Collaboration-Enhanced Receiver Integrity Monitoring (CERIM)

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This paper appears in: IEEE Intelligent Transportation Systems Conference (ITSC), 2011
Issue Date: 5-7 October 2011
Location: Washington, D.C.
ISSN: TBA
Print ISBN: TBA
INSPEC Accession Number: TBA
Digital Object Identifier: TBA
Date of Current Version: TBA

This is a pre-print. Final Version available at <TBA>
Collaboration-Enhanced Receiver Integrity Monitoring (CERIM)

Jason Rife, Member, IEEE

Abstract—This paper introduces a method of monitoring for navigation satellite faults by pooling measurements for a team of vehicles connected through a wireless Vehicle-to-Vehicle (V2V) network. The new method is called Collaboration-Enhanced Receiver Integrity Monitoring (CERIM). Compared to existing satellite-navigation integrity technologies, such as Receiver Autonomous Integrity Monitoring (RAIM), Space-Based Augmentation Systems (SBAS), or Ground-Based Augmentation Systems (GBAS), CERIM has particular advantages for intelligent transportation systems, because of its potential for high sensitivity and fast response time, and because of its ability to operate without an infrastructure of stationary reference receivers. A method for computing the missed-detection probability of CERIM in the face of single-satellite faults is derived and evaluated using simulation.

I. INTRODUCTION

Integrity monitors are systems that assess navigation signal quality on-the-fly. Integrity monitoring has not been necessary in traditional vehicle systems, as human drivers capably and seamlessly integrate anomaly detection into conventional (visual) navigation. The need for integrity monitoring becomes apparent in certifying safety-critical automation systems, however, since automation systems otherwise respond blindly to sensor data, whether the quality of that sensor data is good or hazardously bad. Integrity monitors have already been deployed widely in the aviation community to ensure online safety verification for GNSS sensor data used for safety-critical automated tasks [1]. Similarly, it is logical to anticipate that sensor integrity monitoring will become increasingly essential for certification of ground-vehicle automation.

This paper describes a new, collaborative approach for integrity monitoring of satellite navigation signals to be used in emerging intelligent vehicle systems. A wide range of intelligent vehicle technologies are expected to rely on the Global Navigation Satellite System (GNSS), a term which refers broadly to space-based radionavigation systems including the U.S. Global Positioning System (GPS), the Russian GLONASS, the European Galileo, and the Chinese Beidou systems. GNSS signals are anticipated, for example, to be a key component for emerging Advanced Driver Assistance Systems (ADAS), including lane-departure warning and automated lane-keeping systems [2]-[3]. GNSS signals may also be used for non-safety-of-life applications for which reliability is nonetheless essential, such as in automated vehicle identification and road-user charging [4]-[5]. Because these systems will rely heavily on GNSS positioning measurements, it is essential that users continuously monitor GNSS signal quality.

The methods introduced in this paper enable multiple vehicles to pool their GNSS measurements via Vehicle-to-Vehicle (V2V) communication, to compute position-estimation residuals for the group, and to monitor those residuals to alert for anomalous conditions that might otherwise compromise system safety or reliability.

II. BACKGROUND

In aviation, the most widely used form of GNSS integrity monitoring is called Receiver Autonomous Integrity Monitoring (RAIM) [6]. RAIM examines the residuals from the position estimate for a single vehicle, typically computed using nonlinear least-squares (for conventional GNSS [7]) or a Kalman filter for integrated GNSS-inertial fusion [8]. If a satellite, receiver, or atmosphere fault corrupts a particular GNSS ranging measurement and causes a hazardous large error, then RAIM attempts to exclude that anomaly. If exclusion is not possible, then an alarm is issued to the aircraft pilot to indicate that the navigation data do not support safety-critical flight operations. The greatest advantages of RAIM are that it is self-contained (e.g. built directly into the GNSS receiver electronics) and that it issues an alert instantly, with essentially no latency. The disadvantage of RAIM is that it is relatively insensitive to small and moderate-sized errors. As such, RAIM is useful in ensuring integrity for coarse positioning applications, such as en route flight, but less so for precision applications.

