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HITT TRAFFIC

NLR

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Wide Area Multilateration
Report on EATMP TRS 131/04
Version 1.1

W.H.L. Neven (NLR)

T.J. Quilter (RMR)

R. Weedon (RMR)

R.A. Hogendoorn (HITT)

Approved by author:	Approved by project manager:	Approved by project managing department:

Summary

This report describes the results of a study on Wide Area Multilateration (WAM) performed by a consortium lead by the National Aerospace Laboratory (NLR), and further comprising of Roke Manor Research (RMR) and Holland Institute of Traffic Technology (HITT) for EUROCONTROL in the context of TRS131/04.

The study addresses the advantages and disadvantages of WAM, analyses what performance can be achieved with this surveillance technique and what is required to provide a service at least equivalent to an MSSR/Mode S radar service.
Recommendations for further study and analysis are given for a wider deployment of WAM.

Contents

(81 pages in total)

Objective of the document

This document provides an overview of Multilateration techniques when applied in a Wide Area surveillance environment. It gives a detailed performance analysis of Multilateration systems and describes the advantages and disadvantages of WAM systems compared to current radar systems.

Organisation of the document

The document consists of sixteen chapters, corresponding to the sixteen items describing the task of the study in the TRS.

First, we will give an introduction to Multilateration and describe a number of different airborne transmission types that may be used in a WAM system with a high level assessment of their feasibility, followed by an overview of the different existing WAM system architectures.

Then we will analyse in detail the performance of WAM systems based on 1090 MHz airborne transmissions, both for the horizontal plane and for altitude.

The integration of WAM data into a multi-sensor tracker is investigated, and an overview is given of WAM systems currently available on the market.

We will indicate the average cost of a WAM system, draw a number of conclusions, and give recommendations for further study.

References

1. Guidelines for the Application of the ECAC Radar Separation Minima, Edition : 2.0, Released Issue
2. Radar Surveillance in En-Route Airspace and Major Terminal Areas, SUR.ET1.ST01.1000-STD-01-01, Edition 1.0, Released Edition

1 Introduction to Multilateration

Multilateration techniques have been successfully deployed for airport surveillance for quite some time now. Nowadays, these same techniques are used for larger areas such as en-route or approach areas. Such systems are called Wide Area Multilateration (WAM) systems.

Multilateration is a form of Co-operative Independent Surveillance: it makes use of signals transmitted by an aircraft to calculate the aircraft's position. Since multilateration systems can make use of currently existing aircraft transmissions, WAM systems can be deployed without any changes to the airborne infrastructure.

For the processing of the signals on the ground, appropriate receiver stations and a central processing station are required.

It is important to notice that, depending on the type of signal to be used, certain equipment may have to be mandated for use aboard the aircraft.

1.1 Principle of Multilateration

A multilateration system consists of a number of antennas receiving a signal from an aircraft and a central processing unit calculating the aircraft's position from the time difference of arrival (TDOA) of the signal at the different antennas.

The TDOA between two antennas corresponds, mathematically speaking, with a hyperboloid (in 3D) on which the aircraft is located. When four antennas detect the aircraft's signal, it is possible to estimate the 3D-position of the aircraft by calculating the intersection of the resulting hyperbolas.

When only three antennas are available, a 3D-position cannot be estimated directly, but if the target altitude is known from another source (e.g. from Mode C or in an SMGCS environment) then the target position can be calculated. This is usually referred to as a 2D solution. It should be noted that the use of barometric altitude (Mode C) can lead to a less accurate position estimate of the target, since barometric altitude can differ significantly from geometric height. With more than four antennas, the extra information can be used to either verify the correctness of the other measurements or to calculate an average position from all measurements which should have an overall smaller error.

The following example should clarify the principle. It describes a WAM system consisting of 5 receiver stations (numbered 0 ... 4) see picture
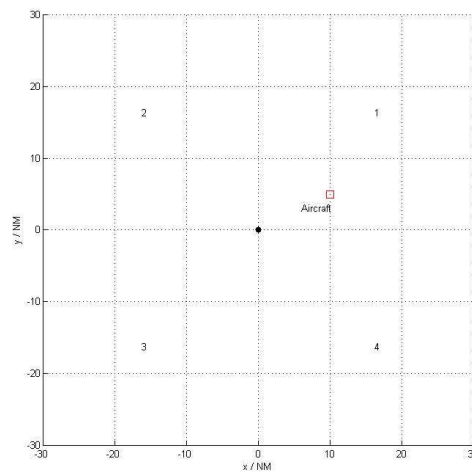
Figure 1 Five Receiver Layout

Assuming that the aircraft's signal is detected at all sites, the first 3 pictures show the hyperboloids corresponding to the TDOA of the signal at sites 0 and 2, 0 and 3, and 0 and 4, respectively. The central processing station calculates the intersection of all the hyperboloids as shown in the final picture.
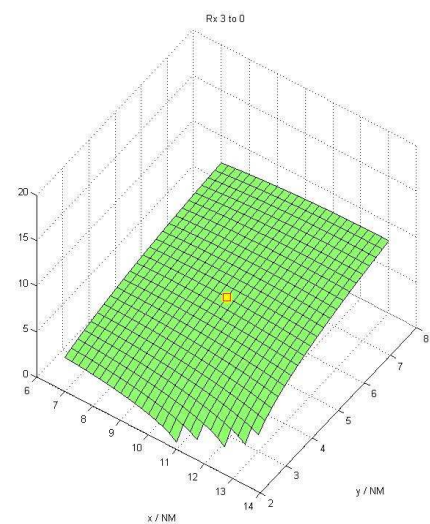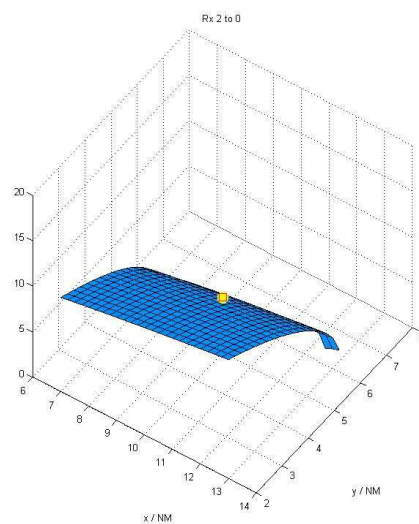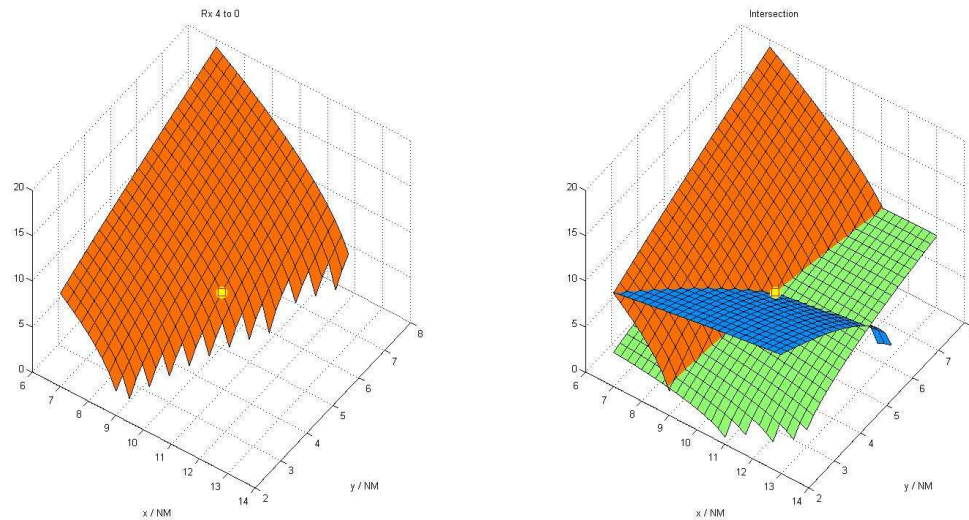
Figure 2 Intersecting Hyperboloids

There may be more than one solution to the multilateration calculation as the hyperboloids may intersect in two places. Typically the correct solution is easily identified.

The geometry of the system has in general a large impact on the accuracy that can be obtained: As long as the aircraft is inside the enclosing 2D-area of the ground antennas, the calculated position will have the highest accuracy; outside this area the accuracy will degrade quickly.

A distinction can be made between active and passive multilateration systems: a passive system consists only of receivers whereas an active system has one or more transmitting antennas in order to interrogate e.g. an aircraft's SSR transponder. The main advantage of an active system lies in the fact that it is not dependent on other sources to trigger a transmission from an aircraft.

2 Airborne transmission types

Since most aircraft are already equipped with a significant number of antennas for the purpose of Communications, Navigation, and Surveillance, it is interesting to investigate which of these transmission types could be used successfully in a WAM system in terms of possibility of aircraft identification, and detection performance.

2.1 Surveillance signals

In this section we will describe a number of surveillance signals and their potential use in a WAM system.

2.1.1   Primary Surveillance Radar (PSR)

The primary radar system used to be the main surveillance system for ATC, but this role has been taken over by more modern radar systems. It consists of a high-power transmitter and a receiver. The radar beam from the transmitter is reflected by an aircraft (or any other object in the path of the beam) and the reception of a reflected signal allows the position (consisting of range and azimuth) to be measured.

Due to some major disadvantages of this system (high power and thus expensive, clutter sensitivity, lack of aircraft identification and altitude information), it has been superseded by the secondary surveillance radar (SSR).

PSR will not be considered for use in a WAM system in the remainder of this document.

2.1.2   Secondary Surveillance Radar (SSR)

The secondary surveillance radar (SSR) system is the successor of the PSR system and was designed to be an improvement in terms of cost, reliability, and performance.

It consists of a ground component (the radar) and an airborne component (transponder) onboard an aircraft. The radar emits a signal (at 1030 MHz) which triggers a response from the airborne transponder (at 1090 MHz). When the radar detects this response, it can determine the position (range, azimuth) of the aircraft.

As part of the transponder message, the aircraft sends identification information (Mode A code) or pressure altitude information (Mode C code), depending on a bit encoded in the radar signal. An SSR receiver in a WAM system might have a problem to distinguish between a Mode A and a Mode C reply; this will be described in section 9.2.

Since all commercial aircraft are equipped with SSR transponders, this makes an obvious candidate for a WAM system. Aircraft identification is possible (although not always uniquely due to non-unique codes) through the Mode A codes, and SSR receivers are generally available. A limitation of the SSR antenna signal is the line-of-sight visibility that is required between the transponder and the ground receiver: when the path is obscured by e.g. a building, the signal strength will degrade very strongly.

The maximum range of an SSR signal is about 250 NM (depending on the sensitivity of the receiver), but especially in regions with high density traffic interference problems may limit the useful range.

Within a passive WAM system, the update rate will depend on other surveillance sources, whereas an active WAM system can provide a high update rate if required.

2.1.3 SSR Mode S

SSR Mode S is a new type of radar surveillance system that offers a number of significant advantages over conventional SSR systems. It makes use of the same frequencies as SSR (1030 MHz uplink, 1090 MHz downlink) and is backwards compatible with SSR systems. It allows selective interrogation of a transponder, makes use of a 24-bit aircraft address for identification, unique for each aircraft, and allows 25-foot altitude resolution (versus 100-foot in an SSR system).

Some of the restrictions of SSR also apply to Mode S: the line-of-sight visibility and interference problems due to RF occupancy.

Mode S is internationally standardised and is already present in many commercial aircraft; within the next few years all IFR and VFR aircraft will be equipped with Mode S transponders. Since the same technology is used for the reception of SSR and Mode S signals (from a WAM point-of-view), the use of SSR Mode S is an obvious improvement over SSR allowing reliable identification of aircraft.

2.1.4 Mode S Squitter

An aircraft equipped with a Mode S transponder emits a signal, called Acquisition Squitter, approximately once per second. The acquisition squitter consists of a Mode S All-call reply containing the 24-bit technical address of the aircraft. The high update rate makes them very useful for a passive WAM system.

2.1.5 ADS-B link technologies

Automatic dependent surveillance — broadcast (ADS-B) technologies have been under development for more than a decade. The fact that an aircraft broadcasts messages makes them very suitable for a passive WAM system. Three different types of link technology are currently under development: Mode S Extended Squitter, VDL Mode 4, and UAT.

2.1.5.1 Mode S Extended Squitter

Mode S Extended Squitter is agreed to be the first global datalink for international commercial flight. It makes use of the Mode S transponder to emit periodically, with a frequency up to about 6 Hz, the aircraft's 24-bit technical address accompanied by either aircraft state information or callsign. Just as with Acquisition Squitter, the high update rate is ideal for a passive WAM system.

2.1.5.2 VDL Mode 4

VDL Mode 4 was developed as a generic data link supporting communications, surveillance and navigation functions. The applicability was initially restricted to surveillance applications like ADS-C and ADS-B, but the latest development in ICAO has removed all regulatory restrictions so VDL Mode 4 is now available as a CNS data link. The system supports broadcast and point-to-point communications in traditional air-to-ground manner as well as air-to-air. VDL Mode 4 is a narrow-band system operating on multiple 25 kHz channels in the VHF band (108-137 MHz). Access to the channels is synchronised to UTC and based on the Self-organising TDMA scheme that allows all communicating units to select free slots for transmissions. A number of protocols are available in support of the various modes of communication. A VDL Mode 4 system has an operational coverage of 200 NM.
During the process of developing the ICAO provisions for VDL Mode 4 as an ADS-B system, it was commonly understood that Mode S Extended Squitter should address short range applications requiring rapid updates (like ACAS) and that VDL Mode 4 should support long range applications (like ADS-B). Although a VDL Mode 4 system is less restrictive with respect to line-of-sight visibility between aircraft and ground station than SSR technology (due to the lower frequency used by VDL Mode 4), other effects (propagation, earth curvature, weather) may have an impact on the signal quality. VDL Mode 4 contains identification data which means it is potentially useful to a WAM system. However the low bandwidth of the signal means that TDOA accuracy is likely to be very poor making it unsuitable for surveillance. Instead of a TDOA method, a time of flight positioning method could be implemented, estimating the time of transmission from the slot time information. Such a solution would still be hampered by the low bandwidth and also the accuracy of the estimated time of transmission

would be limited by the accuracy of the GNSS equipment aboard the transmitting aircraft (400 ns as 2-sigma value).

2.1.5.3 UAT

Universal Access Transceiver (UAT) has been developed within the US as an ADS-B system. UAT is a broadband system operating on one 1 MHz channel in the L-band (960 – 1215 MHz). The US are proposing to use 978 MHz, but there is no international agreement on the availability of this channel. Because UAT is not likely to be implemented within the ECAC area anytime soon, it is not a primary candidate for a WAM system.

The bandwidth of the system of 1 MHz, however, appears to allow more accurate TDOA measurements than e.g. VDL Mode 4, but less accurate than the 1090 MHz system, which has a bandwidth of 6 MHz.

2.2 Navigation signals

The currently available aircraft navigation systems are based on a few very distinct physical concepts, i.e. inertial, magnetic, pressure (for the vertical plane) and finally radio navigation. For the assessment of possible sources for WAM only radio navigation based technologies are applicable. In this context two distinct methods of radio navigation exist, i.e. the passive radio navigation techniques in which the aircraft navigates on received radio information only and the active radio navigation techniques in which the aircraft participates both as receiver and transmitter of information.

The following navigation systems can be categorised as passive RF navigation techniques from the aircraft's point of view: ADF, VOR, ILS, MLS, GPS and low frequent hyperbolic navaids (DECCA, OMEGA and LORAN-C). These RF navigation systems are from the WAM point of view of no interest and will not be discussed further.

As active RF navigation technique, of interest for WAM purposes, from the aircraft's point of view only the DME and the Radio Altimeter are in use. These two systems will be discussed in more detail concerning their prospects for WAM application.

2.2.1 Radio Altimeter

The Radio Altimeter is a system used by aircraft during the approach phase-of-flight for determining its ground clearance. The principle is straightforward: radio pulses are transmitted in a narrow beam in vertical direction to the ground, which reflections are received. The radio pulse's time of flight determines the aircraft-ground distance.

This guidance technique is not capable of supporting WAM techniques due to the fact that the signal is not transmitted omni-directionally but as a narrow vertical beam. For this reason the assessment of RA applicability for WAM is not further detailed.

2.2.2 DME

Using DME (Distance Measurement Equipment) the distance between aircraft and beacon can be determined. A DME station is generally collocated with other radio beacons such as VOR, ILS and MLS. Together with VOR the aircraft is capable of determining its position unambiguously via direction (VOR) and distance (DME). In line with ICAO Annex 10, the DME frequencies are paired with the VOR, ILS and MLS frequencies, i.e. for each VOR, ILS or MLS frequency a DME counter frequency is available. Using one frequency selector in the cockpit a combination is chosen, which means that the airborne DME is activated each time an ILS, VOR or MLS frequency is selected for guidance.

Two different kinds of DME exists: narrow band DME (DME/N) and the precision (DME/P), which is only used in combination with MLS and therefore rarely used. The precision of DME/P is higher due to the fact that a steeper Gaussian shaped pulse side slope is applied than for DME/N.
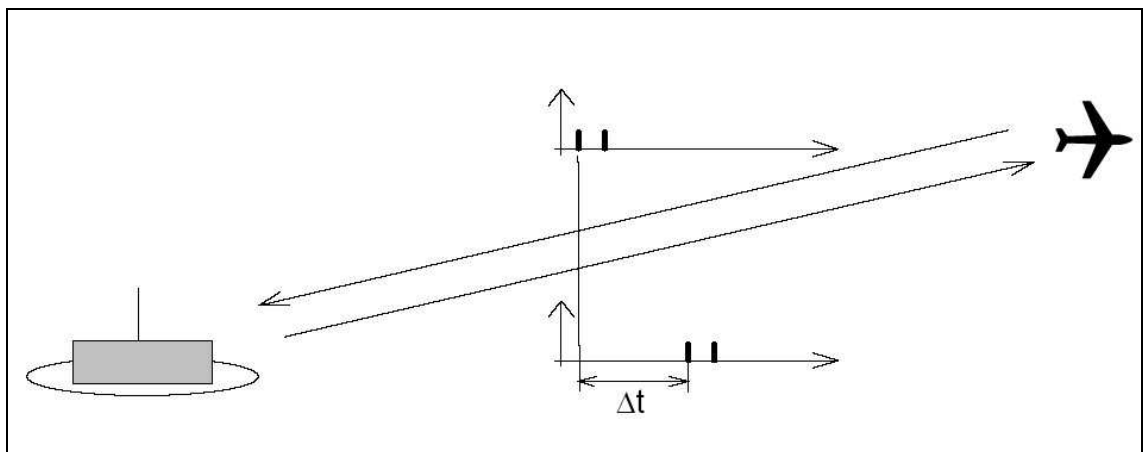
Figure 3   The principle of DME

The principle of DME resembles somewhat the secondary radar (SSR). The DME system has two physically separated sub-systems, an airborne interrogator and a ground transponder. The aircraft emits an omnidirectional pulse pair, which is received by and triggering the ground transponder. After a fixed delay the ground transponder on its turn emits a pulse pair. The airborne DME frequency applies the 1025 – 1150 MHz range with 1 MHz spacing providing for 126 frequencies, while the ground transponder applies the 962 – 1213 range. Two DME pulse

modes (distinguishing only by inter pulse pair time spacing) double the available number of channels to 252 of which 199 channels are available for civil aviation. The double-pulse repetition rate generally is in the range of 15 to 150 Hz (during start-up the repetition rate is higher for identification purposes). The aircraft – DME beacon distance is determined by the pulse's time-of-flight (compensating for the fixed transponder delay). Note that the measured distance between aircraft and DME is the slant range distance (i.e. line of sight) and not the horizontal distance.

According to specifications a DME transponder shall be capable of accommodating at least 100 aircraft in parallel. The on-board equipment also receives the beacon transmits initiated by other traffic, from which its 'own' signals must be filtered and used for the on board DME indicator. The DME is designed for en route guidance, which means that it supports guidance up to 250 NM, limited by line of sight. The combined air-ground accuracy of the system is approximately 0.5 NM. DME equipment shall be compatible with ICAO standards recommended in Annex 10 and conform to the Eurocae ED57 MOPS.

For assessing the applicability of this system for WAM its equipment availability in aircraft, the signal availability during the various phases of flight (especially en route and approach), signal reach (in NM), the update rate and finally its identification capabilities must be determined. Also important but more difficult to assess is the accuracy and integrity that can be obtained. Concerning equipment availability, DME can be considered as standard aircraft equipment, mandatory for aircraft that support IFR usage and civil aviation, however also for aircraft that are generally used under VFR conditions this system is generally available. DME signal availability is close to 100% dependant of Airspace Class. Since DME 'pairs' with VOR, ILS and MLS , DME signals are transmitted whenever the aircraft is operated under IFR. This means for Class A airspace the DME signal availability is 100%. The 15 to 150 Hz update rate makes it an excellent means of tracking aircraft. Since the DME signal reach is limited by line-of-sight, i.e. in the order of 250 NM, the signal should be suitable for WAM application in the domestic en route domain. The only disadvantage of DME for WAM purposes is the fact that DME does not provide means of aircraft identification. In the case of WAM application this identification should come from other sources.

Concerning the position accuracy of WAM based on DME, as was stated above, the accuracy of standard DME is better that 0.5 NM. This can be seen as a lower limit for the WAM accuracy based on DME, however it is probable that using several ground systems the obtained WAM accuracy while using airborne DME signals is (much) higher. This accuracy is to be determined by simulation and field tests. Another aspect is the system integrity of WAM as based on DME. DME ground transponders are passive repeaters of received signals without any intelligence.

Filtering its own signal responses is performed by the aircraft's interrogator. This filtering functionality shall be included in WAM ground systems in order to distinguish all aircraft. The integrity requirements of WAM shall be defined and subsequently it shall be determined whether this integrity requirement is feasible for DME based WAM under all traffic conditions.

It can be concluded that the prospects of DME for WAM application look very promising.

