Distributed integrity monitoring of differential GPS corrections

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Abstract

This Master thesis is done for a degree in Mechanical engineering at University of Linköping 1998. The thesis concerns integrity monitoring of Differential Global Positioning System (DGPS) corrections and is done for Luftfartsverket (The Swedish civil aviation administration).

Luftfartsverket is working to develop a system for satellite based navigation for civil aviation where the aircraft itself broadcasts its position to surrounding aircraft via a radio communication link. Global Positioning System (GPS) is used to derive the position for the aircraft, and differential corrections are used to improve accuracy and integrity.

In this thesis an integrity concept for differential GPS corrections using distributed redundancy is developed and implemented. Distributed redundancy implies that corrections from base stations spread out in a regional area are used to achieve redundancy. To do this the corrections has to be normalised.

An integrity concept to find possible errors and a method to normalise corrections from different base stations is developed. The concept has been implemented in a real time program that collects GPS corrections, normalise and compare the corrections and present results in graphs and statistics. The program has found many problems in the existing system, most of them depends on differences in user equipment.

The result is showing that base stations with 600 km separation is showing the same correction characteristic and after normalisation similar magnitude, which means that a distributed integrity concept is providing good integrity monitoring with a low cost.
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1 Introduction

Luftfartsverket (The Swedish civil aviation administration) is running a project to develop a concept for future air traffic control. The CNS Applications - Research & Development (CARD) project is working to develop and standardise a Communication, Navigation and Surveillance (CNS) concept [1]. The aim of this development is to get safer and more efficient air traffic control for the future.

The concept is that aircraft are using a satellite navigation system to determine its position, and the aircraft itself broadcasts the position to surrounding traffic via a radio communication link. The radio communication link is also used to broadcast data to improve the navigation accuracy and integrity (that you can trust what the system is telling you).

The thesis contains a study of concepts to improve accuracy and integrity for the civil aviation, background information of acronyms and concepts that are involved in the CARD project. Possible errors that may occur for the differential corrections and analysis of how it is possible to find each of these errors. A program is specified and implemented will find the errors that occur. The program is used to test the navigation system to get information of how the system works.

1.1 Background

Luftfartsverket is working with a technology that was introduced by Håkan Lans who invented a radio communication data link that would suit air traffic CNS applications very well. Luftfartsverket started the CARD project to develop and standardise this technology in 1991.

Below are some explanations for the concepts and acronyms involved in the CARD project, which will be useful for the rest of this report.

1.1.1 Global Navigation Satellite System (GNSS)

The concept of GNSS is to provide the aircraft with safe and accurate navigation by using satellite systems. The following systems have to be used to achieve high accuracy and integrity [2].

- GPS
- GLONASS
- Augmentation systems, to enhance the accuracy and integrity of above

Basically GNSS means accurate and safe navigation using satellite based navigation systems.
1.1.2 Global positioning system (GPS)

GPS is a satellite based navigation system developed by US DoD (United States Department of Defence).

GPS is specified to have 24 satellites that orbit earth sending their positions and a code sequence to identify them to the user receiver. The GPS receiver estimates the distance to each satellite, and by knowing the position and distance to three satellites it is possible to determine receiver position in three dimensions. The receiver needs one extra satellite to synchronise the receiver clock with the satellite clocks (needed to get the distance to each satellite).

The GPS receiver determines its position with four satellites, three to determine position in space and one to determine the time (more information in [2] and [3]).

The major error sources for the GPS system and their typical values are [4]:

- Satellite clock error 20 m
- Satellite ephemeris (position) error 10 m
- Selective availability (SA) 30 m
- Tropospheric delay 1 m
- Ionospheric delay 10 m
- Multipath (signal reflectance) 0.5 m
- Receiver noise 0.5 m

These are typical error values, but the specified position accuracy is 100 meters in horizontal plane and 156 m in vertical plane, both with a 95% confidence interval [5].

Selective availability (SA) is a clock error added for civil usage. Military receivers use an extra coded frequency from the satellites. Since the two frequencies deflect differently, the SA error and most of the ionospheric error can be removed giving a horizontal accuracy of 22 meters and vertical accuracy of 22.7 meters, with 95% confidence interval [5].

1.1.3 Global orbiting navigation satellite system (GLONASS)

GLONASS is Russia’s equivalent system to the USA’s GPS and works in a similar way. GLONASS is not fully operational and therefore not used in the CARD project at the moment.
1.1.4 Differential GPS (DGPS)

Differential GPS aims to improve the integrity and accuracy for the position given by GPS. The idea is to place a GPS receiver at a known position and hence by measuring the distance to each satellite at a known position, it is possible to calculate the error for each satellite. This error is similar for the surrounding area around the reference station with the accuracy decreasing at about 2-mm/km [6].

It is possible to broadcast this error via a radio communication link to users in surrounding area, which can use this error to determine a more accurate position.

![Figure 1.1: Differential GPS](image)

This method will eliminate most of the error sources for the position except multipath (reflectance of the radio signals around the antenna) and receiver noise. This improves the position accuracy to 1-metre [6].

1.1.5 Very high frequency data link mode 4 (VDL Mode 4)

VDL Mode 4 [7] is a Self-organising Time Division Multiple Access (STDMA) data link invented by Håkan Lans, and is the fundamental technique used in the CARD project.

The data link divides the time into time slots, and sends data messages in these slots. The accurate GPS time is used to synchronise the data link. Self organised means that a communicator by itself can find a free slot to broadcast its message. This means that different types of data can be sent on the data link, using just one frequency. Possible messages are position reports, differential corrections, text messages, flight plans and so on. All communicators in radio distance will hear the message. The data link is currently being standardised by the International Civil Aviation Organisation (ICAO) to be world standard for civil aviation.

1.1.6 Communication navigation surveillance (CNS)

CNS is an integrated concept for communication, navigation and surveillance using GNSS and data links. International Civil Aviation Organisation (ICAO) has decided that the future Air Traffic Management (ATM) systems are going to be based on CNS.
1.1.7 Automatic dependent surveillance broadcast (ADS-B)

An aircraft can get its position using GNSS and broadcast it automatically via the data link. The surveillance part of CNS can receive the aircraft position from this data link without requiring radar or other ground equipment.

1.1.8 Base station

A base station is the equipment on the ground that calculates and broadcasts differential corrections to the aircraft, and receives position reports from surrounding traffic. It consists of a GPS receiver with known position to calculate differential corrections (called reference receiver) and a GNSS transponder that manages the communication at the data link. The aircraft has the same equipment, except that a GPS receiver replaces the reference receiver. The base station is connected to a ground computer network to send the data it receives from the air to the ground network.

1.1.9 North European ADS-B network (NEAN)

NEAN is a working test bed to use the VDL MODE 4 data link for CNS (Communication Navigation Surveillance). It is built up by 16 base stations in Sweden, Denmark and Germany, 20 transponders in aircraft and 30 transponders in airport related cars. The base stations collects ADS-B messages, position reports and text messages from surrounding aircraft and cars via VDL MODE 4 data link. The base stations alternate between listening to messages from mobiles and sending differential corrections in different time slots to the VDL MODE 4 data link.

![Figure 1.2: CNS application using VDL Mode 4](image)

This means that the mobiles (aircraft and cars) get information about surrounding mobiles position and differential corrections to improve the position with GPS. This method will give a safer system, because aircraft can get information about surrounding traffic and more people share the information, not just to the air traffic controller like it is done today.

By connecting the base stations in a network on the ground, it is possible to collect all information in a ground network, which is done in NEAN.
The circles in the picture show the coverage area surrounding each base station. By placing base stations close enough, it is possible to cover a larger region and receive position reports and broadcast differential corrections for the whole region. The figure below shows the coverage of the current NEAN network.

The NEAN project is sponsored by the European Community (EC) and some of the participants in NEAN are Luftfartsverket, Deutche Flugsicherung (Germany civil aviation administration), Scandinavian airline systems (SAS), Lufthansa, Maersk helicopters, Statens luftvaesen (Danish civil aviation administration).

1.2 Requirements for GPS navigation for civil aviation

The civil aviation has some special requirements that have to be fulfilled to ensure safety [2]. Specific values for these requirements are listed in [8].

1.2.1 Availability

Is it possible to use the system? Does the signal exist, and is it possible to determine position from the existing satellite configuration?
1.2.2 Accuracy
The GPS gives the position with an accuracy of 100 meters in horizontal plane and 156 m in vertical plane, both with 95% confidence interval. This is not enough for navigation, especially for takeoff and landing. Therefore an improvement in accuracy is needed. The following chapter shows different techniques on how this can be achieved by using differential corrections.

1.2.3 Integrity
Integrity is about trusting what the system is providing. The system should be able to provide a timely warning when the system must not be used for navigation. Integrity is the most important requirement because it has a direct impact on safety. The definition of integrity from ICAO GNSS panel [9].