To support precision navigation, higher performance integrity monitors have been developed that leverage Differential GNSS (DGNSS) infrastructure. DGNSS uses stationary receivers at surveyed locations to measure systematic GNSS biases (including ionosphere, troposphere, ephemeris, and satellite clock errors), common to all users over a local geographic area, and to broadcast corrections to those users [7]. It is convenient to integrate integrity monitoring capabilities into such a system because (a) differential GNSS receivers typically use multiple, high quality antennas and receivers (b) integrity messages can easily be broadcast to users through the communication infrastructure already used to distribute GNSSS differential corrections. To date, integrity monitors have been integrated into two forms of DGNSS architecture: Space-Based Augmentation Systems (SBAS) and Ground-Based Augmentation Systems (GBAS).
SBAS operates by collecting data from reference stations distributed over a continent-scale area and broadcasting the data to satellites in geosynchronous orbit, which rebroadcast the data across the coverage area. Currently two such systems are in operation: the Wide-Area Augmentation System (WAAS) in North America and the European Geostationary Navigation Overlay Service (EGNOS) in Europe. The advantage of an SBAS is that it provides wide-area coverage, providing sensitive integrity monitoring using data from very high quality equipment spread over wide baselines. The disadvantage of SBAS is that the indirect “bent pipe” communication path introduces a substantial delay, such that SBAS integrity alerts may take 10-12 seconds to arrive at the user [9].

By comparison, GBAS operates by generating differential corrections from one or more co-located reference receivers; these corrections are broadcast over a compact service region (tens of kilometers) via a ground-based VHF antenna. Because corrections are generated closer to users, they result in higher accuracy positioning. Namely, GBAS offers sub-meter accuracy as compared to approximately 2m accuracy (95%) for SBAS. GBAS also provides a more direct communications pathway than SBAS, and can hence reliably alert a user of a GNSS fault within 2 to 6 seconds after the fault occurs. Rapid alert times and high sensitivity make GBAS more suitable than either SBAS or RAIM for high precision applications. The major limitation of GBAS is that it covers such a localized area. As such, it is most cost effective in major transportation hubs. For instance, the FAA is developing a GBAS called the Local Area Augmentation System (LAAS) to support precision approach and landing at airport facilities. Though deploying GBAS capabilities over a wide (continent-scale) region would require an expensive infrastructure, such systems are being considered, in the form of the Nationwide Differential GPS (NDGPS) system in the U.S. and the Ground-Based Regional Augmentation System (GRAS) in Australia.

III. CERIM Concept

This paper proposes an alternative GNSS integrity monitoring architecture, one which could match (or exceed) the sensitivity and rapid alert times of GBAS, but without requiring an infrastructure of stationary reference antennas. The proposed approach re-envision the basic premise of RAIM (monitoring of position-estimation residuals) in a manner that is not autonomous but that is rather collaborative. Thus the new integrity monitoring architecture is labeled Collaboration-Enhanced Receiver Integrity Monitoring (CERIM). A brief comparison of the CERIM to other integrity systems, including RAIM, SBAS and GBAS, is given in Table 1.

CERIM assumes collaborating vehicles share raw ranging measurements via a wireless network. Thus any networked user can compute a position estimate (absolute or relative) for all other nearby collaborators. Measurement residual vectors for each collaborator can also be computed. By combining these residuals vectors together, as described in the subsequent sections, it is possible to achieve a much greater signal-to-noise ratio for detection of common-mode errors, such as a satellite faults. Generally speaking, a greater number of collaborating vehicles provides greater sensitivity; hence the benefits of CERIM are potentially greatest where automotive traffic is most dense.

A potential application of CERIM is to provide GNSS integrity for map-referenced navigation systems that do not rely on differential corrections generated by stationary reference antennas [10]-[11]. In fact, CERIM could also be used to enhance a differential correction system (such as an SBAS or a GBAS) in order to improve integrity monitoring sensitivity or to shorten time-to-alert.

The remainder of this paper will describe an algorithm for implementing CERIM as well as simulations that explore the algorithm’s sensitivity. These simulations consider both the ideal case in which all collaborators view the same set of GNSS satellites and the more realistic case in which certain satellites are tracked only by a subset of users.