2.3 Communications signals

2.3.1 VHF Direction Finder

In the context of communication signals VHF (voice) communication between pilot and ATC might be used of WAM as well. Already VHF Direction Finder stations provide for efficient controller's surveillance functionality (see fig. 2). Pilot's VHF voice is used by the Direction Finder, which consists of a directional antenna and a VHF radio receiver, for determining the direction of the transmitter. Distance from direction finder to the aircraft cannot be retrieved by a single direction finder system, for this at least two stations are required. DF equipment is of particular value in locating lost aircraft and in helping to identify aircraft on radar. The obtained direction finder lines presented onto the radar plot in general efficiently helps the controllers to identify the related airspace vehicle.
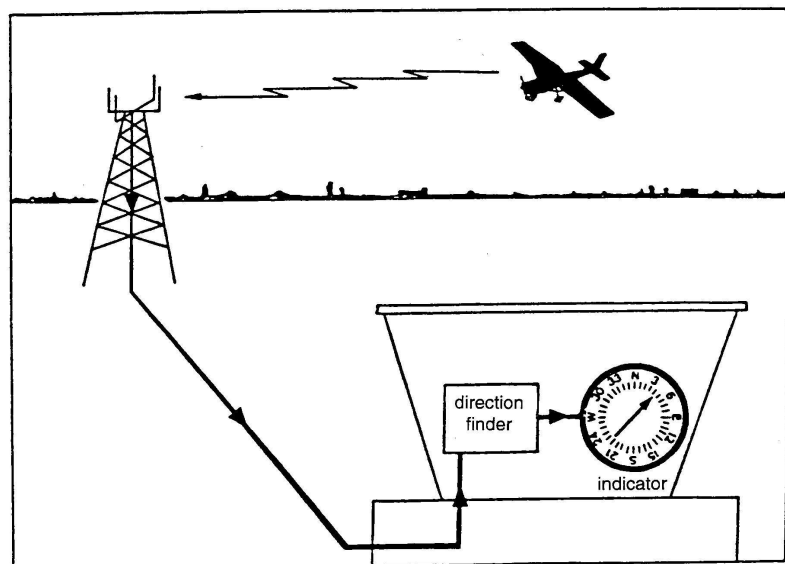

Figure 4 Principle of VHF Direction Finder

For assessing the applicability of the VHF DF for WAM, its related equipment availability in aircraft, the signal availability during the various phases of flight (especially en route and

approach), signal reach (in NM), the update rate and the signal's identification capabilities must be determined. Considering system availability almost all aircraft are VHF voice com equipped. Possibly in the near future VHF voice com capability will be mandatory for all airspace users. Therefore system availability is close to 100% for all Airspace Classes and equal to 100% for Class A airspace. Omnidirectional signal availability and related update rate however is low: VHF DF can only be applied when the pilot communicates by VHF com, which might result in limited and irregular position updates.

Concerning the VHF DF integrity and accuracy, the systems integrity can be considered as high, especially when antenna redundancy is applied. The systems accuracy depends on the physical geometry of the system and the involved number of antennas. In general the angle accuracy of the directional antenna is better than 0.5 degrees.

From the assessment above it can be concluded that the prospects of VHF DF for WAM seem limited, mainly due to the limited and irregular VHF signal availability.

2.3.2   ACARS

ACARS (Aircraft Communications, Addressing and Reporting System) is a digital system of communications between aircraft and ground stations. It is in operational use by many, but not all airlines in Europe, North America, and the Pacific Rim; in other areas its use is less common.
ACARS makes use of a number of VHF channels around 131 and 136 MHz in AM mode with a low bandwidth. This low bandwidth means that TDOA accuracy is likely to be very poor making it unsuitable for surveillance.
Furthermore, communication between aircraft and ground stations occurs most frequently close to airports; in other flight parts there is likely not enough communication to feed a WAM system with measurements.

2.3.3   VDL Mode 2

VDL Mode 2 is a digital data link to be shared between both Air Traffic Service (ATS) and Aeronautical Operational Control (AOC) communications within the framework of the ICAO standardized Aeronautical Telecommunications Network (ATN). VDL Mode 2 was standardized by ICAO in 1990 and is an evolution of the ACARS system providing increased capacity.
Although it is intended as the successor to the ACARS communication system, solving some of ACARS' limitations, its use is currently not widespread, but is expected to increase.

Just as VDL Mode 4, VDL Mode 2 makes use of a 25 kHz VHF signal, which means that it is not well suited for accurate TDOA measurements.

Since communication between aircraft and ground stations occurs most frequently close to airports, just as with ACARS, the usefulness of this signal type is further limited.

2.4 Miscellaneous airborne RF transmitting systems

Apart from the CNS related systems onboard the aircraft that actively use RF signals, one additional system is available that is not categorised as one of those (although coming close to surveillance), which is the airborne weather radar. The functionality of this system will be dealt with shortly and its prospects for WAM will be assessed.

2.4.1 Airborne Weather Radar

Airborne weather radar is used by aircraft for avoiding areas of heavy turbulence. This turbulence is measured indirectly. Generally speaking, precipitation levels and turbulence go hand in hand, the heavier the precipitation the heavier the turbulence; thunderstorms show severe turbulence levels together with strong precipitation. Weather radar sends out a powerful RF signal, in the order of 1 kW, which partly is scattered by rain drops (snow and hail are less effective scatterers) and some of the reflected radiation is received back by the airborne weather radar's antenna. The selected RF signal wavelength is in the order of 2 cm, which best matches the raindrop sizes of interest.

For the assessment of the prospects of the airborne weather radar for application in WAM, its related equipment availability in aircraft, the signal availability, signal reach (in NM), the update rate and the signal's identification capabilities must be determined. Airborne weather radar is mandatory equipment for civil aviation aircraft and apart from this category aircraft many other aircraft are weather radar equipped as well. Therefore the equipment availability should be categorised as high.
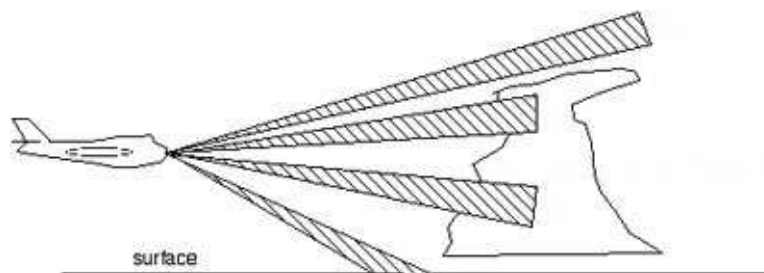
Figure 5 Airborne weather radar tilt

The signal availability for future ground based WAM stations however is low. The weather radar is switched off during clear weather conditions. Another issue is that the airborne weather radar is non-omnidirectional. The antenna, which is generally located inside the radome, emits a slice shaped beam towards heading +/- 60 degrees at maximum. The beam's tilt is selectable by the pilot to the area of interest (see fig. *3*), which not necessarily points towards the earth surface. The general procedure for optimum 'default' setting of the tilt is to tilt the antenna first down until the ground return is being displayed. Then tilt up until ground return is at a minimum, but still present. In active usage the tilt feature is used to scan the storm in a vertical fashion, allowing the pilot to get a true 3D mental picture of the storm.
The signal's reach (line-of-sight) and update rate (1 Hz domain) are good, while aircraft identification capabilities as absent.

Summarising, the airborne weather radar should be considered as useless for future WAM applications mainly due to its low signal availability for ground based stations.

2.5 Summary

In the following table, all the transmission types described in this chapter are given with their expected usefulness in a WAM system, based on the possibility of aircraft identification and detection performance.

	Identification	Equipment availability	Signal properties
PSR	No	High	Poor
SSR	Mode 3/A	High	Good
SSR Mode S	Mode 3/A, 24-bit address	Increasing	Good
Mode S Squitter	24-bit address	Increasing	Good
Mode S Extended Squitter	24-bit address	Increasing	Good
VDL Mode 4	24-bit address	Regionally high	Poor
UAT	24-bit address	Regionally high	Average
Radio Altimeter	No	High	Poor
DME	No	High	Average
VHF DF	No	High	Poor
ACARS	No	High	Poor
VDL Mode 2	No	Increasing	Poor

Airborne Weather Radar	No	High	Poor

3 Existing WAM architectures

WAM systems can be categorised by two different criteria. Firstly they can be divided by the method that is used to calculate the time difference of arrival (TDOA) of the signal and secondly they can be categorised by the method (if any) used to synchronise the receivers. The following Sections describe the various methods and systems used for 1090MHz signal reception.

It should be noted that the output of a WAM system may be either position messages akin to ADS-B or a Radar-like report giving range and azimuth. In general the position message approach is considered more appropriate due to the WAM accuracy being difficult to model with Radar range-azimuth approaches.

3.1 TDOA Methods

There are two methods of calculating the TDOA. Either the signals received are cross-correlated to produce a TDOA or the time of arrival (TOA) is measured and the time differences of these are calculated.

TOA systems are typically used with signal waveforms where it is easy to measure a defined pulse edge such as with aircraft SSR transponder signals. Cross-correlation can be used with any signal but the suitability depends on the auto correlation properties of the signal. The TOA method is the most common method for SSR multilateration. The two methods are described in more detail below.

3.1.1 Cross Correlation Systems

Cross-correlation is commonly used in military Electronic Surveillance Measure (ESM) systems and in systems that locate a cell phone during an emergency call. The diagram below shows the simplified data flow in a cross-correlation system:
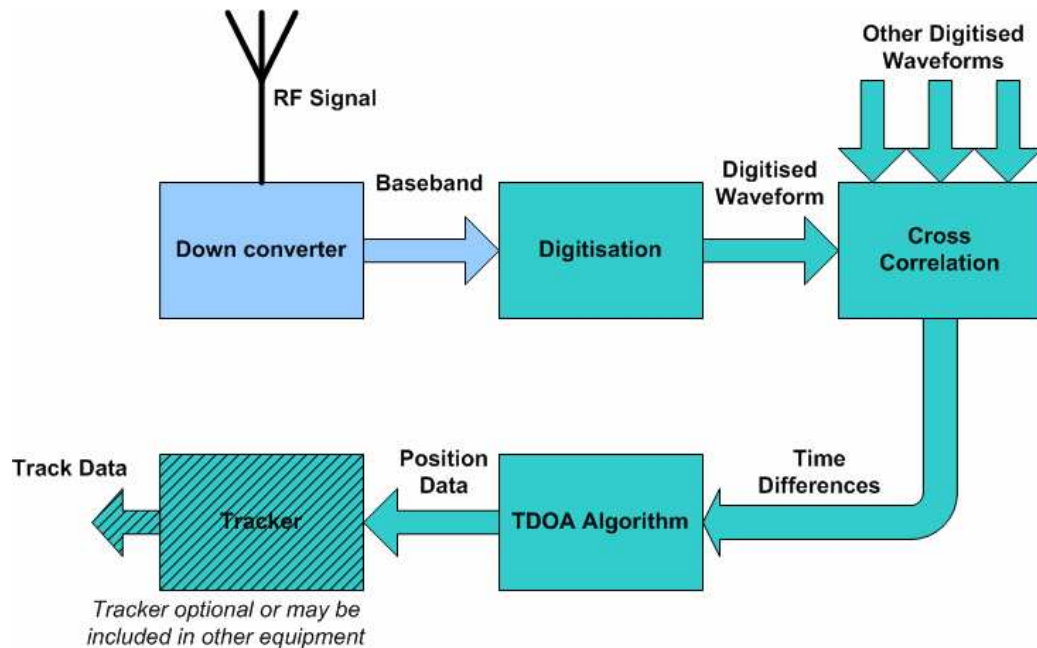
Figure 6 Cross Correlation Data Flow

Taking each of these sections in turn:

- The 'Down Converter' receives the 1090MHz RF signal and down-converts to either a baseband I/Q signal or video signal to allow digitisation

- The 'Digitisation' block utilises an appropriate Analogue to Digital Converter or similar to convert the analogue I/Q or video signal into a digital representation

- Following digitisation, the 'Cross-Correlation' section then performs a series of cross-correlations on the digitised data for pairs of sites. Assuming that the same signal is present in the signal from both sites, this operation results in a TDOA value between the given pair of sites. The accuracy of this process is influenced by the type of signal digitised and multipath amongst other factors. Algorithms must be used to ensure that ambiguous or incorrect results are not obtained when using cross-correlation with signals such as SSR replies which do not intrinsically have good auto- or cross-correlation properties.

- Given a series of TDOA values, a TDOA algorithm is used to calculate the aircraft position in X/Y/Z

- Finally, a 'tracker' is typically used to take the raw X/Y/Z plots and produce an aircraft track, thus improving accuracy and rejecting erroneous data.

A cross-correlation system differs fundamentally with a TOA system (as described below) as the actual time of arrival of the signal at a receiver is never calculated, only TDOA values are available.

3.1.2 TOA System

TOA systems are widely used for SSR multilateration. The diagram below shows a simplified data flow for a TOA system.
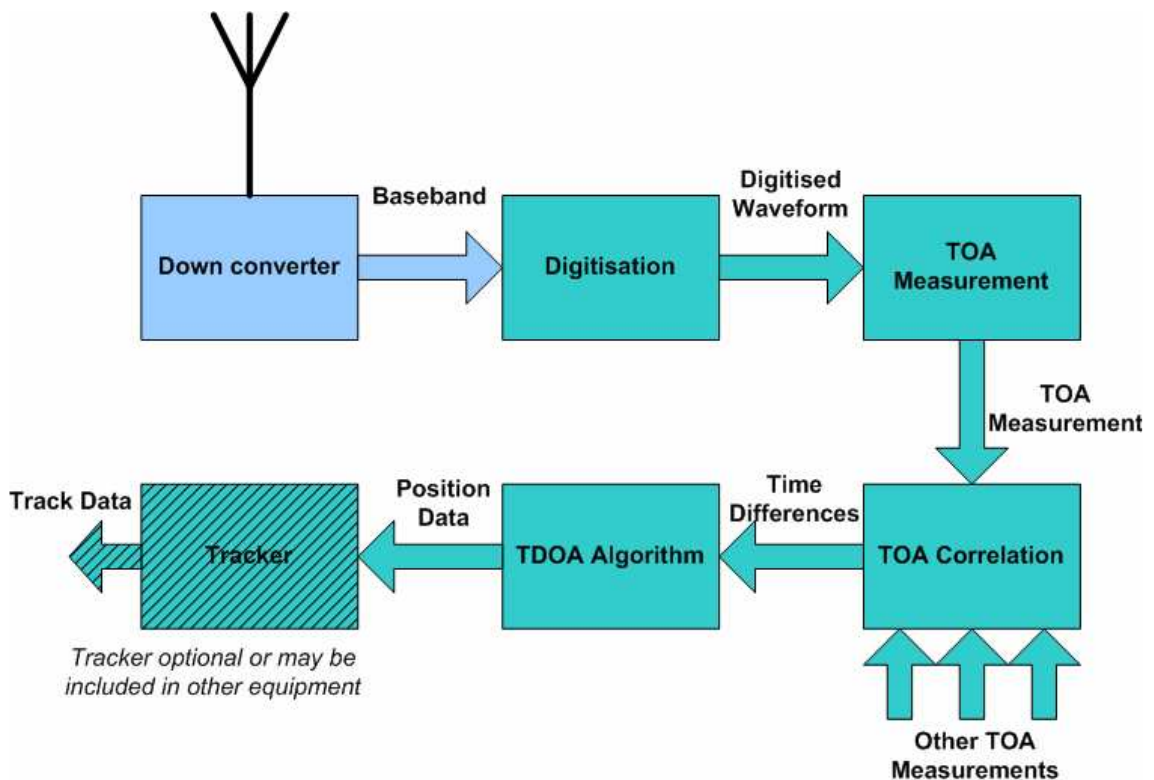
Figure 7 TOA Data Flow

Taking each of these sections in turn:

- The 'Down Converter' and 'Digitisation' blocks operate as for the cross-correlation approach, converting RF to a video or baseband signal and then digitising it
- Following digitisation, a TOA system will now calculate the signals' time of arrival local to the receiver, information not calculated with the cross-correlation system. Additionally, the SSR codes within the waveform are typically identified and extracted at this stage to aid correlation
- Having calculated a series of TOAs for each receiver, these must now be correlated to associate a group of TOA values calculated for a given aircraft transmission. Having performed this correlation or grouping, the TDOA values may be calculated
- The 'TDOA Algorithm' and 'Tracker' blocks operate as for the correlation based system

3.2 Synchronisation Methods

Synchronisation is fundamental to both cross-correlation and TOA multilateration systems, although the method of applying synchronisation generally differs. In order to calculate the position, it is necessary to know the time difference from a signal arriving at one antenna in the system to the arrival of the signal at another antenna in the system. This is commonly termed the TDOA. However, the signal is time stamped during the digitisation process, which is delayed in time relative to the time of arrival at the antenna by the group delay of the down-conversion process. Therefore, to accurately calculate the TDOA this delay must be exactly known and taken into account. Additionally, the digitisation process for each receiver chain must be referenced to a common time base, otherwise the signals at the various sites will be referenced to differing clocks and not directly comparable. Figure 8 below shows the group delay and synchronisation components. Synchronisation is defined as the method by which the digitisation processes of the signals to each site are tied together.
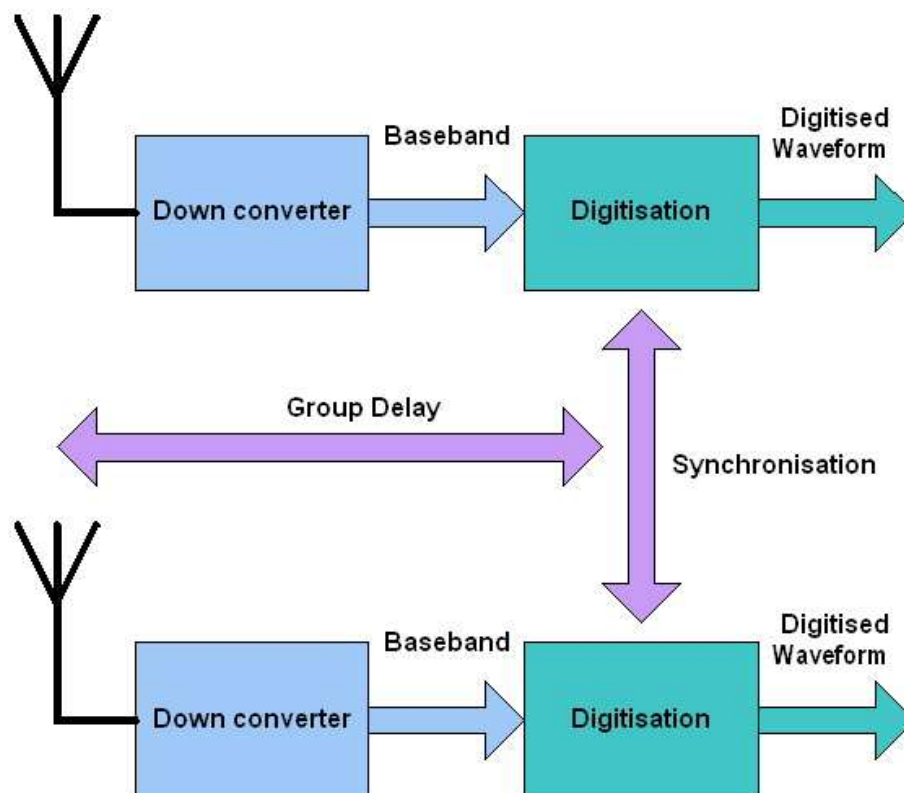
Figure 8 Group Delay and Synchronisation

The diagram below shows the topology of the various synchronisation technologies in use on WAM systems, required for both TOA and cross correlation methods. The technologies are described in more detail in the following Sections.
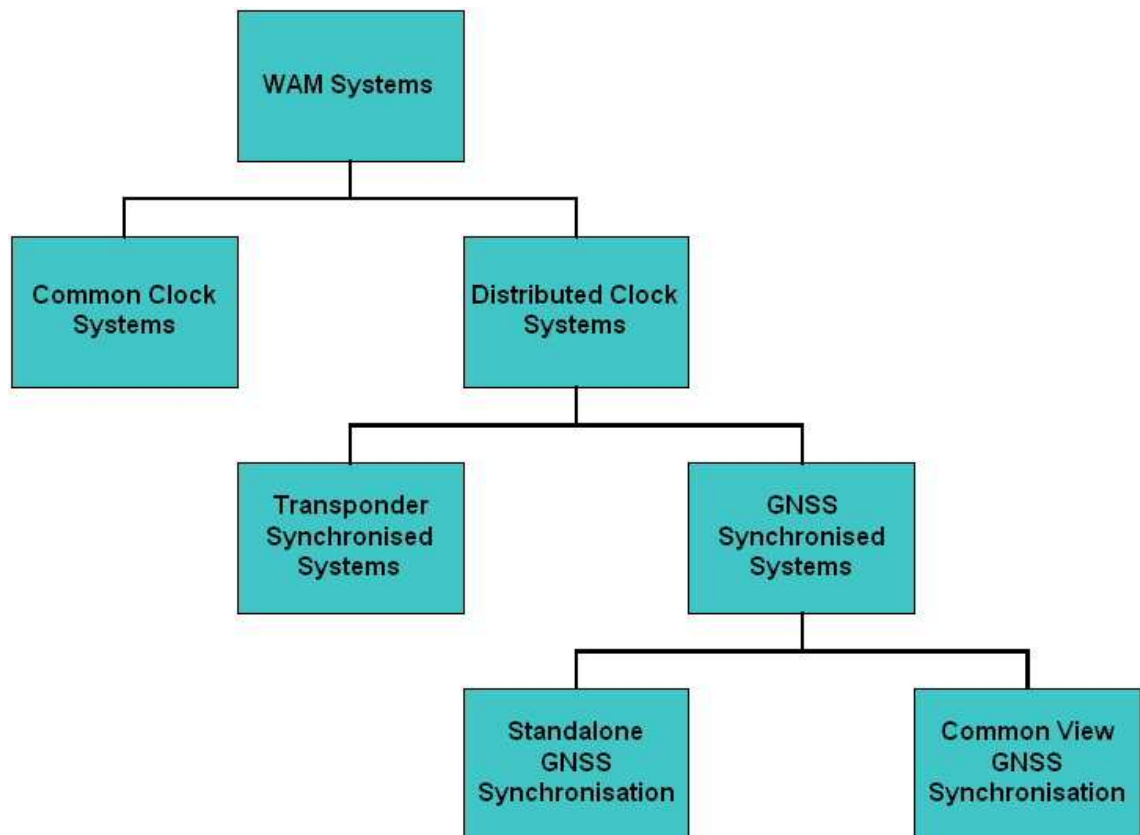
Figure 9 WAM Synchronisation Topology

3.2.1   Common Clock Systems

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. As the delay in the link increases, often due to an increased link distance or system baseline[1] achieving a given accuracy will become more difficult as delays will vary as a fraction of the total. Thus, for example, if delays are known to within 1% and an accuracy requirement

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[1] The 'baseline' is generally defined as the typical spacing between adjacent receiver sites.

of 1ns exists, a 100ns delay is tolerable but 200ns is not. This fractional relationship arises as delays vary with environmental conditions.

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. Typically a single hop custom microwave link is used, or dedicated fibre is laid between the sites as illustrated below. The location of the multilateration processor must typically be at the centre of the system to minimise communication link distances.

