“GPS synchronisation of WAM systems - pros and cons”

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ABSTRACT:

There has been much debate about the synchronisation of Wide Area Multilateration (WAM) systems and in particular the use of GPS based synchronisation, some of it well informed but some less fact-based. The purpose of this paper is to provide clarity and technical evidence to allow potential users and regulators to properly assess the relative merits and risks of different WAM synchronisation technologies.

The paper starts with an overview of the main WAM synchronisation techniques which have been developed and deployed to date. This is based on information contained in the EUROCONTROL WAM Report (Neven, Hogen (NLR) Quilter, Weedon (Roke), 2005). It then focuses on GNSS Common View synchronisation and its strengths and potential vulnerabilities.

The effects of potential disruption to GPS on the validity and accuracy of the surveillance data output of a WAM system are discussed. This includes both natural effects such as solar flares and their impact, together with man made effects such as jamming either accidental or intentional.

The arguments are supported by a theoretical analysis and lab test results which back up the experience from operational VigilanceTM WAM systems which have been using GNSS common view synchronisation successfully for over 10 years.

BIBLIOGRAPHY

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MULTILATERATION SYSTEM OVERVIEW

Any multilateration system operates by determining the distance between one or more transmitters and one or more receivers.

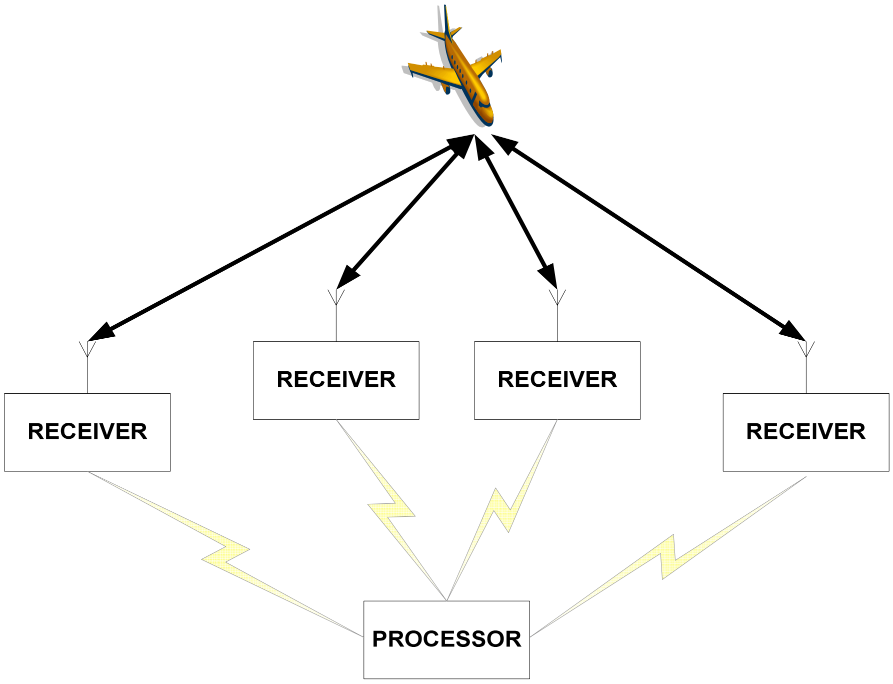

FIGURE 1 MAIN MULTILATERATION SYSTEM ELEMENTS

Figure 1 shows how a multilateration system comprises of a number of spatially separate multilateration receivers (the minimum for 3D position, four, is shown), a multilateration processor unit and a means of communication between them.

When the time of signal transmission is known, as for GPS, the distance from transmitter to receiver can be calculated by measuring the Time Of Arrival (TOA) and subtracting this from the time of transmission. However, multilateration systems of interest operate using the 1090 MHz Secondary Surveillance Radar (SSR) transponder transmissions from aircraft, of which the time of transmission is not known.

Given this, the Time Difference Of Arrival or TDOA may be used. By subtracting TOA calculated by one receiver from another, the common transmission time will cancel, assuming that each receiver is synchronised or a common clock mechanism is employed (see below).

Each TDOA value corresponds to a hyperboloid in space on which the transmitter (i.e. aircraft) position must lie (in the absence of any error). By way of example, the following figures illustrate the surfaces in space corresponding to three TDOA values and how they intersect to show aircraft position.

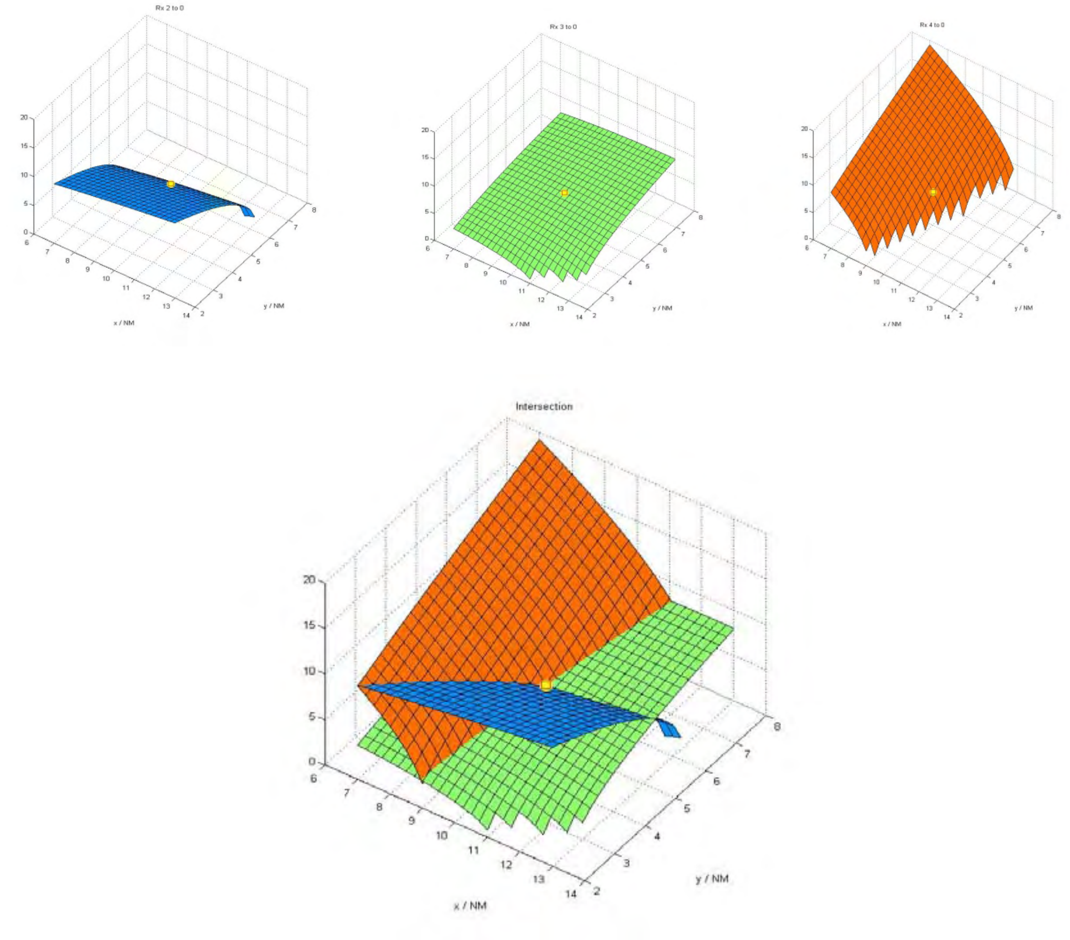

FIGURE 2 INTERSECTING HYPERBOLAS

As shown in this example, if the signal is received at 4 receivers three surfaces are produced and the intersection of those surfaces indicates the 3D target position.