Table 1. Comparing CERIM to SBAS, RAIM, and GBAS

<table>
<thead>
<tr>
<th></th>
<th>High Sensitivity</th>
<th>2 Second or Better Alert</th>
<th>No Required Infrastructure</th>
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<tbody>
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<td>SBAS</td>
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<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>RAIM</td>
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IV. Satellite Fault Model

The purpose of this section is to provide a model for GNSS satellite faults and to describe the impact of such faults on conventional GNSS processing. Though GNSS satellite faults are uncommon, such faults do occur. For the constellation of GPS satellites, significant satellite faults occur approximately once per year [12]-[13]. The most common form of satellite fault is a satellite clock error, in which one of the atomic clocks onboard a GPS satellite suddenly begins to diverge from the time reference for the rest of the GPS constellation. These failures are eventually corrected by the GPS Operational Control Segment (OCS), which can switch the faulty satellite to a redundant clock and confirm that the new clock is operating properly. During this verification period GPS data messages flag the faulty satellite as “unhealthy.” For precision navigation, the hazardous period occurs in the minutes or hours that elapse before the OCS detects the fault. During this period the satellite is still flagged as “healthy,” even though ground users may experience errors of a few meters (or even hundreds of meters) in magnitude. Left undetected, such fault-induced errors constitute a loss of integrity, in which the probability of a hazardously large sensor error exceeds that for nominal operating conditions.

To model the satellite fault, GNSS ranging-measurement errors (either code or carrier-phase pseudoranges, possibly differentially corrected) are considered to be a sum of

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To model the satellite fault, GNSS ranging-measurement errors (either code or carrier-phase pseudoranges, possibly differentially corrected) are considered to be a sum of
random terms subject to a systematic bias. Thus the total ranging error vector $\mathbf{e}$ has elements $\varepsilon_k$ (for each satellite $k$) that combine a random scalar value $\varepsilon_k$ with a systematic bias $\overline{\varepsilon}_f$ (for a faulted satellite $f$).

$$
E_k = \begin{cases} 
\varepsilon_k & k \neq f \\ 
\varepsilon_f + \overline{\varepsilon}_f & k = f 
\end{cases} 
$$

(1)

In this paper, when a satellite fault is present, it is assumed that the systematic bias is the same for all users viewing that satellite.

In conventional GNSS processing, a nonlinear set of algebraic equations is solved to compute receiver position and time from a set of pseudorange measurements. Typically, this estimation problem is solved iteratively using the Newton-Raphson method to compute a weighted least-squares solution. At each iterative step, the linearized problem has the following form [7].

$$
\delta \mathbf{p} = \mathbf{G} \begin{bmatrix} \delta \mathbf{x} \\ \delta b \end{bmatrix} 
$$

(2)

Here, the vector $\mathbf{p}$ refers to the set of ranging measurements, the vector $\mathbf{x}$ is the user-receiver position vector, the scalar $b$ is the user-receiver clock offset, and $\delta$ indicates a linearized perturbation. The matrix $\mathbf{G}$ is the so-called geometry matrix, in which each row consists of the unit pointing vector $\mathbf{u}_k$ (from the user to a particular satellite $k$) augmented with a fourth element equal to one.

$$
\mathbf{G} = \begin{bmatrix} 
: & : \\
-(\mathbf{u}_k)^T & 1 \\
: & : 
\end{bmatrix} 
$$

(3)

In addition to its utility in estimating user position and time, the geometry matrix $\mathbf{G}$ is also useful in relating the pseudorange error vector $\mathbf{e}$ to the position-error vector $\mathbf{E}$ and the clock-error value $E_b$.

$$
\begin{bmatrix} 
\mathbf{E} \\
E_b 
\end{bmatrix} = \mathbf{G}^{w+} \mathbf{e} 
$$

(4)

Here $\mathbf{G}^+$ is the left weighted pseudoinverse of $\mathbf{G}$.

$$
\mathbf{G}^{w+} = (\mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T 
$$

(5)

In the equation for the weighted pseudoinverse, the weighting matrix $\mathbf{W} \in \mathbb{R}^{K \times K}$ is square with dimension equal the number of visible satellites $K$. The optimal weighting matrix, which minimizes error for linear state-estimation, is equal to the inverse of the noise covariance matrix for the random error vector $\mathbf{e}$. It is not always possible to implement optimal weighting, however, since the exact covariance matrix is not always known. Instead, GNSS receivers often model $\mathbf{W}$ as a diagonal matrix, in which each diagonal entry is approximated as $1/\sigma_k^2$, the inverse of the variance for satellite $k$.

For typical ground-vehicle applications, the horizontal components of the error vector $\mathbf{E}$ are most relevant. Hence, in the analysis of this paper, the position-error vector (generally defined in XYZ coordinates in an Earth-centered, Earth-fixed reference frame) is projected into the plane of the road. This scalar projection of the position error is labeled $E_h$:

$$
E_h = \|\mathbf{E}'[\mathbf{u}_n \ \mathbf{u}_n]\|. 
$$

(6)

In this equation, the Euclidian magnitude of the horizontal error is computed from the East and North components of the error vector, which are obtained by dotting the total state estimation error with the unit vectors in the east and north directions, $\mathbf{u}_n$ and $\mathbf{u}_n$, respectively.