This architecture is used in WAM systems deployed by ERA a. s.
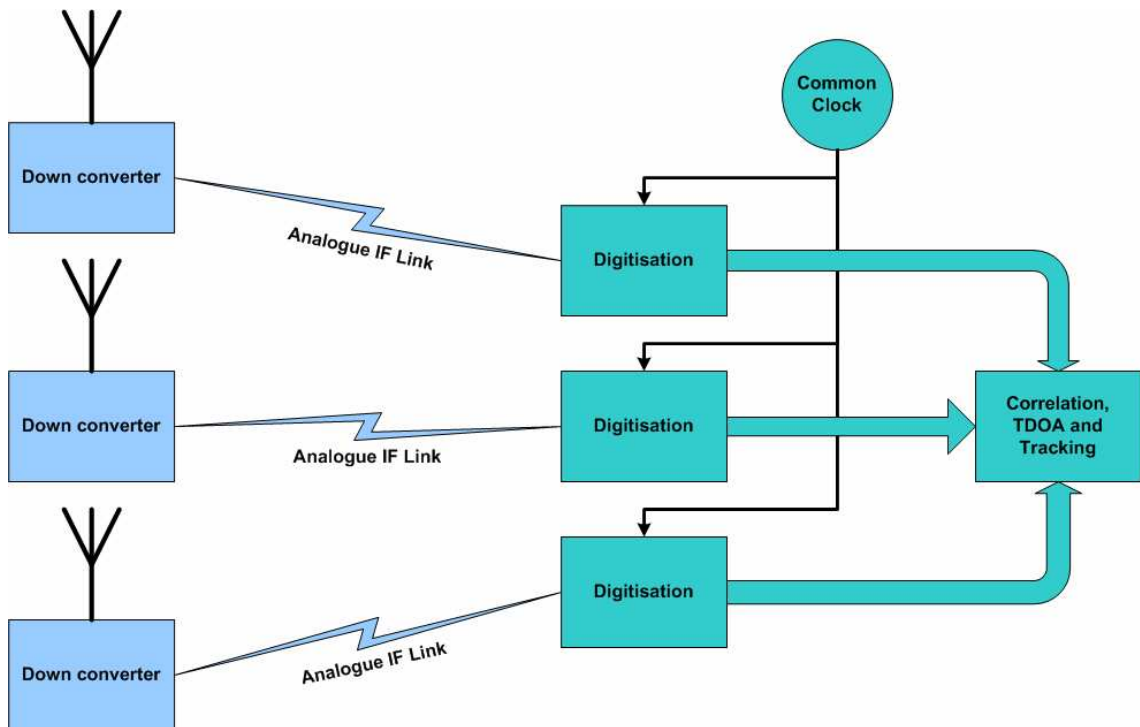
Figure 10Common Clock Architecture

3.2.2 Distributed Clock Systems

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 great 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 and WAM systems have been deployed by Rannoch Corporation, Roke Manor Research, and Sensis Corporation using this approach.
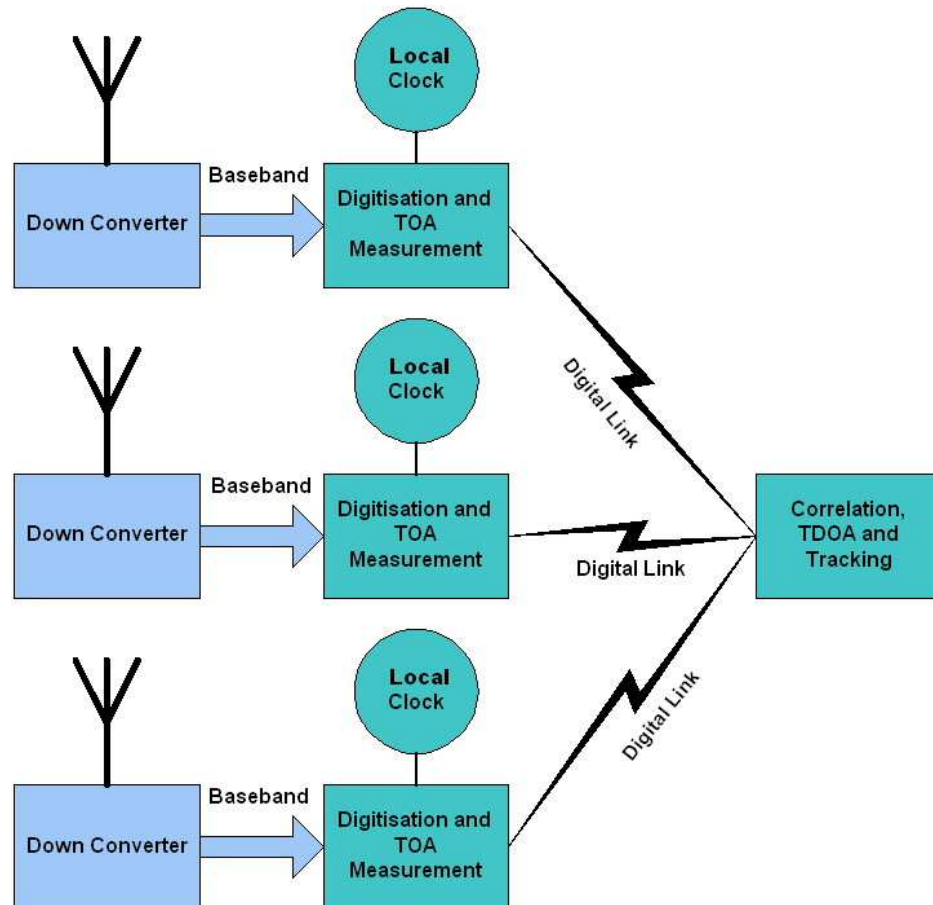
Figure 11 Distributed Clock Architecture

3.2.3 Transponder Synchronised Systems

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 means that tall masts or towers will typically be needed.

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.

Roke Manor Research and Sensis Corporation have deployed multilateration systems using this approach.
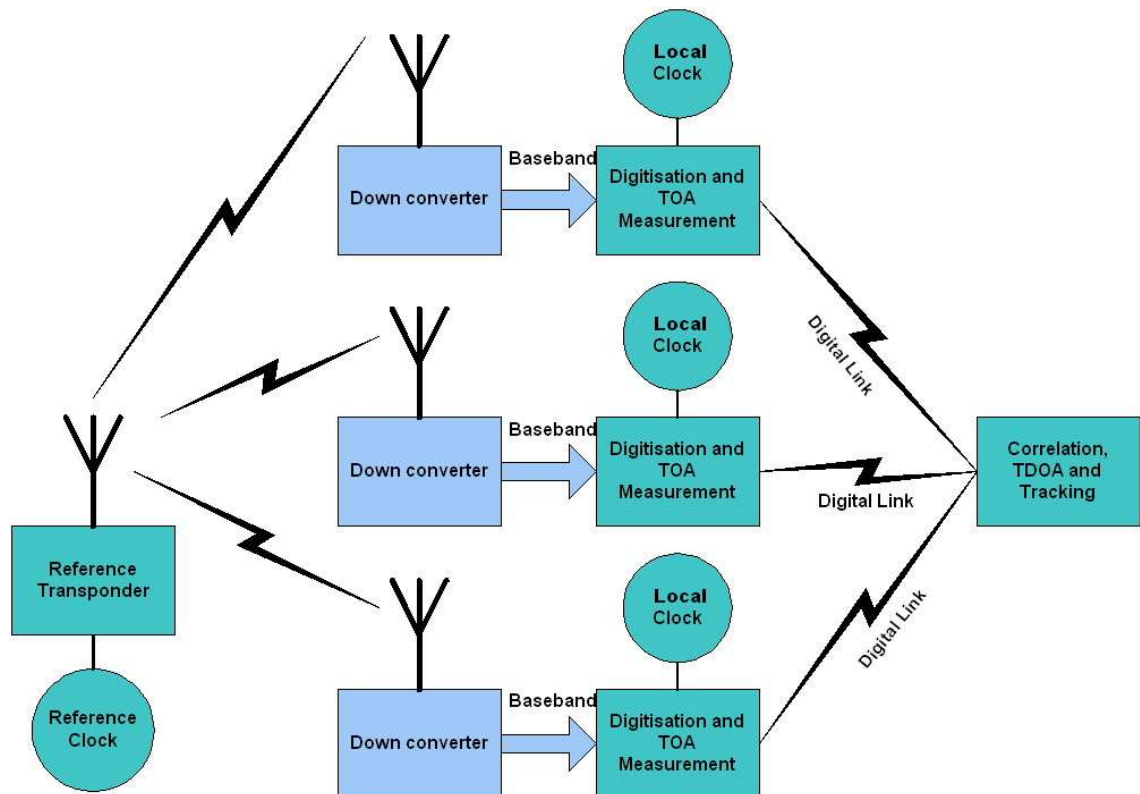
Figure 12 *Transponder Synchronised Architecture*

3.2.4 Standalone GNSS Synchronised System

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 essential. The architecture is illustrated below.

Rannoch Corporation has deployed WAM systems using this approach.
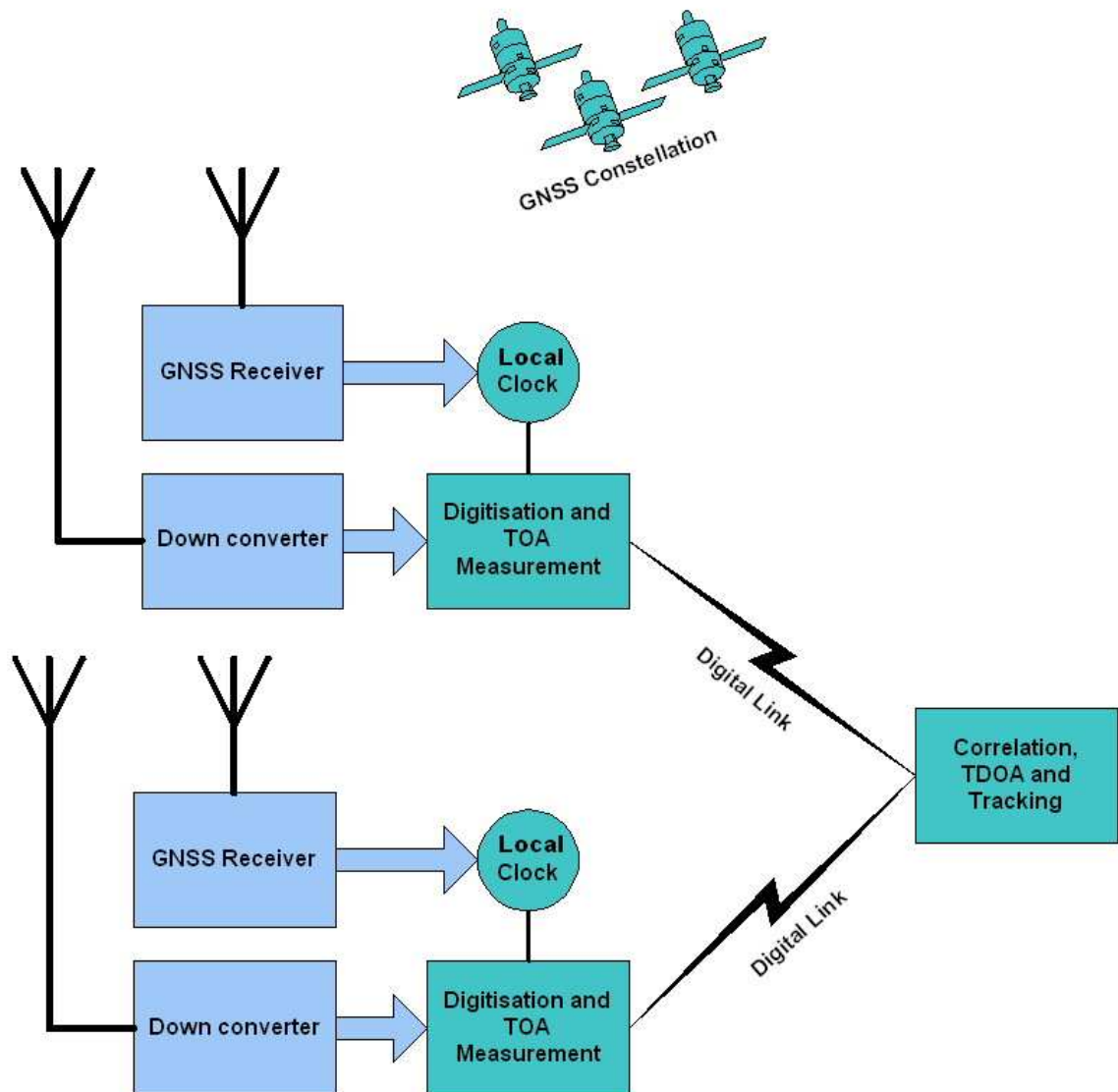
Figure 13GNSS Synchronised Architecture

3.2.5 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.

Roke Manor Research has deployed systems using this approach.
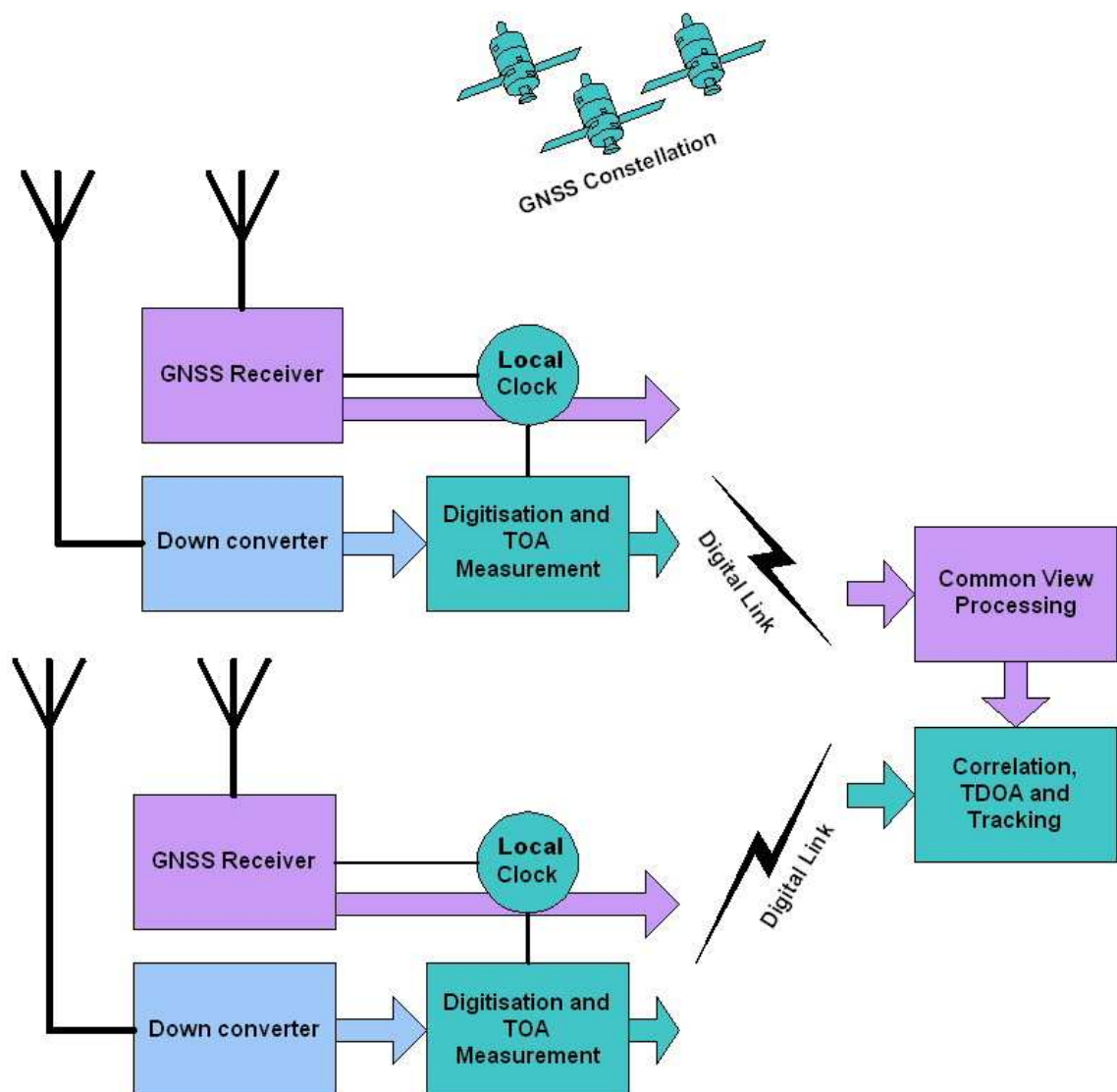
Figure 14Common View GNSS Synchronised Architecture

3.3 Synchronisation Summary

The characteristics of the various synchronisation schemes with respect to their application to WAM are summarised in the table below. It should be emphasised that this is an attempt to summarise the fundamentals of each architecture over long baselines and not to comment on specific deployments.

	Accuracy[*]	Baseline	Link Choice	Mast	Line of Sight
Common Clock	Medium	Medium	Microwave	High	Yes
			Fibre	Low	No
Transponder Sync	Medium	Medium	Any	High	Yes
Standard GNSS	Low	Any	Any	Low	No
Common View GNSS	High	Large	Any	Low	No

Table 1   WAM Synchronisation Characteristics

[*]Accuracy may be approximately defined as:
- Low – worse than around 10-20ns
- Medium – between 2-5ns and 10-20ns
- High – better than 2-5ns

It should be noted that defining 'Accuracy' is a complex task, having to distinguish between short term noise & long term drift and those components which are random and systematic. Additionally, standard measures such as the Allan Variance for frequency sources are not appropriate for this application as they relate to frequency stability and not timing accuracy.

	ERA	Rannoch	Roke Manor	Sensis
Common Clock	X			
Transponder			X	X
Standard GNSS		X		
Common View GNSS			X	

Table 2   WAM Architecture Deployments by Manufacturer

3.4 Combining Receiver Data Based Upon Differing Architectures

A thorough investigation of this topic is beyond the scope of this report; especially relating to issues such as reliability & interfaces. However, it is possible to make some general statements.

For the purposes of this Section, it is assumed that all data can be converted to some standard format and thus interoperability issues are ignored.

At a top level, three fundamental issues exist:
1. Is the receiver a common clock or distributed clock system (see Figure 9)?
2. Assuming a distributed clock, what TOA accuracy is achieved, and what averaging (if any) is applied?
3. With a distributed clock, what timebase is used?

With the first issue, it is difficult to envisage combining common clock and distributed clock receivers into a combined single system due to the fundamental differences. If this is required, it is probable that a break within the central site after TDOA calculation would be used rather than combining Receivers.

Assuming a distributed clock system, combining different receivers is potentially possible although the reference time against which the TOA's are measured would need to be converted to one standard before a TDOA could be calculated. For example, if two GNSS synchronised receivers were used but one TOA was referenced to UTC and the other to GPS time they could not be directly used to form a TDOA. This issue becomes far more complicated when combining Transponder Synchronised and GNSS Synchronised Systems as the transponder system need only be referenced to its own time – not a standard such as UTC (indeed performing this link would be very difficult). Aside from common timebase issues, the TOA accuracy must be considered. The TOA accuracy will have both systematic and random components, some systematic components will be common to all similar receivers, thus accuracy can be improved when calculating the TDOA as the common error is removed. However, dissimilar receivers are unlikely to share the same systematic components and thus the error could increase.

In summary, combining common clock and distributed clock receivers would be difficult to achieve. Combining different distributed clock systems is feasible in principle, although differences in the digitisation timebase used and accuracy offered could make this a difficult task in practise.

4 Acquisition of Airborne Derived Data

Multilateration systems can acquire any data that is transmitted by the aircrafts transponder. This can either be acquired passively by listening to any transmissions from the transponder or actively by interrogating the aircraft directly. These differences are covered in chapter 4.

Full details of all the downlink formats (DF) that a multilateration system could use are given in ICAO Annex 10 Aeronautical Telecommunications Volume IV. The main civil formats of interest to multilateration systems are given below.

Format	DF	Type of Information
Mode A		Identity
Mode C		Altitude
Mode S acquisition squitter	11	Technical address
Mode S extended squitter	17	Technical address, Identity, Altitude, ADS-B
Mode S short ACAS	0	Technical address, Altitude
Mode S long ACAS	16	Technical address, Altitude, air-air coordination
Mode S short surveillance	4, 5	Technical address, Identity, Altitude
Mode S long surveillance	20, 21	Technical address, Identity, Altitude, Data Link

Table 3   Main Transmissions used by Multilateration

It should be noted that there is an ambiguity between Mode A & C upon initial reception as discussed in Section 9.2.

4.1 Mode A/C Replies

Multilateration systems can extract the identity and pressure altitude of an aircraft from the Mode A/C replies received. Pressure altitude is available to a 100ft resolution. Passive multilateration systems will acquire this data from aircraft within range of a Mode A/C interrogator or a ACAS equipped aircraft. In busy areas of Europe with existing surveillance infrastructure a multilateration system will often receive more than 100 Mode A/C replies a second from a single aircraft.

4.2 Mode S Squitter

The standard short squitter or all-call reply provides the aircraft Mode S address to the multilateration system. The extended squitter also provides ADS-B data to the multilateration system. This includes pressure altitude, WGS-84 position and state vector information. Pressure altitude is available to a 25ft resolution on suitably equipped aircraft. These squitter messages are transmitted periodically by equipped aircraft. Passive multilateration systems will acquire this data from aircraft within range.

4.3 Mode S ACAS

Multilateration systems can detect air to air transmissions in order to determine additional information. With the short air-air surveillance message, the pressure altitude and Mode S Address can be determined. The long air-air surveillance message also provides air to air coordination information. This includes the Resolution Advisory (RA) information within the MV field. The RA information can be decoded to identify any RAs in force. Pressure altitude is available to a 25ft resolution on suitably equipped aircraft. Passive multilateration systems will acquire this data from ACAS equipped aircraft that are within range of other ACAS equipped aircraft.

4.4 Mode S Surveillance

Multilateration systems can derive the Mode S address, Mode A identity and the pressure altitude from the short surveillance transmissions. In addition the long surveillance transmissions provide access to the Comm-B data link messages. Pressure altitude is available to a 25ft resolution on suitably equipped aircraft. Passive multilateration systems will acquire this data from aircraft that are subject to Mode S interrogations.

The surveillance replies (DF 0,4,5,16,20,21,24) differ from the squitter Mode S formats in that the Mode S Address is encoded with the message parity by an XOR of the two values. The Mode S address can be extracted by calculating the parity and performing an XOR of the parity with the AP field. If a parity error exists a false address will be calculated and this will have to be resolved in the tracker.

5   Active and passive WAM systems

Multilateration systems can be either passive or active. Passive systems rely on the transmissions from an aircrafts transponder that are solicited by other equipment and on unsolicited squitter responses. Active systems can solicit their own response from aircraft in addition to any detected passively. The systems are described below.

5.1 Passive WAM Systems

Passive WAM systems do not interrogate the aircraft transponder; this offers two advantages in terms of spectrum usage. Firstly no transmission license is required for the installation and use of the system. Secondly there is no increase in the number of 1030 interrogations or 1090 replies caused by the system.

In general passive WAM systems will acquire aircraft within range of the system if one or more of the following is true:
- The aircraft is equipped with a Mode S transponder
- The aircraft is equipped with a Mode A/C transponder and within range of one or more interrogators
- The aircraft is equipped with a Mode A/C transponder and within range of one or more ACAS equipped aircraft

This means that in general passive WAM systems are best suited to
- Busy areas with a high volume of ACAS equipped traffic
- Areas with existing MSSR surveillance infrastructure
- Areas where Mode S use is mandatory

In general passive WAM systems will not perform as well with Mode A/C only aircraft at low altitude as there will be fewer mode A/C interrogators to illuminate the aircraft.

