Sensitivity Analysis of the JPALS Shipboard Relative GPS Measurement Quality Monitor

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ABSTRACT

The Joint Precision Approach and Landing System (JPALS) is being developed as a single replacement for the navigation, precision approach and landing systems currently used by military aircraft. Shipboard Relative GPS (SRGPS) is a JPALS variant being developed to support flight operation in the shipboard environment. Because of the stringent SRGPS performance requirements, differential carrier phase solutions are being pursued. In the system architecture currently being considered, the JPALS Shipboard Integrity Monitor (JSIM) is a reference station based integrity monitoring concept being explored. To some extent, JSIM is a shipboard analog of the LAAS Ground Facility (LGF) and its function is, in part, to detect, isolate, and alarm signal-in-space and reference receiver failures. Unlike the LGF however, JSIM is a mobile system and has to deal with reference receiver antenna motion. Because it operates within a shipboard environment, it must also be robust to the effects of multipath. The effect of antenna motion and multipath is to introduce un-modeled correlated carrier-phase measurement errors. This paper presents the results of a sensitivity analysis to assess the performance of a JSIM integrity monitor known as the Measurement Quality Monitor *relative* to its equivalent IMT monitor in the presence of un-modeled correlated carrier-phase measurement errors. A method for analyzing the effect of un-modeled carrier-phase noise, which involves developing a frequency response for the MQM, is presented. The analysis method used is to develop a relationship between carrier-phase measurement noise and MQM alarm limits. The results of this analysis method are used to show that large, un-modeled correlated noise triggers the JSIM's fault detection logic unnecessarily, increasing the false alarm rate and adversely affecting system continuity. The increase in false alarm rate as a function of un-modeled carrier-phase measurement error is quantified.

1. INTRODUCTION

The Joint Precision Approach and Landing System (JPALS) is being developed as a single replacement for the multiple systems currently used to provide navigation, precision approach, and landing services for US military aircraft. In some respects, JPALS is similar to the Local Area Augmentation System (LAAS) being developed by the Federal Aviation Administration (FAA), in that it will provide differential corrections and navigation system integrity messages to users in the vicinity of the local reference station. Shipboard Relative GPS (SRGPS) and Local Differential GPS (LDGPS) are two variants of JPALS. SRGPS is being developed to support precision approach and landing operations (including automated landings) in the shipboard environment. LDGPS will support similar operations at land based facilities

In SRGPS architectures under current evaluation, the task of integrity monitoring is shared between the user and the shipboard reference station. The objective of such integrity monitoring is to, in a timely manner, detect, alarm, and isolate any failures that can degrade SRGPS performance. To this end, the JPALS Shipboard Integrity Monitor (JSIM) is one of the SRGPS reference station based integrity monitoring concepts being explored. The function of the JSIM is to provide integrity monitoring with respect to signal-in-space and reference receiver failures. In addition to its integrity monitoring functions, JSIM is responsible for generating and broadcasting high quality carrier- and code-phase corrections for multiple GPS frequencies.

To some extent, the JSIM can be viewed as a shipboard analog of the LAAS Ground Facility (LGF) and its prototype, the Stanford University Integrity Monitor Testbed (IMT) **[1, 2]**, and as such, some of the integrity monitoring algorithms of IMT will be used as a starting point for the design of the JSIM integrity monitors **[3]**. A simple reuse of *all* of the IMT integrity monitors however, is not possible because there are sufficient differences between SRGPS and LAAS (or LDGPS). For example, SRGPS is being designed as a carrier-phase based system while LAAS is a carrier-smoothed code-phase system. More importantly, there are two major assumptions built into algorithms of the IMT integrity monitors that are not necessarily valid in SRGPS applications. These assumptions are:

1. The reference antennas providing the measurements used by the integrity monitors are static.
2. The GPS antennas providing measurements used by the integrity monitors are situated such that the multipath they see, if any, is uncorrelated.

Motion of a reference antenna that is assumed or believed to be static, has the effect of introducing correlated carrier-phase measurement errors, dj , equivalent to the motion of the antenna. **Figure 1** depicts a case where structural motion induces a carrier phase measurement error from a satellite directly overhead.

In order to deal with carrier-phase measurement errors resulting from reference antenna motion due to structural flexing, the use of a strapdown Inertial Navigation System (INS) collocated with the SRGPS reference antennas has been proposed. The output of the INS would provide an *independent* measurement of, and compensation for, the reference antenna motion. It is postulated that carrier-phase multipath has an effect similar to uncompensated antenna motion. To mitigate the effects of shipboard multipath, novel GPS antennas, receivers, and signal processing techniques have been proposed. These include controlled reception pattern (phased array) shipboard antennas, as well as beam-forming and null-steering GPS receivers **[4]**.