In general, any satellite fault that causes a bias will corrupt the absolute position estimates for all users, resulting in an elevated horizontal error $E_h$ for those users. The goal of integrity monitoring is to detect such events before they pose a safety threat to users. Once a detection occurs, the integrity monitor can warn users that GNSS positioning should not be trusted for precision navigation.

V. CERIM ALGORITHM

This section introduces one possible implementation of CERIM, in the form of an algorithm that combines together measurement residuals for many collaborating users to enable high sensitivity detection of common-mode ranging errors, such as those caused by a satellite faults.

In this CERIM implementation, it is assumed that a particular user has obtained pseudorange measurements from several collaborators via a wireless network. In this paper, it is assumed that multiple pseudorange measurement vectors, each from a different vehicle $n$, are acquired simultaneously and made available after that brief delay to a particular vehicle, which is identified as Vehicle 1 without loss of generality. Thus, corresponding to any given moment in time, Vehicle 1 has available to it a collection of $N$ measurement vectors $\mathbf{\rho}_n$. By running the Newton-Raphson separately on each of these measurements vectors, Vehicle 1 can compute position estimates $\hat{x}_n$ for itself and its $N$-1 collaborators. The vector of measurement residuals $\mathbf{r}_n$ for each vehicle $n$ is equivalent to the converged value of $\delta \mathbf{p}$ from (2), after the final Newton-Raphson iteration, and is thus computed as the difference between the measured pseudorange $\mathbf{\rho}_n$ and a pseudorange model $\hat{\mathbf{\rho}}_n$.

$$
\mathbf{r}_n = \mathbf{\rho}_n - \hat{\mathbf{\rho}}_n 
$$

(7)
Element of the pseudorange model vector $\hat{\rho}_n$ each describe a different satellite $k$ as seen by receiver $n$. The $k^{th}$ element of this model vector is computed by the following nonlinear equation, where $x(k)$ refers to the known position of satellite $k$, $\hat{x}_n$ refers to the estimated position of receiver $n$, and $\hat{\delta}_n$ to the estimation clock offset of the same receiver.

$$\hat{\rho}_{n,k} = \|x(k) - \hat{x}_n\| + \hat{\delta}_n$$  \hspace{1cm} (8)

For a particular residual vector $r_n$ to be useful for fault detection in CERIM, it must contain at least five elements. When at least five satellites measurements are available, the system of equations (2) is overdetermined and so the magnitude of the residual vector is nonzero. The residual vector is useful in detecting satellite faults, because fault-induced errors usually cause a dramatic increase in the magnitude of the residual vector. In CERIM, it is possible to monitor for satellite faults using data from other receivers; hence, Vehicle 1 can still apply the CERIM algorithm using measurements from other vehicles, even if Vehicle 1 is tracking only four satellites (such that its own residual vector has a magnitude of zero).

In order to detect a satellite fault using all available residual vectors, a monitor statistic must be defined. As a baseline, it is useful to consider conventional RAIM, in which the monitor statistic is simply the square of the magnitude of the residual vector:

$$m_{RAIM} = r_r^T r_r.$$  \hspace{1cm} (9)

Several strategies might be used to generalize this monitoring statistic to the multiple vehicle scenario of CERIM. For instance, one approach would be to average residuals vectors across all vehicles before computing the monitoring statistic:

$$m = \bar{r}^T \bar{r}$$  \hspace{1cm} (10)

with

$$\bar{r} = \frac{1}{N} \sum_{n=1}^{N} r_n.$$  \hspace{1cm} (11)

Although such an approach is straightforward to implement, and the averaging processes used in (11) clearly attenuates the effects of random noise (thermal noise and multipath) which otherwise obscure detection of any systematic bias caused by a satellite fault, this simple averaging approach is not practical. Realistically, not all vehicles see the same set of satellites in typical ground-vehicle applications. Instead, tall buildings, terrain features, and interference sources block certain receivers from tracking one or more satellites that are tracked by other collaborating receivers. Thus the monitor statistic should allow for the length of each measurement vector $p_n$, and hence for the length of each residual vector $r_n$, to vary from one vehicle to the next.