"Integrity is that quality which relates to the trust which can be placed in the correctness of information supplied by the total system. Integrity includes the ability of system to provide timely and valid warnings to the user when the system must not be used for the intended operation.

The integrity risk is the probability of an undetected failure which will result in the loss of the specified accuracy.”

1.2.4 Continuity
Continuity is the time when availability, accuracy and integrity requirements are fulfilled.

1.3 Aims and objectives
The aim with this project is to develop and specify an integrity and quality concept for the differential corrections in the NEAN network.

The specified concept is going to be implemented in a computer program that works in real time to collect differential corrections from different base stations in a regional area. The program has to report errors, present statistics and provide information about the system to satisfy accuracy and integrity.

The specific objectives are

• Study other concepts to improve accuracy and integrity for civil aviation
• Study how the NEAN systems base stations are built up
• Study what information the differential corrections in NEAN contains
• Find possible error sources for base stations and differential corrections in NEAN
• Develop a concept for how to find each error that might occur
• Specify a program to find errors in current NEAN network
• Test the differential corrections in NEAN to find possible errors
• Propose changes in NEAN to improve integrity monitoring

There are some other techniques for differential corrections, integrity monitoring and distributing the information to the users. It is interesting to investigate their integrity concepts and how they fulfil integrity requirements [2].

2.1 Receiver autonomous integrity monitoring (RAIM)

RAIM is an integrity concept built in the GPS receiver that does not need any additional equipment outside the aircraft. The receiver needs four GPS satellites to determine its position. If the receiver tracks five satellites it can check the position by using five different satellite constellations, and it is then possible to determine if one satellite is out of order. If the receiver has six satellites it can tell which satellite that is out of order. The drawback with this integrity method is that it will lower the availability, because at least one extra satellite is needed.

2.2 Aircraft autonomous integrity monitoring (AAIM)

AAIM is using several different navigation systems to achieve integrity requirements. This is usually done by combining GPS with an aircraft based navigation system, e.g. an inertial navigation system [10].

2.3 Satellite based augmentation system (SBAS)

Satellite based augmentation system (SBAS) is a concept to send up geostationary satellites to increase the accuracy, availability and integrity needed to support aviation requirements. The projects to developing SBAS are the USA working with Wide Area Augmentation System (WAAS) and Europe with European Geostationary Navigation Overlay Service (EGNOS), to cover their respective continents.

2.1.1 Technical description

The American WAAS test bed consists of a network of 30 reference stations covering USA which are connected to one master station. The reference stations send their differential corrections to the master station, in this case at Stanford University. The master station is using state space filters to calculate the correction messages that are sent up to a geostationary satellite and from there distributed to the users.

![Figure 2.1: Space based augmentation system](image_url)
The master station divides the measured GPS errors into four different types of errors; satellite clock, satellite ephemeris (satellite position), Ionospheric delay and local errors (Troposphere delay, multipath, receiver noise and hardware bias).

Satellite clock and satellite ephemeris are errors due to each satellite and therefore it is possible to measure those and give them specific values. The Ionospheric delay is varying over the area, but the master station builds an error model over the ionosphere. The values for the clock, ephemeris and the ionosphere model are broadcast to the users via the geostationary satellite.

The corrections are broadcast at the same frequency as the GPS satellites, which means that the user receiver does not need any extra antenna. The geostationary satellite is also used as a ranging satellite for positioning, like an extra GPS satellite. So the geostationary satellite provides integrity data, differential corrections and works as an extra GPS satellite to improve availability.

### 2.1.2 Performance

The SBAS broadcast message improves signal accuracy from 100 meters to approximately 7 meters [11]. This would be enough for en-route and non-precision approach of flight operations, i.e. not takeoff and landing. SBAS also increases availability because the geostationary satellite is used for positioning. The broadcast message also contains integrity information about the entire GPS constellation.

### 2.1.3 Integrity concept

The integrity data includes use/do not use information of all satellites in view. It is the aircraft avionics that are responsible for achieving integrity, based on SBAS integrity message and satellite geometry.

It is suggested that the aircraft avionics uses the RAIM algorithm on the corrected data to determine integrity. It is also suggested that integrity is established with monitor stations that estimate position (with differential corrections) at a known position and therefore can alarm if the error becomes too large.

### 2.4 Ground based augmentation system (GBAS)

A ground based augmentation system consists of a locally placed reference station that broadcasts corrections to the surrounding area. GBAS is intended to complement the SBAS by providing precision approach flight operations, which means that GBAS will be able to support landing in the worst weather conditions.

To provide the best accuracy, the GBAS reference stations are placed at the airport and the GBAS signal allows the user to have highly accurate position information anywhere in the airport vicinity. This means that the accuracy is enough to have one reference station at each airport to serve all runways, instead of two Instrumental Landing Systems (ILS) per runway as is used today. This will decrease the installation and maintenance costs.

The American implementation of GBAS is called Local Area Augmentation System (LAAS) and work is still focused at research and development, but the earliest time to have a LAAS working is 2002.
2.2.1 Technical description

GBAS is a local augmentation system which means that a reference station stands at a known position and calculates differential corrections for a local area, which it broadcasts to the aircraft via a VHF data link. GBAS uses one correction per satellite that includes all the errors together.

![Ground Based Augmentation System (GBAS)](image)

**Figure 2.2: Ground Based Augmentation System (GBAS)**

GBAS consists of multiple reference receivers that make independent pseudorange measurements on GPS satellites that are compared and used to check integrity. At least two reference receivers are required so that their output can be smoothed, averaged and compared.

Since multipath is the biggest error difference between reference station and aircraft, and multipath at a reference station directly impacts the position accuracy for the aircraft, special multipath limiting antennas must be used.

It is also proposed that GBAS will contain pseudolite (short for pseudo satellite, ground based satellite) to provide higher availability and better satellite configuration, especially to determine altitude. However it seems that pseudolites will not be used in GBAS, because of high cost and bad performance.

2.2.2 Performance

GBAS has the capability to provide accuracy of the order of 1 meter [12]. The accuracy will decrease at around 2 mm/km. This means that it may be possible to use one base station for several close at hand airports.
2.2.3 Integrity concept

GBAS integrity monitoring is based on redundancy with multiple reference stations that are checked against each other. Below is a figure over a GBAS integrity function [6].

Integrity in GBAS can be divided into five sub functions [6]:

- **Signal quality monitoring**: Monitors GPS signal parameters, such as carrier to noise ratio and code carrier coherence.
- **Data quality monitor**: Checking if the reference receivers are receiving the same data, and perform bit error control.
- **Measurement quality monitoring**: Detects pseudorange correction jumps (steps in correction for a certain satellite), large range acceleration (derivative of the pseudorange) and abnormal correction magnitude. The detection is based on a threshold.
- **Multiple reference consistency check**: Compare corrections from several reference stations to detect inconsistencies, and compare the results to a certain threshold that is set to continuity requirements. Here it is possible to exclude any defective receiver and to detect multipath.
- **Sigma monitor**: To see the error characteristic it is interesting to see the nominal standard deviation of the measurement as a function of satellite elevation angle. If the error characteristics are different from their desired values, maintenance alert is indicated, and the reference receiver is no longer used until it is back within tolerance.

Note that Signal quality and Data quality monitor are monitoring the signals from satellites into the receiver and Measurement quality monitoring and Multiple reference consistency check are monitoring the calculated corrections.
3 Structure of North European ADS-B Network (NEAN)

As said earlier, NEAN [1] is a working test bed for a network of base stations in Sweden, Denmark and Germany that are connected in the NEAN ground network. In this ground network it is possible to send position reports from aircraft and cars, as well as differential corrections.

Since the aim with this project is to develop an integrity concept for NEAN it is interesting to know how GPS works, how the differential corrections in NEAN is build up, and which information they contain.

3.1 GPS position determination

The receiver measures the distance to the satellite by matching a code sequence that is known by both satellite and receiver. If the code sequences are started at exactly the same time it is possible to correlate the code sequences and then see how long time the radio signal has travelled from the satellite, and hence it is possible to calculate the distance to the satellite.