It should also be noted that whilst it is technically feasible to track aircraft based on Mode S squitter only; this does not provide enough information for current operational requirements. Currently both the ID and pressure altitude are required by controllers. Using a Mode S address and a geometric height would be a major operational change.

5.2 Active WAM Systems

Active WAM systems perform all the same functions as passive systems do, and in addition they can solicit their own replies from aircraft.

A WAM interrogator is much simpler than an MSSR interrogator. A rotating antenna is not required; instead either an omni-directional or sectored antenna is used. In addition the power level of the interrogation can be limited to provide a shorter range than for equivalent MSSR surveillance.

One scenario that may require the use of an active WAM system is for terminal area surveillance. Passive techniques can be used to acquire surrounding aircraft that are within the range of existing MSSR systems. A short range interrogator can be used to acquire low level aircraft on approach that fall below the coverage of existing MSSR systems.

In a Mode S environment long range aircraft can be acquired from squitter transmissions. For the terminal area application, aircraft on approach could benefit from a higher update rate as this improves accuracy and probability of detection. Therefore individual aircraft can be selectively interrogated more frequently.

Active WAM systems can also be used to acquire specific data. For example an active WAM system could be used instead of an MSSR for Mode S surveillance. The Mode S squitter can be used to acquire the aircraft passively by Mode S address and surveillance requests can be used to obtain additional data such as the Mode A ID and pressure altitude.

In the terminal area consideration must be given to aircraft on the ground potentially responding to all call interrogations. It may be possible to site the active antenna so that it does not illuminate the taxiways or apron. Directional antennas are another method of excluding certain areas.

The use of selectively addressed surveillance requests will reduce unwanted replies. If this is used in conjunction with a sectored antenna it will be possible to limit uplink requests to a particular sector.

Active WAM systems can also be used to calculate the range to the target in the same way that MSSR and ACAS systems do. This information may supplement the position calculated using TDOA although the benefit of this is normally minimal as TDOA position is likely to be more accurate.

5.3 Operational and Technical Identification

There is a difference between the requirements for technical identification and the current requirements for operational identification.

Technically the Mode S address is adequate information to accurately track and identify an aircraft. This means that the Mode S short squitter provides adequate information for a multilateration system to detect, identify and track an aircraft including determining its geometric height.

Operationally the controller also needs to know the ID and pressure altitude of the aircraft. This means that an active system may be required for operational rather than technical reasons. In the future it is conceivable that operation concepts could be modified to reflect the capabilities of this technology.

6 Technical limitations of WAM systems

6.1 Receiver Characteristics

For the purposes of this Section the receiver is considered to be both the analogue RF section and the baseband, digital section of the receiver. In common clock architectures (3.2.1) these two components are not co-located, in distributed clock architectures they are (3.2.2). The antenna choice is described separately in the next Section.

A receiver has a number of key parameters which are described below.

6.1.1 Sensitivity

Sensitivity is commonly defined as the minimum power signal that the system can detect. As the power of any signal drops with the square of the distance (for one-way) clearly the sensitivity will dictate the range of the multilateration system. Additionally, as TOA accuracy is a function of signal to noise ratio (SNR) which is affected by sensitivity, the accuracy of the system will also be affected.

6.1.2 Dynamic Range

The dynamic range dictates what range of power levels may be detected simultaneously by a receiver. Ideally a receiver must have sufficient dynamic range to detect aircraft at the minimum and maximum required range simultaneously. If this is not possible, lower signals may be lost (even when the power is above the sensitivity level) or a receiver sent into compression distorting the output signal. Therefore dynamic range and sensitivity must be considered jointly when predicting a receiver's coverage.

6.1.3 Clock Rate

Following conversion to I/Q baseband or log-video, the signal must be digitised as shown in Figure 6 to Figure 8. The rate this digitisation occurs at is often termed the Clock Rate. Fundamentally, the faster the clock rate the higher the accuracy of the TOA or TDOA measurement. This not only applies to 'raw' accuracy (without signal processing improvements) but the potential improvement any applied algorithms could bring.

6.1.4 Group delay Issues

As noted in Section 3.2 and other sub-Sections, the delay of the signal between antenna and digitisation must be known. This delay is far greater for Common Clock systems than for Distributed Clock systems as the digitisation occurs after the signal has been transmitted to the central site. It may be assumed that group delay will be measured and calibrated during system

commissioning activities for any WAM system. Therefore, the main area of concerns is how accurate this initial calibration is and how the delay will vary in use. To this end, the system should be designed to ensure that delay changes are either calibrated or known with variation of received power level & frequency and environmental effects such as ageing or temperature related variations.

6.2 Antenna Choice

The choice of antenna, both for SSR 1090MHz signals and GNSS (if required) is critical and are discussed separately.

6.2.1 SSR Antenna

The SSR antenna has three critical parameters for this application:
1. Peak gain: The maximum gain will, coupled with the receiver sensitivity, dictate the system coverage
2. Gain/beam pattern: By careful design of the beam patter, multipath can be limited whilst ensuring uniform coverage against elevation angle. If required, non omni-directional antennas may be used to increase range in a given direction
3. Bandwidth: Careful choice of bandwidth will limit out of band noise and improve system performance

6.2.2 GNSS Antenna

If a system is utilising GNSS synchronisation, it is important that an appropriate antenna is chosen to minimise the effect of multipath and interference. Various other RF components are required in addition to reduce internal reflection and thus improve the Voltage Standing Wave Ratio (VSWR).

6.3 Signal Corruption

The transponder signal received by the system may be subject to corruption. This can be caused by a combination of multipath, garble and potentially malicious or unintentional interference (jamming) conditions.

Multipath is where multiple copies of the same signal are received due to reflections from objects such as the ground, water, buildings or other aircraft. Antenna choice can help to reduce multipath.

Short path differences cause the same reply to arrive at multiple times with the pulses overlapping. Typically the direct and earliest path will be at a higher level than the reflected paths. These overlapping but attenuated pulses cause the pulse shape of the direct received signal to deform. This can have a serious impact on TOA accuracy.

Long path differences result in multiple copies of the same reply to be received. If this is undetected it can cause ghost tracks.

Garble is where two or more different signals are received that overlap in time. The probability of garble occurring on any given signal increases with the density of the SSR signal environment.

Both multipath and garble have an impact on the accuracy of multilateration receivers as well as affecting probability of detection. In many cases, especially with multipath, the signal itself can be recovered sufficiently for identification purposes. However the deformation of the signal affects the accuracy of any TOA measurement or cross correlation. Accuracy can be maintained by rejecting these signals but at the expense of probability of detection.

If higher than expected levels of interference occur at a receiver this will also degrade accuracy. This is because the SNR of the received signal has a direct influence upon accuracy. If the SNR is particularly poor, the probability of detection and decoding ability may also be affected. In general multilateration receivers are relatively narrowband, being restricted to the 1090MHz signals, and thus interference is either directly in-band (typically malicious) or unintentional sidebands of other systems (e.g. DME).

6.4 System Baseline

The baseline is defined as the distance between adjacent sites.

The minimum height that a multilateration system can see down to is governed by the baseline of receivers. With an MSSR system the minimum coverage height is governed by the radar horizon. With a multilateration system the radar horizon of multiple receivers must be taken into account.

The maximum baseline between receivers is determined by the horizon of multiple receivers. A full 3D position solution requires 4 or more receivers to see the target. If only 3 receivers see the target a position can be determined if height information is available from another source (e.g. Mode C).
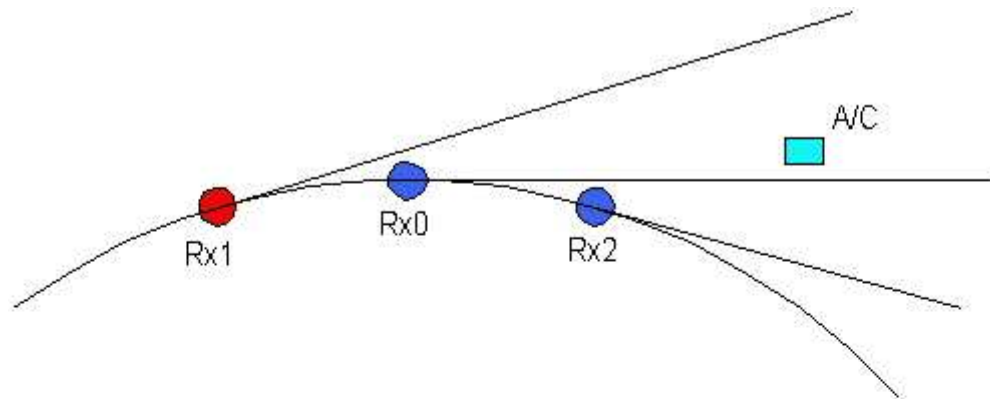
Figure 15 Line of sight variation with baseline

Figure 15 shows the impact of the earth's curvature on the visibility of an aircraft assuming flat terrain with receivers at ground level. In this case the target is visible to Rx0 and Rx2 but not to Rx1. From this it can be seen that the wider the receiver baseline of a multilateration system the worse the low level coverage of the system will be.

The most basic multilateration layout is a 4 receiver system as shown in Figure 16 below. In general baselines of 10-20NM are used to achieve low level coverage. However the impact of terrain and antenna heights must be considered in any specific system design.

Figure 16 Basic 4 Receiver Layout
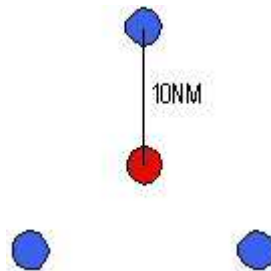
The basic layout can be extended by adding receivers to increase the coverage area whilst maintaining low level coverage. Figure 17 below shows a 5 receiver layout which offers a very even coverage area and a 6 receiver system which offers an elongated coverage area. The system can be extended to any number of receivers to cover any area although some architectures may limit this.
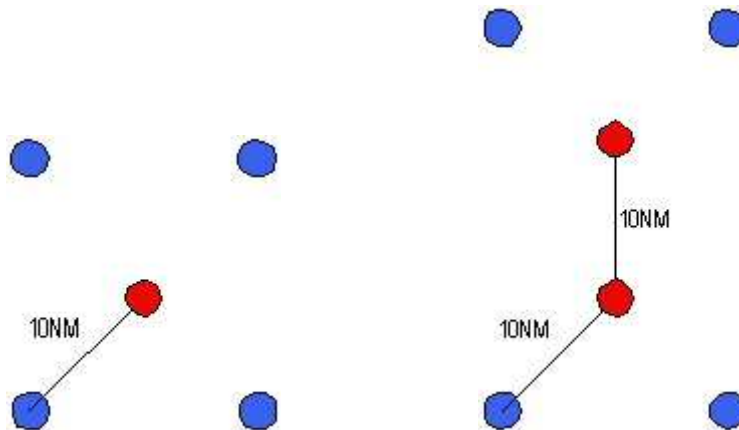
Figure 17Extended 5 and 6 Receiver Layouts

For covering large areas with multiple receivers it should be noted that the shape of the GDOP (see below) dictates that certain layouts are more suitable than others. It is not simply a case of identifying the geometry with the lowest receiver density.

6.5 Geometric Dilution of Precision (GDOP)

Geometric Dilution of Precision (GDOP) is a feature that affects multilateration position accuracy, linking the TDOA accuracy with position accuracy. This is encompassed in the following equation, linking the RMS 3D position accuracy and RMS TDOA accuracy:

$$\sigma_{xyz} = GDOP \times \sigma_{TDOA}$$

Equation 1

GDOP varies with target position with respect to the receivers; therefore the same accuracy need not be achieved with differing target positions or receiver layouts even with the same TDOA accuracy.

GDOP can be split into a number of constituent parts:
- TDOP – Time DOP; may not be present for TDOA systems as the time of transmission is not required
- HDOP – Horizontal DOP; the root-sum-square of *x* and *y* (lateral) geometry errors. This is typically lower than for VDOP (below)
- VDOP – Vertical DOP; the vertical component of DOP governing height accuracy. VDOP increases as aircraft height decreases (i.e. lower altitudes are less accurate)

For RVSM applications, VDOP plots are generally given. VDOP and HDOP are illustrated below for the Square 5 topology illustrated in Figure 17 above for an aircraft height of 35,000 feet.
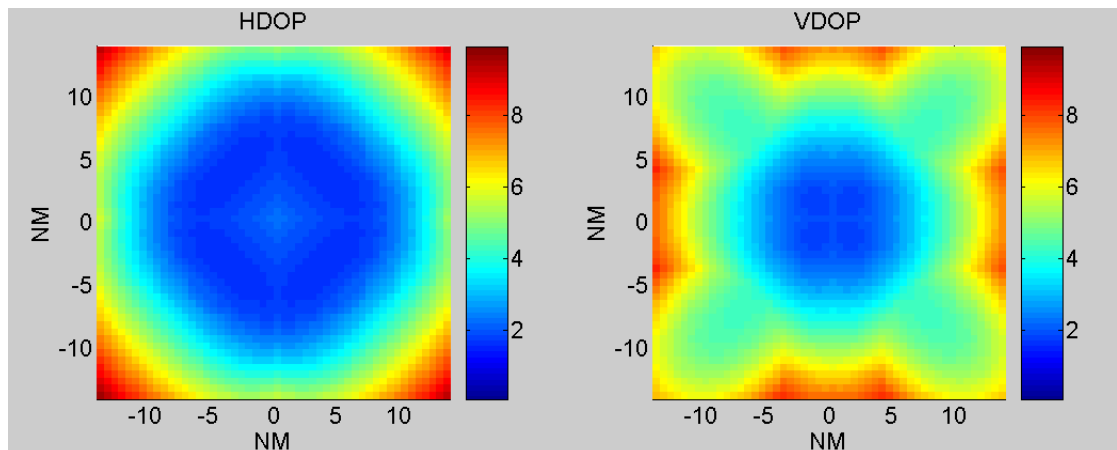

Figure 18GDOP for square 5 receiver layout

7 Receiver locations and horizontal performance

The required number of receivers to meet specific horizontal accuracy requirement of an MSSR system is addressed in this section as is the requirement for ADS-B verification.

7.1 MSSR Performance

These comparisons are based on the following assumptions about MSSR performance. The specification of the SSR is taken from the EUROCONTROL document "SUR.ET1.ST01-STD-01-01 Radar Surveillance in En-Route Airspace and Major Terminal Areas" The key parameters are shown in Table 4 below. It should be noted that most modern MSSRs are better than this.

Range Accuracy	70m
Azimuth Accuracy	0.08°

Table 4   MSSR Random Errors

In order to compare MSSR and WAM performance the approximate MSSR accuracy with range to target is calculated and transformed into the horizontal plane to produce lateral accuracy (RMS) at a specific flight level. This can be expressed as an accuracy plot as shown in the graph in Figure 19 below. The graph shows accuracy assuming the typical 4/3rds Earth path variation governing maximum range.
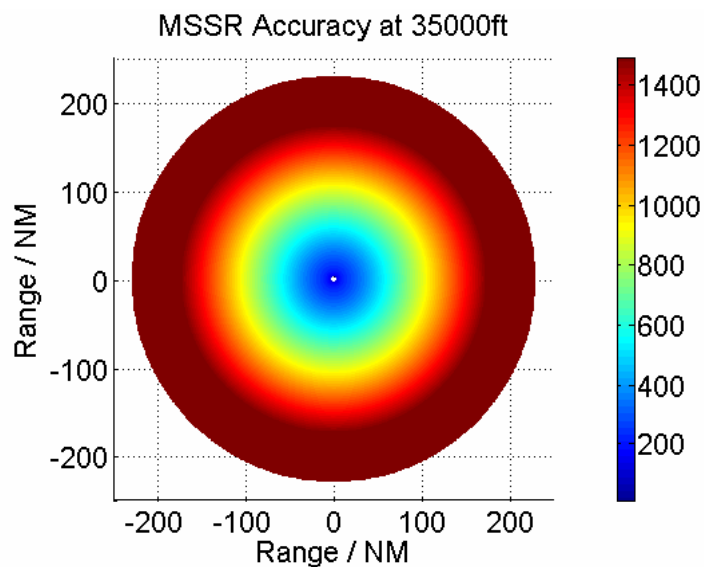

Figure 19MSSR Accuracy (ft) with range

Data for different flight levels is not shown as the lateral accuracy varies very little over height. The azimuth error dominates over the range error except for very short ranges.

7.2 Use of WAM to achieve MSSR Performance

It is possible to match and exceed MSSR performance with a WAM system, however in practical systems the WAM accuracy will vary in distance differently to the MSSR accuracy. This implies that a different 'shape' will be seen, as illustrated in the following plots. Additionally, MSSR accuracy will not vary significantly with height, whereas a WAM system will, especially in height performance (see Section 7). Therefore en-route and terminal area applications are considered separately.

Common to both applications are the assumptions for WAM system performance, required to calculate the σ_{TDOA} term in **Error! Reference source not found.**, which is in turn required to calculate actual accuracy rather than HDOP or VDOP. These are shown in the following Table and are generally based upon the ECAC HMU WAM system including the high performance synchronisation architecture with 1ns RMS error (see Section 3.3)

Parameter	Value	Description
Sensitivity	-85dBm	Minimum power at receiver
Reply Rate Factor	2.5	Accounts for signal processing used in ECAC HMU system
Antenna	dB systems DME antenna with 3° squint	HMU antenna with squint to give increased range
Bandwidth	22MHz	ECAC HMU Rx. bandwidth
Transmit Power	24dBW	Typical SSR transmit power
Synchronisation Accuracy	1ns ('High' from Table 1)	Minimum TOA accuracy is 1ns

Table 5 Assumed WAM Performance

Given these parameters, σ_{TDOA} may be calculated using the root-sum-squares of synchronisation accuracy and the TOA accuracy achievable in the presence of thermal noise. The noise floor is governed by the bandwidth coupled with an assumed noise temperature of 290K. In calculating the data it is assumed that the SSR signals from aircraft to receiver follow an approximate 4/3rd Earth radius.

7.2.1   En-Route Monitoring

This application involves long-range surveillance at typical altitudes of 29-41,000 feet. As accuracy will not degrade noticeably over this height range (although line-of-sight distance may imply high central sites are required) data is calculated for FL350.

The most directly comparable 'single system' to a single Radar is considered to be a square-5 layout as per Figure 17 but with a large baseline of 60NM. This reasonably matches the variation with distance and shape of the accuracy plot for a single Radar as below. Only horizontal accuracy is shown as the MSSR cannot calculate height. If required, more outlying receivers could be added at the 60NM baseline to form a pentagon, hexagon etc. However, this would generally be done for availability or coverage reasons as it will not have a significant impact upon accuracy and thus is not shown below.
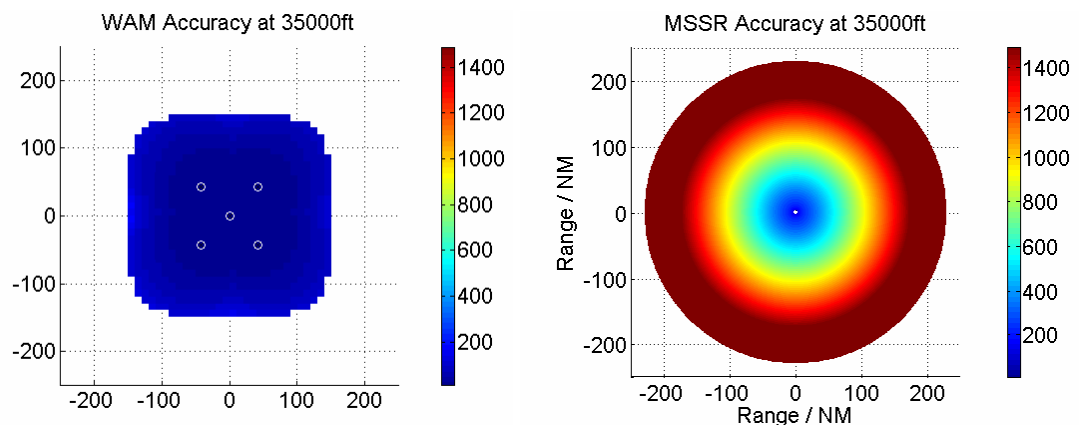

Figure 20 WAM vs. MSSR Accuracy (ft) for En-Route Applications

These plots assume 1ns synchronisation accuracy which can be achieved using a Common View GNSS Synchronisation method as described in 3.2.5. For lower accuracy techniques there will be some degradation in horizontal accuracy and a more significant degradation in vertical accuracy. The impact of synchronisation on accuracy is dealt with in 8.4.

The white area around the edge of the WAM plots indicates the maximum range the aircraft can be seen; with lower baselines this area of no coverage will shrink but the accuracy will rapidly decrease. Using a 60NM is considered to be a 'happy medium' between these two opposing requirements, although it must be noted that not all synchronisation architectures could support baselines of this size. However, this does reduce overall coverage as not only the closest site is required to see the aircraft. For example, considering the left hand graph above, in the North-Eastern corner, not only the most North-Easterly receiver must receiver the SSR pulse but also the central site and North-West & South-East receivers. This effect, common to all

multilateration systems, implies the coverage will be limited by line-of-sight issues at shorter ranges than a single-site system. In order to extend the WAM coverage above approx. 180NM shown above, three options exist:

1. Form a contiguous single system comprising of many receivers, e.g.
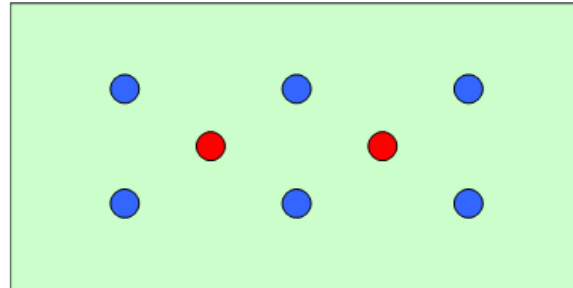
Figure 21 Extended Multiple Receiver Layout

2. Utilise multiple sets of receivers e.g.
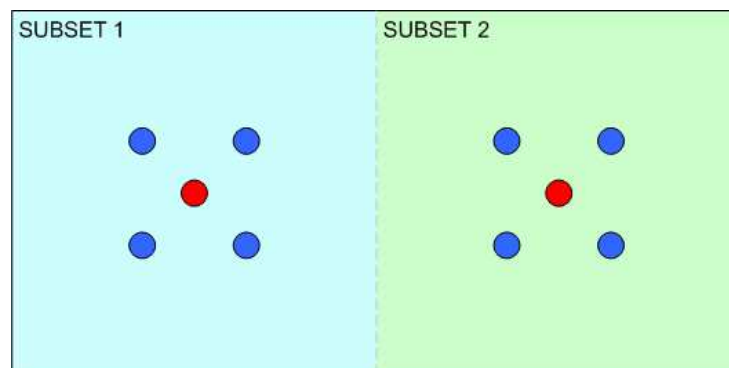
Figure 22 Extended Multiple System Layout

3. Raise site heights – this is likely to be required to ensure the MSSR coverage is available to the full 250NM.

Note that these site layouts are illustrative, and may not offer the best solution for integrity monitoring or other requirements.