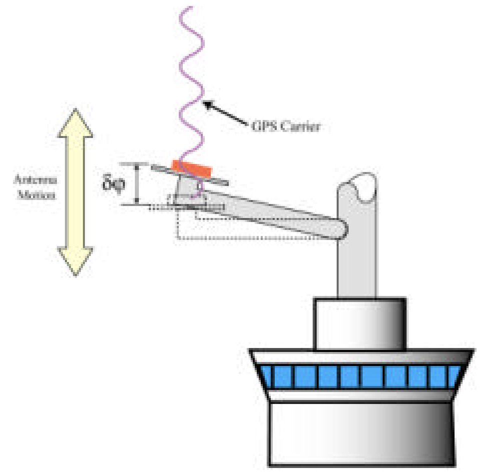

Figure 1. Carrier-Phase Measurement Error Due to Antenna Motion

Regardless of the methods and quality of sensors used to deal with antenna motion, there will always be some residual carrier phase measurement error because our knowledge of the antenna's location cannot be perfect. More importantly, however, these errors in our knowledge of the antenna's precise location are time varying. Consequently, they are different from the time invariant survey errors encountered in other differential systems such as LAAS. Similarly, multipath mitigation techniques cannot be perfect and will also introduce residual carrier-phase measurement errors. Thus, during the design and development of JSIM, an important question that needs to be addressed is to what degree the performance of the integrity monitors are affected by reference antenna motion and other correlated carrier phase measurement errors?

The objective of the work reported in this paper is to assess the performance of *a particular* JSIM integrity monitor *relative* to its equivalent IMT monitor in the presence of antenna motion and other correlated carrier-phase measurement errors such as multipath. The integrity monitor we focus on in this paper is the Measurement Quality Monitor (MQM) and we will be interested in answering the following questions:

1. What is the sensitivity of the MQM to residual carrier phase measurement errors?
2. What is the performance (especially, increased false alarm rate) of the MQM in the presence of

residual carrier phase error due to antenna motion and multipath?

Accordingly, the remainder of this paper is organized as follows: Section 2 provides an overview of the JSIM and MQM. This will include a qualitative discussion of the effect of uncompensated reference antenna motion on the MQM's performance. In Section 3, the frequency response of the MQM is derived and presented. In section 4, the effect of residual carrier phase error on the MQM false alarm rate is discussed. For conclusions, a summary and directions for future work are presented as Section 5

2. OVERVIEW OF JSIM AND MQM

The JSIM architecture under evaluation currently consists of multiple GPS receiver-antenna pairs which are installed shipboard. Multiple receiver-antenna pairs provide robustness to equipment failure, and as well, a redundant set of measurements for distinguishing reference receiver failures from signal-in-space failures. The redundant measurements from the receiver-antenna pair are the input to various integrity monitors. The integrity monitors are algorithms that determine the occurrence of a postulated failure mode. In addition to the integrity monitors, an integral part of the JSIM architecture is the Executive Monitor (EXM). Based on the input from the various integrity monitors, the Executive Monitor makes the decision whether to flag the SRGPS systems as unavailable for operation.

One of the many integrity monitors in JSIM is the Measurement Quality Monitor (MQM). The MQM ensures that only high quality carrier-phase measurements are used in formulating SRGPS position solutions. To accomplish this, the MQM detects, alarms, and isolates reference receiver failures, as well as signal-in-space anomalies due to GPS satellite clock failures.

The MQM detects such failures by monitoring the carrier-phase measurements obtained from the multiple receivers that are part of the JSIM. More precisely, it monitors the statistics of the computed variable $f^*(n)$ which is related to the carrier-phase differential correction **[1, 2]**. This derived quantity is used to form a second order polynomial fit of the following form:

$$f^*(n) = b_0 + b_1 t + b_2 t^2 \qquad \textbf{(1)}$$

At each measurement epoch, this polynomial fit is used to compute a predicted value of $f^*(n)$ which is denoted by the variable $f^*_p(n)$. This variable $f^*_p(n)$ is in turn used to compute a *carrier-phase step error*, $e(n)$, in the following manner:

$$e(n) = f^*(n) - f^*_p(n) \qquad \textbf{(2)}$$

It is assumed that values of $e(n)$ larger than certain prescribed limits are indicative of a carrier-phase anomaly. Such values of $e(n)$ will cause the MQM to alarm. In addition to carrier-phase step errors, the MQM also monitors carrier phase ramp and acceleration. This is accomplished by monitoring the values of the ramp and acceleration terms given by b_1 and b_2 in Equation (1) above. Excessive ramp and acceleration beyond prescribed limits will also cause the MQM to issue an alarm.