In a two-dimensional case the satellite and user constellation would look like:

![Figure 3.1: Position solution with GPS in the two dimensional case](image)

Since the satellites also broadcast its almanac, or timetable where it will be, the receiver knows the position of the satellites, and then it is possible to determine the receiver position using Pythagoras theorem.

\[
\begin{align*}
(S_{1x} - U_x)^2 + (S_{1y} - U_y)^2 &= R_1^2 \\
(S_{2x} - U_x)^2 + (S_{2y} - U_y)^2 &= R_2^2 \\
(S_{3x} - U_x)^2 + (S_{3y} - U_y)^2 &= R_3^2
\end{align*}
\]

The distance between satellite and receiver, R1 - R3, is the time it takes for radio signals to go from satellite to receiver (with the speed of light). This gives

\[
\begin{align*}
R_1 &= c \cdot \Delta t_1 = c \cdot (t_1 - t) \\
R_2 &= c \cdot \Delta t_2 = c \cdot (t_2 - t) \\
R_3 &= c \cdot \Delta t_3 = c \cdot (t_3 - t)
\end{align*}
\]
where \( t \) is the synchronisation time, to synchronise the cheap clock in the receivers with the precise atomic clocks in the satellites. This is why one extra satellite is needed, three satellites in the two dimensional case and four satellites in the general case. Putting this together gives the GPS navigation solution, where \( U(x,y,t) \) is the sought user position.

\[
(S_{1x} - U_x)^2 + (S_{1y} - U_y)^2 = c^2 \cdot (t_1 - t)^2 \\
(S_{2x} - U_x)^2 + (S_{2y} - U_y)^2 = c^2 \cdot (t_2 - t)^2 \\
(S_{3x} - U_x)^2 + (S_{3y} - U_y)^2 = c^2 \cdot (t_3 - t)^2
\]

### 3.2 Differential corrections

To calculate the differential corrections, place a GPS receiver at a known position and measure a GPS position. It is then possible to calculate and broadcast the error via radio communication link to surrounding users.

#### 3.2.1 Basic differential corrections

It is possible to calculate a position error in \( X, Y, Z \) and broadcast this error. Another better alternative is to calculate and broadcast one distance error per satellite in sight. This method requires that lots of more data has to be broadcast, but the advantage is that user receiver and reference receiver can use different satellite constellations to determine their respective position.

![Figure 3.2: Measure GPS position at known position.](image)

If the receiver knows the position and the distance to each satellite in view, it is possible to calculate the distance error to each satellite. This error will be broadcast to the users.

![Figure 3.3: Error for each satellite that are broadcast to the users.](image)
3.2.2 Reference station

In a reference station, where GPS receiver stands at a known position, \( U_x, U_y \) will be known, as well as the satellites position.

\[
\begin{align*}
(S_{1x} - U_x)^2 + (S_{1y} - U_y)^2 &= c^2 \cdot (t_1 - t)^2 \\
(S_{2x} - U_x)^2 + (S_{2y} - U_y)^2 &= c^2 \cdot (t_2 - t)^2 \\
(S_{3x} - U_x)^2 + (S_{3y} - U_y)^2 &= c^2 \cdot (t_3 - t)^2 
\end{align*}
\]

Then the unknown in this equation system will be

\[(t_1 - t), (t_2 - t), (t_3 - t)\,.
\]

This is the true time it takes the signals to go from respective satellite to a known position, including all errors. Since there are four unknowns and just three equations, it is possible to set \( t \) to an appropriate value.

One way to choose \( t \) is so that the mean value of \( t_1, t_2 \) and \( t_3 \) will be around zero. That means that \( t_1, t_2, t_3 \) will be as small as possible, so they will get better dissolution when the corrections are broadcast as differential corrections.

If choosing \( t \) in a good way gives the differential corrections that are broadcast per satellite:

\[
\tilde{t}_1, \quad \tilde{t}_2, \quad \tilde{t}_3
\]

The broadcast corrections will not be the error or distance to any satellite. The corrections will be a relative distance to respective satellite and dependent on the term \( t \), which is set in the base station, usually to normalise the sum of the corrections to zero.

The corrections are relative to each other and depend on the term \( t \) and therefore corrections from two different reference stations are not comparable. They will differ with a term that will be common for all satellites at one reference station.

3.3 GPS position determination with differential corrections

To calculate the corrected GPS position \( \hat{U} \) the following equations are used (where \( \hat{U} \) and \( i \) are corrected user position and time distance to satellite respectively, \( \tilde{t} \) are the broadcast correction).

\[
\begin{align*}
(S_{1x} - \hat{U}_x)^2 + (S_{1y} - \hat{U}_y)^2 &= c^2 \cdot (i_1 - i - \tilde{t}_1)^2 \\
(S_{2x} - \hat{U}_x)^2 + (S_{2y} - \hat{U}_y)^2 &= c^2 \cdot (i_2 - i - \tilde{t}_2)^2 \\
(S_{3x} - \hat{U}_x)^2 + (S_{3y} - \hat{U}_y)^2 &= c^2 \cdot (i_3 - i - \tilde{t}_3)^2 
\end{align*}
\]

In the general case with three dimension positioning, the only difference is to add one extra equation when determine position for the \( z \) direction. This will also need one extra satellite to solve the equation system, so the general case will need four satellites for 3 dimensional navigation.
3.4 Normalisation

The reference station scales the corrections to get the best dissolution, and the satellite error for each reference station is relative to each other. This gives that it is not possible to compare the corrections for one satellite from two reference stations.

Divide the error for each satellite into three terms:

\[ X_{i,j} = b_j + e_{i,j} + k_i \]

where:
- \( X_{i,j} \) - the broadcast correction for a specific satellite from a reference station
- \( i \) - defines a specific reference station
- \( j \) - defines a specific satellite
- \( b_j \) - bias error for a satellite that are common for all reference station
- \( e_{i,j} \) - local error per reference station and satellite, multipath and receiver noise
- \( k_i \) - Normalisation term for all satellites at one base station

If the normalisation term \( k_i \) can be estimated, it would be possible to determine the error between reference stations \( e_{i,j} \) and the satellite error \( b_j \). One way to estimate the normalisation term is shown in chapter 5.1.5.

3.5 Quality check in the reference station

The reference station is capable of detecting if a satellite pseudorange becomes too large. It can also detect any significant variation in the signal or change in the signal that might be caused by selective availability or some other error mechanism.

3.6 Standard for broadcast differential corrections

The differential corrections in NEAN are following Magnavox standard for differential corrections. This standard builds on RTCM 104 [13], which is a maritime standard, and NEAN corrections contains the same information as RTCM 104.

The differential corrections are divided into messages, which is the main difference with RTCM 104 that is broadcast continuously. In the NEAN ground network the corrections are transformed into hexadecimal form to get easier data handling. The correction message contains two separate parts, head and correction for each satellite.
### 3.6.1 Message head for differential correction

Below is the head for each correction [14]:

<table>
<thead>
<tr>
<th>$PRGPS</th>
<th>Type</th>
<th>DGPS ID</th>
<th>Hours in week</th>
<th>Number of satellites</th>
<th>Seconds in the hour</th>
<th>Corrections for each satellite</th>
<th>1 - No satellites</th>
<th>Checksum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$PRGPS</strong></td>
<td>Tells that the message is a differential correction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Type of message. 671 tell that data is from a satellite using a new calendar. 672 tells that data is from satellite using old calendar (671 is normal).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DGPS ID</strong></td>
<td>Binary identity for the reference station. Based on the position of the reference station.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hours in week</strong></td>
<td>How many hours that is been in the week, resets at 00:00 (Universal mean time, UTC) between Sunday and Monday each week.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of satellites</strong></td>
<td>The number of satellites that the reference sends corrections for.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Seconds in the hour</strong></td>
<td>GPS time, the time when the correction is determined. 3600 seconds, so in hexadecimal range 0000 - 0E0F. The number is byte shifted which gives that it counts 0000, 0100, 0200, 0300, 0400 and so on. Gives the range 0000 - 0F0E.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Corrections for each satellite</strong></td>
<td>Corrections for each satellite in view for the base station. The corrections are in 10 hexadecimal numbers representing 40 binary bits (see correction below to understand how the corrections are build up). 10 hexadecimal numbers for each satellite.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Checksum</strong></td>
<td>The checksum contains ‘<em>’ followed by the checksum. The checksum is obtained by XOR of all bytes between the ‘$’ in the start and ‘</em>’ in the checksum frame.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 3.4: Head for differential corrections*

The length of the correction message depends on how many satellites that are in view and therefore this message is comma separated.
3.6.2 Correction for each satellite

10 hexadecimal numbers or 40 binary numbers represent each differential correction per satellite. Below is a figure that shows the correction message and the information in each bit. This is the same information as in RTCM 104 Message type 1 [13].

<table>
<thead>
<tr>
<th>Scale factor</th>
<th>UDRE</th>
<th>Satellite ID</th>
<th>Pseudorange Correction</th>
<th>Range-Rate Correction</th>
<th>Issue of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale factor</td>
<td>UDRE</td>
<td>Satellite ID</td>
<td>Pseudorange Correction</td>
<td>Range-Rate Correction</td>
<td>Issue of data</td>
</tr>
</tbody>
</table>

Figure 3.5: Differential correction message for each satellite

Scale factor

Scale factor for pseudorange- and range-rate correction for best dissolution. If Scale factor = 0 multiply Pseudorange correction with 0.02 and Range-rate correction with 0.002. If Scale factor = 1 multiply Pseudorange correction with 0.32 and Range-rate correction with 0.032.