The advantages of a contiguous systems are:
- Potentially reduced number of receivers
- Lower cost as only one multilateration processor is required

The disadvantages are:
- Requires either Distributed Clock System or possible large distance dedicated microwave links / optical fibres for Common Clock system (see Section 3.2)

- Increased complexity of algorithms for multiple receivers

For this en-route application, where coverage extends a large distance beyond the baseline, it is probable that the second option will be more cost-effective with discrete subsets of sites forming the overall system. A single processing site can still be used if the synchronisation architecture will support the large baselines required.

When in coverage, the WAM system offers far better accuracy than MSSR except at very low ranges (<10NM) where similar results may be achieved.

The receiver sensitivity and antenna type listed in Table 5 will affect coverage and accuracy. Given below is a sequence of graphs illustrating the effect of lowering sensitivity from -90dBm through to -80dBm. As can be seen, the 60NM baseline requires high sensitivity to obtain good coverage.
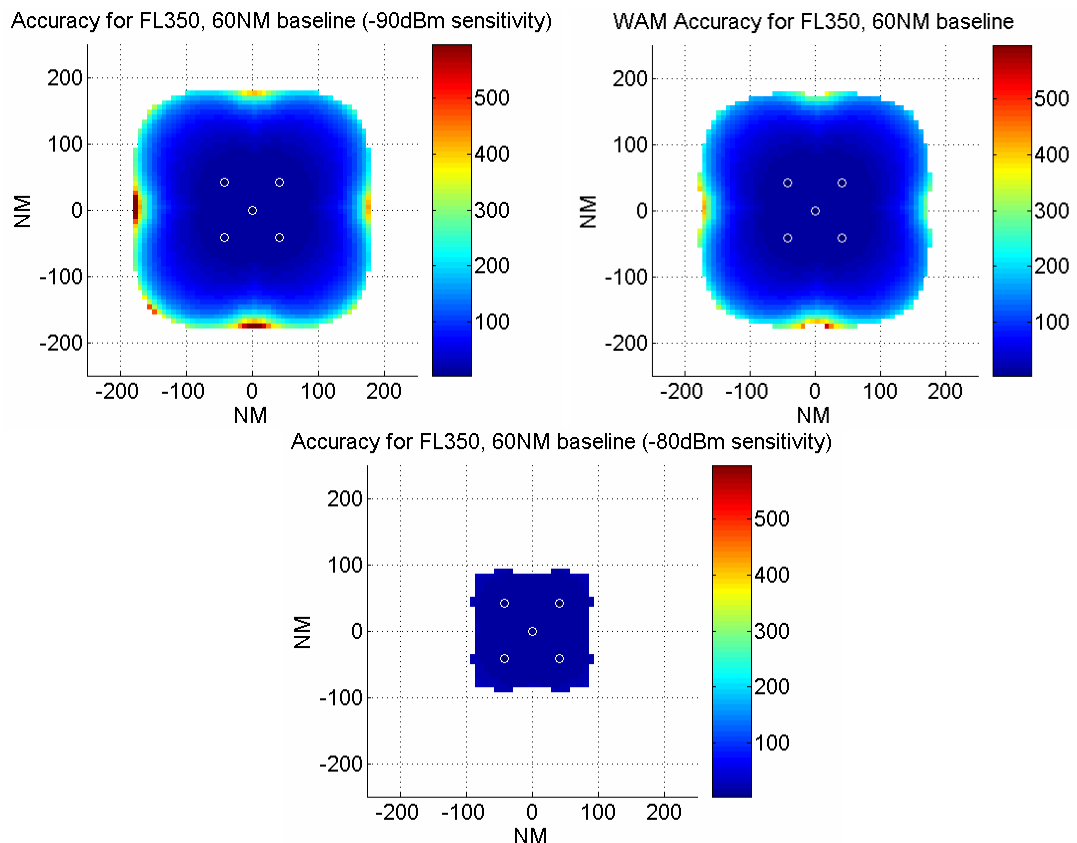
Figure 23 Effect of Sensitivity on WAM Coverage for MSSR Comparison (accuracy in ft)

In addition to sensitivity, the antenna choice will affect coverage. The antenna used for ECAC HMU and used in the above analysis offers an approximate inverse $cosec^2$ pattern:
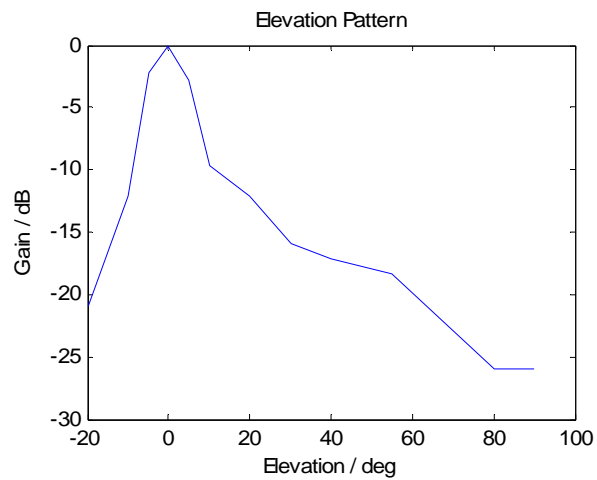
Figure 24 ECAC HMU Antenna elevation Pattern

It is also possible to consider other antennas such as the VOA4, VOA7 and VOA10 antennas available as COTS items from European Antennas:
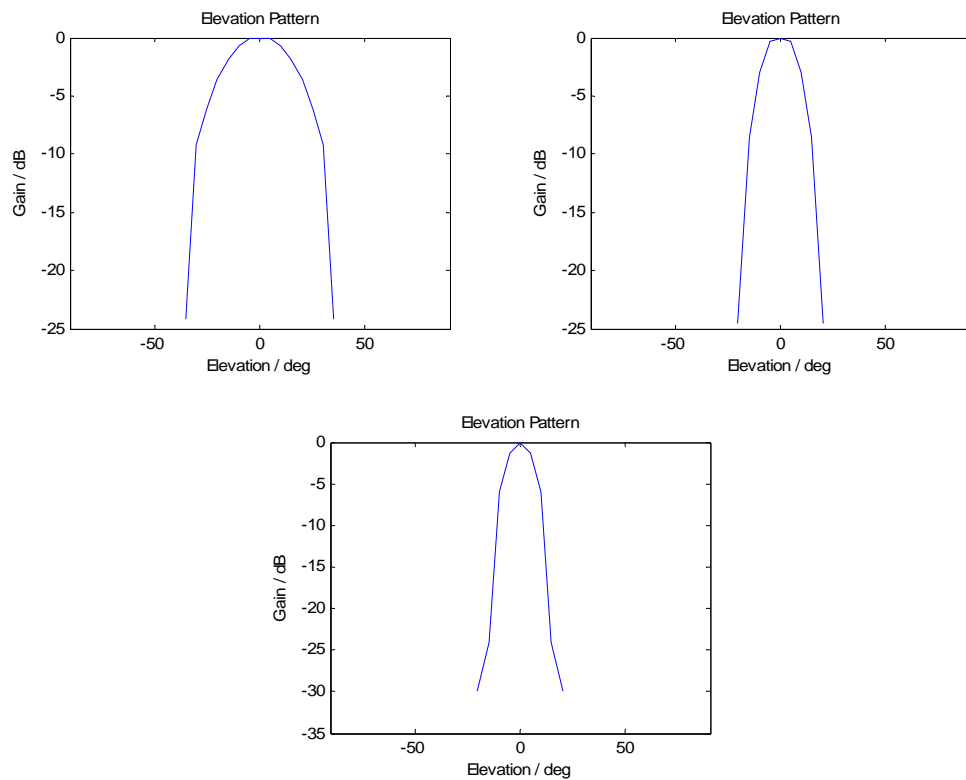
Figure 25 VOA4, VOA7 & VOA10 Elevation Patterns.

The graphs below illustrate the results from VOA antennas:
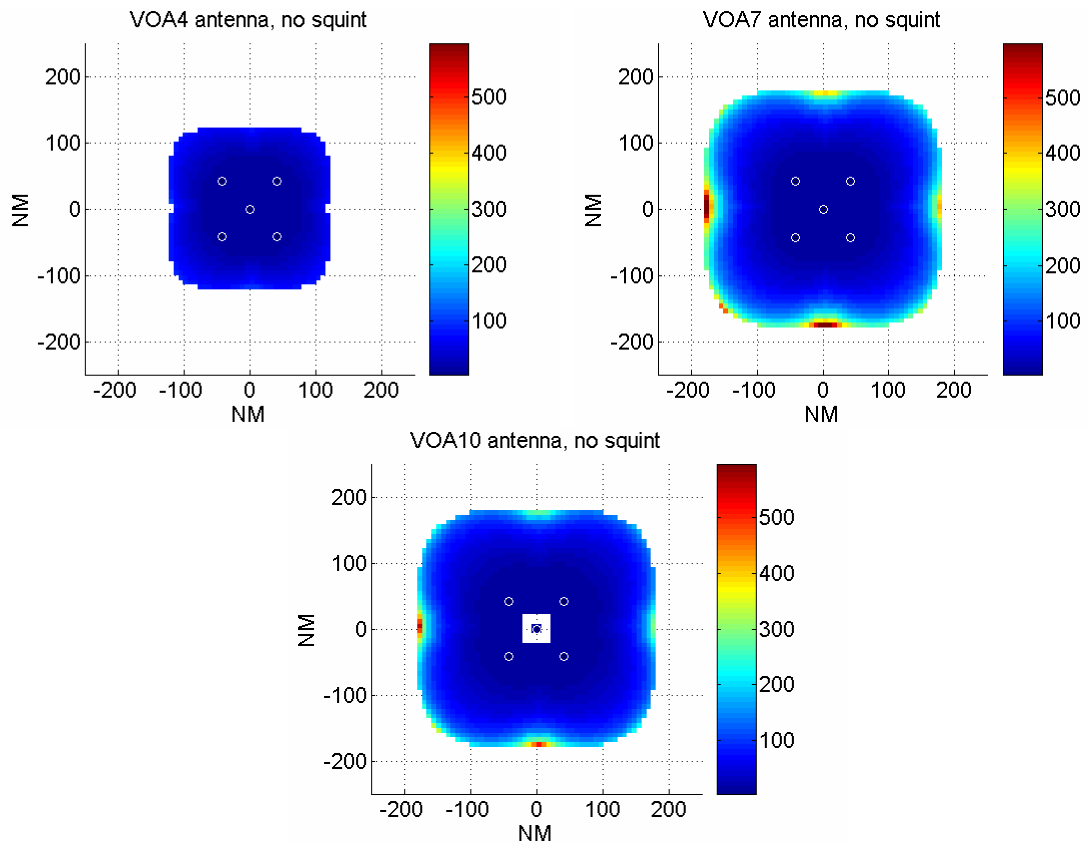
Figure 26 Effect of Antenna on WAM Coverage for MSSR Comparison (accuracy in ft)

Where line-of-sight issues are unimportant, the effects of antenna and sensitivity are similar in that coverage is decreased when gain and/or sensitivity decreases below a certain threshold. In the final graph of Figure 26 the beam pattern is narrow enough to affect overhead coverage, denoted by the white 'hole' in the centre. In addition to coverage, it should also be noted that antenna choice will effect multipath rejection which is not shown in these diagrams (see Section 6.2).

As a final point in this Section, the graph below illustrated how a nine-site configuration matches the long-range coverage of MSSR whilst offering far higher accuracy.
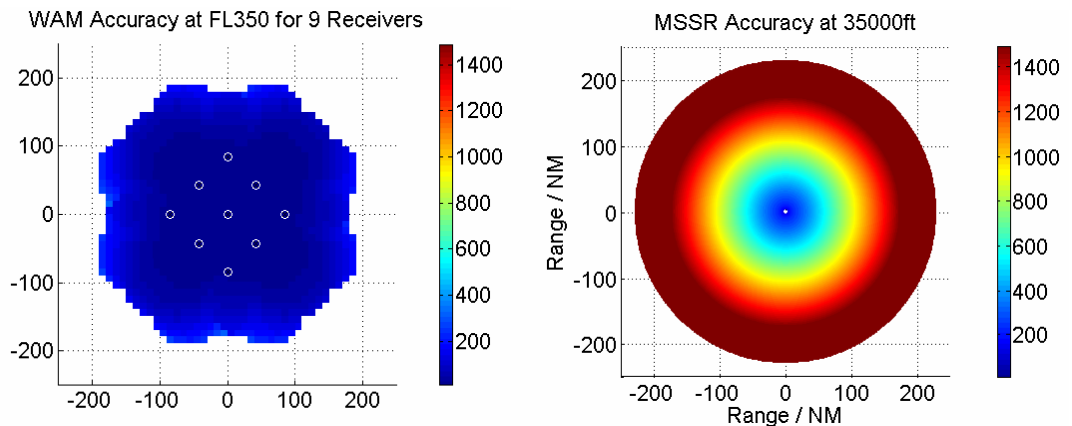
Figure 27 Extended WAM System vs. MSSR (accuracy in ft)

7.2.2 Terminal Area Monitoring

Terminal Monitoring applications are typically lower level and shorter range than en-route applications. For the purposes of this report, it coverage is assumed required up to 60NM and is calculated at 1,000 & 3,000 feet. As in the previous Section, results are curtailed using the standard 4/3rds Earth radius assumption.
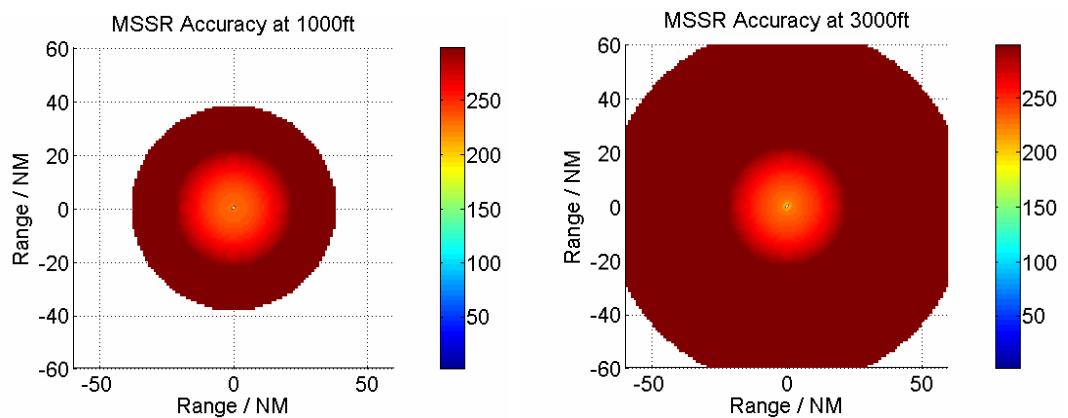
Figure 28 MSSR Accuracy (ft) in Terminal Area Application

In comparison, WAM accuracy for the familiar square-5 arrangement is shown below. Both 10NM and 20NM baseline results are illustrated.
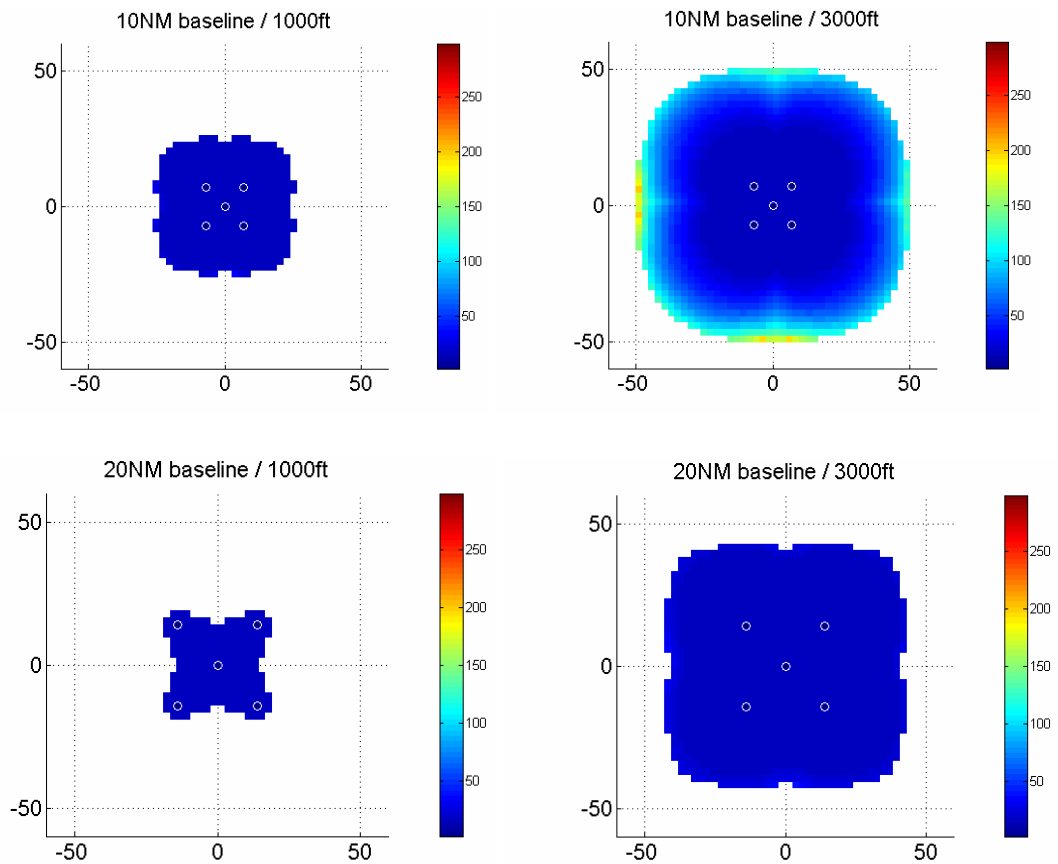
Figure 29 WAM Accuracy (ft) MSSR in Terminal Area Application

As can be seen, where coverage exists a WAM system will generally outperform MSSR for accuracy. At these low heights, line-of-sight visibility dominates over sensitivity and antenna requirements. The graphs below show comparison between 4dBi & 10dBi antennas.
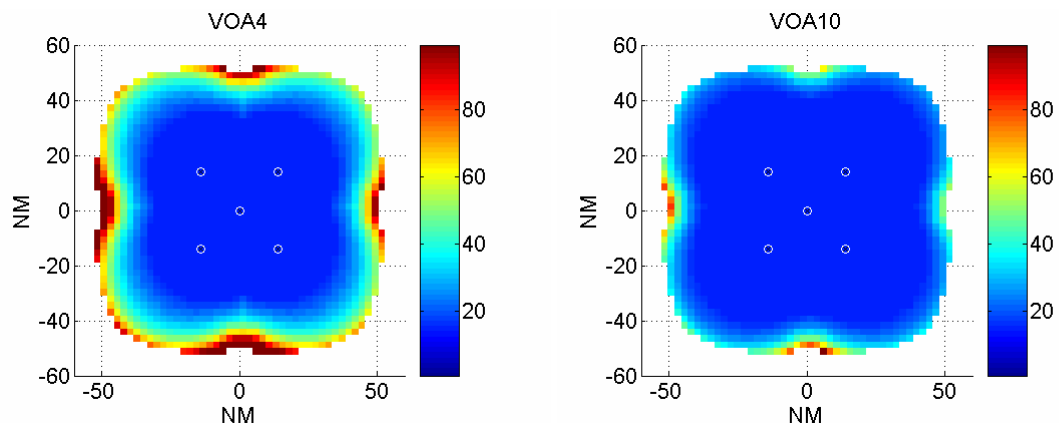
Figure 30 WAM Accuracy (ft) and Antenna Type for Terminal Area Application

Sensitivity variations from -70dBm to -90dBm inline with the en-route variation show no noticeable variation in accuracy or coverage.

As is clear from Figure 26, at low heights the system baseline is important, with a larger baseline increasing long range accuracy at the expense of low height performance. This can be more fully quantified when considering the following Table of line-of-sight distances against aircraft height. Note that zero receiver height has been assumed along with a spherical Earth[2].

Height / feet	'True' line-of-sight / NM	Line-of-sight with 4/3^{rds} Earth approximation / NM
500	23.8	27.5
1,000	33.7	38.9
2,000	47.6	55.0
3,000	58.3	67.3

Table 6 Line-of-Sight Distances against Aircraft Height

This Table must be viewed in conjunction with the distance from the site. Unlike MSSR systems, a WAM system must have visibility to the target from at least four receivers. As illustrated in the below Figure, this increases the range to target from the furthest receiver to $\sqrt{d^2 + b^2}$ for plan-range d from the central site and baseline b – which in turn will *decrease* the maximum range of the system.
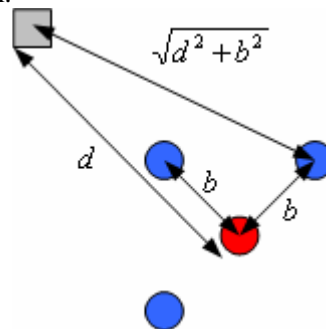
Figure 31 Range to Furthest Site for WAM

The graph below illustrates the drop in coverage with increasing baseline assuming the maximum distance a receiver can see is 38.9NM (1,000 feet 4/3^{rds} distance). It can be seen that for an aircraft at 1000ft, a zero length baseline provides the maximum range of 38.9NM. As the baseline is increased the range of the system at 1000ft will reduce. When the baseline reaches 38.9NM it is no longer possible to see any aircraft at 1000ft because insufficient receivers will see the aircraft.

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[2] Whilst this is adequate for this application, any deployment would need to consider both the WGS84 spheroid and local terrain / buildings which is beyond the scope of this study
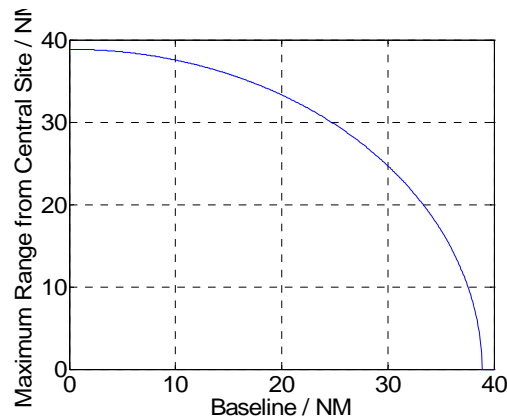
Figure 32 Maximum Coverage at 1000ft with Increasing Baseline

This illustrates that a baseline beyond around 20NM will require a non-uniform receiver layout to maintain visibility of the aircraft. Therefore, in contrast to en-route applications, terminal area systems may be specified as a receiver density dictated by the minimum height required. Using a Square-5 arrangement with 1,000ft minimum height and 20NM baseline this is approximately one receiver for 400NM^2.