The distributions of $e(n)$, b_1 and b_2 are not necessarily Gaussian. They can, however, be over-bounded by a Gaussian distribution **[1, 2]**. The MQM limits for $e(n)$, b_1 and b_2 are therefore established using the Gaussian over-bound. These limits are set in order to maintain the false alarm rate at or below some prescribed limit.

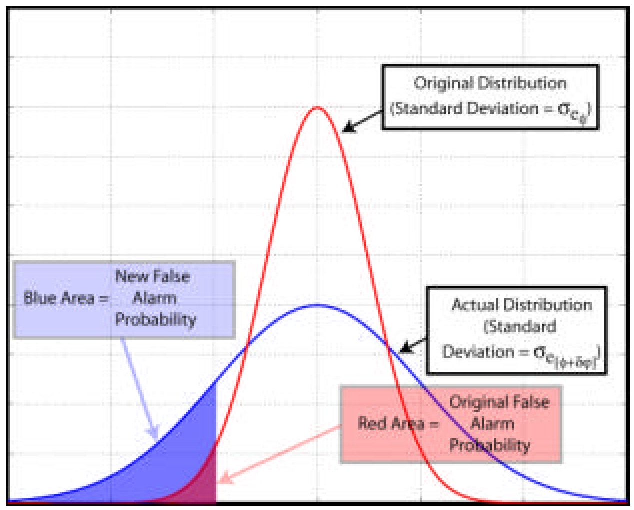

Figure 2. Effect of Carrier-Phase Error on MQM Test Statistics. (In this case, step test statistic)

Figure 2 qualitatively depicts the effect of carrier-phase measurement errors due to antenna motion or multipath on the performance of the MQM. The Gaussian over-bound distribution marked "original" represents the distribution of $e(n)$, b_1 and b_2 in the absence of antenna motion or multipath. The distribution marked "actual" represents the distribution of these variables in the presence residual carrier-phase errors after compensation for antenna motion and multipath (i.e.

perceived carrier-phase). The protection limits for $e(n)$, b_1 and b_2 are established based on the original distribution because we are unaware of the actual distribution. If the MQM limits are based on the original distribution and the standard deviation of actual distribution is larger than that of the original distribution, then there will be an increased false alarm rate. One of the objectives of this work is to precisely quantify this increase in false alarm rates. As will be shown later, the increase in false alarm rates is a function of the increase in the standard deviations of $e(n)$, b_1 and b_2 which are denoted by s_e, s_{b_1} and s_{b_2}, respectively. But first we will have to establish a relationship between the additional carrier-phase measurement error, dj, caused by antenna motion and multipath, to standard deviations of the carrier-phase step error, s_e, ramp error, s_{b_1}, and acceleration, s_{b_2}.

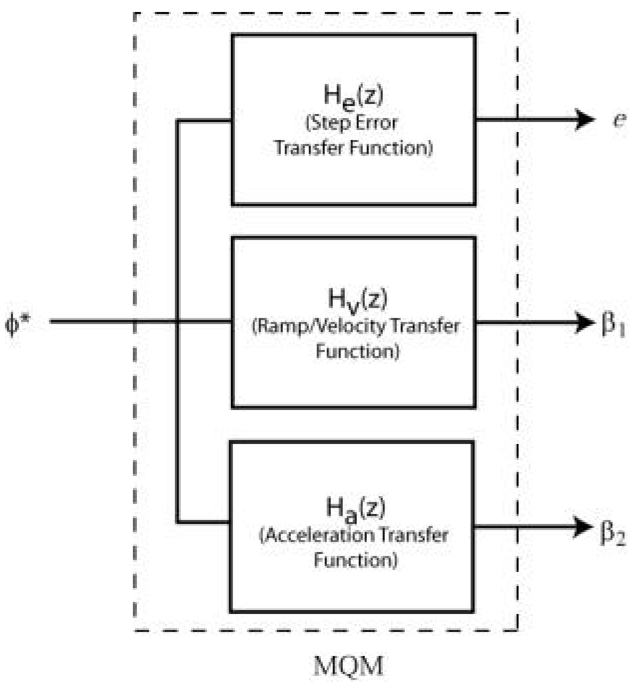

Figure 3. MQM Block Diagram

3. MQM FREQUENCY RESPONSE

The MQM targets rapidly varying carrier phase errors. Stated differently, the MQM is designed to detect errors with high frequency content. Therefore, it is reasonable to expect that both the magnitude and frequency content of dj influence the MQM's performance. We will show that this is indeed the case by analyzing the MQM's frequency response.