UDRE

User Differential Range Error (UDRE) is an estimate from the reference station of how well the range agree with the true range. Also called one-sigma differential error.

<table>
<thead>
<tr>
<th>Code</th>
<th>Number</th>
<th>One sigma differential error</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0</td>
<td>≤ 1 meter</td>
</tr>
<tr>
<td>01</td>
<td>1</td>
<td>&gt; 1 meter and ≤ 4 meters</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>&gt; 4 meters and ≤ 8 meters</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>&gt; 8 meters</td>
</tr>
</tbody>
</table>

Satellite ID

Identity for each satellite, numbered from 0 - 31. Each satellite has a specific number. GPS contains 24 satellites, but has 32 satellite identity numbers. Also called PRN.

Pseudorange correction

PRC

Range error to the satellite, as a 2’s complement number. In the range ± 655.34 meters if scale factor is 0, and ± 10485.44 meters if scale factor is 1. Binary 1000 0000 0000 0000 indicates that the satellites are not going to be used.

Range-rate correction

RRC

Range rate correction is how the range error changes. Basically the derivative of the PRC, as a 2’s complement number. In the range ± 0.254 meter/second if scale factor = 0, and ± 4.064 meter/second if scale factor = 1. Binary 1000 0000 indicates that the satellites are not going to be used.

Issue of data

Special for carrier phase correction computation, which is not used in the NEAN.

Table 3.2: Information for each satellite in NEAN differential corrections

Below is a screen capture of corrections from four different reference stations using Telnet:
3.7 Error sources for differential corrections in NEAN

The reference station calculates the differential corrections and the GNSS Transponder marshal the correction into standard format and broadcasts on the data link. It also sends the corrections to the NEAN ground network.

Below is a figure of a base station in the NEAN, what it contains and the possible errors that might occur which would give wrong or no corrections to the users. The errors can be divided into five different parts of the base station: GPS satellites, GPS antenna, Reference station, GNSS Transponder and VHF data transmission.

<table>
<thead>
<tr>
<th>Error</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS Satellite Constellation</td>
<td>Not enough with satellites or too bad satellite geometry, to perform navigation</td>
</tr>
<tr>
<td>Jamming</td>
<td>Another transmitter sends at the same frequency as GPS satellites so that the GPS receiver cannot detect the GPS signals</td>
</tr>
<tr>
<td>Spoofing</td>
<td>Another transmitter is sending false GPS data so that the GPS receiver does not estimate the right position</td>
</tr>
<tr>
<td>Satellite message</td>
<td>Something goes wrong with the satellite message, i.e. bit error in transmission</td>
</tr>
<tr>
<td><strong>GPS Antenna</strong></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Wrong position of the GPS antenna</td>
<td>If the antenna falls down or is moved, the antenna position is not where the reference station thinks it is. This will give that the corrections will be wrong</td>
</tr>
<tr>
<td>Antenna failure</td>
<td>The antenna break down and will miss satellites or be unable to track any satellite at all</td>
</tr>
<tr>
<td>GPS antenna cable</td>
<td>The antenna cable may be damaged or too long so the signal / noise ratio will be so low that the reference station will not use some satellite for navigation</td>
</tr>
<tr>
<td>Multipath</td>
<td>GPS signals reflects around the GPS antenna which will give wrong distance to the satellite and therefore the corrections will be wrong</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Reference station</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong setting of position parameters</td>
<td>The reference receiver knows the GPS antennas position, but if the GPS antenna is not where reference receiver think it is, corrections will be wrong. Problem if antenna or reference station is moved and parameters are not changed</td>
</tr>
<tr>
<td>Wrong setting of angle parameters</td>
<td>It is possible in the reference station to set parameters of the satellites angle over the horizon to leave corrections (usually 4-6°). If those parameters are wrong, the corrections will not be as expected</td>
</tr>
<tr>
<td>Noise in reference receiver</td>
<td>The electronic circuits in the reference station introduces noise that will affect the measured position and hence the corrections</td>
</tr>
<tr>
<td>Hardware, Software and Power supply failure</td>
<td>Errors due to the equipment. Probably no corrections will be broadcast or its values will be wrong</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>GNSS Transponder</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Network error</td>
<td>The ground network may be down or bit errors in the network</td>
</tr>
<tr>
<td>Hardware, Software and Power supply failure</td>
<td>Errors due to the equipment. Probably no corrections will be broadcast or its values will be wrong</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Data link</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF antenna or antenna cable may break or be bad</td>
<td>The data link does not broadcast any differential corrections or the signal is too low so that no one will receive the corrections</td>
</tr>
<tr>
<td>Jamming</td>
<td>Another transmitter send on the same frequency so that the users will not be able to receive any corrections</td>
</tr>
<tr>
<td>Spoofing</td>
<td>Someone sends false GPS corrections, so that the receiver might be fooled of wrong corrections</td>
</tr>
<tr>
<td>Data link failure</td>
<td>Bit errors in the data link</td>
</tr>
</tbody>
</table>
3.8 Monitor stations

The monitor station is a differential GPS receiver at a known position. The monitor station calculates its position and sends it out at the NEAN ground network. Since the position is known it is possible to calculate the position error for the monitor. It is then possible to see how accurate the GPS solution is with differential corrections. If this error exceeds a threshold it is possible to broadcast that the differential corrections are not going to be used. The monitor is also able to tell that the corrections from the reference station are broadcast.
4. Integrity concept for differential corrections in NEAN

NEAN is today a test bed for a communication, navigation and surveillance (CNS) system for civil aviation, even if it is not allowed to use as a primary navigation source. One reason why systems like NEAN are not allowed to be used for navigation is that they do not fulfil integrity requirement (find and communicate errors within specific time limits) that is the most important requirement for aviation.

For the moment NEAN has no good integrity monitoring of broadcast corrections, and it will take time to find out if something goes wrong. Because of the goal with the CARD project is to set world standard for CNS applications and NEAN is used for larger tests and evaluation, it is necessary to get a tool for integrity monitoring.

This chapter will look at how different error sources in NEAN can be detected, and how a program that is going to find those errors shall work.

4.1 Possible Errors

In section “3.4 Error sources for differential corrections” figure 3.7 contains the error sources for a base station in NEAN. It is interesting to investigate how it is possible to detect each of those errors to fulfil integrity requirements. Below is a list with all the errors from chapter 3.4 and solutions for how they may be detected.

<table>
<thead>
<tr>
<th>Error</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>Not a big problem. The reference receiver and the user receiver will detect if it is not enough with satellites or the satellite geometry is so bad that it is impossible to navigate. Impossible to navigate but all users will detect the problem immediately.</td>
</tr>
<tr>
<td>Satellite Constellation</td>
<td>The satellite signal will look like random noise and the receiver will be unable to detect any satellites, so it will be impossible to navigate, but it will be detected immediately.</td>
</tr>
<tr>
<td>Jamming</td>
<td>May be a big problem because GPS look-alike data is broadcast that have stronger signal than the satellites (satellites broadcast very weak signals), and the reference receiver calculate correction for this wrong data, which gives that the corrections are wrong. Possible to detect with a monitor station that tells when position goes out of bounds, or by comparing corrections with corrections from another reference station, that is not affected by spoofing.</td>
</tr>
<tr>
<td>Spoofing</td>
<td>Discovered by checking that the checksum corresponds with the broadcast checksum.</td>
</tr>
<tr>
<td>Satellite message</td>
<td>Comparing close at hand reference stations or long term bias at monitor station.</td>
</tr>
<tr>
<td>Issue</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Antenna failure</td>
<td>Average the number of satellites and compare with close at hand reference stations during the same time</td>
</tr>
<tr>
<td>GPS antenna cable</td>
<td>Measure signal to noise (S/N) ratio or average number of satellites for each reference receiver and compare with close at hand reference stations</td>
</tr>
<tr>
<td>Multipath</td>
<td>Characteristic by quick jumps in the corrections for a specific satellite. Can be detected by comparing corrections from two different reference stations, or jumps in position for a monitor station. Jumps in monitor position might depend on multipath at monitor antenna</td>
</tr>
<tr>
<td>Reference station</td>
<td>Normal distance is quite small and therefore not a big problem, but if the noise will grow it will be detected by comparing reference stations or by monitor station</td>
</tr>
<tr>
<td>Noise in reference receiver</td>
<td>If the parameters is very wrong the reference station will detect and shut down, but if the position error is small, it can be notified by comparing reference stations or by monitor station</td>
</tr>
<tr>
<td>Wrong setting of position parameters</td>
<td>The reference station will not send out corrections for the satellites it should or send corrections for satellite it should not. This can be notified by taking the average of all satellites the reference send corrections for, and compare with close at hand base stations</td>
</tr>
<tr>
<td>Wrong setting of angle parameters</td>
<td>The monitor station will not receive any differential corrections. The monitor has to check which reference station it receives corrections from. If the nearest reference station stops broadcasting corrections the monitor may take corrections from another close at hand reference station, which will be wrong. The monitor can also check the signal/noise ratio</td>
</tr>
<tr>
<td>Hardware, Software and Power supply failure</td>
<td>Avoided by using multiple reference stations from different manufactures and battery backup</td>
</tr>
<tr>
<td>GNSS Transponder</td>
<td>Bit error in the network is very unlikely, but can be checked with the checksum. Messages can also be delayed which can be checked with the corrections time stamp.</td>
</tr>
<tr>
<td>Network error</td>
<td>Avoided by using multiple reference stations from different manufactures and battery backup</td>
</tr>
<tr>
<td>Hardware, Software and Power supply failure</td>
<td>Avoided by using multiple reference stations from different manufactures and battery backup</td>
</tr>
<tr>
<td>Data link</td>
<td>The monitor station will not receive any differential corrections. The monitor has to check which reference station it receives corrections from. If the nearest reference station stops broadcasting corrections the monitor may take corrections from another close at hand reference station, which will be wrong. The monitor can also check the signal/noise ratio</td>
</tr>
<tr>
<td>VHF antenna or antenna cable may break or be bad</td>
<td>The reference station will not send out corrections for the satellites it should or send corrections for satellite it should not. This can be notified by taking the average of all satellites the reference send corrections for, and compare with close at hand base stations</td>
</tr>
</tbody>
</table>

