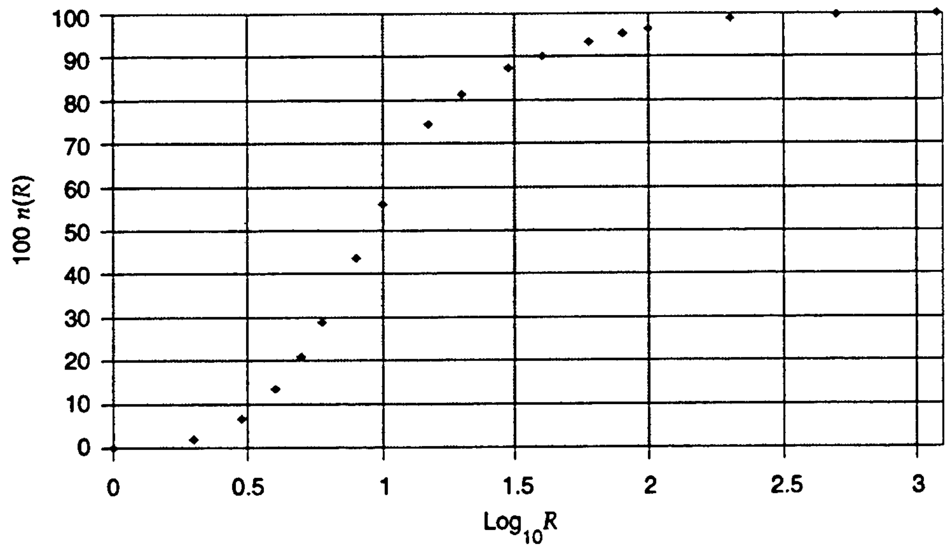


Figure 7. Percentage of position errors within a sphere of radius *R*.

Conclusions

The size of the anomalies, when they occur, seems fairly random. We note that most short MAGR runs would show a much smaller standard deviation. The longer the data span considered, the larger the standard deviation seems to become. It is not at all clear that we have sampled its worst behavior, and runs longer than six weeks might catch still poorer performance. But it seems clear that this anomalously large error distribution tail raises questions about the MAGR's suitability for some Army-critical functions, such as precision guidance.

Discussion

A draft copy of this report was circulated to interested parties. We have had the following feedback.

Rockwell Corporation has written a white paper (MAGR Technical Direction Note, June 15, 1998) discussing a MAGR anomaly that can occur during satellite acquisition. This feature remains in the MAGR software through Link 10. The GDOP (geometric dilution of precision) gives no hint of a problem in connection with this type of anomaly. However, the anomalies we see are not confined to acquisition or the other circumstances documented by Rockwell.

Joe Clifford of Aerospace Corp. notes the similarity of the detailed anomaly in figure 6 to a "constellation singularity," where the fourth satellite being tracked goes through the plane of the other three. He wondered if our MAGR might have been inadvertently set in "hover mode" or some other setting that freezes the constellation (private communication). Brian Baeder of MICOM, who set up the MAGR at GSFC, is quite certain no such settings were made, inadvertently or otherwise. We do agree, however, that the signature of the anomalies is like that of a constellation singularity.

Paul Olson of CECOM writes with some data from another MAGR at the Starfire Optical Range (SOR). In eight runs of roughly four hours length each, over a four-day span in October to November 1996, he also reports one large anomaly with a similar character to that in our figure 6, but cautions that other sampled data had 50-percent CEP values ranging between 3.9 and 8.1 m, with 95-percent CEP values between 7.0 and 20.7 m. He questions whether the anomalies can be as frequent as we report. He further notes that the GDOP did deteriorate during the anomaly, beginning with a MAGR constellation change, going off-scale with a second change, and then gradually recovering as the GDOP fell again to values that are more reasonable. He notes that good constellations were available to the MAGR during the anomaly, but were not used. He suggests this might be related to the characteristics of the Ashtech antenna used with the MAGR for their and our runs, perhaps inhibiting the MAGR from locking onto low-elevation satellites (private communication).

Olson's report led us to check the time distribution of our anomalies again. We noted that we also had only one large anomaly and a few much smaller ones in our first half-week of operation. During that period, our 50-percent CEP was 4.2 m, and our 95-percent CEP was 18 m, figures in the range of those seen at SOR. Then things got much worse. This lasted until an 8-day break over the Christmas–New Year's holidays, following which the MAGR was again well-behaved for several days, performed worse for the next several days, and then performed poorly for almost every run. This suggests a problem that worsens with the length of time that the MAGR has been in continuous operation—a matter of definite interest and concern to the Army.

Acknowledgments

We are indebted to Paul Olson and his group at U.S. Army CECOM for coordinating data acquisition with a CECOM MAGR at SOR, and for supplying plots that showed similar anomalies. This assured us that the problem was not unique to the particular MAGR or site we used. Charmaine Gilbreath provided laboratory facilities at SOR for data acquisition with CECOM's MAGR. We also acknowledge Cedric Lewis, the Navy's Senior GPS Systems Engineer for Aircraft Integrations at Pax River, who informs us that anomaly problems have existed at least since Link 7 of the MAGR firmware, and still exist in the latest (Link 10) release (private communication).

Carroll Alley at University of Maryland Physics provided the initial impetus for this project and some equipment needed for security at GSFC. Tom Clark provided facilities at NASA Goddard to house the receiver and associated equipment. Chuck Kodak at GSFC monitored the data acquisition. Brian Baeder at Aviation and Missile Command (MICOM) configured the MAGR in Huntsville, brought it to Maryland for data acquisition, and translated the outputs. William C. McCorkle of MICOM provided support and encouragement for the project.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

At a fixed, well-surveyed location, position determinations from a MAGR (Miniaturized Airborne Global Positioning System Receiver) averaged over a six-week period were correct to within 0.5 m. However, the standard deviation of an individual position determination was 56 m. Almost 20 percent of the individual position determinations had errors exceeding 20 m. One in every 300 position determinations had an error exceeding 0.5 km. This anomalously large error distribution tail raises questions about the MAGR's suitability for some Army-critical functions, such as precision guidance.

14. SUBJECT TERMS
GPS, MAGR, precision guidance, time transfer

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