WHITE PAPER

ANGLE OF ARRIVAL/ DIRECTION FINDING TECHNIQUES

Prepared by **Dr Alasdair Edge**

CRFS

EXTRAORDINARY
RF TECHNOLOGY

CR-003676-WP-3

Angle of Arrival (AoA) or Direction Finding (DF) techniques are perhaps the most widely-used ways to geolocate radio frequency signals. In this white paper, we outline the various forms of AoA , including how they work, how they can be applied in practice, and how they can be combined with other geolocation techniques such as time difference of arrival (TDOA).

CONTENTS

1. AOA BASIC OPERATING PRINCIPLES

Angle of Arrival (AoA) or direction finding (DF) techniques are perhaps the most conceptually straightforward geolocation techniques available. We simply measure the direction from which a signal arrives, and then project a line of bearing (LOB) back out along the same direction. Doing this with receivers at two spatially separated locations allows two LOBs to be drawn, which will intersect at the signal source position.

This conceptual simplicity at the surface level, though, obscures a more complicated picture. The devil is in the detail, and in this case, the detail is in the seemingly simple task of working out the direction of the incoming signal. In this white paper, we will examine a series of techniques that can be used to determine this. These techniques fall roughly into two categories - amplitude comparison, which measures differences in the amplitude of the incoming signal with direction, and phase comparison, which relies on measuring differences in the phase of the signal.

1.1 PSEUDO-DOPPLER

As the name suggests, pseudo-Doppler techniques rely on exploitation of the Doppler effect, whereby the apparent frequency of incoming signals depends on the relative movement of the emitter and the receiver. Signals appear higher in frequency when the emitter and receiver approach each other, and lower when they are moving away from each other. The very simplest way to exploit this is to use a setup where the receiver is mounted on a rapidly-spinning circular disc. The received signal will then be at its highest frequency when the receiver is moving directly towards it (point A in Figure 1), and at its lowest when moving directly away from it (point in Figure 1). In this way, a line of bearing to the emitter can be generated. This is a “True Doppler” means of determining the angle of arrival. The frequency of the received signal will vary with a period equal to the period of rotation of the disc, and the phase of this frequency variation can tell us the direction of arrival of the signal - perfectly in phase with the rotational frequency when signals come from a direction of 0º, in anti-phase when signals come from a direction of 180º, and phase-shifted accordingly for all directions in between.

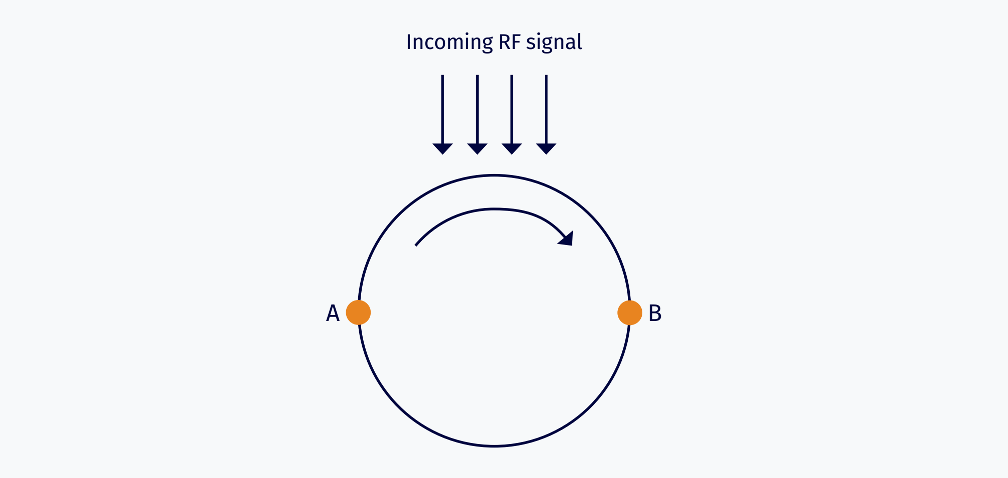


Figure 1
True Doppler Setup

Pseudo-Doppler systems use a series of aerials positioned along the perimeter of a circle in order to achieve the same effect without the need for a rotating disc. The aerials are rapidly switched on and off in sequence around the edge of the circle, which will once again cause the received frequency to modulate with a period equal to the time it takes to complete this sequence. We can then perform the same calculation as in the true Doppler case, with the phase offset between the recovered and original tones giving us a line of bearing to the source.