We start this analysis be noting that the MQM can be viewed as a Single-Input Multiple-Output (SIMO) dynamic system as shown in **Figure 3**. As such, we can derive a transfer function for the MQM using standard methods developed for handling such systems. The MQM is a discrete-time or sampled-data system and, therefore, generating a transfer function for it involves taking the z-transform of Equation 1. Deriving transfer functions for such discrete-time systems is a standard technique discussed in most system engineering text books such as **[5]** and will not be discussed in any more detail in this paper.

When the MQM is viewed as a s SIMO, the input to the system is the derived quantity, $f^*(n)$ described earlier. The outputs of the system are the carrier-phase step error, velocity, and acceleration. The discrete transfer functions $H_e(z)$, $H_v(z)$, and $H_a(z)$ relate the computed value of $f^*(n)$, to $e(n)$, b_1 and b_2, respectively. Given these transfer functions, it is easy to relate the standard deviation of the carrier-phase measurement error due to antenna motion and multipath, to the MQM test statistics.

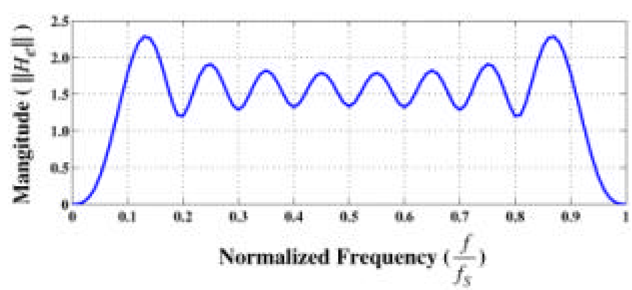

Figure 4. MQM Step Test Frequency Response

Figure 4 is a plot of the frequency response for $e(n)$. **Figure 5** and **Figure 6** are similar plots for b_1 and b_2, respectively. The abscissa of this plot is presented in the normalized (or digital) frequency form. That is, 1.0 on the abscissa corresponds to the JSIM sampling frequency, which is the rate at which the carrier phase is sampled for processing by the MQM. Therefore, given the standard deviation and correlation (i.e., the power spectrum) of dj, determining the standard deviation for $e(n)$, b_1 and b_2 is just a matter of integrated convolution.

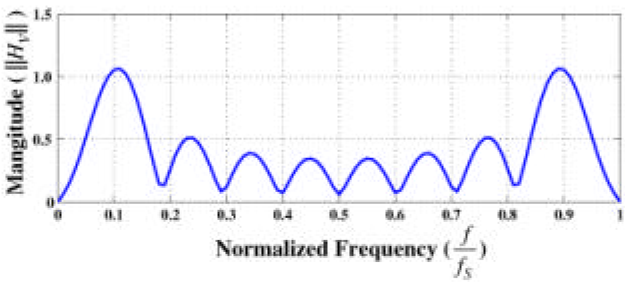

Figure 5. MQM Ramp Test Frequency Response

Figure 4 highlights several important aspects of the MQM's performance in the presence of antenna motion or multipath. Perhaps the most important aspect, is that the output of the MQM is affected by both the magnitude and frequency content of the input. Therefore, to determine the effect of antenna motion on the MQM one needs to know the *power spectrum* of the antenna motion. A description of antenna motion by simply stating the magnitude of displacement is not sufficient. Another significant point to note is that the magnitude of the frequency response at zero frequency ("DC") is zero. This means that antenna installation or survey errors do not affect the MQM's ability to detect carrier-phase steps or excessive accelerations.