![Table of Issues and Solutions](image-url)
Jamming  The problem is very similar to jamming on the GPS signals, the
GPS receiver will not detect any corrections and will identify the
problem immediately. Jamming will be detected by monitor
station. It is also possible to divide the data link into two
frequencies so that the corrections broadcast every second time at
each frequency.

Spoofing  Can be detected by monitor station, but directed radio signals
with false corrections will be very hard to detect. The only way to
detect this is in the airborne autonomous integrity monitoring
(AAIM, see section 2.2) where position is compared with inertial
navigation system.

Data link failure  The monitor station and the user receiver has to check the data
bits with the checksum.

### 4.2 NEAN Integrity concept

Integrity is the most important requirement for aviation. Integrity means to find the errors that
sooner or later will occur, and to tell everyone who is using the system about the error. The
key to integrity is redundancy, and a cheap way to get a good integrity control for NEAN
would be to compare differential corrections for reference stations that are spread out in a
regional area, to obtain an integrity concept with distributed redundancy. This is possible in
NEAN because the reference stations are connected to NEAN ground network.

In a regional area of Sweden’s size all base stations will see almost the same satellites, and the
corrections will not differ that much, so it is possible to compare the corrections from several
base stations which would give distributed redundancy. The Swedish part of NEAN could
look like:

![Figure 4.1: Integrity concept with distributed redundancy](image)

Chapter 4.1 shows that monitor stations should be included to see the position accuracy with
differential corrections, and that corrections are broadcast via the data link. Unfortunately no
monitor stations are connected to NEAN ground network at the moment.
4.3 NEAN integrity program

To obtain the integrity concept that is described in the previous section it is possible to collect data to one computer that runs a program to decode the messages and does all necessary tests.

4.3.1 Aims and objective with integrity program

The program is going to work by a central computer that collects differential corrections from reference stations in a regional area, and signal process those corrections so that they will be comparable. The program will work in real time and it has to alert when corrections go out of bounds. The program has to run over a long period of time without manual control, and store data for later investigation. It shall also count statistic for interesting data.

It is interesting to think of what such a program will be allowed to do if it detects errors, for instance it could be allowed to shut down a reference station and send alerts to operators. But in this case it will not be allowed to do anything at the moment, the program is just going to have a passive monitoring function, and save detected errors for investigation.

4.3.2 Requirement Specification

From previous chapters it is possible to derive the requirements that an integrity program has to fulfil.

<table>
<thead>
<tr>
<th>User requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Stable, work for long time and handle that base stations are going down and are restarted.</td>
</tr>
<tr>
<td>R2 Work as a monitoring program as well as an analysing program</td>
</tr>
<tr>
<td>R3 Work on an ordinary table computer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Functional requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4 Work on-line to check differential corrections</td>
</tr>
<tr>
<td>R5 Store data to analyse and investigate results</td>
</tr>
<tr>
<td>R6 Calculate Range error correction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Presentation requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>R7 Show graphs of how the range error is varying with time</td>
</tr>
<tr>
<td>R8 Show status for each base stations that are connected to the program</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Testing requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>R9 Calculate average of how many satellites each reference ”sees”</td>
</tr>
<tr>
<td>R10 Alarm if one satellite correction for one base station differ very much from other base stations</td>
</tr>
<tr>
<td>R11 Test the checksum for each correction message</td>
</tr>
</tbody>
</table>
5. NEAN integrity program

The computer program that is going to monitor the differential corrections in NEAN is named NEAN Integrity Monitoring System (NIMS), and in the rest of this report NIMS is used to refer to the program.

5.1 Special problems that has to be taken care of

5.1.1 System dynamics

One problem to monitor the GPS system is that the system is so dynamic. The nature of the GPS system is that the satellites orbit earth, so the satellite constellation is changing all the time. Another problem is that the base stations in NEAN are not so reliable. A monitoring system has to handle that they are going down. Therefore the program has to check which base stations that are connected and which satellites these base stations ”see”. Those checks has to be performed within a constant time interval each time the program updates all values.

5.1.2 Get corrections from base stations

The corrections are broadcast from the base station via NEAN ground network, which is a part of Luftfartsverkets Intranet. This net builds on TCP/IP (Transmission Control Protocol / Internet Protocol) which is the standard data transmission method for Internet connections. In this type of network it is easy to receive corrections to one computer.

5.1.3 Number of base stations

Because of computational and design problems, it is necessary to limit the highest number of base stations that are possible to connect at the same time. Eight base stations are chosen to start with, but this number has to be easy to expand.

5.1.4 Corrections from different time

The base stations are sending corrections to the ground network within specific time intervals, that are not synchronised between the base stations, so the Range error values that is calculated will differ some seconds in time. The correction message contain a time stamp when the corrections are generated in GPS time (called Z-count) multiplied with Range rate correction, which is the derivative of the Range error corrections. It is possible to synchronise the Range error to the same time using:

\[
\text{Range error (synchronised)} = \text{Range error (unsyncronised)} + \text{Range rate} \cdot Z \text{- count} \quad (5.1)
\]

where Z-count is the latest correction time -minus the time when correction is generated. The Range error (unsynchronized) has to be the normalised range error.
5.1.5 Normalisation term

From section 3.1 it is possible to see that the corrections for the same satellite from two different base stations are not comparable, they will differ with a term, $k_i$, that is the same for all satellites for one base station. The broadcast differential correction for one satellite at one base station can be divided into

$$X_{i,j} = b_j + e_{i,j} + k_i$$

where:
- $X_{i,j}$ - the broadcast correction for a specific satellite from a reference station
- $i$ - defines a specific reference station
- $j$ - defines a specific satellite
- $b_j$ - bias error for a satellite that are common for all reference station
- $e_{i,j}$ - local error per satellite and reference station, multipath and receiver noise
- $k_i$ - Normalisation term for all satellites at one base station

From this equation it is interesting to get the error per satellite and base station, which is

$$b_j + e_{i,j}$$

One way to estimate the normalisation term would be to assume that the range error for one satellite that is visible for all base stations is zero ($b_j + e_{i,j} = 0$). Since this satellite is "seen" by all base stations $k_i = X_{i,j}$ is the normalisation term for respective base station.

It would then be possible to subtract $k_i$ from all other satellites for each base station. The value for the subtracted satellite is zero, and therefore comparable, and the other satellites get comparable values.

$$b_j + e_{i,j} = X_{i,j} - k_i$$

This is not a good way to solve the normalisation, because of the assumption of zero error for one satellite. The error that will be at this satellite will immediately affect the error at all the other satellites.

Developing this idea would be to take the mean value of all satellites that are seen by all base stations. This means, first to find which satellites that are ”seen” by all base stations, then for each base station take the mean value of those satellites. This will be the normalisation term.

$$k_i = \frac{-\sum_{j=1}^{N} (b_j + e_{i,j})}{N}$$

where $N$ is the number of satellites that all base station provides corrections for. This will be a good estimate, because

$$\frac{1}{N} \sum_{j=1}^{N} X_{i,j} \to 0$$

when $N$ increases. The normalisation term has then to be subtracted from all range errors for that base station.

$$b_j + e_{i,j} = X_{i,j} + k_i$$
The result of this method depends on how many satellites that are seen by all connected base stations, and about five common satellites would give a sufficient result. This means that the base stations that are connected to the program have to be in a regional area so that all the base stations ”see” some common satellites.