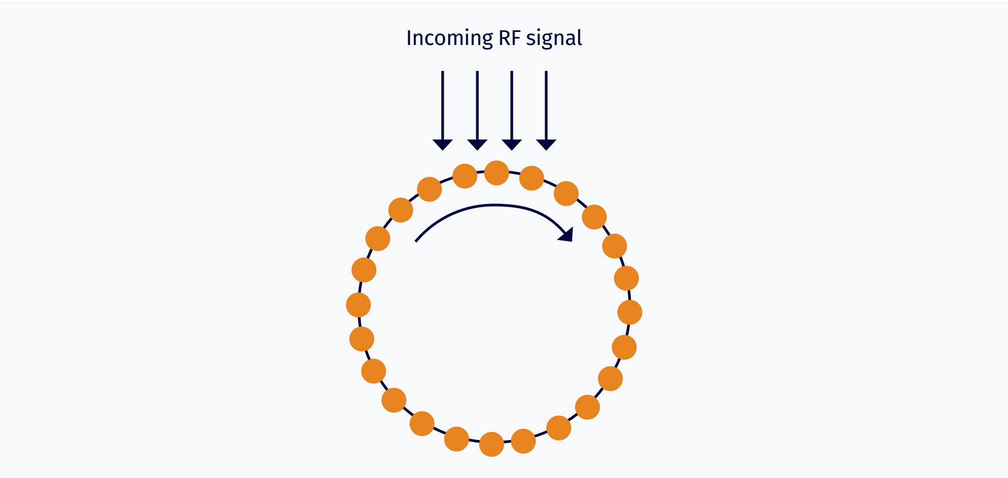


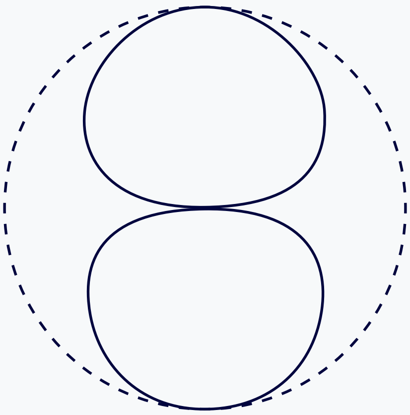
Figure 2
Pseudo-Doppler setup

Pseudo-Doppler systems have relatively straightforward antenna requirements, usually deploying loop-based arrays. The effect of this in practice is that direction finding can be carried out at a wider range of frequencies when compared to techniques (such as Watson-Watt, see below) with more complicated antenna setups. They are also less susceptible to site error, as their wider system aperture gives more wavefront averaging, and reducing the effects of multipath (see section 2.1).

However, pseudo-Doppler systems struggle when locating pulsed signals, as short duration signals may not allow a complete revolution of the system to take place.

1.2 WATSON-WATT

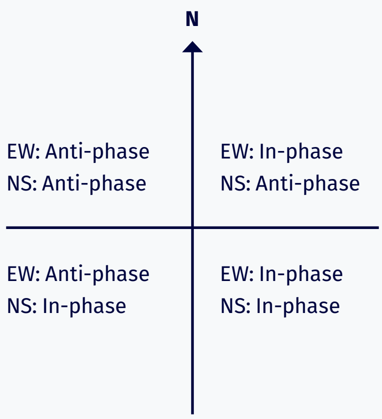
Watson-Watt direction finding is an amplitude comparison technique. Two sets of antennas (referred to as North-South and East-West antennas) are set up at 90º to each other. Each set of antennas has a directional gain pattern (ideally) linearly decreasing from 1 at 0º to 0 at 90º as shown in Figure 3, which means we can determine the incoming signal direction by comparing the strengths of the signal as recorded by each antenna set. So, for example, the extreme case where the N-S antenna records a signal and the E-W does not corresponds to a signal exactly parallel to the N-S antenna.



*<< **Figure 3** Watson-Watt N-S antenna gain pattern*

There is a slight additional complication that must be taken into account. For each given ratio of amplitudes recorded by the two antenna sets, there are in general two possible incoming directions. So, for example, in the extreme case above, the signal could be coming exactly from the north or exactly from the south. In the case where the two amplitudes are exactly equal, there are actually four possible incoming directions (from the NE, NW, SE or SW).

To break this ambiguity, it is necessary to include a third, omnidirectional antenna, and to compare the phase of the signal at this antenna with the phase recorded by the N-S and E-W antennas. There are four possible combinations for this - both N-S and E-W in phase, both in anti-phase, N-S in phase and E-W in anti- phase, or N-S in anti-phase and E-W in phase. Each of these possible combinations is associated with one quadrant of possible incoming signals, as shown in Figure 4. This breaks the ambiguity and allows the Watson-Watt setup to give a conclusive angle of arrival.



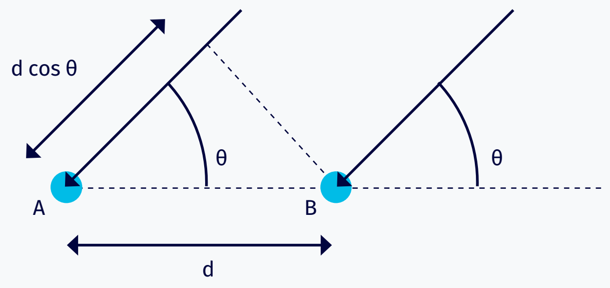
*<< **Figure 4** Signal phases by incoming quadrant*

Watson-Watt systems will in general have superior DF performance when compared to pseudo- