EXPERIENCES WITH RAIM, ALTITUDE AIDED RAIM, AND FDI: RISKS AND BENEFITS

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ABSTRACT

In continuing work by NAVSYS Corporation & the United States Coast Guard R&D Center, a proven GPS receiver autonomous integrity monitoring (RAIM) algorithm is being augmented with fault detection and isolation (FDI) and altitude aiding features to establish whether or not these features provide an operational advantage. In this context, RAIM refers to a monitoring function which provides a measure of the position accuracy achieved by a GPS receiver; RAIM is performed after the position is computed. In contrast, FDI refers to a function which actively excludes satellite measurements from the position computation if they are suspected of being faulty; FDI is performed before the position solution is computed. The work discussed here concerns RAIM and FDI functions performed autonomously at the user's site, which may be non-stationary.

Initial results show that FDI can, by wrongly identifying faulty satellites, degrade both the accuracy and integrity of the solution. This result has strong theoretical justification which will be presented in the paper along with an example. It is often assumed that FDI is a logical extension to RAIM, but the results of our work indicate that this assumption may be invalid.

1 INTRODUCTION

GPS has already proved itself an extremely reliable and capable navigating system. Like any system,, however, GPS can produce an erroneous navigation solution due to satellite errors [16], incorrect differential corrections [4,9] or local multipath effects. There are many applications where a definitive indication of the correctness of the GPS navigation solution is required before GPS can be trusted for sole-means use. Among such applications are positioning aids-to-navigation, aircraft landing, and mine countermeasures.

This paper discusses the application of the technique of receiver autonomous integrity monitoring (RAIM) to provide a measure of the position accuracy achieved by a remote GPS receiver. It goes on to explore the technique of fault detection and isolation (FDI) as a means of making GPS errors transparent to the user, and explains some of the risks of doing so.

Simple RAIM techniques rely on measurement of the magnitude of the receiver pseudo-range residuals. Such techniques have the drawback that, since they do not make any adjustments based on the geometry of the satellites, they cannot give a direct indication of the magnitude of any navigation error. Thus, their monitoring of integrity is largely qualitative.

NAVSYS has developed a RAIM software package, NAVSAFE, to overcome the shortcomings of a simple magnitude-of-residuals RAIM implementation. The software runs on an IBM-compatible PC receiving industry standard NMEA outputs from the GPS navigation receiver. A design goal for NAVSAFE was to create a clear-cut, informative interface requiring no interpretation by the user. In line with this goal, a "traffic light" format was chosen, where green means the integrity requirements are met, red means they are not met (i.e. receiver position output is in error) and yellow means that there is insufficient data to make either assurance. Such an approach has the benefit of allowing relatively untrained personnel to use and have confidence in the GPS navigation solution.

In any well designed GPS navigation system using differential GPS (DGPS), the signal errors that are common to both the reference station and the remote receiver are eliminated by the differential processing. The most insidious GPS errors are those which are purely local to the receiver (typically, multipath errors), and these can only be trapped using RAIM techniques. Fortunately these errors are usually fairly short-lived. Many applications can cope with a short-lived RAIM alarm, the response to such a alarm being either to suspend operations (as in buoy laying) or to switch to an alternate means of navigation until the alarm clears. However there are applications (aircraft landing, etc) where these are not viable options. In such cases, the receiver must have the capability not just to recognize the error, but to independently identify the erroneous satellite measurement and isolate it from the navigation solution. This is the principle of FDI.

The benefit of FDI is that by transparently isolating the fault, the user is not even aware of the error condition. The drawback is the risk that FDI can misidentify the biased measurement, thus leading to the exclusion of a good measurement. This leads to an improvement in precision and availability, but a degradation of both accuracy and integrity.

2 FUNDAMENTALS OF INTEGRITY MONITORING

2.1 RESIDUALS AND GEOMETRY

As the name implies, RAIM is a type of integrity monitoring that is receiver autonomous. It is performed autonomously at the user's receiver, in contrast to other forms of integrity monitoring such as differential monitoring which uses monitoring stations in the vicinity of the user. This distinction gives RAIM the great advantage of being the only form of integrity monitoring that "sees" all the errors that occur at the user's receiver.

The RAIM method uses redundant range measurements to provide range residuals. As an introduction to this concept, we describe a basic RAIM technique which makes use of pseudo-range residuals. A pseudo-range residual is defined as the difference between the estimated range to a satellite and the measured pseudo-range. This is illustrated in , where the arcs represent the measured pseudo-ranges and X marks the navigation solution.