SYNCHRONISATION

In order to calculate the TDOA there must be some method of synchronising the clocks that measure the TOA. The TOA data from each receiver must therefore have a common timebase. This can be implemented using a common clock or distributed clock. For a distributed clock system, synchronisation can be achieved by one of two basic methods:

1. A synchronisation transmitter, located in line-of-sight view of all receivers, is used to transmit a unique SSR signal at some defined rate or in response to a request. As the position of synchronisation transmitter and receivers and thus the path lengths are known, this can be used to calculate the difference in receivers clock offsets.

2. Alternatively, a GNSS receiver may be incorporated inside each multilateration receiver. By using data from the GNSS receivers, the offset of the 1pps between the various receivers can be calculated and thus the TOAs referred to a common timebase within the Multilateration Processor. Very high accuracy synchronisation can be achieved with high-end receivers and Rubidium oscillators using advanced common view processing of raw data reported by the receivers and subsequent disciplining of the oscillators. Lower accuracy synchronisation may be implemented by correcting the TOAs by some value as output by the GNSS receiver.

OVERVIEW OF SYNCHRONISATION METHODS

The diagram below shows the hierarchy of the various synchronisation techniques in use on WAM systems. The techniques and their strengths and weaknesses are described in more detail in the following Sections.

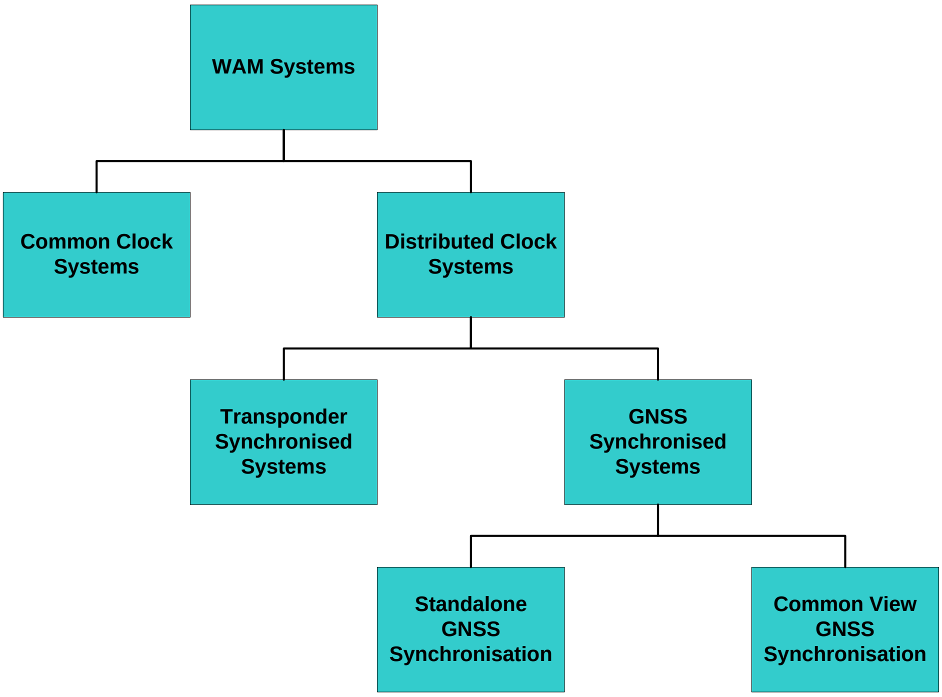

FIGURE 3 WAM SYNCHRONISATION HIERARCHY

Common clock systems use a simple receiver with most of the complexity at the central processing site. Common clock systems receive the radio frequency (RF) signals from the aircraft and down convert to an intermediate frequency (IF). This IF signal is transmitted from each receiver to a central site over a custom analogue link. Conversion to baseband or video and subsequent digitisation is then carried out at the central site with reference to a common clock for each receiver.

With this architecture, there is no need to synchronise each of the outlying receivers with each other as digitisation occurs at the central site. However, the group delay between signal reception at the antenna and digitisation at the central site is large as it includes the delays of the custom analogue link which must be accurately known for each receiver. This means both the receive chain and the data link must be rigorously calibrated to measure group delay.

This architecture benefits from a simple receiver with low power consumption and most of the complexity in the central multilateration processor. However the signal delay between the antenna and the multilateration processor puts stringent requirements on the type and range of the link. The location of the multilateration processor must typically be at the centre of the system to minimise communication link distances.

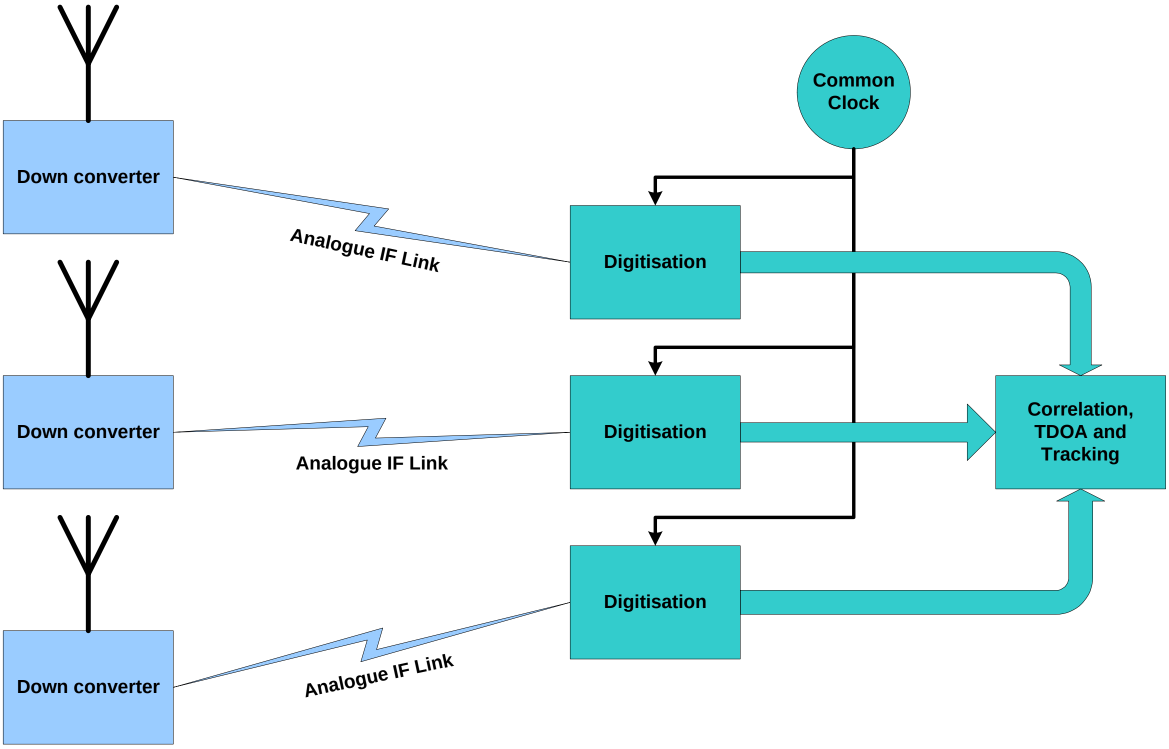

FIGURE 4 COMMON CLOCK ARCHITECTURE

Distributed clock systems use a more complex receiver to reduce the demands on the data link. The RF signal is down-converted to a baseband or video signal and then the digitisation, code extraction and TOA measurement are all done at the receiver. This gives flexibility in the data link as just the SSR code value and the TOA need to be transmitted to the processing site from each receiver. Any digital data link can be used and the link latency is not critical. However a mechanism must be used to synchronise the clocks at the local sites. This is the approach most commonly used in modern WAM systems.

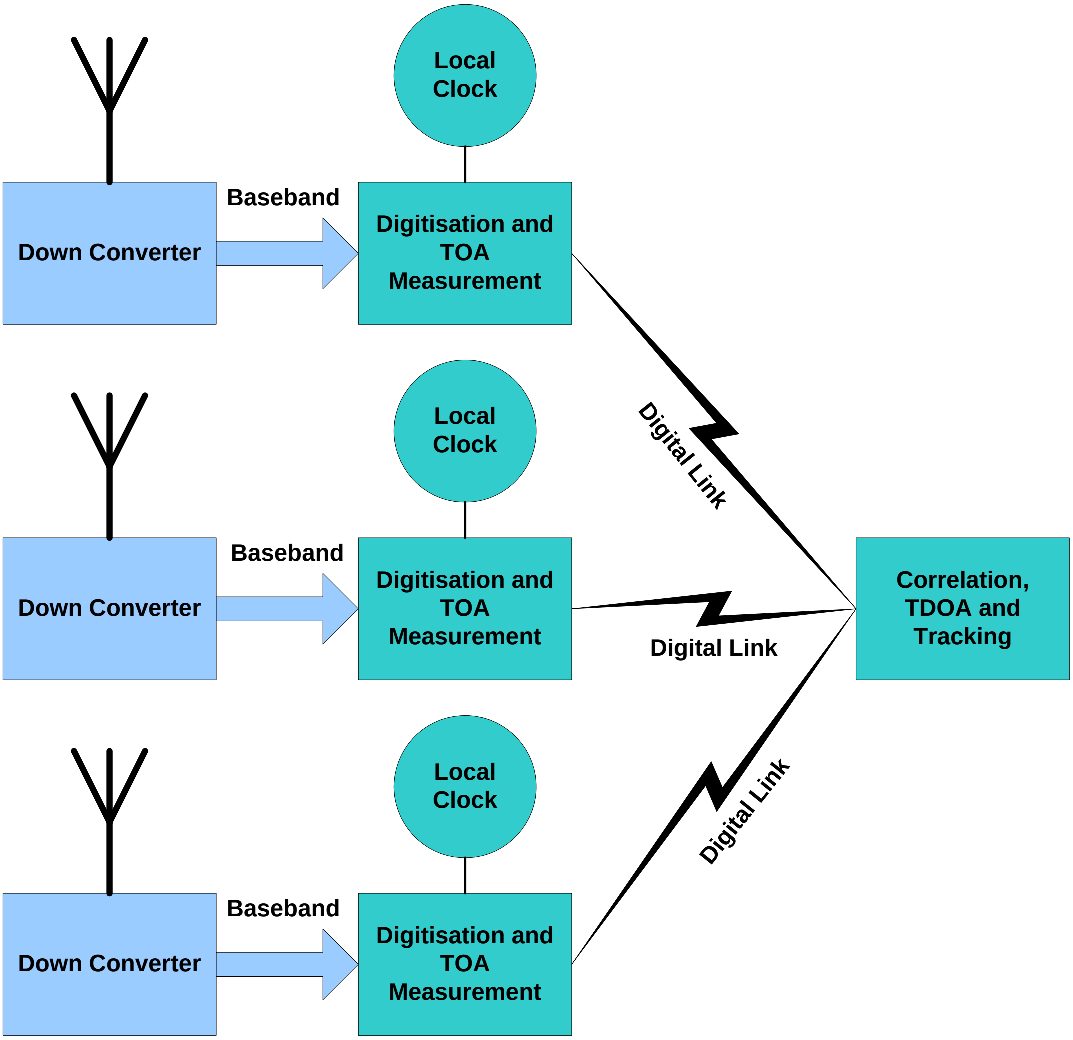

FIGURE 5 DISTRIBUTED CLOCK ARCHITECTURE

Transponder synchronised systems use transmissions from a reference transponder to tie up the clocks at each of the receiver sites. The reference timing signal and the aircraft's SSR transmission pass through the same analogue receive chain. This means that common delays cancel out the delay bias caused by the analogue components. This allows an accurate system to be produced for short baselines. At longer baselines atmospheric delays have an impact reducing accuracy. The synchronisation transponder does not need to be co-located with the central multilateration processor but it does need to have line of sight to each of the receivers. For a WAM system this can mean that tall masts may be needed and some preferred receiver sites may not be useable. It is possible to use multiple synchronisation transponders on an extended system providing every pair of receivers can be linked to every other pair by means of common references.

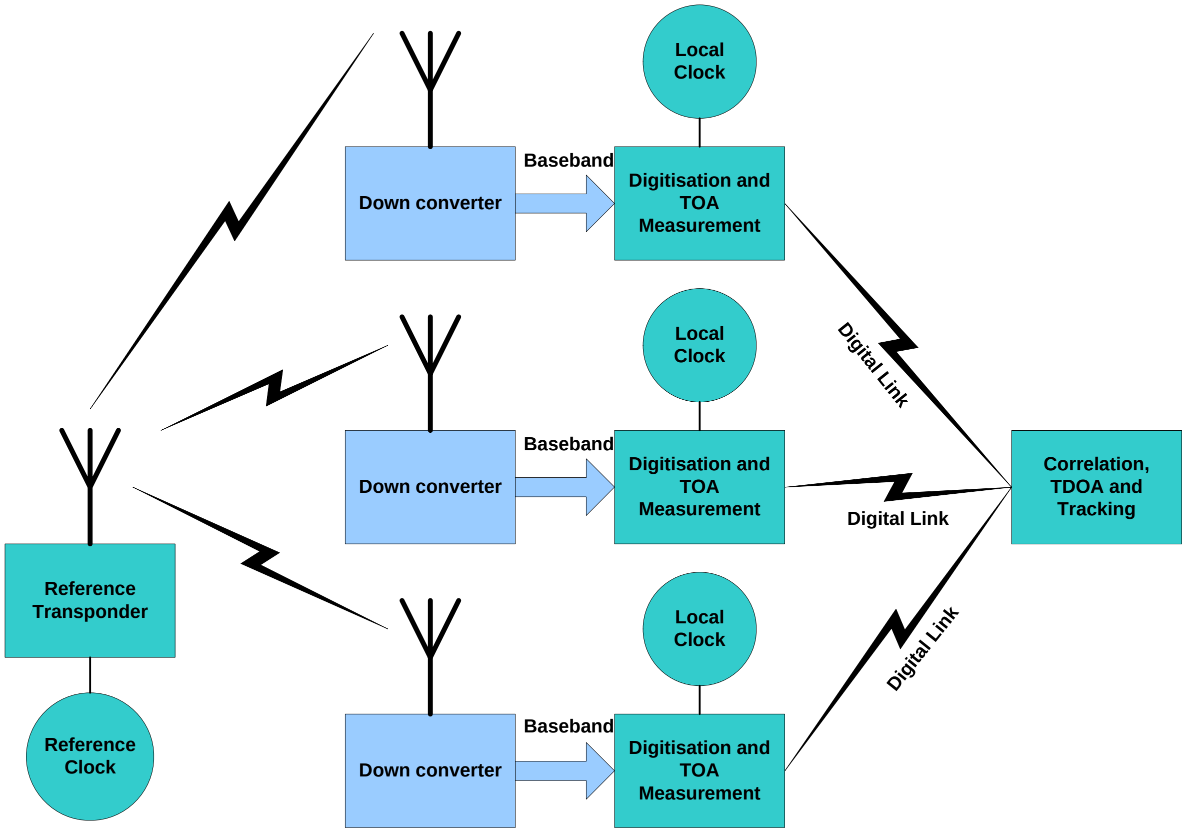

FIGURE 6 TRANSPONDER SYNCHRONISED ARCHITECTURE

An external common timing reference such as a Global Navigation Satellite System (GNSS) can be used to provide a common timing reference for each of the receivers. The timing of the GNSS systems is maintained very accurately as this is essential for navigation accuracy. For example the GPS constellation provides accurate time to within 100ns of UTC. This time can be used as a common reference for the receivers. For multilateration systems it is only the time difference between receiver sites that is of interest not the absolute time. It is therefore possible to synchronise the receivers of a multilateration system to within 10-20ns by using a GPS disciplined oscillator at each site. GNSS synchronised systems are much easier to site than common clock and transponder systems as they do not need tall towers for synchronisation and any digital data link can be used. Integrity checking of the GNSS timing relies on the integrity of the GNSS receiver so selection of a suitable receiver with RAIM capabilities is important. The architecture is illustrated below.

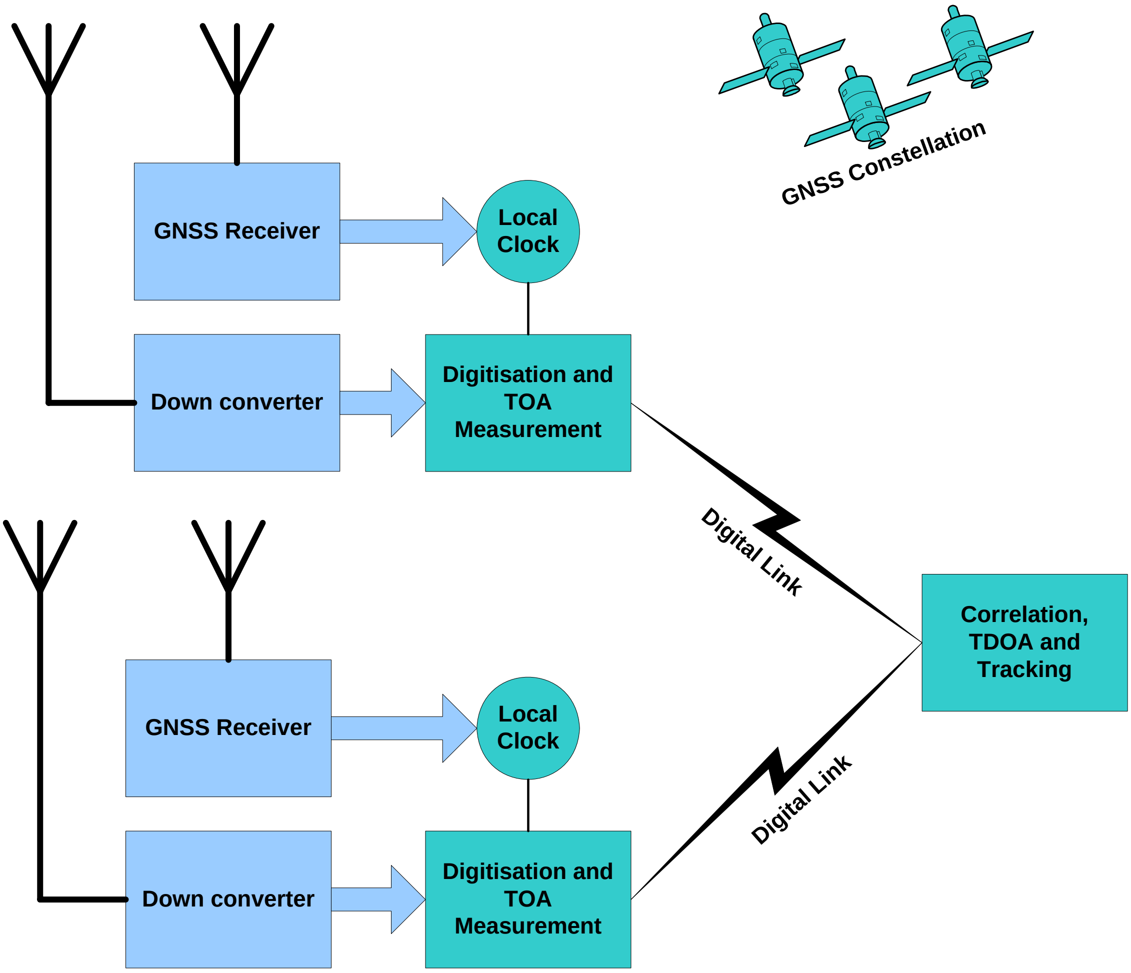

FIGURE 7 GNSS SYNCHRONISED ARCHITECTURE

COMMON VIEW GNSS SYNCHRONISED SYSTEM

For situations where the standalone GNSS synchronisation between receivers is not accurate enough a common view synchronisation method can be used. Common View systems use GNSS satellites that are in view of all the receivers and calculated differential data - i.e.: satellite A at Rx. A – satellite A at Rx. B. This allows a large amount of the errors sources to be removed as they are common between signals, and thus provides a significantly more accurate synchronisation solution. Sub-nanosecond accuracies can be achieved using this technique. The calculated synchronisation data may either by applied directly to the TOA data at each receiver, or to the TOA data upon arrival at the central site. In either case, no GNSS receiver is required at the processing site as the data has been captured at the receivers. Due to the common view processing approach RAIM like integrity checking of the quality of the synchronisation data between sites can be implemented ensuring a high integrity solution.

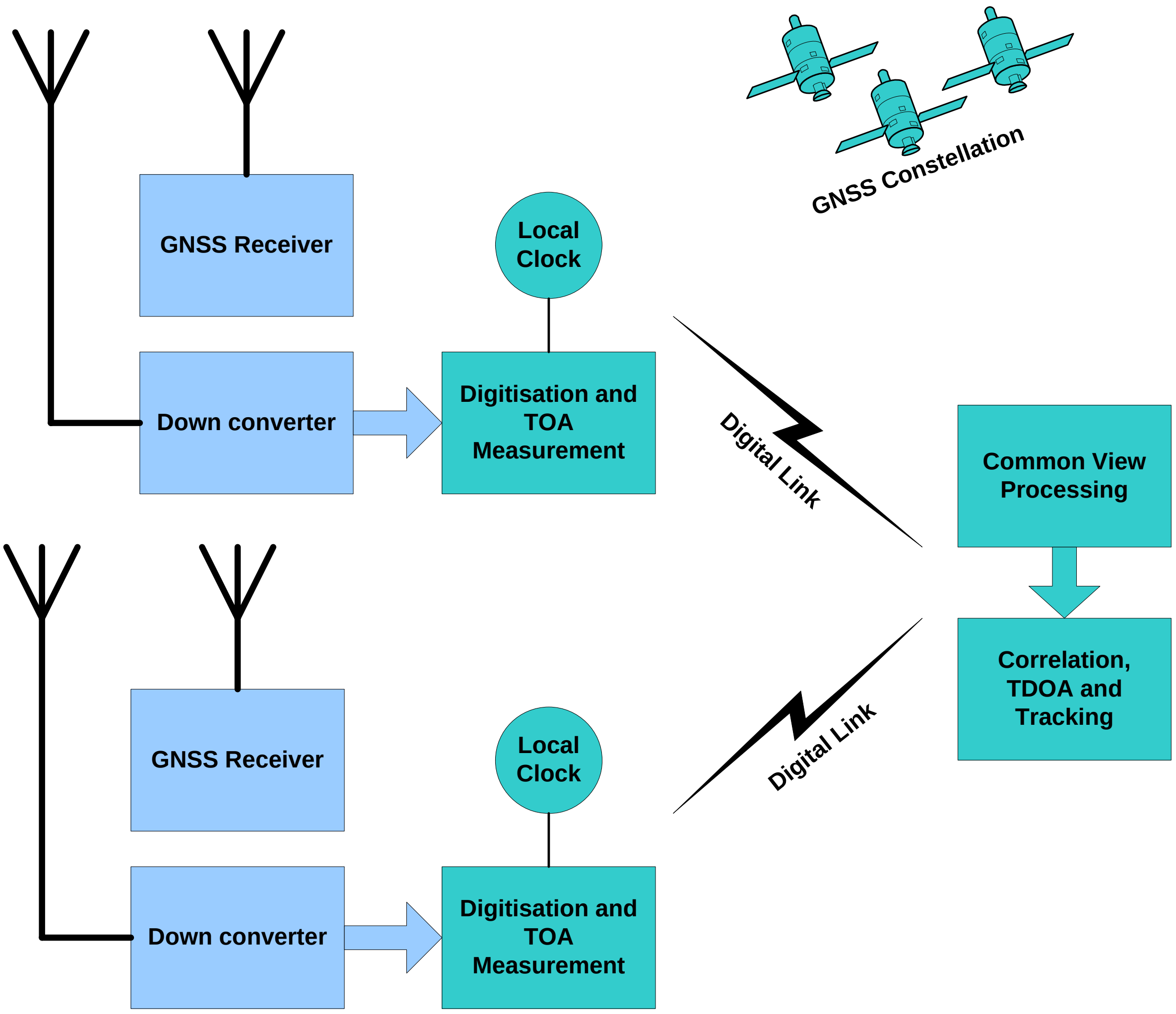

FIGURE 8 COMMON VIEW GNSS SYNCHRONISED ARCHITECTURE

SYNCHRONISATION SUMMARY

The characteristics of the various synchronisation schemes with respect to their application to WAM are summarised in the list below.

- Common Clock Systems
  - Baseline limited by link requirements
  - Limited accuracy
- Transponder Synchronisation
  - Baseline limited by line of sight requirements
  - Accuracy reduces with baseline
- Standalone GNSS Synchronisation
  - Unlimited baseline (non line of sight)
  - Lower accuracy
- Common View GNSS Synchronisation
  - Baseline effectively unlimited for surveillance applications (non line of sight)
  - High accuracy

It can be seen that the use of GNSS for synchronisation can bring significant benefits, particularly when using the common view GNSS method. However, concerns have been raised about a dependence on GNSS and in particular its vulnerability to outages either natural or intentional jamming. The second half of this paper addresses those concerns.

WAM SYSTEM VULNERABILITY TO GPS OUTAGES

The solar flare problem:

Patches of electron density irregularities develop inside the ionosphere, these patches affect the propagation characteristics of radio waves passing through them. This causes scintillation of the GPS signal, resulting in rapid fluctuations of phase and amplitude of the carrier, which can lead to degradation in positioning accuracy and in extreme cases the loss of carrier lock with a satellite. Areas of high latitudes or equatorial regions experience ionospheric scintillation more frequently than the mid latitude regions.

As we head towards the next solar maxima in 2012 the expectation is that these ionospheric time-varying electron density irregularities that cause scintillation will increase in magnitude (measured in Total Electron Content (TEC)) and frequency. However we are currently experiencing less sun spot activity than expected during this part of the 11 year solar cycle. One theory is that there is another much longer under lying solar cycle lasting 100s of years and we have recently experienced the “grand maxima” around 1985 and will now see a slow long term trend of reduced solar activity for the next few hundred years.

Other causes of GPS outages are also possible, including system failures or intentional jamming. The effects of these outages will be the same as described below. In the case of intentional jamming however, it should be noted that this will typically be at a signal level such that only one WAM receiver would be affected, therefore if the system has been designed with redundancy, WAM system performance would not be significantly impacted in this case.

GPS STANDARD OPERATION FOR POSITION FIX

For standard operation a GPS receiver must lock onto four satellites before a position fix can be obtained. Assuming the receiver has a relatively unobstructed view of the sky it will receive signals from multiple GPS satellites (typically at least 6) and will be able to select the satellites with high signal strengths and favourable geometric positions with which to make the position measurement. Ionospheric scintillation that reduces the signal strength or even removes some satellites from this available set will impact the potential quality of the position fix.

Satellites at lower elevations are more likely to be affected by ionospheric scintillation as the propagation path will pass through a larger section of the ionosphere.

It will be manufacture specific how the tracking loops in a GPS receiver cope with rapid fluctuation of the GPS carrier and if the signal is lost how quickly the carrier is reacquired. This will impact the severity scintillation the receiver can cope with and the probability of an outage of a given duration.

GPS COMMON VIEW SYNCHRONISATION

An important difference with this synchronisation method is that any receiver pair only need to receive a signal from a single GPS satellite in common view to operate. Therefore, this architecture will use the strongest remaining signal in the event of interference, thereby having a significantly higher tolerance to jamming or solar activity.

20 MINUTE GPS OUTAGE

A question has been asked by the EUROCONTROL Multilateration Task Force (MLTF) about the impact of a 20 minute GPS outage on a WAM system employing GPS synchronisation. This will obviously be manufacture dependant, but before a general answer can be given it is important to be clear on what is meant by a "GPS outage".

For the purpose of this discussion it is assumed this means that all satellites experience a prolonged simultaneous 20 minute fade sufficient to cause a complete GPS outage across all of the WAM receivers. This represents an absolute worst case because in practise interference effects would be more localised.

As has been outlined earlier a GPS receiver requires 4 satellites to generate a position fix whereas GPS common view synchronisation only requires a single satellite. If scintillation is continually causing the receiver to lose lock on the satellites and the receiver has a significant re acquisition time, for example 30 seconds, it is possible that for prolonged periods of time the receiver is unable to simultaneously lock onto four satellites for sufficient time to make a position fix measurement.

With GPS common view synchronisation we only require a single satellite to be in lock at any one time, thus the probability of losing all satellites for the 20 minute period will be significantly lower.

THEORETICAL IMPACT OF A COMPLETE 20 MIN GPS OUTAGE ON VIGILANCE™ WAM

The length of time a WAM system using GPS common view synchronisation can coast without receiving GPS timing corrections will be design dependant, but will ultimately be limited by the stability of the local timing references in each receiver.

Vigilance™ uses Rubidium clocks to maintain short term stability of the local receiver clock and employs GPS common view synchronisation to provide longer-term corrections (once every 60 seconds) to maintain long term stability across the system.

As soon as the system goes into the GPS outage the synchronisation between receivers will start to deteriorate. This will cause a gradual degradation of position accuracy as the outage continues. The loss in timing accuracy the system can tolerate before it fails to meet the system accuracy requirements will depend on the accuracy requirement of the deployment and the position and number of receivers. By over dimensioning the system with additional receivers the maximum HDOP within the coverage area can be reduced, relaxing the synchronisation requirements on the system and increasing the time duration the system may operate without GPS data.

The Rubidium clocks used have an Allan deviation of less than 3 E -11 (t = 1s). If it is assumed that at the point we go into the GPS blackout we have synchronisation across the network, then after 20 minutes without any corrections we will have a standard deviation timing error relative to a perfect reference source of about 1 ns as shown below.

$3\times10^{-11}\times\sqrt{1200}=1.04\times10^{-9}$ Standard deviation of timing error after 20 minutes

If we assume that the error between receivers is uncorrelated the differential error between receivers is given below as 1.47 ns

Differential standard deviation timing error = $\sqrt{\left(1.04\times10^{-9}\right)^2+\left(1.04\times10^{-9}\right)^2}$ =1.47 ns

To convert the expected timing error into a horizontal positional accuracy figure we need to make an assumption about the geometry of the deployment, if we assume the system has been configured for a worst case HDOP of 25 within the coverage area, this would result in an additional positioning error of 11m.

Given that the Technical Specification for WAM Systems ED-142 (EUROCAE WG-70, 2010) defines a horizontal position accuracy of 350m rms for the en-route application, it can readily be seen that it would be straightforward to design a system to cope with an additional degradation of 11m due to this effect with minimal impact.

PHYSICAL MEASUREMENT OF IMPACT OF 20 MIN GPS OUTAGE ON VIGILANCE™ WAM

The theoretical calculation of the synchronisation error implies that by allowing a small additional margin for impaired synchronisation in the configuration of the deployment the system should be able to continue to function during a GPS outage of 20 minutes.

To verify this result a simple test was conducted to measure the drift in the timing measurements when the GPS synchronisation data was removed.

TEST 1:

Three receivers were configured in parallel with their SSR antenna inputs connected to an SSR signal generator configured to generate a single SSR reply once per second, see Figure 9. The resulting TDOA messages generated in the central processor are then recorded. The system is left to run for a short time to establish an average TDOA for receiver 0 to receiver 1 and receiver 0 and receiver 2. Then the GPS antenna is disconnected from receiver 0 to simulate a complete GPS outage for that receiver.

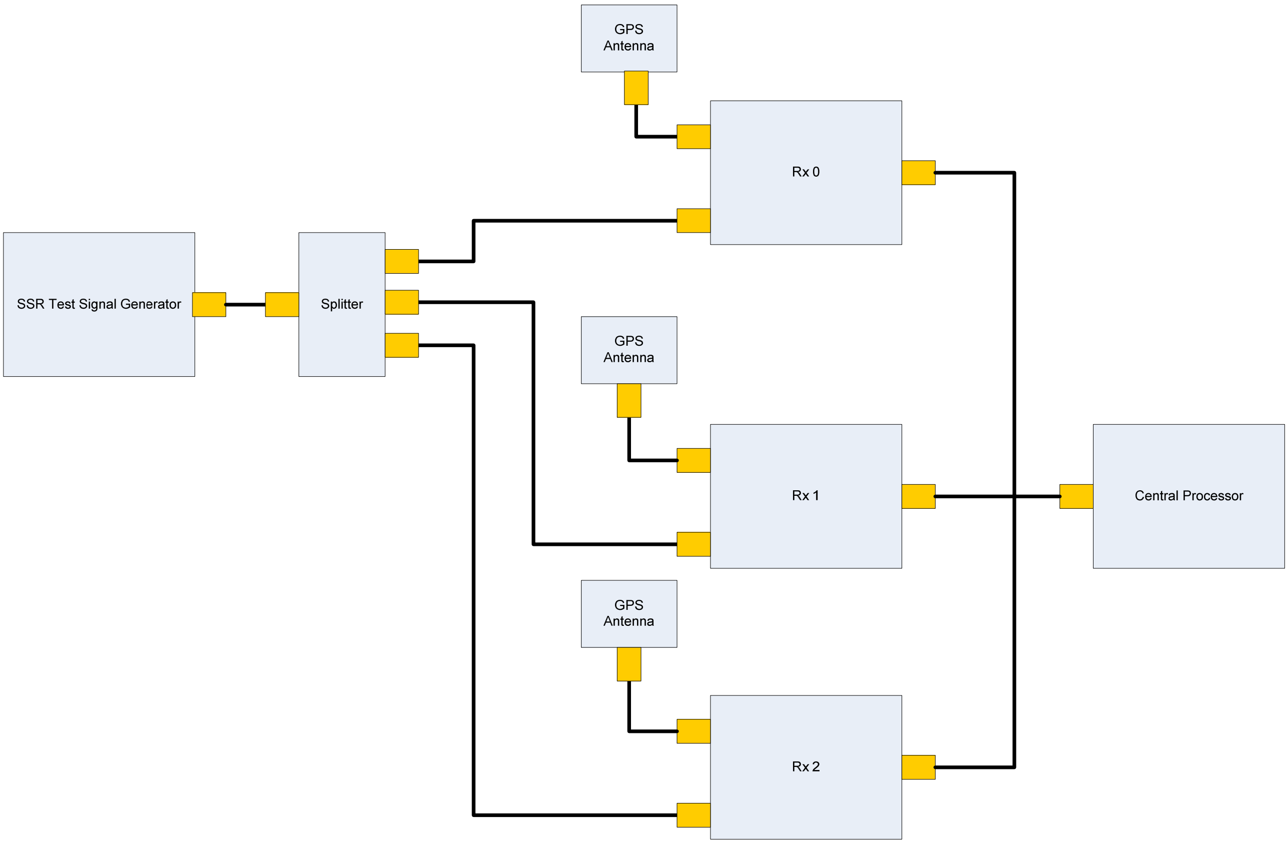

FIGURE 9 TEST SETUP

TEST 1 RESULTS:

The graph below shows the deviation from the mean TDOA, rx0 to rx1, rx0, rx2. The mean is calculated over the period before the GPS antenna is disconnected. The GPS antenna is disconnected at time t = 0.

As can be seen from Figure 10 the synchronisation deteriorates from the point the GPS antenna is disconnected, however after 20 minutes the average synchronisation error is about 1 to 1.5 ns which is in line with the theoretical value derived above.

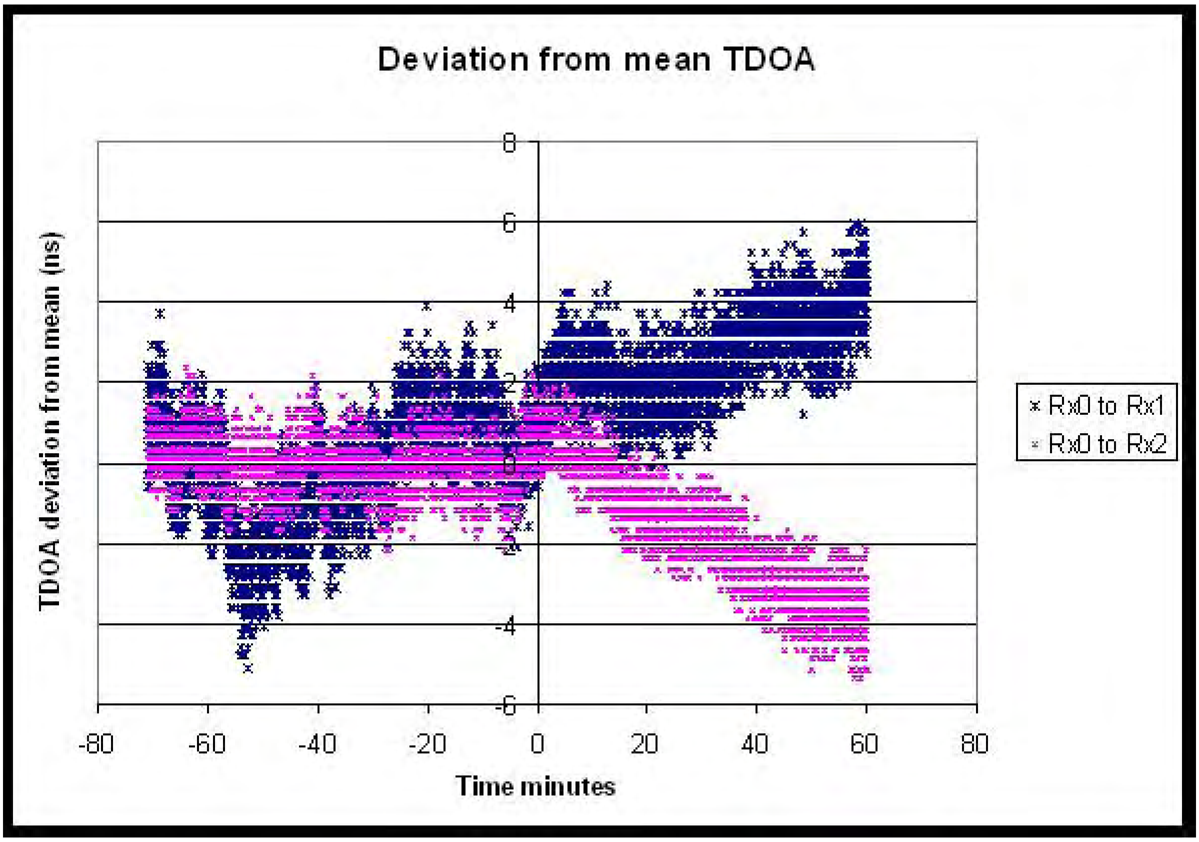

FIGURE 10 TDOA DEVIATION DUE TO GPS OUTAGE ON REFERENCE RECEIVER (HIGH DRIFT RB)

TEST RESULTS 1A:

Test 1 was repeated using a different Rubidium clock in rx0 which has a slightly higher performance than in test 1. The results are shown in Figure 11 although the close correlation of the two series makes the results difficult to distinguish, therefore the results are repeated in Figure 12 after averaging the results over a 10 second sliding window.

The performance of the free running receiver is improved due to the higher quality Rubidium clock, making the synchronisation error in first 20 minutes of free running hard to distinguish at all in this single test run.

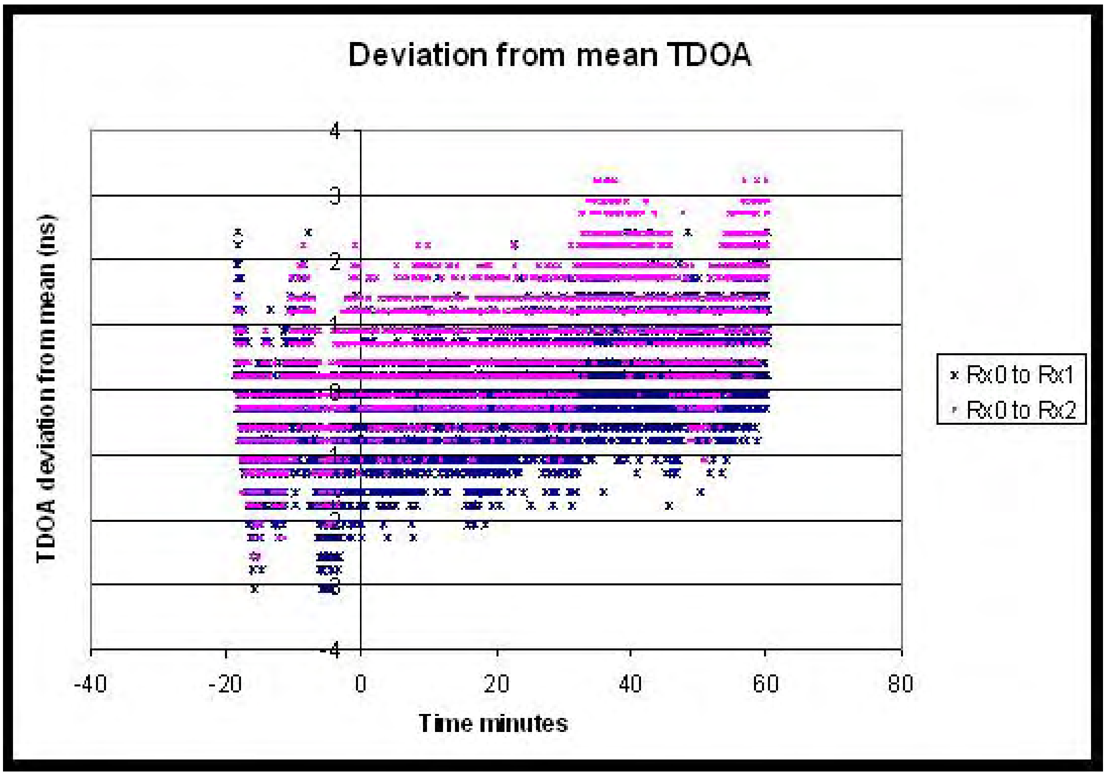

FIGURE 11 TDOA DEVIATION DUE TO GPS OUTAGE ON REFERENCE RECEIVER (LOW DRIFT RB)