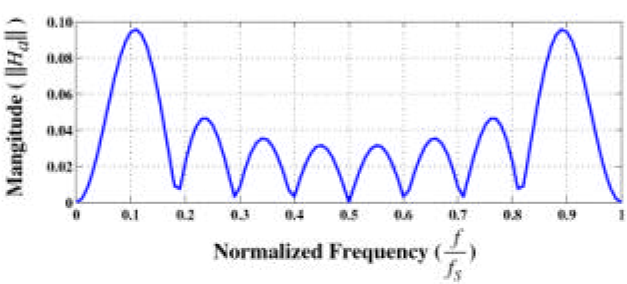

Figure 6. MQM Acceleration Test Frequency Response

4. MQM PERFORMANCE

Throughout this paper we have noted that antenna motion and multipath can be treated as an additive carrier phase measurement noise. This is a consequence of modeling the MQM as a linear system. The MQM frequency response analysis discussed in the previous section showed how to account for this added carrier phase measurement noise. In this section we present the effect of this additive noise on the performance of the MQM. In particular, we are interested in the following: Firstly, given an additive noise of some magnitude, what is the increase in false alarm rates of the MQM? Qualitatively, one can foresee that increased measurement noise will result in the MQM alarming at a higher rate. These will be false alarms, of course, because there are no inherent failures in the GPS signal as the uncompensated antenna motion is appearing as noise. Secondly, in the presence of uncompensated antenna motion of a given magnitude and frequency, what do the MQM limits have to be to maintain a false alarm rate that is similar to that of the IMT?

Before we present the analysis results answering the aforementioned questions, it is worth noting a few points. Firstly, when we use the term false alarm rate, we mean false alarm rate of the MQM only. At this point in the design of the SRGPS architecture, we cannot quantify the false alarm rate of the entire JSIM. This is because, as noted earlier, the ultimate decision to declare the system unavailable for use is made by the Executive Monitor. The Executive Monitor makes this decision based on, in part, input from other integrity monitors. In the absence of the complete design of the other integrity monitors, it is difficult to quantify the entire JSIM's false alarm rate.

With this caveat, we can now discuss the MQM's performance quantitatively. **Figure 7** shows the MQM step test false alarm rate as function of the error ratio, *r*, which is defined as follows:

$$r = \frac{\sigma_{e_{\delta\phi}}}{\sigma_{e_f}} \qquad \textbf{(3)}$$

This is the ratio of the standard deviation of the distribution of *e(n)* due to residual carrier-phase error in the presence of antenna motion or multipath to the standard deviation of this test statistic in the absence of antenna motion or multipath.

In **Figure 7**, we have elected to plot the false alarm rate as a function of *r* and not the ratio $\frac{\sigma_{\delta\phi}}{\sigma_f}$. This is because a plot based on $\frac{\sigma_{\delta\phi}}{\sigma_f}$ would not be general. That is, such a plot would imply that we know the spectrum of the additional carrier phase measurement error. This is made clear by the curves in **Figure 8** which show the effect of carrier phase error, $\delta\phi$, (modeled as a first order Gauss-Markov process with a standard deviation, $\sigma_{\delta\phi}$, of unity and a correlation time τ) on the MQM test statistics σ_{e_f} and σ_{b_2}. What is apparent from **Figure 8** is that the effect of $\delta\phi$ on σ_{e_f} and σ_{b_2} depends on the correlation time (or frequency content) of $\delta\phi$.

Another point to note about **Figure 7** is that, the false alarm rates have been parameterized by the MQM alarm set-points. The alarm set points are established at six-, seven- and eight-σ_{e_ϕ}. We use σ_{e_ϕ} to establish test limits and not the actual distribution obtained when antenna motion and multipath are present because that distribution is unknown.

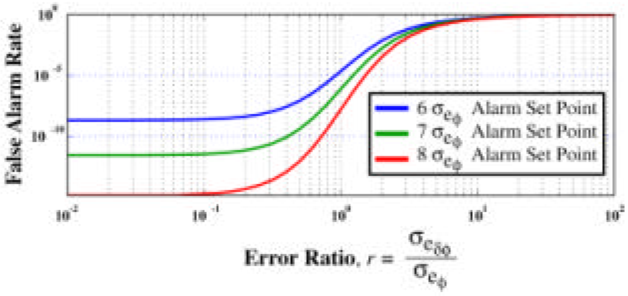

Figure 7. MQM Step Test False Alarm Rate As Function of Error Ratio.

From **Figure 7** we note that the false alarm rates are almost constant for error ratios less than approximately 10%. This implies that if the additional carrier phase measurement error due to antenna motion and multipath is kept at a value that yields an error ratio value less than of approximately 10%, then additional carrier-phase measurement noise can be almost ignored when establishing the MQM alarm set points. The same argument also applies to the ramp and acceleration tests because their plots of false alarm rate as a function of error ratio are identical to **Figure 7**.