From , one can see that precise navigation solutions will correspond to small residuals, while imprecise navigation solutions will correspond to large residuals. This observation leads to a RAIM technique which is based on the magnitude of the sum of squares of residuals. Let *z* denote the vector of pseudo-range residuals. Then a detection function *DF* is defined as
If *DF* is small, then the navigation solution is deemed to be precise; if *DF* is large, the navigation solution is considered imprecise. This simple RAIM function is useful, but it has obvious limitations in using qualitative evaluations such as "small" or "large" *DF*, and "good" or "bad" navigation precision [6]. Furthermore, it does not take satellite geometry into account. This is a major failing, because "small" residuals and "bad" geometry ("large" DOPs) can correspond to big, bad navigation errors.

As an example of how this can happen, consider the case shown in . The ideas presented in this 2-D illustration relate directly to the actual 4-D case. The top diagram in shows unbiased pseudo-ranges intersecting very close together, as expected for good measurements. However, if satellite 3 experiences a large bias and satellites 1 and 2 simply have noisy measurements, then the situation can change as shown in the lower diagram. In both situations, the residuals are small, but in the second case the bias produces a very large navigation error. This is the result of bad "integrity geometry."

Integrity geometry is the worst navigation geometry (or DOPs) that would occur by excluding any one satellite from the picture. Referring to , it is obvious that by removing satellite 3, the geometry would indeed be bad, since the pseudo-ranges of the remaining satellites intersect at extremely acute angles. Note that with satellite 3 in place, the navigation geometry is good. This is why a distinction must be made between navigation geometry and integrity geometry.

Integrity geometry was first discussed in [14]. In developing a RAIM package for the US Coast Guard R&D Center, NAVSYS Corporation realized the significance of integrity geometry and developed the NAVSAFE software package to perform RAIM that takes integrity geometry into account.

In some circumstances (is an example), integrity geometry will not be good enough to perform reliable RAIM. In these cases, NAVSAFE provides a yellow warning alarm. The software alarm states distinguish definite navigation errors (red alarms) from bad integrity geometry (yellow) from accurate navigation (green).

Bad integrity geometry means that it is very difficult to detect possible biases on measurements originating from some satellites. Simply ignoring these satellites doesn't help either, because this reduces the redundancy by one and, as is clear from , the geometry only gets worse by removing a satellite. Luckily, there is a technique for dealing with these problems. This is to consider all satellites, but if integrity geometry gets bad enough, raise a warning alarm.

2.2 ALTITUDE AIDING

All RAIM techniques require an over-determined GPS navigation solution in order to work. A 3-D GPS navigation solution requires 4 satellites in view. RAIM requires a minimum of 1 further visible satellite, and benefits greatly (fewer false alarms) from additional observables. NAVSAFE will show a green go-ahead status only if the integrity conditions can be met. With inadequate information for a definitive statement of integrity, NAVSAFE will set the yellow caution flag.

When satellite visibility is poor the degree of redundancy decreases and RAIM performance degrades. The less expensive GPS receivers have fewer channels available to track the satellites, and again RAIM performance can be degraded. If carefully applied, altitude aiding can be a useful way of adding a further observable to the RAIM algorithm.

A beta-test version of NAVSAFE has been developed for shipboard applications. Here a tide model entered by the user is continuously checked against the GPS altitude solution, using the RAIM algorithm to measure accuracy. Through this process of calibrating the altitude during periods of good visibility, the effect of operator error in entering the tide model can be mitigated. Then when satellite geometry deteriorates, the software accesses the tide model for altitude aiding, thereby providing a reliable extra observable for use by the RAIM algorithm and increasing the level of redundancy by one.

2.3 FAULT DETECTION

Apart from simply flagging navigation errors, it is desirable to detect which satellite is responsible for the errors. The standard technique for doing this is based on the premise that only one satellite is biased. This assumption is motivated by experience with DGPS which shows that bias errors occur very rarely, and so the possibility of two biases occurring simultaneously is extremely small. Having made the assumption that a single satellite is biased, it is a straightforward matter to derive a maximum likelihood method of identifying the biased satellite.