5.1.6 Filtering of the normalisation term

The problem with the normalisation method is that it introduces noise, since the normalisation is based on the satellites that are ”seen” by all base stations. If one base station stops to broadcast corrections for one satellite that is used as normalisation satellite, this will affect the normalisation term for all base stations with a quick jump. The normalisation term for six base stations can look like figure 5.1

![Figure 5.1: Unfiltered normalisation term](image)

This noise will immediately affect the range error for all the satellites because the normalisation is added to the broadcast corrections.

Filtering the normalisation term by taking the mean value of the ten latest calculated normalisation terms gives the following normalisation factor.

![Figure 5.2: Filtered normalisation term](image)

The filter reduces much of the noise, and the normalisation terms have the same amplitude as the unfiltered one, except in the initial stage. So no data should be lost by filtering of the normalisation term and filtering should be possible to do in real time in the program.
5.1.7 Local error

Continuing on the idea about the normalisation term in 5.1.2, it would be possible to estimate $b_i$, which are the error terms common for all satellites. This could be done by taking the mean value for one satellite, after normalisation, and subtract this error from the total error. This would then be the local error per satellite and reference station.

$$e_{i,j} = X_{i,j} - k_i - b_j$$

Since the objective is to monitor if the corrections go wrong, and it may go wrong for one satellite at all base stations, the error would not be discovered. It is therefore not interesting to calculate the local error and this function will not be included in the program.

5.1.8 Presentation of results

To present results it would be interesting to see a table for the range error for each satellite at each base station. This table could look like:

<table>
<thead>
<tr>
<th>Satellite $S_1$</th>
<th>Base station 1</th>
<th>Base station 2</th>
<th>......</th>
<th>Base station M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>$X_{1,1}$</td>
<td>$X_{2,1}$</td>
<td>......</td>
<td>$X_{M,1}$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$X_{1,2}$</td>
<td>$X_{2,2}$</td>
<td>......</td>
<td>$X_{M,2}$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$X_{1,3}$</td>
<td>$X_{2,3}$</td>
<td>......</td>
<td>$X_{M,3}$</td>
</tr>
<tr>
<td>......</td>
<td>......</td>
<td>......</td>
<td>......</td>
<td>......</td>
</tr>
<tr>
<td>$S_N$</td>
<td>$X_{1,N}$</td>
<td>$X_{2,N}$</td>
<td>......</td>
<td>$X_{M,N}$</td>
</tr>
</tbody>
</table>

Table 5.1: Range error values per satellite and base station

A table with real data is shown below. It is possible to see which satellites each base station tracks.

<table>
<thead>
<tr>
<th></th>
<th>ESSA</th>
<th>ESGG</th>
<th>ESSB</th>
<th>ESDB</th>
<th>ESFP</th>
<th>ESMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat. 24</td>
<td>-12.54</td>
<td>-13.75</td>
<td>-13.5</td>
<td>-24.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. 14</td>
<td>-13.08</td>
<td>-9.04</td>
<td>-12.47</td>
<td>-11</td>
<td>-6.5</td>
<td>-17.07</td>
</tr>
<tr>
<td>Sat. 30</td>
<td>-0.5</td>
<td>1.51</td>
<td>-4.42</td>
<td>-11.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. 25</td>
<td>-12.72</td>
<td>-17.08</td>
<td>-9.77</td>
<td>-11.1</td>
<td>-15.6</td>
<td>-3.83</td>
</tr>
<tr>
<td>Sat. 16</td>
<td>-16.7</td>
<td>-17.2</td>
<td>-19.19</td>
<td>-17.82</td>
<td>-8.08</td>
<td>-28.31</td>
</tr>
<tr>
<td>Sat. 15</td>
<td>-25.34</td>
<td>-19.26</td>
<td>......</td>
<td>40.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat. 4</td>
<td>0.9</td>
<td>-1.54</td>
<td>-0.75</td>
<td>0.2</td>
<td>2.32</td>
<td>-2.35</td>
</tr>
<tr>
<td>Sat. 10</td>
<td>30.68</td>
<td>33.06</td>
<td>29.71</td>
<td>23.45</td>
<td>20.22</td>
<td>20.95</td>
</tr>
<tr>
<td>Sat. 7</td>
<td>10.95</td>
<td>12.62</td>
<td>12.47</td>
<td>11.24</td>
<td>-0.98</td>
<td>23.89</td>
</tr>
</tbody>
</table>

| Norm.tak. | -33.86 | -6.8 | -3.85 | -6.3 | -1.2 | 69.55 |

Figure 5.3: Normalised range error for six base stations

This table has to be updated each time new data are calculated. The table could show if the range error value for one satellite at one base station differ very much from other base stations. This warning could be done by average the range error for all base stations and compare each value with the average. The result will be better if many base stations are connected so that each base station does not affect the mean value so much.
One marked column would indicate that the base station is sending bad corrections, or that the base station is placed far away from other base stations. It would also be interesting to see how the range error values for one satellite is varying with the time. This can be done in a graph that shows all base stations.

### 5.1.9 Log files

One important task is to monitor and report errors, it is important to save all data in log files. This means that the original corrections have to be stored as well as calculated Range error. It must also be possible to run the program from logged corrections, for investigation and for demonstrations when no real time data are available.

### 5.2 Program specification

The program has to be updated at specific time interval, and at each time interval the main program has to do all the necessary calculations. The program must be easy to change with functions that are easy to replace.

A data flow diagram for the main program is shown below:
Figure 5.4: Data flow diagram for main program
Timer | The timer is a function that generates an event each time the time interval is reached. This event starts the main program with the specified time interval
---|---
In_out_log | If the program is going to save real time data to log file, or if the program is going to run from logged data
Connection_test | Test of which base stations that recently have sent corrections, and therefore going to be treated as connected
Count_sat | Test of how many and which satellites that are "seen" by all base stations. This information is used to estimate the normalisation term
Output | Output data about the correction that comes from the base station. These data include base station name, time when data are generated, number of satellites the message contains and other information that is common for all the satellites within one correction message
Rawdata | Present a table with the raw range error values, which is the range error before the normalisation. The data are used to calculate the normalised Range error
Norm | Calculating the normalisation term for all base stations. Uses the data from rawdata and which satellites that are seen by all base stations
Range_error | Subtracting the normalisation term from all rawdata for each base station
Diagram | Saving range error values in an array, and plotting the data in graphs. Implemented as a cyclic array to get faster execution
Log_range_error | Saving calculated Range error values in a text file, so it is possible to plot the data in another program, for instance Matlab or Microsoft Excel

5.3 Program implementation

5.3.1 Program language

The program language that is chosen is Visual Basic 5.0 because of:

- Simple to code
- Exists in the CARD project
- Easy handling of TCP/IP connections
- Easy to plot tables and graphs
- "Visual program", easy to do good looking program

So Visual Basic is a language that can be used to fulfil the requirements, the only drawback may be the speed, but version 5.0 is compiling, so that will probably not be a problem. This program version is developing programs for Windows 95 / Windows NT, so to run the program one of those operating systems has to be used.
5.3.2 Graphical layout

In Visual Basic you start to do a “form” which show how the program is going to look, and then program the functions that are going to be included in the program. To do the program clear, understandable and good-looking, the program is divided into what is called “Tabs”, which is an ordinary Windows function to hide information. Those Tabs are divided into “Status”, “Statistic”, “Data input”, “Raw data” (pseudorange correction before normalisation), “Range error”, “Diagrams” and “Output log”.

The status is the front page of the program and is going to tell the status of each base station for the novice that does not know how the program is working. The status is indicated with coloured boxes where green indicates that everything is fine, yellow that something is bad, and red that something is really bad. Black box indicates that the base station is not working at all. The status is built up by threshold of the statistical parameters, which are set in the set-up form (see below).

The ”Statistic” tab outputs statistical data, that tells about the condition of each base station. Mean number of satellites is the average of number of satellites for that base station since the program started. Percent updated corrections test how often the program updates values with new corrections. Percent corrections inside limit mean how many percent that is inside the range error interval, set in the Range error tab. This gives a measure of the accuracy of the base stations compared to the other base stations. Percent Connected is how many percent the indicator in bottom left corner is green or red.
The "Data input" tab handle corrections in to the program, either real time data from a network or data from a log file. All original corrections are printed in the text boxes, so that it is possible to see the input data to the program. The Start and Stop buttons sets if the data are going to be updated or not. It may also be useful to stop execution if something unexpected happens and more time is needed to analyse data, but that means that real time data is missed.

In the bottom left corner the form contains indicators that indicate the income corrections. Green means that a correction has been received since last update. Red means that no new message has been received, but an old message is used. Black means that the base station is not connected, because it is not working or has not sent corrections for a long time, so that the latest correction is too old to use.

The "Raw data" tab outputs the Range error value that is sent from the base station, i.e. Range error before normalisation.
The "Range error" tab outputs Range error data after normalisation, the correction values are normalised and comparable. Possible to set a "Range error warning" value that will mark if one cell value differ more than interval from that satellite in other cells. The Range error is in meters, but because of the normalisation it has no physical meaning, the warning is just relative between base stations.

The "Diagrams" tab is plotting how the Range errors are varying with time for maximum 10 satellites. Because of memory and execution problems, hundred range error values are stored for each base station, which gives hundred times the update interval, around 8 minutes of data are plotted. The data is stored as cyclic arrays, which gives one step in the range error plots.
The "Diagram" tab plots a bigger graph for one of the satellites shown in previous tab. Possible to get by clicking at one graph in previous tab, or choose in the list box in bottom right corner.

The "Output log" tab is saving data to log files. Possible to save Range error values, Original differential corrections, Raw data before normalisation and how often the statistical data are going to be stored in a text file.

In the Set-up form it is possible to set all parameters, which include base stations binary identity used to recognise from which base station the message is coming, base station name, parameters for the Status form and so on.
5.4 Testing of NIMS

Running NIMS gives some interesting results about the GPS system and how well NIMS fulfils the requirement specification.

5.4.1 Stability

NIMS has been running for two weeks without any problems, so it handles that satellites are coming and going and that base stations are switched on and off.

5.4.2 Normalisation term

To test how well the normalisation method is working, the following test was done. Plotting the Raw data corrections before normalisation.

![Figure 5.14: Range error before normalisation](image)

Here it is possible to see that the corrections from different base stations are following each other well, but that they differ a factor in the Range error. So after normalisation the Range error is the normalised Range error.

![Figure 5.15: Range error after normalisation](image)

In this plot the Range error is very close together and they are following each other very well. In this graph it is possible to see if the Range error from one base station is different from other base stations. Comparing these plots shows that the normalisation method that is used
works very well. The only problem is that the normalisation introduces some noise, which can be reduced with the normalisation filter shown previously.

The range error value for one base station is said to be centred around zero, and therefore the normalisation has to be done. Plotting the normalisation factor for 24 hours shows the following graph.

![Image of graph showing normalisation term for 24 hours]

*Figure 6.16: Normalisation term for 24 hours*

In this graph it is possible to see that the highest graph (ESMS, Malmö) has a mean value around 80, the lowest graph (ESSA, Arlanda) has a mean value around -30 and the rest of the base stations have mean values around zero. This is a general behaviour that is shown all the time and it is not clear why, but it does not affect the results of the corrections.
5.4.3 GPS Error characteristic

Plotting the error for one satellite gives the following characteristic for the error.

![Figure 5.17: Period time for GPS error](image)

In this plot it is shown that the GPS error has something like a sinusoidal characteristic. The plot that is shown is between 10:15 to 11:40 which gives that the error has a period time of about 6 minutes.

5.4.4 Requirement specification

Running the program shows that the most of the specified requirements are fulfilled. The program is clear and easy to understand, it works on a table computer and it presents results in a clear and easy way. In general NIMS works like what was specified in the requirement specification.
6 Testing of differential corrections in NEAN

NIMS generates lots of data and the best way to find errors in the differential corrections is to save Range error values in a text file and plot it in another program for investigation. Matlab functions have been developed to read in Range error values and plot the data. Analysing the graphs in Matlab, strange behaviour is found, and to find out what it depends on, it is possible to run NIMS for that specific time period, or decode the original differential correction message by hand.

During development and testing of the program some problems with the differential corrections have been found.

6.1 Transponder 2 (T2) Vs Transponder 3 (T3)

A new transponder, T3, has been developed and recently started to be used. Most of the problems that have been found are because that the new transponder does not work in the same way as the old transponder, T2, and it is good to know what difference it is between them.

6.2 ASCII port T3 transponder

During development of the program the T3 base stations were sending raw data corrections that alternate with quick jumps all the time. They also send several corrections for the same satellite, which is totally wrong. Therefore a test was done by logging corrections from a T3 base stations ASCII port and corrections from a T2 transponder that gets corrections from the T3 base stations data link. The corrections are coming from the same reference station, but from two different outputs. So the data to those logs should be exactly the same.

Corrections via T2 transponder:

$PRGPS,671,5AEE,09,9,A505,1BF5B5418B,15FA8FF876,1AFFE915C2,13F758E3E4,170058D6C5,1605CC445,1F00840802,1103F8417B,0306420AEE*4B

Corrections via ASCII port:

$PRGPS,671,5AEE,09,9,05A5,EE0A420603,7B41F80311,020884001F,45C44C0516,C5D6580017,E4E358F713,C215E9FF1A,76F88FFA15,8B41B5F51B,*67

After contact with the manufacturer it was found that the T3 base station byte shifted the corrections that was sent via the ASCII port to the network, so the correction EE0A420603 should be 0306420AEE (two hexadecimal letters is one byte). The correction that was broadcast at the radio link was correct, and therefore the test with logging from T2 and T3 ASCII gave different results. Since the corrections on the data link were correct, no one had noticed the error. All users, except NIMS, get corrections from the data link. The problem is a program bug, which will be fixed in next program version. To be able to continue with this project NIMS has a function to do this swapping in the code. This function has to be removed when next program version for T3 is implemented.
6.3 672 Messages

One problem that has been known is that a T3 transponder did not use corrections from a T2 base station for about five minutes each hour. This problem was noted, but nobody knew the reason. Logging with NIMS gave these plots.

![Figure 6.1: Plots of Range error](image)

In these plots ESSA, ESGG and ESSB are T2 base stations while ESDB and ESSP are T3 base stations. In these plots it is possible to see that the T2 base stations suddenly are sending corrections that are near zero for all satellites at the same time, and goes back to normal values after some seconds, repeated for about five minutes. This behaviour is for corrections from T2 base stations, but the T3 base stations is not affected.

Analysing the original corrections that are sent in to NIMS during this time period.

```
$PRGPS,672,6A07,3F,7,0E00,1900020017,1000030024,12FFFE001C,04FFFE0074,1EFFD30090,0E FFFF002C,07FECC00C1*31
$PRGPS,672,6507,3F,7,0E00,1900020017,1000030024,12FFFE001C,04FFFE0074,1EFFD30090,0E FFFF002C,07FEED00C1*42
$PRGPS,671,4DB4,3F,6,1200,040176BF75,10FACA5525,0E049B9B2D,12F83ED11D,99FFE0818,87 FFFB08C2*69
$PRGPS,671,5AEE,0F,8,0011,18FA56E92D,04035AC075,19FEEF8018,10FD5E5425,3EF2A318A3,12 F8C4C61D,0E05D1942D,"
$PRGPS,671,38BC,0F,7,0011,0405B8E775,07FC3442C2,0E0811D42D,10FE862C25,12FB84F01D,18 FEE1002D,1903033F18,"
$PRGPS,672,6A07,3F,7,0E00,1900020017,1000030024,12FFFE001C,04FFFE0074,1EFFD30090,0E FFFF002C,07FECC00C1*31
```

Those corrections show that the correction type (letter 9 - 11) is changing between 671 and 672. Correction type 671 means normal correction that is broadcast nearly all the time. 672 are broadcast when satellites are updating its almanac (position). Those 672 messages do not co-operate with the T3 GPS receiver.
Modern GPS receivers handle updating of almanac without 672 messages, and therefore the T3 transponders does not make any difference between 671 and 672. Therefore when a T3 transponder receives a 672 message from T2 base station, it detects that the correction is wrong, and stops to navigate with differential corrections. The solution to the problem is to turn off the 672 messages from T2 base stations.

6.4 Correction messages from T3

Sometimes when looking at plots they can be very "jumpy" and that corrections for one satellite is going down to zero and back for a couple of minutes.

![Figure 6.2: Range error plot for four base stations](image)

In this case it is done for ESSP which is a T3 base station. If exactly the same graph is plotted without ESSP base station the graph looks much smoother and nicer.

![Figure 6.3: Range error plot for three base stations](image)
In the first plot, all the base stations are jumping. This is because the satellite is visible for all base stations. When one base station stops sending corrections for this satellite, the satellite cannot be used to calculate the normalisation term, which will jump, and affect that the result for all base stations will jump.

The problem is that the T3 base station is much more sensitive and stops to broadcast corrections for one satellite just to start again the next second. This raises the question if the corrections should be filtered and send corrections for some extra seconds, or the base stations are just going to send corrections for what happens just for the moment. It also raises the question about filtering of the normalisation term.

### 6.5 Spike in ESDB

ESDB is an airport that is going to be used for large scale landing tests. Therefore it has a SCAT 1 reference station, to improve the integrity for the broadcast correction. SCAT 1 means that the base station consists one reference stations and one integrity reference station (more like a GBAS base station) to fulfil higher requirements (see chapter 2.4). Plotting corrections from this reference station for 24 hours shows the following graphs. Note that the scale is different in the plots.

![Figure 6.4: 24 hour plots from ESDB base station](image)

The GPS satellite orbit earth with 12 hours interval, and in the graph it is possible to see that the satellites are visible twice a day. It is also possible to see that it is corrections for 27 satellites even that the GPS system is said to have 24 satellites. This day it has been three active satellites in spare. The plot that does not show any corrections is satellite identities that do not belong to any active satellite at the moment.

It is possible to see "spikes" in the corrected signals, there are two spikes that is for all visible satellites and one spike for two satellites at the same time. Plotting one of those satellites.
Zooming in and looking at the values of those ”spikes” it is possible to see that all of the ”spikes” has the value -655.36. Look at one of the original correction for one of the spikes that affect all satellites

"980818 15:35.16
$PRGPS,671,38BC,0F,9,0850,04800000AF,0A800000BC,0D80000007,10800000E3,1280000D1,13800000C3,1680000019,188000006C,1B8000005E,*19"

Decoding of the range value for those corrections to binary form gives 1000 0000 0000 0000, which in RTCM 104 means ”do not use this satellite”. So the spikes in ESDB means that the corrections are not going to be used. When the transponders gets this message it stops to use differential corrections, so those spikes will lower the availability.
6.6 One week test

During the 7-14 October 1998, a one week test was done logging statistical data for the base stations.

<table>
<thead>
<tr>
<th></th>
<th>ESSA</th>
<th>ESGG</th>
<th>ESSB</th>
<th>ESDB</th>
<th>ESSP</th>
<th>ESMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean number of satellites</td>
<td>9,61</td>
<td>7,79</td>
<td>9,46</td>
<td>7,64</td>
<td>8,65</td>
<td>4,62</td>
</tr>
<tr>
<td>Updated corrections (%)</td>
<td>96,53</td>
<td>99, 97</td>
<td>99,91</td>
<td>99, 99</td>
<td>99,97</td>
<td>99,86</td>
</tr>
<tr>
<td>Range error inside interval (%)</td>
<td>99,05</td>
<td>96,33</td>
<td>92,64</td>
<td>99,60</td>
<td>66,09</td>
<td>73,51</td>
</tr>
<tr>
<td>Connected (%)</td>
<td>99,99</td>
<td>100</td>
<td>100</td>
<td>99,27</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Checksum</td>
<td>99,99</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>99,99</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 6.1: Statistical data from one-week test

6.6.1 Mean number of satellites

Average of number of satellites the base station is sending corrections for during the test period. The parameter is affected of antenna position, antenna cable and parameters set in reference station.

The ESMS base station has very low values depending on too long antenna cable, making that sometimes it only broadcast corrections for three satellites and the aircraft cannot use the corrections to navigate perfect. This problem is noticed and is going to be fixed. The base station ESDB is used for landing test and has different parameters for satellite over the horizon to leave correction. Therefore it is understandable that it has lower mean value of satellites.

6.6.2 Updated corrections

How many percent of the times the program updates values with new correction from base stations. This parameter is more a test of the network than the corrections. It would be more interesting to make this tests with data from a monitor station, then it would be possible to see how many corrections that are broadcast via the data link. This parameter is also affected of the update interval the program has, and the frequency that the base station is sending corrections to the network.

6.6.3 Range error inside the interval

Parameter that warn if correction for one satellite at one base station differ more than an interval value from the mean value for all base stations. Tells how good the correction is, compared with corrections from other base stations.

The parameter affects of how well the antenna position is measured, multipath, and that parameters in reference station are correct. It is also affected of where the base station stands, compared with other base stations. Because if the base station stands far away from other base stations it has a natural variation in the corrections, that will be included in this parameter. The value is also affected of how the interval parameter is set in the program.

ESSP has the lowest rate inside the limit, and in the CARD project it is known that this base station has wrong parameter in the altitude of the antenna, which is immediately shown in this
parameter. ESDB has highest rate inside the limit, which is because the base station are specified to fulfil higher requirements for the landing tests.

6.6.4 Connected

If NIMS does not receive any corrections from the base station for a specific time, NIMS treat the base station as not working. The number of times the program uses an old correction is the parameter No_of_old_corrections * update_interval, in this case 5*4=20 seconds.

In this test ESDB has the lowest value, but that is because the base station is rebooted each night. It would be more interesting to see if it sends out data on the data link, which could be done with a similar test with data from a monitor station.

6.6.5 Checksum

Some of the correction messages are going wrong in the transmission from base station to NIMS, which makes NIMS going down. This can be avoided by calculating the checksum as XOR for all bytes within the message and compare with the broadcast checksum. This is more a test of the network, and at ESSP it is verified that it is a modem at the base station that sometimes introduces errors in the message.

6.7 Multipath test

At Monday the 24’th of August 1998, a multipath test was performed at ESSP base station. This test was made with a 1m² big sheet metal that was held around the antenna at one to two meters distance. Trying to get the satellite signals to go via the sheet metal. The test was done during one hour when the sheet metal was placed around the antenna, and writing the exact times, that was synchronised with computer time. Plots from this time period.

![Figure 6.6: Multipath test at ESSP](image-url)
No significant effect from the multipath test could be seen in the diagrams. One reason may be that during the test period the corrections was not behaving very well, and affects described in 6.3 and 6.4 was shown.

### 6.8 Large correction for satellite 22

During the 8’th to 9’th of October the Range error was drifting away for satellite 22 up to 7000 meters. This occurred for all the T2 base station but not for the T3 base station.

After check in at status for this satellite at The U.S. Coast Guard Navigation Centre (NAVCEN) [15] it was verified that this satellite was unusable from 7/10 to 17/10 1998. The problem is how the base station handle this satellite. The base stations should detect that the satellite is wrong, and they should not broadcast corrections that are this large.
7 Conclusions and Recommendations

This project shows an interesting concept to achieve integrity monitoring by distributed redundancy in the NEAN network. An integrity concept is specified that shows that by comparing corrections, monitor stations and average the number of satellites that are seen, will be able to detect most of the error sources for the differential GPS corrections in NEAN. The aim with a monitoring program that checks corrections and gives a statistical status for each base station in real time without any extra equipment is satisfied.

Differential corrections in current NEAN network are investigated and several errors and "strange" behaviour was found. Most of this was regarding differences between new and old type of base stations. But it is also found that base stations from different manufactures are required to achieve high integrity.

Monitor station is an important tool to achieve high integrity and should be included in NEAN as fast as possible, both to estimate accuracy, but more importantly because it is just monitors that really check what has been broadcast at the data link. No integrity program can be really reliable if there is not a check of the corrections at the data link.

The program is estimating a normalisation term that is used to normalise corrections from different base stations so that they can be compared, but the normalisation method that has been developed introduces noise in the output range error, therefore it is necessary to filter the normalisation term. To do long time testing, data have to be saved in log files, and better tools to plot data have been developed for Matlab and Microsoft Excel.

The statistical tests have found that ESSP (Norrköping) and ESMS (Malmö) are the worst base stations, both of them need their position to be remeasured and ESMS needs also a shorter antenna cable so it does not loose so many satellites.

After development and testing of NIMS it would be interesting to give it an active role in the integrity process, to allow NIMS to shut down base stations, and to tell which satellites that not are going to be used.
List of References

[1] CARD, CNS Applications Research & Development
http://www.lfv.se/ans/card/

[2] Required Navigation Performance for Precision Approach and Landing with GNSS Applications
R.J. Kelly and J. M. Davis.

Bradford W. Parkinson and James J. Sprinkler Jr.
AIAA, 1995

David Wells
Canadian GPS associates, 1986

[5] Understanding GPS, principles and applications
Elliott D. Kaplan
Artech House Publishers, 1996

[6] Description of the FAA’s Local Area Augmentation System (LAAS)
Federal Aviation Administration (FAA)
Ronald Braff MITRE technical report 1997
http://gps.faa.gov/Library/Documents/tech-frame.htm

CARD Project
Luftfartsverket, March 1997

RTCA, Washington DC, 1991

Working group meeting, Atlantic City 16 - 27 September 1996
GNSS Integrity monitoring presented by J C Lawson

Jan Palmqvist
Department of Electrical Engineering, Linköpings University, 1997

International Civil Aviation Administration (ICAO)
Middle East air navigation planning and implementation regional group
Cairo, December 1997
[12] Local Area Augmentation System (LAAS) update
Raymond Swider, Ronald Braff, John Warburton
http://gps.faa.gov/Library/Documents/documents.htm

[13] RTCM recommended standards for differential Navistar GPS service
version 2.1 RTCM paper 194-93/SC104-STD
January 1994

[14] The GNSS Transponder T2 / R2
Integration of external systems
LFV GNSS Transponder, Revision 4

[15] GPS Active NANU list as of 10/13/98 at 8:09:59 AM EST
The U.S. Coast Guard Navigation Centre (NAVCEN)
http://www.navcen.uscg.mil/ado/GpsActiveNanu.asp