7.2.3 Systematic Errors

In considering the accuracy of WAM systems the major focus has been on the impact of random errors that correlate over a short time period (seconds) as these errors are generally much larger and less controllable than systematic or long correlation errors.

Systematic errors on an individual receiver in a multilateration system generally cause a non linear distortion in position measurement across the area. Like MSSR errors all aircraft are measured in error by the same amount but unlike MSSR the error is generally not linear across the region.

Flight trials on existing WAM systems have shown that the magnitude of these errors is small, typically less than 10m.

The minimisation and control of these errors is an important part of WAM system design.

A full consideration of all the errors that can occur in a multilateration system and their characteristics is beyond the scope of this study.

7.2.4 Summary

In summary, for en-route applications a high-performance square-5 system with large baseline will exceed the accuracy of MSSR up to ranges of approx. 170NM from the central site. To go beyond this range, either more receivers must be added or the five existing receivers must be mounted at higher levels. It is difficult to assess a required receiver density, that is the number of receivers required for a given area, as there is a non-uniform layout of receivers over the region and the coverage depends on a large number of factors. However, the results above indicate that a high-performance WAM system which supports large baselines should give approx. 170NM radius coverage with five sites clustered in the centre. To increase coverage, a further discrete cluster of sites could be added some distance away (i.e. Figure 22 above).

The Terminal Area application is markedly different to en-route monitoring as visibility to the aircraft is the main constraint rather than sensitivity or antenna choice (although these may well affect accuracy). In this case, receiver baseline becomes increasingly important as a higher baseline will increase long-range accuracy but decrease low-level coverage. In light of this, typical baselines of 10-20NM are considered appropriate. Low-level coverage is best increased by continuing the initial layout (i.e. Figure 21 above) rather than adding separate systems.

7.3 ADS-B Performance

The performance of ADS-B is dependant on the navigational accuracy of the avionic equipment from which the downlink data is derived. The current requirement for P-RNAV is a track keeping accuracy of better than 1NM. In practise GNSS derived positions are likely to be significantly better than this in most cases. Lateral position measurement accuracy in the order of tens of metres is typical for GPS. The ADS-B downlink includes a figure of merit to indicate the resolution of navigation data.

7.4 Use of WAM to verify ADS-B performance

WAM may be used to monitor the performance of ADS-B systems. There are a number of roles that multilateration could play.

- *Verification of Navigation Accuracy*. The ADS-B data can be checked against the multilateration data to verify the track keeping performance of the avionics.
- *ADS-B Integrity Monitoring*. WAM can be used to monitor the integrity of ADS-B as a surveillance technique. This could be done to gather data for a safety case and to monitor the integrity of in service systems. For example a bias in one aircrafts position is a serious safety issue for ADS-B only surveillance but a WAM system could identify this immediately.

- *Anti-spoofing*. ADS-B is vulnerable to spoofing. WAM systems can be used to identify genuine aircraft and the source of spoof transmissions.
- *Migration path to ADS-B*. WAM can provide ground based surveillance similar to existing MSSR type surveillance. In addition each receiver can operate as a 1090 ADS-B receiver providing surveillance for both ADS and non ADS traffic.

The previous sections show that WAM is capable of higher accuracies than MSSR. It is therefore clear that WAM systems can easily provide the accuracy needed to verify P-RNAV requirements. In addition it is possible to provide a comparable accuracy to GNSS in a system that is specifically designed for that purpose. (For example the RVSM HMUs have 25ft height measurement accuracy).

For this application the issue of WAM reliability and throughput arises. To assess this issue, a number of scenarios are presented in the Table below and possible consequences and mitigation strategies discussed.

Problem	Effect	Mitigation Strategy
Receiver Failure	Possible reduced coverage and/or accuracy	The system should be designed with an over-determined solution (more than four receivers for 3D). A single receiver failure will then only reduce the integrity level of the system. Otherwise coverage and/or accuracy will be reduced across the monitoring region
Receiver Overload	Reduced Probability of Detection Possible receiver failure	It is possible that more replies than a receiver is designed for may occur. This may also cause a data link overload or a processing overload. This is most likely to occur in a high interrogation Mode A/C environment. The receiver should be designed to limit the number of replies gracefully. In these situations a high garble rate is also likely which will reduce the probability of detection.
Processing site failure	Possible system failure	Use distributed and/or redundant architecture
Link failure	Possible reduced coverage and/or accuracy	See receiver failure

8   Receiver Locations and Altitude Performance

This Section discusses performance in height measurement in comparison to lateral position performance discussed in Section 6.

8.1 Geometry Effects

As discussed in Section 6.5, the accuracy of a WAM system depends on both TDOA accuracy and geometry factors, termed Dilution Of Precision. In general, vertical & lateral geometry factors, VDOP and HDOP respectively, differ with VDOP ≥ HDOP in general.

This is illustrated below, using the standard Square-5 arrangement with a 10NM baseline at two points marked 'A' and 'B':
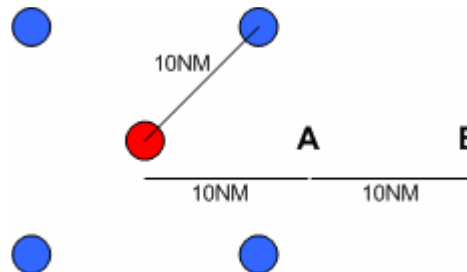

Figure 33 Five Site Arrangement for VDOP & HDOP illustration

Over typical en-route heights of 29,000 – 41,000ft HDOP and VDOP are similar:
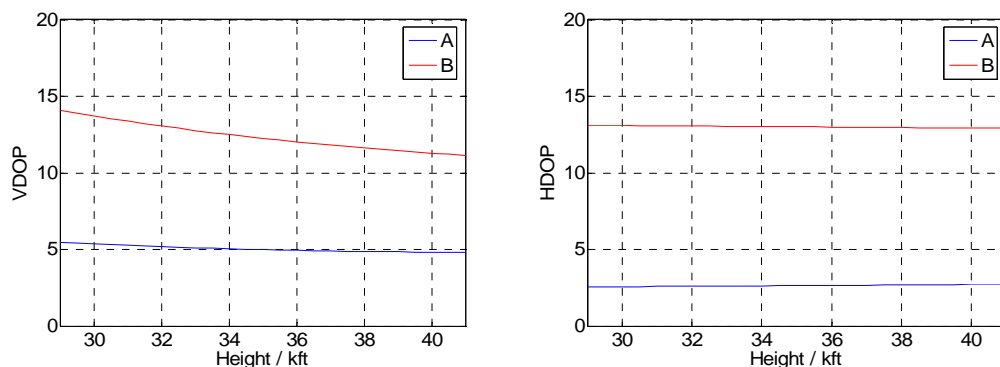
Figure 34 HDOP & VDOP from 29 – 41kft

However, with decreasing height VDOP shows a dramatic increase whereas HDOP does not. Note that the vertical scale is twenty times greater than that above.
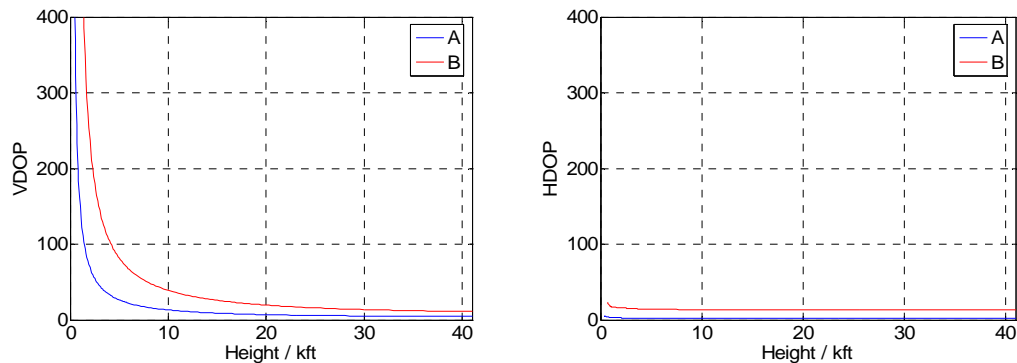
Figure 35 HDOP & VDOP from 0 – 41kft

As is seen, a 'knee' in the VDOP graph exists at approximately 5,000 feet, below which a dramatic increase in VDOP is seen. It should be noted that the exact position of this change depends upon site heights.

This 'knee' in the VDOP effectively dictates the lower extent of WAM altitude measurement, as very high TDOA accuracies are needed for only modest height accuracies. Therefore this Section concentrates on high-level traffic only and RVSM applications specifically.
Should altitude measurement be required at low-levels, a detailed study of the exact application, including possible site positions, would be required to assess where WAM would improve upon Mode C accuracy. This is beyond the scope of this study.

8.2 Baseline & Layout Considerations

In comparison to the lateral accuracy required to match MSSR performance, RVSM accuracy is more stringent and generally taken to be 25ft RMS. This implies that the baseline and subsequent coverage area must be reduced from the lateral case in order to improve the signal to noise ratio and corresponding timing accuracy and thus position. An increased baseline will also lead to a non-uniform coverage area, not allowing the typical *x* by *y* NM regions required for RVSM. This is illustrated below using the parameters in **Error! Reference source not found.** but using a 9.5° antenna squint to improve accuracy. All graphs are for an altitude of 35,000 ft. These plots have a lower 'floor' limit of 15ft accuracy, crudely corresponding to the difference in SSR transponder heights when mounted above and below an aircraft giving an intrinsic uncertainty in position when taken together.
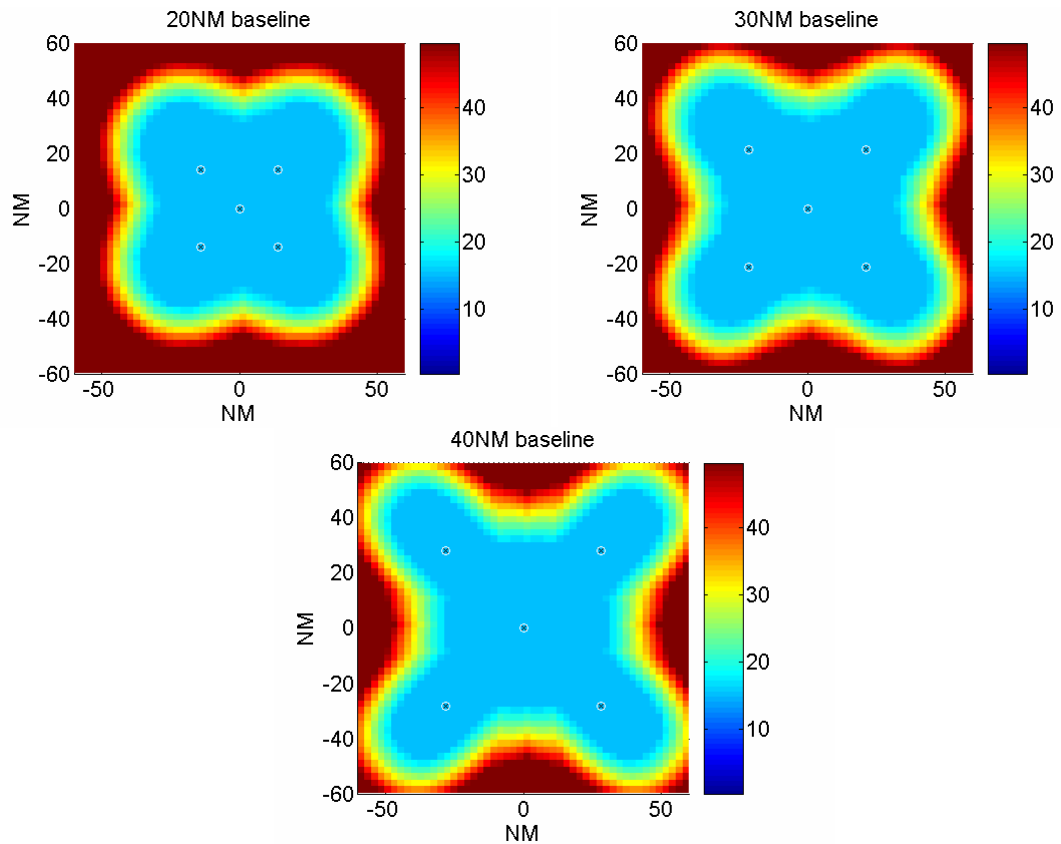
Figure 36 Height Accuracy (ft) against Baseline

As is seen, above 30-40NM baselines the coverage becomes markedly non-uniform. This is in contrast to baselines of up to 60NM that can be employed to match lateral MSSR accuracies and coverage or the 10-20NM baseline for low-level lateral coverage.

The receiver layout also has a marked effect upon coverage as the following diagrams illustrate. A nominal 30NM baseline is used.
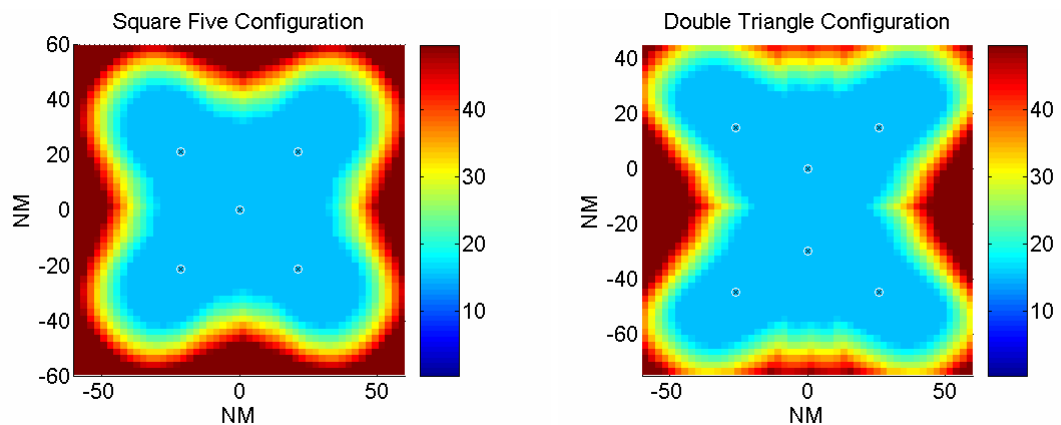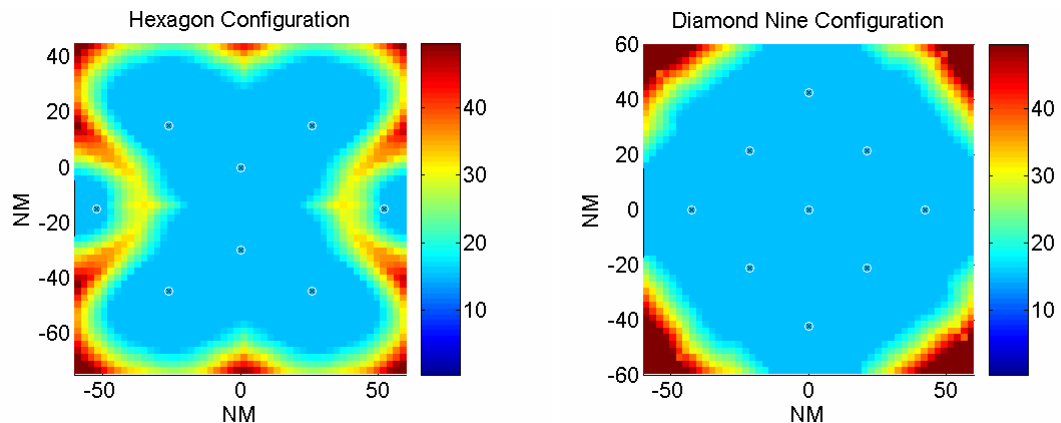
Figure 37 Vertical Accuracy (ft) with Various Configurations

As can be seen, choice of coverage pattern is not dictated solely by the coverage of each receiver; the geometrical effects mean that certain configurations are notably better than others for a similar number of receivers. In addition to the geometrical layout, the antenna choice has a more pronounced effect for RVSM applications due to the required SNR being higher than for producing lateral MSSR accuracies. This is discussed below.

8.3 Antenna Choice

Due to the increased SNR requirements for RVSM accuracies, the antenna choice becomes increasingly important. By way of example, the graphs below illustrate how changing the squint angle and also the antenna elevation shape will change coverage.
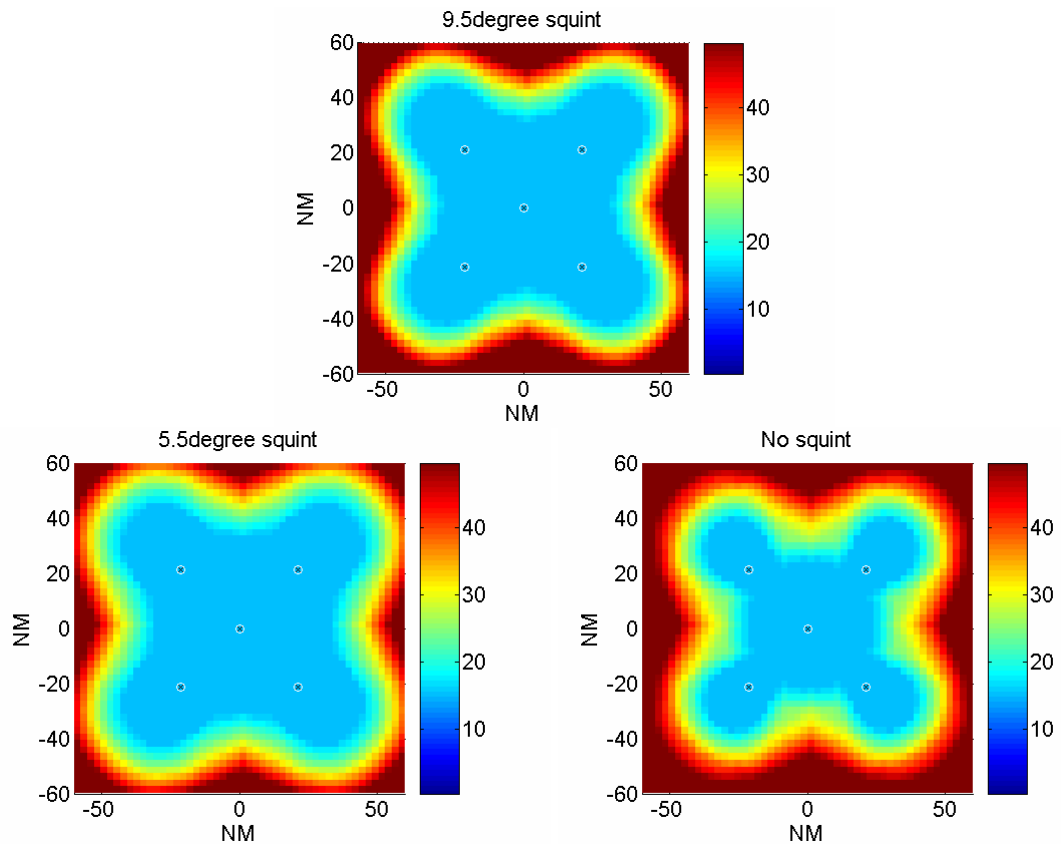
Figure 38 Accuracy (ft) against Squint Angle for RVSM (cosec² pattern)

In addition to the optimal cosec² elevation pattern given by Linear Vertical Array (LVA) patterns, it is possible to consider more general purpose 'Dipole-like' patterns as typified by the European Antennas COTS items. This is shown below for the COTS 15° squint and no squint options.
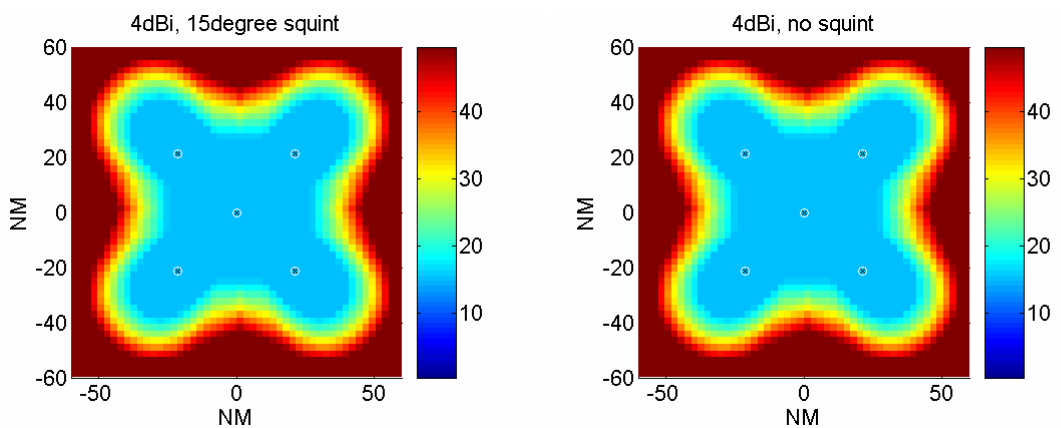
Figure 39 Accuracy (ft) against Squint Angle for RVSM (dipole-like pattern)

These graphs illustrate that antenna choice coupled with baseline and receiver layout is important for an RVSM application.

8.4 Synchronisation

Timing accuracy has a major impact on the accuracy of the system. This is particularly true where the GDOP is unfavourable as any timing errors are multiplied. Timing errors are made up of random errors on the TOA measurement, random errors on the synchronisation system and systematic errors on both of these. To show the impact of synchronisation accuracy the diagrams show the impact of increased random timing errors corresponding to different synchronisation accuracies. The graphs below show the influence on a 20NM baseline TMA System over a 60NM range at FL350. The scale is chosen to demonstrate the 100ft accuracy limit.
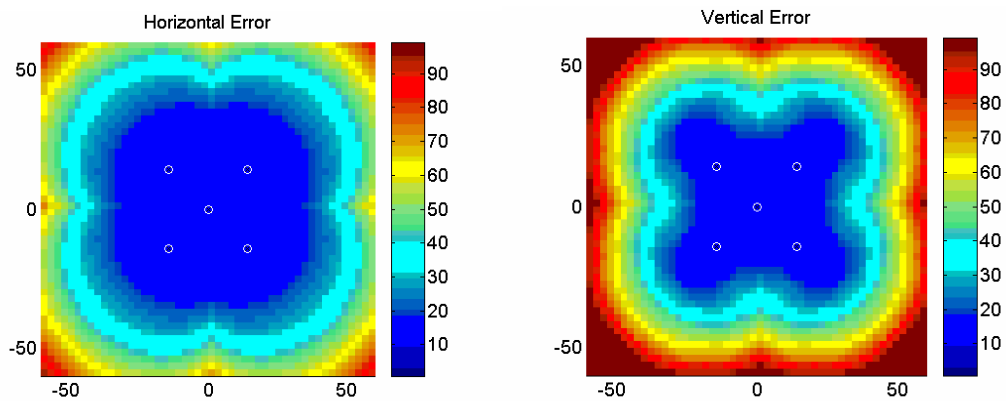
Figure 40 Accuracy (ft) of TMA System with 1ns Random Timing Error
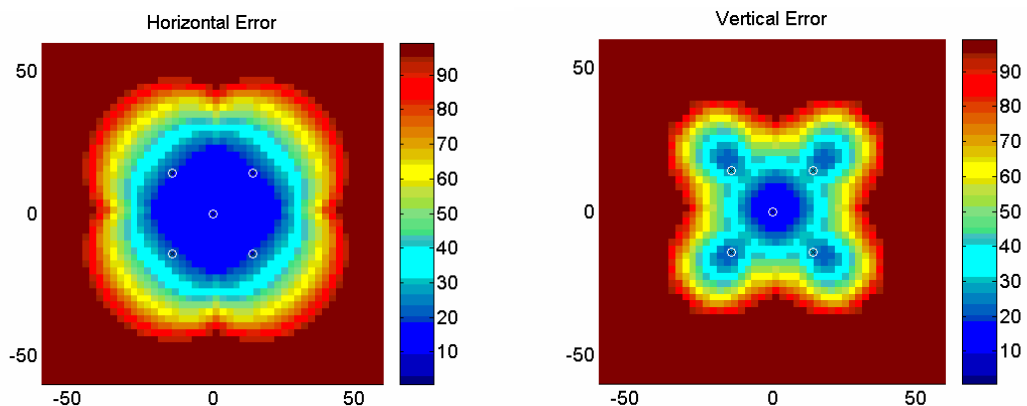
Figure 41 Accuracy (ft) of TMA with 10ns Random Timing Error

The following points should be considered when looking at the influence of synchronisation accuracy.