Each satellite measurement has associated with it a vector in space pointing from the user to the satellite. If one satellite is biased, then the residuals will be biased in the direction of the vector pointing to that satellite. This concept is discussed in detail in [11] and [12], where the algebraic equations are derived to detect the biased measurement. This technique uses the so-called "parity vector" and is well known. However, a problem that is often ignored is the rare event of two simultaneous biases. In that case, it is quite possible for the standard detection method to choose the wrong satellite, as in the example shown in and discussed below.
The NAVSAFE RAIM algorithm was developed to overcome this problem by detecting not only the maximum likelihood bias, but also the second most likely bias, the third most likely, and so on. Furthermore, the algorithm also assigns relative probabilities to each of the possible biases and then considers not only the most likely bias, but any bias with probability greater than a user-selected maximum probability of missed detection (PMD_{max}). In this way, when the situation occurs that the most likely bias is not the true bias, the true bias will nonetheless be in the set of possible biases considered by NAVSAFE, and so the correct alarms will be set.

3 EXAMPLES: HOW FDI FAILS WHILE RAIM SUCCEEDS

As in Section 2.1, these 2-D examples extend directly to the 4-D case. In the 2-D scenario illustrated in , satellites 1 and 3 give correct ranges while satellites 2 and 4 are biased by equal amounts. The true position is shown by the circle, the navigation solution by the X. Any FDI algorithm that assumes a bias on a single satellite will falsely detect satellite 3 as the biased satellite, since it has the largest residual and the navigation solution is biased in the direction of satellite 3. If FDI is applied and satellite 3 is isolated (removed) from the solution, then the ranges of satellites 1, 2, and 4 will still intersect at the point marked by the *, and that point will become the new navigation solution. The application of FDI would thus result in a solution that has zero residuals, and high *precision*, but the accuracy would be worse than the solution where no FDI is performed.

It may seem that the only problem is the assumption that only one satellite is biased, but this is not so. Suppose we make the (less likely) assumption that two satellites are biased. Now consider the scenario shown in . This is almost identical with , but here satellite 3 is biased and satellites 2 and 4 are not. The true position, indicated by the circle, is now where the ranges of satellites 1, 2, and 4 intersect. An FDI solution that assumes two biases would eliminate satellites 2 and 4 and produce the a new navigation solution at the *. Again, this would give greater precision but worse accuracy.

The problem is that whatever assumption we base FDI upon, the violation of that assumption can lead to elimination of good measurements. The only satisfactory resolution to the problems raised here is to choose the assumption which has the greatest possibility of occurring, which is the assumption of a single biased satellite at any one time. Then an integrity monitoring scheme must be used that provides a measure of the achieved accuracy without the risk of eliminating a good satellite, even if the assumption is violated. The NAVSAFE RAIM algorithm, by selecting a set of possible biases, will detect the inaccurate solution caused by two simultaneous biases. Even though the algorithm will not be able to isolate the biased satellites, it will generate the correct alarm to alert the user to the problem. The best navigation solution is then obtained by using an alternative navigation aid until the biases disappear and the alarm state changes to green.

4 EXAMPLES FROM FIELD DATA

4.1 NAVSAFE USER DISPLAY

NAVSAFE has now been under trial by the US Coast Guard for some time, with very positive feedback from the users. This section shows some examples, with real screen displays, to indicate how the software works. Various levels of screen complexity are selectable, the most simple being the Watchkeeper display, where only current time, position, track, and integrity alarm are displayed. The following examples use the more detailed Integrity screen to demonstrate more fully the workings of the software.

The NAVSAFE window provides an intuitive display for the navigator, with a simple red/yellow/green traffic light showing alarm state. shows a typical screen for normal operation. The differential navigation setup was updating the receiver data at 1500 bps rate, providing very frequent differential corrections.

For this example the software was configured to alarm if the integrity requirements are not sufficient to guarantee with 95% probability that the true position is within 2 metres of the position solution given by the GPS receiver. The outer circle on the screen represents the alarm threshold setting of 2 m radial position error. The inner circle represents the radial position error at 95% probability (RPE_pmd) (calculated by the software to be 1.1 m) centred on the current GPS position output by the receiver. The ellipse shows the 95% confidence distribution of the actual position. The vector, known as the "bias vector," points to the unbiased position if the selected bias is in fact the true bias. The square integrity window is centred at the user-entered waypoint (for the purposes of this example the known static position of the receiver antenna was entered as the waypoint). The dots represent the most recent navigation positions output by the receiver. Note that all the integrity and accuracy values, such as 95% accuracy, can be set by the user to suit the application.