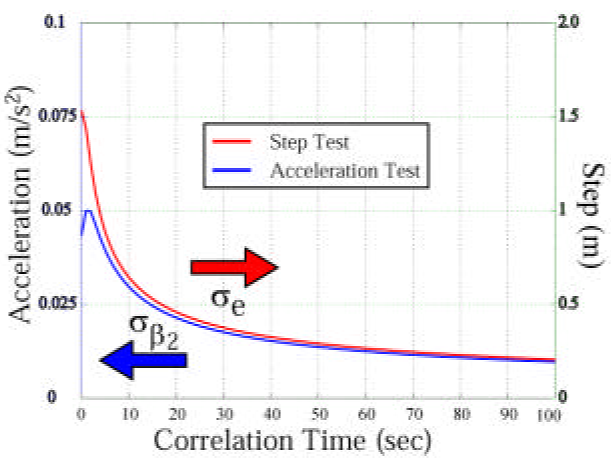

Figure 8. Mapping of Carrier Phase Measurement Error with a Standard Deviation of Unity into MQM Step and Acceleratio Test Statistics

For a fixed false alarm set point, **Figure 7** shows that a large error ratio leads to a higher false alarm rate. Stated in practical terms, for a fixed false alarm set point, large antenna motion or multipath leads to an increased false alarm rate. In the presence of such large antenna motion or multipath the false alarm rate can be maintained at a constant value if the false alarm set point is increased relative to its initial value. To illustrate this point we consider the case where, in the absence of uncompensated antenna motion and multipath, we want to maintain a MQM false alarm rate consistent with a 7-σ_{e_ϕ} alarm set point. To continue maintaining this same false alarm rate in the presence of uncompensated antenna motion or multipath (i.e., in the presence of increasing values or r) will require changing the MQM alarm set point to a value of k-σ_{e_ϕ} where k is some number larger than 7.

Figure 9 shows the relationship between the multiplier k of σ_{e_ϕ} used in establishing MQM alarm set points (or the "k-factor") and the error ratio r for a given false alarm rate. While **Figure 9** shows that increasing the k-factor in the presence of an increasing values of r can allow maintaining a constant false alarm rate, the required value of k can be very large for high values of the error ratio. The value of k cannot be increased indefinitely because there is an upper limit on the acceptable values of carrier phase step, ramp or acceleration. Simply increasing the k-factor to maintain a desired false alarm rate can adversely affect the overall system's integrity by increasing the number of MQM missed detections.

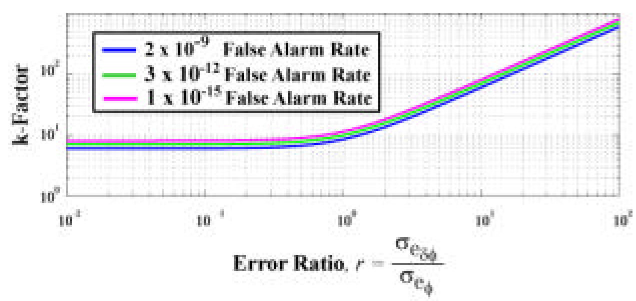

Figure 9. MQM Alarm Set Point Limit As a Function of Error Ratio.

5. CONCLUSIONS AND FUTURE WORK

This paper presented a methodology for relating the carrier phase measurement errors to the MQM alarm set points. The relationship highlights the important fact that the MQM alarm set points are a function of both the magnitude as well as the frequency content (or correlation) of the carrier-phase measurement errors.

It was shown that large, un-modeled carrier-phase measurement errors due to antenna motion or multipath adversely affect continuity by triggering the MQM alarm set points unnecessarily. The JSIM's protection limits can be relaxed to accommodate such uncompensated antenna motion. While this may decrease the false alarm rates (and enhance continuity), it has the potential of adversely affecting the system's integrity by increasing the number of MQM missed detections. Assessing the effect of these relaxed limits on overall system continuity and integrity is difficult. This is because when we when discuss missed detections, we are quantifying the number of times the MQM fails to flag a carrier phase jump or acceleration that is larger than the alarm. This does not mean however, that the JSIM as a whole has ignored an unsafe condition, because there are other monitors that could potentially flag the unsafe condition. Quantifying the effect of relaxed limits of specific individual integrity monitors on the overall system performance, therefore, can be accomplished after all the integrity monitors that will be part of JSIM have been designed. This is the subject of ongoing work.

6. ACKNOWLEDGEMENTS

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