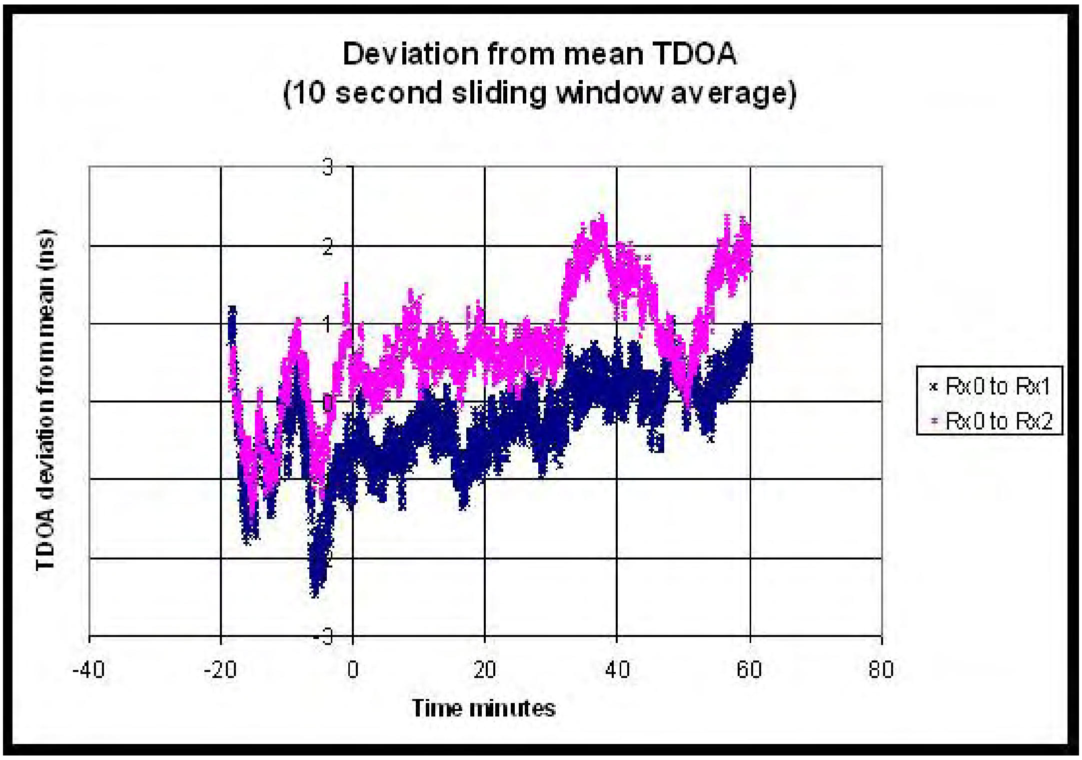

FIGURE 12 TDOA DEVIATION DUE TO GPS OUTAGE ON REFERENCE RECEIVER (LOW DRIFT RB) RESULTS AVERAGE OVER A 10 SECOND SLIDING WINDOW

TEST 2

The test system was configured as for test 1 and data logged under normal operating conditions for 30 minutes, then the GPS connectors for all receivers were disconnected and the results logged. The results show an error of about 2.5 ns after a 20 minute outage.

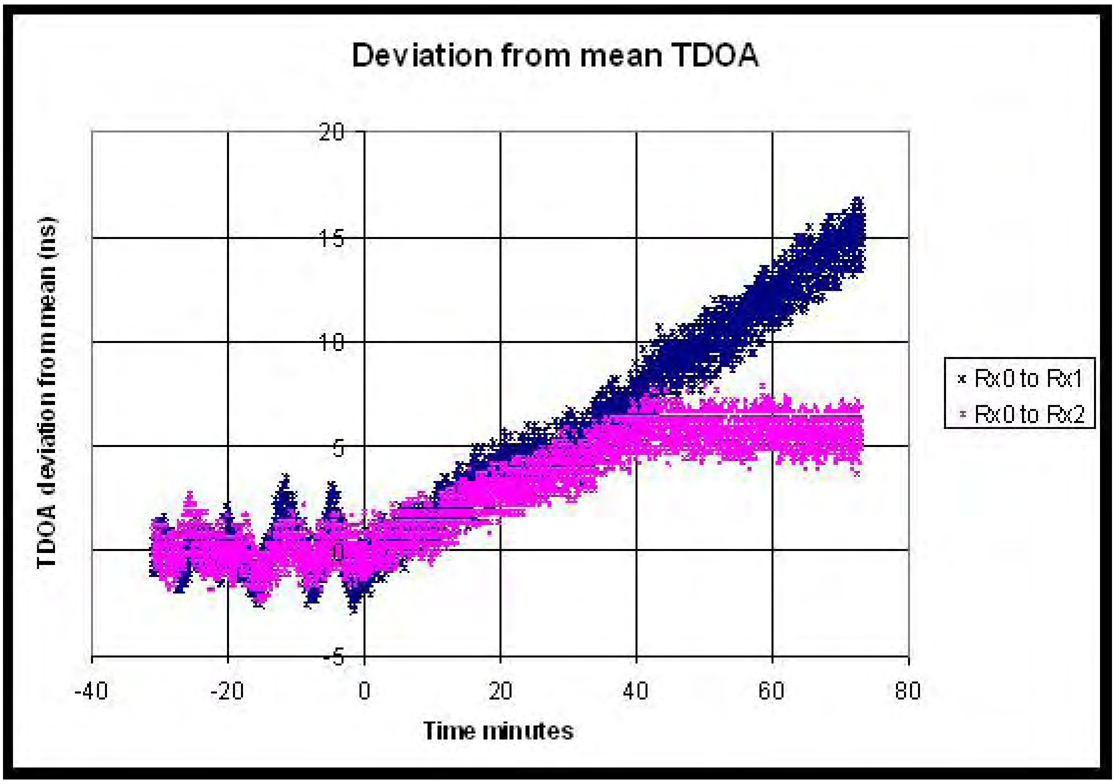

FIGURE 13 TDOA DEVIATION DUE TO GPS OUTAGE ON ALL RECEIVERS

CONCLUSIONS:

These results indicate that the Vigilance™ common view GPS synchronisation scheme is robust and can tolerate complete GPS outages for extended periods. In these test we have considered the proposed 20 minute outage period and from the test results the synchronisation between receivers can drift by around 2 to 3ns by the end of the 20 minute period. This is aligned to the theoretical analysis and is considered to be a tolerable degradation in performance which can be readily catered for in the system design.

Therefore, a WAM system using GNSS common view synchronisation can be designed to provide full performance during a complete outage of all GPS signals for 20 minutes.