The first text line below the integrity window lists which satellites are in view (8 total), and marks satellite 15 as the (possible) biased satellite. The alarm display shows a green alarm state (integrity requirements are met). This alarm is correct, as the small bias results in an error less than 2 m. Such a display indicates all is well, and the GPS position can be relied upon.

4.2 DELIBERATELY INDUCED BIAS

The previous example showed normal operation with no significant bias detected. This will of course represent the situation most of the time. To provide controlled test circumstances with erroneous pseudo-ranges, a hardware module was used that intercepted the RTCM-104 differential corrections from the communications link and, under operator control, corrupted the corrections to one pseudo-range with a ramping bias before passing the corrections to the remote receiver. This setup is equivalent to the receiver directly observing an incorrect pseudo-range. This experiment was carried out with a differential bit rate of 100 bps.

shows the track of the test vehicle (following a repetitive route) before the bias was applied. Here the software is indicating an RPE_pmd of 3.2 m. The value of this figure under a no-bias condition is predominantly a function of the latency of the differential corrections. The software is set to alarm at a 10 m error level, so the display indicates all is well with a green flag.

shows the same setup, but with a ramped bias applied to satellite 3 . As can be seen from the traces of the previous pass, the dots in this figure showing the current position are in error. However, NAVSAFE correctly flags this error, computing a RPE_pmd of 10.1 m (which exceeds the user-specific alarm threshold), and setting the red alarm flag.

Since the software has also calculated that the worst case integrity error would occur if the bias was on satellite 11, in this case the "corrected" position vector points away from the true position, actually compounding the receiver error. (The "corrected" position vector is indicated by the end of the bias vector, at the center of the small ellipse.)

is from a few seconds later, with the bias even larger. This time the software correctly identifies the worst case integrity bias as satellite 3 (the corrupted signal) and the bias vector points to the correct true position. In fact, there is an exact mathematical equivalence between the bias vector and the FDI solution obtained if the correct satellite is isolated [13].

Since the radial position error of the GPS receiver output (without correction) is greater than the threshold, the integrity alarm conditions have not been met, and the red alarm is set.

These two last figures show the danger of relying on FDI alone. With the information available, integrity was maintained (error flags in both cases). If the software had simply isolated the possible biased satellite using the best information available, in the first case () the wrong satellite would have been disallowed, and the output position would have been in error.

It is important to note that although NAVSAFE is providing a graphic indication of the corrected position, it is not performing FDI, since it does not ignore any satellites. NAVSAFE computes what the effect of a bias is, and then indicates that graphically and sets the appropriate alarm. As demonstrated by the examples in this paper, this RAIM technique is considered to be the best way of guaranteeing integrity.

5 CONCLUSIONS

The conditions for autonomous correction of erroneous satellite ranges (FDI) and those of guaranteeing the integrity of a GPS navigation solution (RAIM) are not the same. RAIM is already achievable with quantifiable levels of integrity and accuracy, and will provide true performance measures for applications that can either suspend operations or fall-back to alternate navigation sensors during periods of receiver error. Isolating satellites while maintaining integrity is not achievable with the current unaugmented GPS constellation.

In summary, RAIM without FDI is the straight and narrow road which a navigator must travel to *guarantee* integrity of the solution. Sometimes the navigator will have to accept that the GPS solution is incorrect, but this is far better than using FDI and hiding the problem to give a solution that is apparently precise but is in fact worse that the original biased solution.

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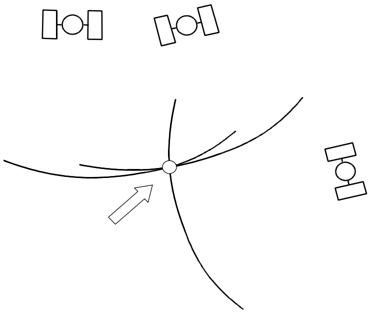

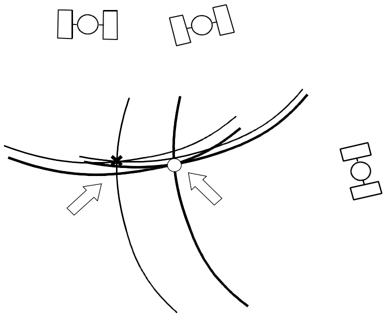

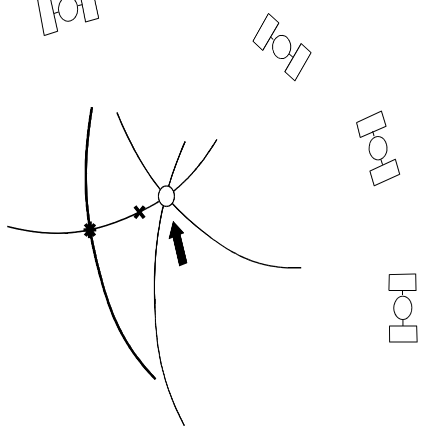

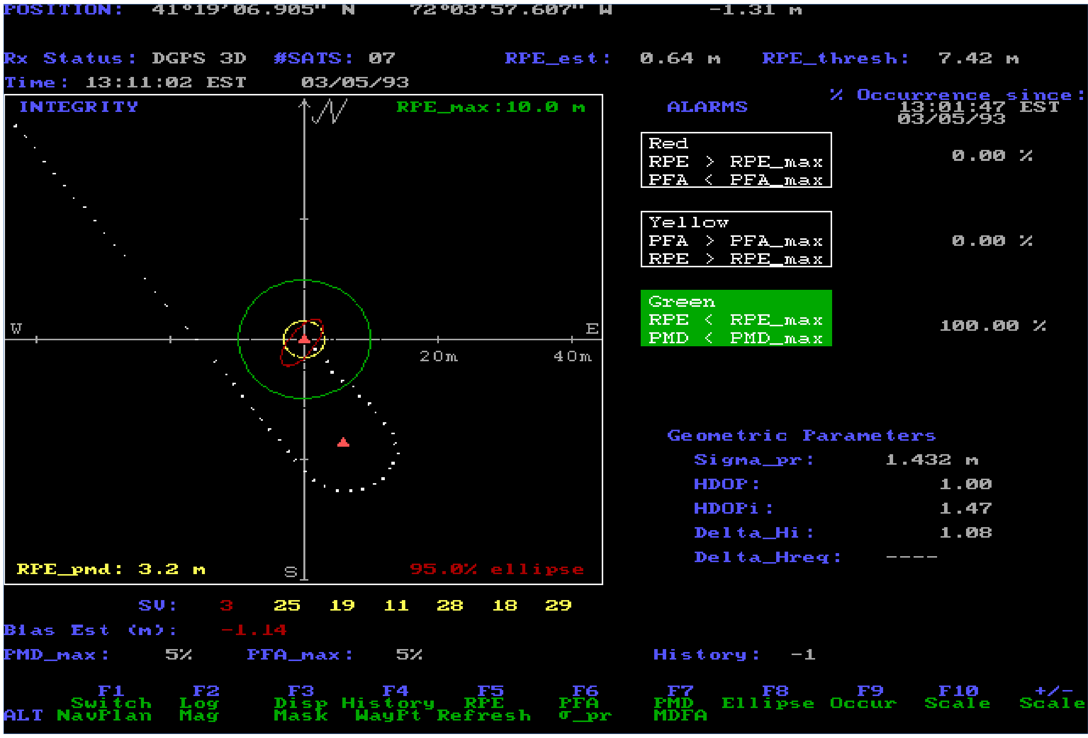

```
POSITION:  41°19'06.905" N    72°03'57.607" W        -1.31 m

Rx Status: DGPS 3D  #SATS: 07        RPE_est:  0.64 m   RPE_thresh:  7.42 m
Time: 13:11:02 EST    03/05/93
INTEGRITY                         RPE_max:10.0 m    ALARMS     % Occurrence since:
                                                                13:01:47 EST
                                                                03/05/93
                                                    Red
                                                    RPE > RPE_max      0.00 %
                                                    PFA < PFA_max

                                                    Yellow
                                                    PFA > PFA_max      0.00 %
                                                    RPE > RPE_max

                                                    Green
                                                    RPE < RPE_max    100.00 %
                                                    PMD < PMD_max

                                                     Geometric Parameters
                                                       Sigma_pr:      1.432 m
                                                       HDOP:           1.00
                                                       HDOPi:          1.47
                                                       Delta_Hi:       1.08
                                                       Delta_Hreq:    ----
RPE_pmd: 3.2 m                    95.0% ellipse
          SV:   3   25  19  11  28  18  29
Bias Est (m):   -1.14
PMD_max:    5%    PFA_max:    5%                    History:  -1
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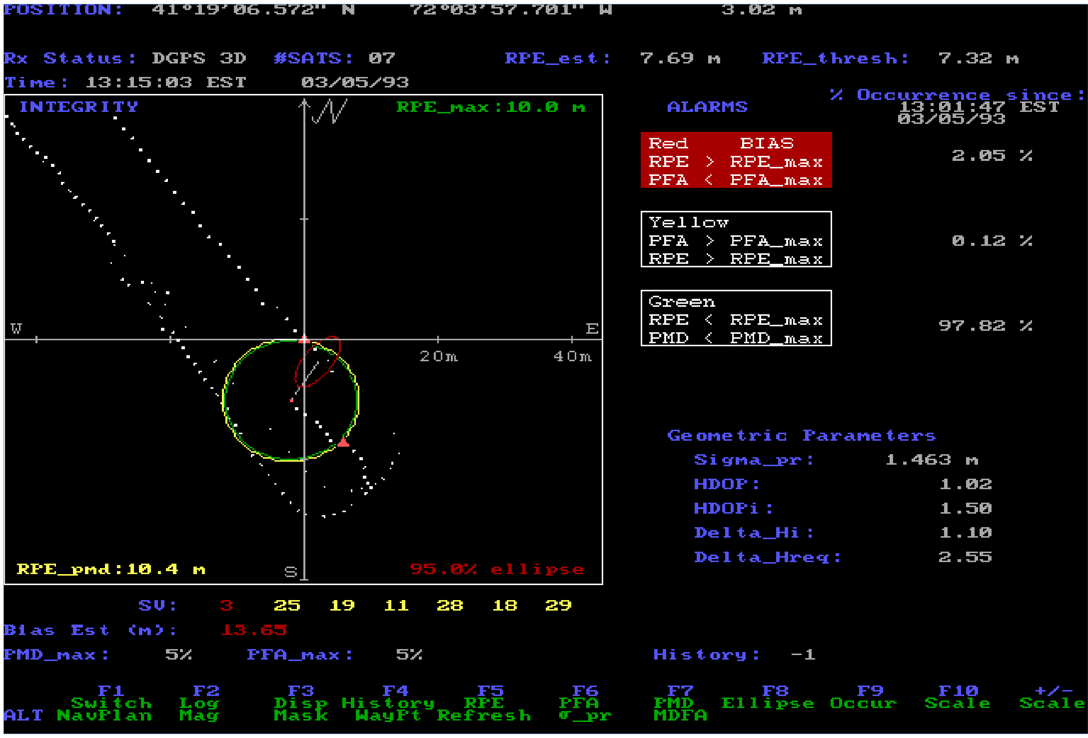

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POSITION:   41°19'06.572" N     72°03'57.701" W         3.02 m

Rx Status: DGPS 3D  #SATS: 07         RPE_est:  7.69 m   RPE_thresh:  7.32 m
Time: 13:15:03 EST     03/05/93
 INTEGRITY                    RPE_max:10.0 m      ALARMS         % Occurrence since:
                                                                    13:01:47 EST
                                                                    03/05/93
                                                 Red     BIAS
                                                 RPE  >  RPE_max        2.05 %
                                                 PFA  <  PFA_max

                                                 Yellow
                                                 PFA  >  PFA_max        0.12 %
                                                 RPE  >  RPE_max

                                                 Green
                                                 RPE  <  RPE_max       97.82 %
                                                 PMD  <  PMD_max


                                                  Geometric Parameters
                                                    Sigma_pr:     1.463 m
                                                    HDOP:             1.02
                                                    HDOPi:            1.50
                                                    Delta_Hi:         1.10
                                                    Delta_Hreq:       2.55
 RPE_pmd:10.4 m               95.0% ellipse

          SV:   3    25   19   11   28   18   29
Bias Est (m):   13.65
PMD_max:    5%     PFA_max:    5%                History:  -1

       F1      F2      F3     F4      F5      F6      F7     F8      F9      F10     +/-
     Switch   Log     Disp  History  RPE     PFA     PMD   Ellipse  Occur   Scale   Scale
ALT NavPlan   Mag     Mask  WayPt  Refresh   σ_pr    MDFA
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