The following monitor statistic, $m_{CERIM}$, has this characteristic that allows for a different number of satellites $K_n$ for each collaborator $n$. Here the weighting matrix $W_n$ is assumed to be an approximate model of the inverse-covariance matrix for receiver $n$.

$$m_{CERIM} = \sum_{n=1}^{N} r_n^T W_n r_n$$  \hspace{1cm} (12)

To determine when an alert should be issued, the monitor statistic $m_{CERIM}$ is compared to a threshold.

$$m_{CERIM} > T_{CERIM} \rightarrow \text{alert}$$  \hspace{1cm} (13)

It is desirable that the threshold $T_{CERIM}$ be as small as possible to enhance detection sensitivity; however, the threshold must be sufficiently large that few false alarms occur. To account for the allowed probability of a false alarm, it is assumed that the risk of continuity loss (i.e. the risk of a false alarm interrupting use of the navigation system) is specified at a value $c_r$. The threshold should be chosen such that the probability of noise tripping a false alarm is less than $c_r$. For the purpose of this paper, it will be assumed that nominal errors are independent and Gaussian distributed, and that the weighting matrix $W_n$ normalizes each measurement by its standard deviation. In this case, the resulting monitor statistic $m_{CERIM}$ is chi-square distributed. The number of degrees of freedom for this monitor statistic is fewer than the total number of satellites seen by all collaborating vehicles. Accounting for the degrees of freedom for all collaborating vehicles, the total number of degrees of freedom $K_{CERIM}$ for the compiled monitor statistic $m_{CERIM}$ is

$$K_{CERIM} = \sum_{n=1}^{N} (K_n - 4).$$  \hspace{1cm} (14)

In this equation, the number of degrees of freedom associated with the $n^{th}$ vehicle is $K_n - 4$. For each vehicle, there are four fewer degrees of freedom than the number $K_n$ of satellites observed by that vehicle because of the constraints imposed by estimating the vehicle’s four states (three-element position vector $x_n$ and scalar time offset $b_n$).

For a chi-square distribution of $m_{CERIM}$, the threshold which meets the continuity risk requirement is

$$T = P_{\chi^2}^{-1}(c_r, K_{CERIM}),$$  \hspace{1cm} (15)

where the inverse of the Cumulative Distribution Function (CDF) for the chi-square distribution is $P_{\chi^2}^{-1}$.
VI. ALGORITHM PERFORMANCE

To study the sensitivity of the proposed algorithm, it is useful to compute its probability of missed detection. The probability of missed detection refers to an event in which an alert is not issued even though a fault is present. To aid in computing the probability of a missed detection, it is useful to plug (1) into (4), (6) and (12) to show that the monitor statistic in the presence of a fault is

\[ m_{CERIM} = \tilde{m}_{CERIM} + \varepsilon_{f} \sum_{n=1}^{N} \gamma_{n}. \tag{16} \]

The first term on the right hand size of (16), \( \tilde{m}_{CERIM} \), is the random, chi-square-distributed term seen also in the absence of a fault. The second term accounts for the systematic bias \( \varepsilon_{f} \) on the faulted satellite, which is assumed to be the same for all users. The scaling coefficient \( \gamma_{n} \) reflects the impact of that systematic bias on each user, given that each user may see different satellites. More specifically, \( \gamma_{n} \) is the \( f \)th diagonal element of the bracketed matrix below.

\[ \gamma_{n} = [I - G_{n}^{T} G_{n}^{n+}]_{f,f}. \tag{17} \]

As defined previously, \( f \) is the index of the faulted satellite.

In the faulted scenario, the monitor statistic distribution becomes noncentral chi-square, where the noncentrality parameter \( \lambda \) is

\[ \lambda = \varepsilon_{f}^{2} \sum_{n=1}^{N} \gamma_{n}. \tag{18} \]

The probability \( P_{md} \) of a missed detection event is the probability that the monitor fails to alert when a fault is present. Assuming a noncentral chi-square distribution,

\[ P_{md} = P_{ncx}(T; K_{CERIM}, \lambda). \tag{19} \]

Here the function \( P_{ncx} \) is the CDF of the noncentral chi-square distribution with \( K_{CERIM} \) degrees of freedom and a noncentrality parameter \( \lambda \). A smaller missed-detection probability corresponds to a more sensitive monitor.