- At long ranges (e.g. at the limits of en-route systems) the timing error will be dominated by random errors on the TOA measurement caused by poor SNR not synchronisation accuracy.
- Random errors are only part of the influence on accuracy, systematic timing errors will also contribute. Different WAM architectures will have a different combination of random and systematic errors. Some systematic errors can be calibrated out either during commissioning or actively.

8.5 Use of Pressure Altitude & Geometric Height

In current operations pressure altitude is used by both pilots and controllers to determine aircraft position and separation. This works well with the traditional operational methods of using barometric altimeters on aircraft and Mode C/S interrogation to provide the controller with that information.

In the future there is no technical reason why geometric height cannot be used by both pilots and controllers. This is the natural output of radar altimeters, GNSS systems and multilateration systems and would work well with an ADS-B and WAM surveillance architecture. However in practise this is unlikely ever to happen as aircraft fly naturally at a constant pressure level and it would be very difficult to transition from one concept of operations to another.

However the geometric height output of a multilateration system is useful in a number of areas.
- It can eliminate the need for primary radar in approach monitoring
- It can provide additional safety and integrity checks in high density airspace (e.g. RVSM)
- It can provide verification of the GNSS position transmitted by ADS-B

Another use of the pressure altitude is in order to calculate a position where only 3 receivers receive a signal. The Mode C, or Mode S height can be used as an approximation of the height to form a solution for the lateral position.

8.6 Summary
Height monitoring with WAM systems is most applicable for en-route altitudes, as the geometry becomes increasingly poor with decreasing altitude. The break-point between using altitude from a WAM system compared to standard Mode C is around 2,000 to 5,000 feet, although this depends on exact site positions and TDOA accuracy.

To allow for RVSM accuracies, careful choice of antenna, receiver layout and inter-site distance must be made and for a standard Square-5 layout this limits the baseline to around 30NM. To increase coverage additional receivers may be used as depicted in Figure 21. By increasing the number of receivers in this fashion, coverage may be extended to the maximum allowed by the WAM synchronisation architecture used.

9   Aircraft with Mode A/C only

This section describes the features of a multilateration system when used to detect aircraft equipped only with Mode A/C transponders.

9.1 Probability of Detection

The probability of detection in an MSSR system is dependant on the probability of reply from the aircraft's transponder when it is stimulated by an interrogation from the MSSR. With a passive multilateration system there is no control of the interrogation so with Mode A/C only aircraft this makes the probability of detection dependant on interrogations from existing MSSR installations or other ACAS equipped aircraft. The probability of detection will therefore be dependant on existing installations and other traffic.

This means that en-route aircraft in areas with existing MSSR infrastructure will have a high reply rate and hence a high probability of detection. For low flying aircraft the reply rate will be patchier. For a terminal area application with no existing MSSR installation an active system may be required to achieve an acceptable probability of detection for low aircraft.

See also chapter 5 Active and passive WAM systems.

9.2 Code Swaps

It is not always possible to distinguish Mode 1, 2, 3/A or C transmissions from an aircrafts' transponder unambiguously without reference to additional information. The problem is described below.

For civil aircraft the system has to determine the difference between the Modes A and C. Mode C uses only 2048 codes compared to the 4096 used by Mode A. It is therefore possible to positively identify 50% of Mode A codes by the presence of the D1 pulse. The identification of the remaining Mode A and C codes can be done in the tracking algorithms with reference to the measured height of the aircraft. This leaves some ambiguity in the result when the allocated Mode A code represents a Mode C altitude close to the measured height of the aircraft. The geometric height of a pressure altitude can vary by more than 1000ft. This means that there are more than 20 overlapping codes for any given flight level. The frequency of Mode A/C code swaps can be significantly reduced if meteorological data is available. This will significantly reduce the number of overlapping codes.

Military aircraft introduce another level of ambiguity as they use Mode 1 and 2 as well as 3/A and C. Mode 1 and Mode 2 can use all 4096 codes and are therefore indistinguishable from Mode A without knowledge of the interrogation or current allocations. In high traffic areas there are many more A/C interrogations than Mode 1/2. This means that an assumption can be made based on the frequency of codes received from the target.

In summary it is straightforward for a multilateration system to associate a series of codes with an aircraft track. These may correspond with Mode A, C, 1 or 2. For civil aircraft it is possible to distinguish the Mode A and C code although an ambiguity exists for a small number of codes. With military aircraft the ambiguity increases for all codes but especially between Modes A and 1 and 2.

10 Analysis of altitude performance

This Section discusses and illustrates how accuracy is effected depending upon the aircraft altitude, specifically considering the geometry and atmospheric effects. It draws heavily on the previous lateral and vertical accuracy work presented in Section 6 and Section 7 respectively.

10.1 Geometry Effects

As previously noted, the raw TDOA accuracy is multiplied by a 'Dilution Of Precision' term to give positional accuracy. Lateral accuracy uses a Horizontal DOP and vertical accuracy uses a Vertical DOP. These are illustrated below against height (these graphs are identical to Figure 34 & Figure 35):
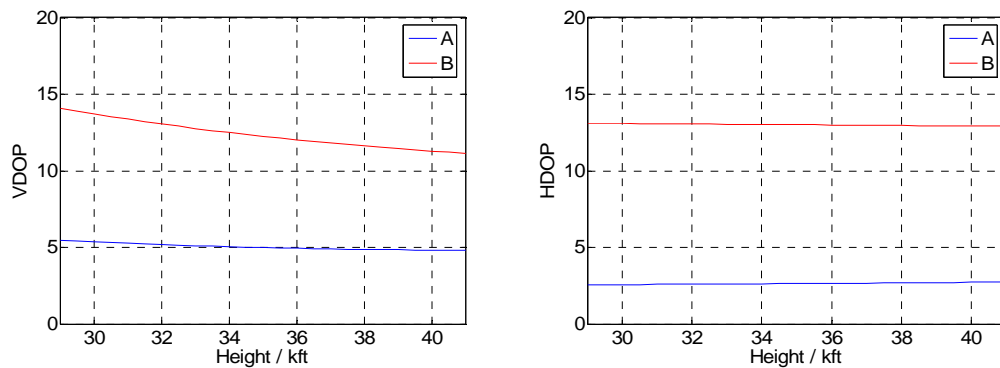
Figure 42 HDOP & VDOP from 29 – 41kft
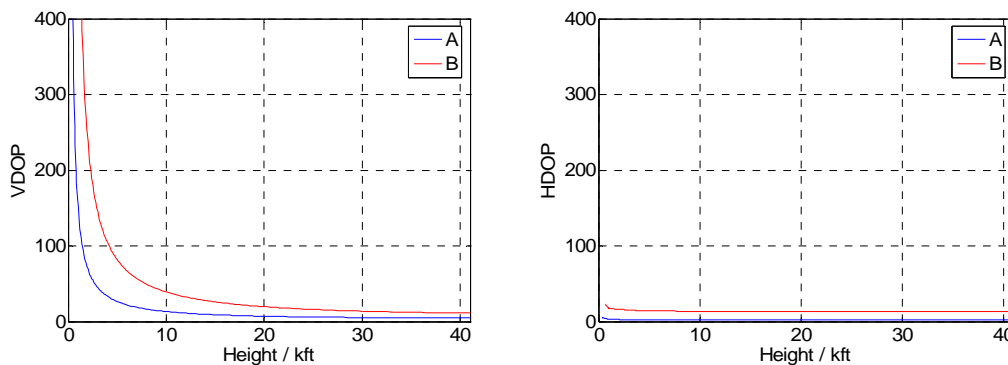
Figure 43 HDOP & VDOP from 0 – 41kft

This shows that decreasing altitude corresponds to decreasing accuracy, with a very rapid change below 10,000 feet. However, lateral geometry is good at all heights.

10.2 Other Effects

Aside from geometrical effects, a number of other factors will affect accuracy with varying aircraft height. These are considered in the remainder of this Section.

Transmitter gain variation:

As an aircraft over flies a WAM system at high altitude, the angle from aircraft to receiver will be broadly similar to that at low level over flying aircraft, although the proportion of time spent at each angle will differ. This implies that the transmit antenna gain pattern seen will equally be similar; therefore this effect can be ignored.

Multipath:

As the aircraft/receiver geometry changes, as will the multipath geometry. This is increasingly important at low altitudes where high gain is required to receive the SSR signals at low elevation angles thus removing the possibility of multipath reject by squinting the antenna pattern. However, this low angle can either arise due to long range / high altitude or short range / low altitude. Therefore, this effect is not unique to aircraft height and is not considered further.

Refractive index variation:

In order to correctly form the TDOA value, account must be made for the travel of the SSR signal through the atmosphere and corresponding delays due to the variation in refractive index to the various receivers. It is expected that this will improve at lower altitudes, as the overall delay will decrease, although the improvement will be modest compared to the geometrical effects. Due to this, the effect is not considered further either.

Obscuration:

As the aircraft drops to very low altitudes, at some point a clear line-of-sight link will not exist between all receivers and the aircraft and system accuracy will decrease substantially. This has been covered in the previous Sections.

Path Loss & Antenna Choice:

Whilst at lower heights the free-space loss will be lower, as the range will be shorter, as noted in the Multipath Section above a squinted antenna may offer less gain and thus poorer overall Signal to Noise Ratio. Correct choice of antenna for the required application is therefore critical to achieve the balance of multipath reject to low-elevation angle gain.

10.3 Summary

In summary, WAM system accuracy may be divided into three discrete sections dependent upon aircraft altitude, detailed in the Table below. Note that it is assumed that the receivers have

appropriate antennas, sensitivity to enable the required baselines/distances/signal-to-noise ratios to be achieved.

Table 7 Height Regimes for WAM System

Title	Altitudes / feet	Lateral Accuracy	Vertical Accuracy	Baseline / NM
En-Route altitude	~25,000+	Very good	Very good	Large (30-60NM) dependent upon accuracy required
Medium altitude	~10,000 to 25,000	Very good	Average	Medium (10-30NM)
Low altitude	<10,000	Very good	Poor	Low to enable good visibility (10-20NM)

11 Analysis of mountain region performance

When a WAM system is to be applied in a mountain region, the main problem is the location of the receiver stations in such a way that the 3D-volume that has (at least) quadruple coverage is as large as possible, and covers at least the complete surveillance area. And this should be accomplished without an excessive amount of receiver stations.
A universal solution to this problem is not possible because of the large amount of different environments that can be found, so we will only give some general guidelines. A detailed analysis needs to be made for each particular environment.

The use of a Transponder Synchronised WAM-system (see section 3.2.3) is probably not feasible because the line-of-sight restrictions cannot be fulfilled.
For the same reason, the use of a Common Clock WAM-system (see section 3.2.1) based on a microwave link is probably not feasible. A Common Clock WAM-system based on a dedicated fibre link would not have the line-of-sight restriction, but it may be more difficult to build the infrastructure for this type of solution.
If the mountain region consists of a relatively narrow mountain chain, the receivers could be located on both sides of the chain. It has to be analysed if the 3D-volume that can be covered this way is large enough, in particular for the altitude.
If the mountain region covers a large 2D area, such as the Geneva HMU system (see section 14.1.3), receivers have to be located at high altitude with as clear view as possible in all directions.

11.1 The Innsbruck WAM system

A good example of a WAM system covering a Terminal Area surrounded by mountains is the Innsbruck WAM system.
Innsbruck, Austria, is surrounded by high mountain ranges to the north and south, up to 8000 ft above airport level, and has a narrow, V-shaped valley in east-west direction.
In order to implement a Surveillance system for the Innsbruck Terminal Area, Austro Control compared radar-based with multilateration-based solutions and chose for a WAM system for a number of reasons:

- Radar coverage would be limited within a mountainous region;
- Radars in a mountainous region are often subject to multipath reflections;
- A radar solution would require additional environmental considerations for RF issues;
- A radar solution would be significantly more expensive in terms of initial acquisition and life cycle costs.

Austro Control chose for the Sensis MDS system, receiving Mode S, Mode A/C, and ADS-B Extended Squitter messages, and consisting of 9 Remote Units (3 Receive/transmit, 6 Receive-only), 2 dual redundant reference transmitters, and a redundant Central Processing System.

The sensors are located at various sites in the Inn Valley in order to optimise the geometry for multilateration purposes. Tests have shown that about 97 % of all measured positions were within 70 m of the actual positions, with an average update rate of once per second or better.

12 Requirements for En-route and Approach use

12.1 Introduction

WAM requirements can be derived using similar methodology as is used for SSR/Mode-S surveillance radar. Basically, the requirements for radar performance are derived from the Target Level of Safety (TLS) requirements. Many factors affect the TLS figure and each of them can be allocated a certain risk budget. As a result, radar separation minima are defined to be used under particular circumstances. The following sections are from the Separation Guidelines [ref. 1]

From Annex A:

The following recommends criteria to determine whether a radar may support given separation minima, based on measurements of performance. For a separation minimum of 5NM applied to a range of 160NM with en-route traffic, the criteria are:

a) the number of errors with absolute value greater than 0.2° must be less than 1% and;

b) the tail of the distribution (beyond 0.4° must have exponential form, or be faster decaying; and

c) the number of errors with absolute value greater than 0.4° must be less than 0.03%; and

d) the mean value of errors with absolute value greater than 0.4° must be less than 0.55°.

The table below sets out the criteria for a radar to support four possible separation minima. They have been optimized for SSRs operating in combined mode (SSR and PSR).

Criterion	2NM	3NM	5NM	10 NM
Less than 1% of errors may be greater than:	0.08°	0.12°	0.20°	0.40°
The tail is defined as starting at: Less than 0.03% of errors may be in the tail, and they must have a negative exponential or faster-decaying form.	0.16°	0.24°	0.40°	0.80°
The mean of errors in the tail (see previous criterion) must be less than:	0.22°	0.33°	0.55°	1.10°

Table 8   requirements en-route

This analysis is based upon the fact that the azimuth error is the major contributing factor in the position error. For 5NM separation, the position error standard deviation at 160 NM must be less than 344 m. The mean of the tail errors should be less than 836 m. The radar surveillance standard values are slightly higher: 0.24°, 0.05% values in the tail and no required mean for the tail values. These figures can be used as required position performance for WAMLAT.

12.2 Approach - Radar Separation 3 NM

States noted that, in essence, the method to assess the radar accuracy for 3 NM radar separation does not differ from the one used for the 5 NM/10NM radar separation. The contributions of France and United Kingdom, set out in Annex 3/Attachment A, are an illustration of the methodologies being used to evaluate the radar capabilities. The EUROCONTROL Standard concerning "Radar surveillance in en-route airspace and major terminal areas" formulates criteria for application of 3 NM radar separation minima in High complexity TMAs, such as

a) Duplicated SSR coverage and single PSR radar, as such assuring continuous availability of radar position information and enabling provision of air traffic services to aircraft unable to respond to SSR interrogations.

b) The coverage within major terminal areas shall extend from the lowest altitudes of the intermediate approach segments for the principle aerodrome concerned. Coverage elsewhere will extend from the minimum levels at which radar services are required to be provided, up to the upper limit of the terminal area.

   Note: The coverage requirements below the lowest altitudes of the intermediate approach segments can be met in accordance with the local aerodrome conditions, provided continuity of services for the high complexity TMA is ensured.

c) Provisions shall be made for the continuity of radar coverage in the areas interfacing with en-route airspace

d) The position accuracy of the surveillance radar data available at the control position shall have an error distribution with a root mean square value (RMS) equal to or less than 300 metres for high complexity TMAs.

e) Surveillance information updates shall enable the display updates to be no more than 5 seconds.

f) A maximum of 2 successive updates by extrapolation for position data.

Requirement a) remains PR support is needed for targets, unable to reply to SSR/Mode-S interrogations. Requirements b) and c) are covered by MLAT if the target is within the convex hull of receiver stations. Requirement d) was covered earlier. Considering the high update rate of MLAT, requirement e) is no longer relevant. Requirement f) shall be modified to include a timeframe, e.g. 8 s without update.

12.3 Approach - Radar Separation 2.5 NM

A further reduction of the minimum authorized radar separation to 2.5 NM on the final approach track within 10NM from the landing threshold is subject to stringent requirements. In addition to the operational aspects, extensively reproduced in paragraph 6.3.2, ICAO's Rules of the Air and Air Traffic Service (Annex 11 and Doc 4444) also provides technical

guidance. It is the capability of a radar system or sensor and the distance of the target from the sensor which determine the prescribed radar separation minimum. The following elements shall be taken into consideration when deciding upon the minima:

a) appropriate azimuth and range resolution;

b) updating cycle of radar display of 5 seconds or less;

c) availability of Surface Movement Radar or Surface Movement Guidance and Control System.

Considering that a MLAT system covers airport surveillance as well approach, given a proper receiver configuration, and given the MLAT measurement characteristics, the above guideline is automatically fulfilled by MLAT.

The following requirements are from the Radar Surveillance Standard [ref. 2]

Detection Requirements

6.3.2.1 Target Position Detection

– Overall probability of detection: > 97 %

6.3.2.2 False Target Reports

– Overall false target report ratio: < 0.1 %

6.3.2.3 Multiple SSR Target Reports

– Overall multiple SSR target report ratio: < 0.3 %

– Multiple SSR target report ratios:

  – from reflections : < 0.2 %

  – from sidelobes : < 0.1 %

  – from splits : < 0.1 %

6.3.2.4 Code Detection

– Overall Mode A probability of code detection: > 98 %

– Overall Mode C probability of code detection: > 96 %

Quality Requirements

6.3.3.1 Positional Accuracy

– Systematic errors:

  – slant range bias: < 100 m

  – azimuth bias (degree): < 0.1°

  – slant range gain error: < 1 m/NM

  – time stamp error: < 100 ms.

– Random errors (standard deviation values):

  – slant range: < 70 m

  – azimuth (degree): < 0.08°

– Jumps:

– overall ratio of jumps: < 0.05 %

6.3.3.2 False Code Information

– Overall false codes ratio: < 0.2 %

– Validated false Mode A codes: < 0.1 %

– Validated false Mode C codes: < 0.1 %

The detection performance characteristics assume a measurement update rate of 0.25 Hz or less. Considering the high update rate of WAM, the detection figures can be taken as 4 s averages for WAM.

12.4 Availability Requirements

12.4.1 General

The frequency with which failures of system occur have a direct impact on the TLS figure. Consider the situation that the system operates normally. In that case, traffic will have a safe separation. If the system suddenly fails, the traffic will not have a safe separation anymore. The traffic will be re-arranged to have a new safe separation. The transition period between these two safe situations is a period of increased risk.

12.4.2 Availability

The Radar Surveillance Standard specifies for individual sensors the following

• A maximum outage time <= 4 hours

• A maximum cumulative outage time <= 40 hours / year

Both figures apply if no alternative surveillance sensors are available.

12.4.3 Redundancy

From a maintenance point of view, WAM receivers are fairly simple. Thus, the availability will mainly be determine by the outage time which, in turn, will, most likely, be determined by the time to get to a remote site. Therefore, some thought must be given to redundant configurations. Duplicate receivers at each location is certainly not the optimum configuration; apart from the cost increase, a communications failure will still make the unit inoperable. A better approach is to separate the coverage into "essential" and "wanted" coverage and site the receiver units such that the "essential" coverage area has always coverage from 5 or more receiver units. Receiver failure results in the loss of "wanted" coverage, but never in loss of "essential" coverage.

12.4.4 (Un-)Intentional Interference

WAM receiver units need to be deployed across a large area. Therefore, it may be impossible to completely control the EMC environment of all receiver units. Hence, receiver units may be subject to interference. Siting of units that use GNSS signals is critical since they must, at all

times, be able to see a satellite. Furthermore, GNSS signals are weak and can be easily disturbed.

The only way to mitigate the effects of interference is by employing a suitably redundant receiver configuration (see the previous section).

12.5 Notes

- The probability of detection characteristics need to be further investigated.
- The TLS figure is mainly affected by the tails of the position error distribution; this needs to be investigated in more detail.
- Close approach situations affect the distribution of position errors. The behaviour of WAM position errors in close approach situations needs to be investigated.
- The main sources of WAM systematic errors are atmospheric propagation and multi-path effects. The precise model needs to be investigated.

13 Impact on multi-sensor tracking and surveillance

13.1 System architecture

13.1.1 The Need for Centralised Tracking

A WAM system uses a local tracker in order to suppress false tracks, caused by multi-path and to resolve the SSR mode-2/3A/3C ambiguities. Furthermore, the reliability of reports is enhanced by the correlation with previous reports. Considering the perceived accuracy of a wide-area MLAT system, the question may be raised whether or not this is sufficient for ATC?

The advantages of integration of WAM with other sensors are

- The reliability and continuity of the tracks in multiple-coverage areas are improved;
- Possible WAM systematic errors, e.g. propagation effects and short multi-path[3] effects can be eliminated;
- WAM may help to reduce systematic errors of other sensors in case of overlapping coverage;
- Seamless transition from and to areas covered by others means of surveillance, like radar.
- Augmentation of the track state with information from other sensors, e.g. ADS-B via UAT or VDL mode-4. Other sensors may provide additional information to the WAM information.

The above benefits, especially the improved reliability and continuity, are strong motivations for continued use of centralised tracking

13.1.2 Tracking Architectures

13.1.2.1 Overview

There are three basic surveillance architectures as far as integration of MLAT data is concerned

- Centralised TDOA Processing and Tracking
- Sensor-level TDOA Processing, Centralised Tracking
- Sensor-level Tracking and Centralised Track Fusion

Each of these architectures will be discussed in more detail in the following sections.

Combinations of the basic architectures are also possible, e.g. using positions from two different WAM systems in combination with processing TDOA measurements from receivers at the edges of the individual coverage. In this way, the gap in-between the two systems could be covered (depending on the actual geometry, of course).

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[3] Multi-path reports from a single target are received closely separated in time; this causes a systematic error by the ambiguity in position resolution

There are some caveats with respect to the centralised processing of WAM measurements. WAM systems may provide measurements at a rate of 100 Hz or more (in areas with extreme SSR coverage). Tracking filters, designed for filtering radar data at 0.2 Hz or less, may not be suitable for filtering this kind of data. Additionally, these frequent updates may create CPU load problems, since present tracking systems are designed for 0.2 Hz or less update rate.

13.1.2.2 Centralised TDOA Processing and Tracking

This architecture means that the multi-lateration TDOA measurements and the other received attributes are sent to the central tracker. The tracking filter processes the TDOA measurements in the same way as measurements from other sensors.

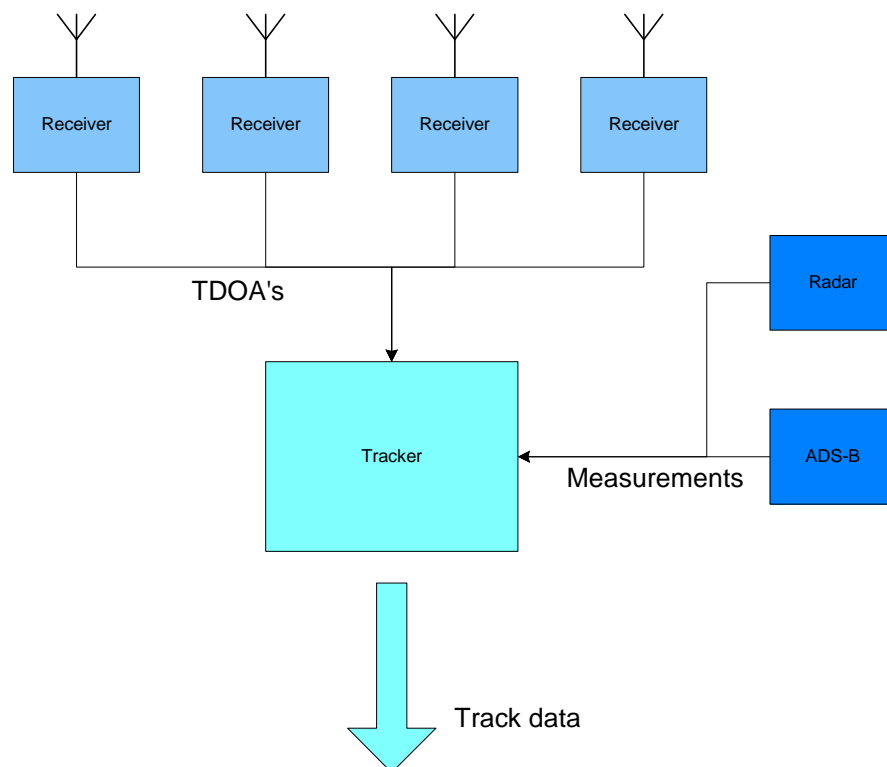
Figure 44 Centralised TDOA Tracking

In this situation, optimum use can be made of all available sensor information. Consequently, continuity, reliability, accuracy and false-track suppression will be better in multi-sensor covered areas. There are some severe disadvantages

- May require wide-area high-bandwidth connections with the MLAT system
- Requires complex, CPU-intensive calculations

13.1.2.3 Sensor-level TDOA Processing, Centralised Tracking

The WAM system independently processes the TDOA measurements to obtain the target position. This position, along with other target attributes, is sent to the central tracker who, subsequently, processes the position. In addition to the calculated position, also the measurement covariance matrix needs to be sent to the tracker in order to properly weigh the measured position in the tracking filter equations.
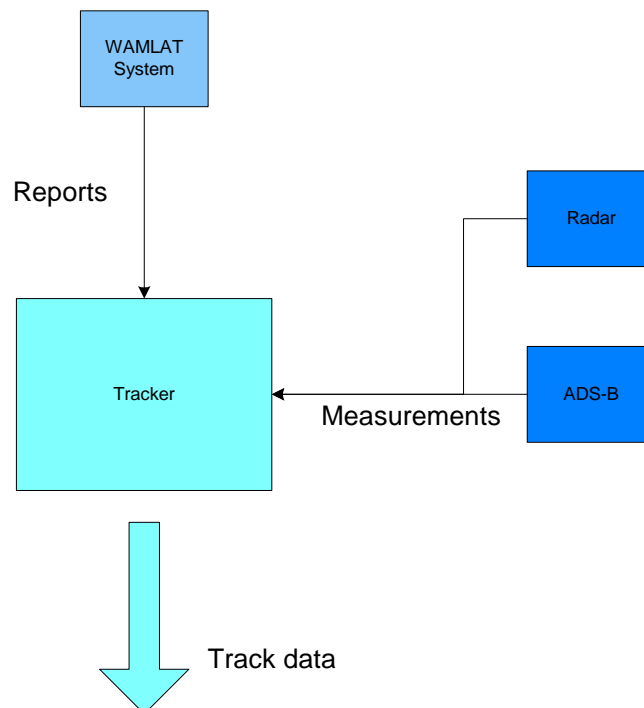
Figure 45 Centralised WAM Position Tracking

This architecture has the advantage that WAM measurements are still optimally used in target tracking. False-track suppression may be worse than in the previous architecture, since the local tracking has no knowledge of the other sensors.

The same disadvantages as in the previous section apply, although less so, because the data rate to the central tracker is considerably reduced.

Furthermore, a model must be made of the errors in the calculated position; the receiver geometry determines, to a high extent, the accuracy of the measurement. In case of independent processing of the position, this geometry may not be known to the multi-sensor tracker. Therefore, a careful analysis must be made of the reported WAM position accuracy.

13.1.2.4 Sensor-level Tracking and Centralised Track Fusion

This architecture combines tracks from two or more trackers by either selecting the "most likely" track or a weighted combination of tracks.

Neither method has a sound mathematical basis; selection or combination is done on a "rule of the thumb" basis with a possibly large set of "special" rules to handle "out of the ordinary" situations.
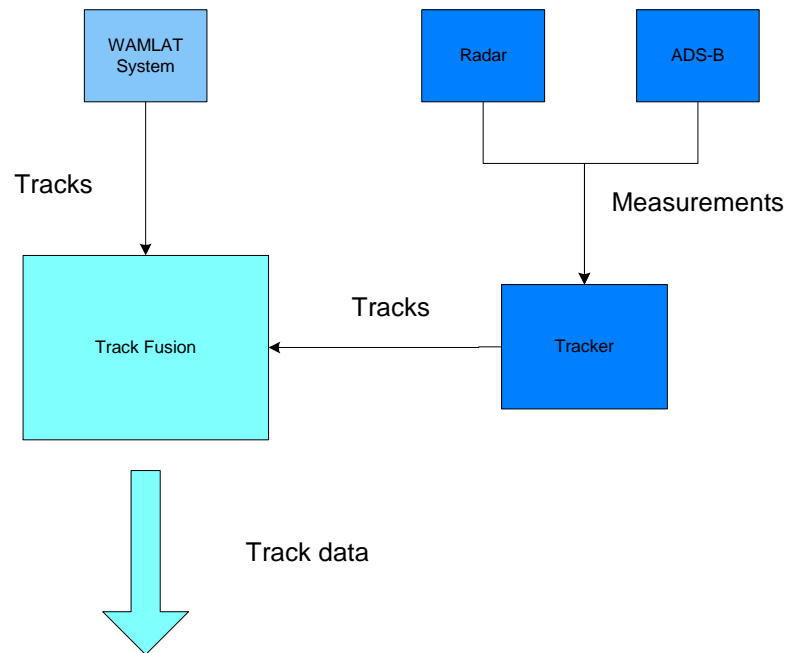
Figure 46 Centralised Track Fusion

The advantage of this architecture is that there is relatively little bandwidth needed to distribute the track data

Depending on the quality of the rule-set, the behaviour of the track may be sub-optimal or even erratic, especially under unusual circumstances

13.2 Possible Surveillance Scenarios

This section briefly describes some possible scenarios that use WAM. Note that this list is not intended to be exhaustive, it provides some examples where surveillance may benefit from the use of WAM.

Terminal Areas. An airport multi-lateration system could be extended with additional receivers to obtain seamless coverage throughout the terminal area.

Mountainous regions. A WAM system can be used as a gap-filler in mountainous regions. Compared to radar, the flexibility of receiver arrangement makes it far easier to obtain the required coverage. Furthermore, the absence of rotating parts means that WAM receivers need less maintenance and may be deployed at sites that are hard to reach.

Off-shore operations. Oil platforms have very rigid requirements with respect to equipment with moving or rotating parts and equipment that emits radiation. By combining passive WAM receivers at the oil platforms with interrogators elsewhere, WAM is a conceivable alternative to ADS-B.

WAM can be used to validate ADS-B/C reported positions. In this case, the accuracy requirements of WAM are not very stringent since they are only used for verification of the reported position.

14 Current WAM systems

14.1 RVSM HMU Systems

14.1.1 Prototype HMU System

The use of Wide Area Multilateration in civil aviation was first developed as an accurate means of measuring aircraft height. The proposed introduction of Reduced Vertical Separation Minimum (RVSM) over the North Atlantic required a means of verifying that aircraft were keeping to their assigned altitude. Existing primary and secondary radar systems cannot measure height accurately and specialist measurement radars cannot provide any aircraft identity. To overcome this EUROCONTROL in cooperation with NATS funded Roke Manor Research to research and develop a prototype Height Monitoring Unit (HMU) for RVSM height measurement. After a series of demonstrations a prototype HMU was installed at Strumble in the UK in 1993.

14.1.2 NAT HMU Systems

In order to monitor the introduction of RVSM in the NAT region NATS and Nav Canada procured 2 HMU systems from Roke Manor Research. The first was installed at Strumble in the UK in 1997 to replace the prototype system and the second was installed in Gander in Canada in 1998.

The NAT HMU systems use the basic 4 receiver geometry shown in Figure 16. One operational disadvantage experienced with this geometry is the lack of redundancy. When one receiver is unavailable due to maintenance activities the whole system is unavailable.

They NAT HMUs use the transponder synchronised architecture described in 3.2.3. This works well over the short range and relatively flat terrain of these systems. However, tall towers are required to allow transponder synchronisation over this range as shown below.

Figure 47 Gander HMU site with sync transmitter and receiver towers

The NAT traffic followed a small number of specific flight paths. This allowed the HMU system covering a 20x20NM region to be placed under one of the flight paths. The systems were specified to measure the height of aircraft in straight and level flight to 25ft (1σ). Flight trials with DGPS equipped aircraft showed the mean offset of the HMU systems from DGPS to be approximately 15ft.

14.1.3 ECAC HMU Systems

The RVSM monitoring requirements for the ECAC region required a much wider area then the NAT region. It was decided that three 90x90NM monitoring regions with the same 25ft (1σ) accuracy would be used to cover the main traffic areas of Europe. Sites around Linz (Austria), Geneva (Switzerland/France) and Nattenheim (Germany/Luxembourg) were chosen.

EUROCONTROL procured one system for Linz from ERA and two systems from Roke Manor Research for Geneva and Nattenheim.

ERA installed a common clock system (3.2.1) at Linz using microwave links to transmit the i/f data back to the processing site. The system completed commissioning in May 2000 and remains operational covering a 60NMx60NM region.

Roke Manor Research used a common view GNSS synchronised (3.2.5) system in order to allow synchronisation without the need for line of sight in the hilly and mountainous terrain around Nattenheim and Geneva. Sites use existing infrastructure sharing with

telecommunication, radio, TV and DME transmitters. Antennas are located on rooftops, existing masts or on small dedicated towers. Flight check of the systems demonstrated the mean offset from DGPS to be less than 15ft. The systems completed commissioning in November 2000 and remains operational covering a 90NMx90NM region.

Figure 48 Geneva HMU antenna on TV tower

All three ECAC HMU systems use a "square 5" receiver geometry (Figure 17). This offers a very even (almost circular) coverage area. If one of the outlying receivers is unavailable the system remains operational with a slightly reduced accuracy and coverage. However, if the central site is unavailable the accuracy is degraded significantly due to the geometry of this layout.

14.2 SENSIS MDS

Sensis' Multistatic Dependent Surveillance (MDS) system is an integrated multilateration and ADS-B system based on Mode A/C/S transponder replies. It is in operational use for ground surveillance at a large number of airports world-wide, including some of the largest such as London Heathrow Airport and Charles de Gaulle Airport Paris.
The MDS system makes use of a transponder synchronised architecture but is being enhanced to use a GNSS-synchronized distributed clock architecture.

In the context of WAM, the MDS system has been installed for enhanced terminal surveillance at Innsbruck Airport (Austria) and Frankfurt Airport (Germany), and for surveillance of the airspace over the Patuxent River Atlantic Test Range (US).

The MDS system is also used in an aviation surveillance research programme in the Gulf of Mexico.

14.3 RANNOCH AIRSCENE

Rannoch's AirScene system is an integrated multilateration/ADS-B system that is suitable for en route, terminal, Precision Runway Monitoring, and surface operations. It makes use of Mode A/C/S transponder replies and uses a standalone GNSS-synchronized distributed clock architecture.

The AirScene system is deployed at a number of locations including Calgary Airport in Canada where an active system is used for the surveillance of the terminal area with an operational range up to 40 NM from the airport.

14.4 ERA multilateration systems

ERA produces several types of passive surveillance systems based on multilateration for airport surveillance, Precision Runway Monitoring, mid-range and long-range surveillance. They use mode A/C/S receivers that can be augmented with an appropriate interrogator to create an active multilateration system. The multilateration system makes use of common clock architecture with microwave links between the receivers and the central processing unit.

ERA has installed multilateration systems for A-SMGCS at a number of locations including Prague Ruzyne International Airport (Czech Republic), Braunschweig Airport (Germany), and Copenhagen Airport (Denmark).

In the context of WAM, ERA has installed a Height Monitoring Unit for RVSM in the Linz area (Austria) consisting of 5 receivers with a monitoring area of 30 NM radius.

The ERA P3D WAM system has been installed at 7 military ATC centres, at Prague Ruzyne International Airport, and at the Ostrava International Airport in the east of the Czech Republic.

The Ostrava TMA has limited radar coverage below 3000 ft (above MSL) due to a complicated terrain profile. The WAM system was the first operational (since 2003) WAM system in the world consisting of 5 Receiving Stations, 2 Mode A/C/S Interrogators, and a Central Processing Station. It covers an area with a radius of approximately 60 NM around the airport with an accuracy comparable to, or better than a standard SSR.

15 System costs

The costs of a WAM system consist of a number of components:
- Hardware equipment (Central Processing Station, Remote Units, Reference Transponders)
- Installation and commissioning
- Operating costs (maintenance, electricity, data line rental fees, site rental fees)

The fundamental hardware equipment cost is most likely cheaper than MSSR.
- Multiple receivers similar to an MSSR receiver
- Optional Transmitter similar to an MSSR transmitter
- Multiple antennas of much lower cost than MSSR
- No mechanical components
- Multilateration Processor

If we compare the estimated hardware cost of an SSR system (2.5 M €) with the estimated prices of WAM equipment (Central Processor 400 k €,Remote Units 50-150 k €, Reference Transponder 50 k €), then the hardware costs of a WAM system are (very roughly) around 50 % of those of an SSR system.

The installation and commissioning is more variable as the cost of sites will be heavily dependent on the location. Installation is simpler than MSSR but there are multiple sites to consider. Commissioning will be more expensive at first until the technology has matured and the approval process is standardised. Then it is likely to be similar.

Concerning architecture: Common clock systems require custom links (single hop microwave link or fibre); this may be costly in some cases. Distributed clock systems can use any digital link over a mix of any technology: copper, fibre or wireless. If there are already links to the sites distributed clock systems can exploit this infrastructure and cut out link installation costs. GNSS synchronised systems are simpler and more flexible to site which makes site selection easier. Transponder synchronised systems and common clock systems that use microwave links have line of sight restrictions between sites. These systems will be unsuitable in hilly terrain, built up areas or for large system baselines.

The maintenance cost of WAM systems will be much lower than MSSR as there are no rotating mechanical parts. A 6 monthly maintenance check at each site to maintain ancillary equipment such as UPS systems may be required; otherwise there is very little to do.

The cost of renting/maintaining multiple data links could be a significant part of the overall operating costs, and certainly the site rental fees will contribute substantially to the operating costs.

Overall, the operating costs for a WAM system are in the order of 50 k € per year, whereas for an SSR system these costs are more likely around 100 k € per year.

Obviously, under very specific circumstances (e.g. Remote Units on mountain tops) the costs for the WAM system can increase significantly.

16 Conclusions and Recommendations

16.1 Conclusions

In this document we have analysed many aspects of WAM systems:
- the possible types of airborne transmission that could be used for WAM,
- detailed descriptions of WAM architectures,
- extensive analyses of WAM accuracies, both for the horizontal plane and for altitude,
- use of WAM systems to verify ADS-B position data and as RVSM HMU,
- the impact of WAM data on a multi-sensor tracker,
- overview of existing WAM systems,
- cost comparison with radar systems.

WAM systems appear capable of height monitoring of en-route traffic and are already being used as such operationally. Also the verification of ADS-B position data is within the capabilities of a WAM system designed for such purposes.
The analysis of WAM accuracies shows that WAM systems are potentially capable of significantly higher accuracies than an equivalent radar service. It is shown that a five receiver WAM system has a higher accuracy than both an en-route and terminal area MSSR. However the range is lower due to the horizon of multiple receivers. A comparable range can be achieved by adding in additional receivers. En-route WAM systems can also provide accurate height measurement information which is not available from MSSR. In terminal area systems height measurement is not available at lower altitudes. The Common View GNSS Synchronised architecture offers an accurate and flexible technique for wide area multilateration, but other architectures could also be used for some applications.

All current WAM systems are based on 1090 MHz technology because of the wide availability of the technology as part of the airborne infrastructure, the extensive experience with this technology in terms of surveillance, and the properties of these signals for use in a WAM system (aircraft identification and accurate TDOA measurements).
Other signal types appear possible but more research and development will be needed before they reach the same level of maturity.

16.2 Further areas of work

In this section we present a number of additional studies that may provide more detailed knowledge about the deployment of WAM systems.

1. <u>WAM Signal Study</u>. A detailed study into the suitability of candidate signals to WAM. DME is a promising signal type as it is suited to the existing TOA architectures used by 1090 SSR WAM systems. UAT is another promising signal type. VDL Mode 4 is also worthy of investigation as the transmissions are synchronised to timeslots so with knowledge of the transmission time it may be possible to apply a TOA location technique. This study will look at the suitability of the proposed signal types to cross-correlation and TOA processing, the achievable accuracies and how the solution could be integrated with existing WAM architectures.

2. <u>WAM error study</u>. A detailed study into error sources in a WAM system and their impact on performance. WAM systems are subject to different errors from radar systems and these errors have a different impact on performance. There are both systematic and random errors that have an impact on the resulting TDOA measurement. These errors are caused by a range of factors such as the signal properties, analogue component group delays, the digitisation process and synchronisation technique. The study should analyse the error sources, propose an error budget for components of a WAM system and identify possible error detection and mitigation strategies.

3. <u>WAM Architecture Interoperability</u> A detailed look at how WAM architectures could be broken down into component parts that are interoperable between manufacturers. This would also look at the required interfaces and the data that needs to be exchanged.

4. <u>Probability of Detection Study</u> Probability of detection in WAM systems is dependant on the probability of reply of the aircraft from all interrogation sources and its squitter transmissions. In addition it depends on the probability of detection of these replies at 4 or more receivers. The study will look at the probability of detection of aircraft in different phases of flight with typical WAM installations (e.g. TMA, en-route) , a range of existing interrogator installations and the presence of ACAS equipped aircraft. The study could optionally include the delivery of simulation software to model these scenarios with different WAM geometries, interrogator locations and flight paths.

5. <u>Atmospheric and Propagation issues affecting WAM systems</u> WAM systems are affected differently from radar systems to signal propagation. This study will investigate how atmospheric propagation affects WAM systems and the impact of anomalous propagation conditions.

6. <u>WAM Tracking and Filtering Study.</u> A detailed study to investigate the feasibility of the use of raw MLAT data (as opposed to MLAT data from an integrated tracker) as direct

input to a multi-sensor tracker. The main aspects to investigate are the potentially very high update rate of the MLAT data (up to 100 Hz), the noise characteristics of the data, Mode A/C/1/2 ambiguities, and the dependence of the set of receivers that recorded the signal.

7. Field Trials. Design field trials to validate study results.

8. Cost Benefit Analysis A detailed cost benefit analysis of multilateration when compared to other surveillance techniques.

9. Redundancy & Integrity Study into the redundancy of receivers and telecommunications means.

10. Operational Improvements. What operational improvements could be achieved based on the technical capabilities of WAM systems.

11. Description of operational services

17 Glossary of Terms

ACAS	Aircraft Collision Avoidance System
Altitude	Measurement derived from the barometric altimeter
Baseline	The typical distance between adjacent receivers in a multilateration system
Common Clock Synchronisation	A synchronisation method where the signal digitisation for all receivers is carried out at the same location with reference to a common clock.
Common View GNSS Synchronisation	A synchronisation method where GNSS satellites in common view of the receivers are used to synchronise a distributed clock architecture.
Cross correlation systems	Multilateration systems where the target signals received are cross correlated to determine the TDOA.
Distributed Clock Synchronisation	A synchronisation method where the signal digitisation is carried out at the individual receivers with reference to a local clock.
Garble	Where two or more replies overlap in time
GDOP	Geometric Dilution of Precision.
Group Delay	The delay in the signal path between reception at the antenna and the signal digitisation process
GNSS	Global Navigation Satellite System. The generic term for satellite navigation systems such as GPS, GLONASS and Galileo
Geometric Height	Height derived from the multilateration calculation
HMU	Height Monitoring Unit. WAM systems used for RVSM height monitoring.
MSSR	Monopulse Secondary Surveillance Radar
Multilateration	The method of determining a targets position from the TDOA of replies at spatially separate receivers.
Multipath	Unwanted reflections of the target signal
Standalone GNSS Synchronisation	A synchronisation method where a GNSS receiver is used to discipline the local clock at a receiver in a distributed clock architecture.
Synchronisation	The method of tying together the digitisation of signals received at different receivers.
TDOA	Time Difference of Arrival. The time difference of signal reception between two receivers.
TOA	Time of Arrival. The time of arrival of a signal at a receiver.
TOA Systems	Multilateration systems where the TOA of the target signal is measured in order to determine the TDOA.
Transponder Synchronisation	A synchronisation method that uses a reference transponder for synchronisation in a distributed clock architecture.
WAM	Wide Area Multilateration. Multilateration systems that monitor aircraft in

| | flight. (As distinct from surface surveillance) |