To estimate how monitor missed-detection probability varies with the number \( N \) of collaborating vehicles, it is useful to note that the noncentral chi-square distribution can be approximated as a Gaussian distribution [14]. In the limit of \( \lambda \gg K_{CERIM}, \lambda \gg 1 \), and \( T = \xi K_{CERIM} \) (where \( \xi \) is a scalar constant), this Gaussian can be expressed in terms of the \( Q \) function, which is the unit-variance Gaussian CDF.

\[ P_{md} \approx Q(\sqrt{\xi K_{CERIM}} - \sqrt{\lambda}) \tag{20} \]

For the simplest case in which all vehicles see all satellites, (14) and (18) imply that \( K_{CERIM} \) and \( \lambda \) are proportional to \( N \), such that the argument of (20) scales as the square root of \( N \).

\[ P_{md} \approx Q(\sqrt{N} Q^{-1}(p_{md, base})) \tag{21} \]

According to this approximation, as long as \( \lambda \) is above the detection threshold \( T \) and all collaborators see the same set of satellites, the missed-detection probability improves monotonically with the number of collaborators \( N \). Thus, if a sufficiently large number of collaborators work together, any error above the threshold can in principle be detected, regardless of the magnitude of the noise on each receiver.

VII. SIMULATION

In this section a simulation is used to assess the performance of the proposed CERIM algorithm. The simulations consider a set of ten collaborating vehicles. The vehicles are assumed each to be equipped with a GPS receiver and a wireless communication system that makes all GPS measurements available to all vehicles.

The sensitivity of CERIM depends in part on the satellites visible above the horizon. To demonstrate proof of concept, a historical satellite constellation (with eight satellites above the horizon) is employed in the simulation. The azimuth and the elevation of each satellite is shown in the skyplot of Fig. 1. In a first scenario, it is assumed that all vehicles see all satellites. In a second scenario, it is assumed that certain satellites are not visible to certain vehicles. Specifically, it is assumed that satellites PRN17 and PRN25 are not visible to vehicles 1, 3 and 5, and that PRN19 is not visible to vehicles 5, 6 and 8. These are all low-elevation satellites, likely to be blocked by buildings or terrain.

For each of the two scenarios, missed-detection probabilities were computed for each satellite using (19), assuming a CERIM threshold \( T \) computed using (15) with a continuity risk \( c_{r} \) of \( 10^{-5} \). The coefficients \( \gamma_{n} \) were computed from the geometry matrices \( G_{n} \) for each vehicle \( n \), constructed from the pointing vectors to the satellites visible by that vehicle. All ranging measurements were assumed

Fig. 1. Satellite Positions: Elevation and Azimuth Angles.
Gaussian distributed with standard deviation $\sigma$. The projection $E_h$ of the fault-induced error into the horizontal plane was held constant (at a level of $E_h = 3\sigma$) and evaluated on each individual satellite. For both scenarios, $P_{md}$ values were computed for an increasing numbers of vehicles $N$, with $N$ varying between 1 and 10. It was assumed that new vehicles were added in order from Vehicle 1 counting upwards toward vehicle 10. (Order matters only in the second scenario, when certain satellites were not visible to certain vehicles.) Results of $P_{md}$ against $N$ are illustrated in Fig. 2, for the case of all satellites visible, and in Fig. 3, for the case in which not all vehicles saw all satellites.

Because of the constellation geometry, faults are harder to detect for some satellite than others. In both scenarios, faults on PRN31 are hardest to detect (largest probability of missed detection). For a team of ten vehicles, $P_{md}$ for PRN31 falls below $10^{-6}$ in the first scenario and to nearly $10^{-4}$ in the second. In the second scenario, the change in $P_{md}$ is not monotonic when each new vehicle is added, since each vehicle sees different satellites.

Characterizing the variability in $P_{md}$ with varying satellite visibility is a topic for future work. Verifying the CERIM concept experimentally, characterizing latency effects, and mitigating spoofed signals (e.g., “malicious collaborators”) are additional relevant topics for future research.

VIII. SUMMARY

A new concept for integrity monitoring was presented called Collaboration-Enhanced Receiver Integrity Monitoring (CERIM). The technique has potential benefits for intelligent transportations systems in which satellite navigation measurements are critical for system safety or reliability. CERIM functions by pooling satellite ranging measurements from a number of collaborating vehicles via a wireless network. From these data, a monitoring statistic is computed and compared to a detection threshold. The CERIM concept has the potential for high sensitivity and GBAS quality time-to-alert, without requiring stationary reference stations or other fixed infrastructure.

REFERENCES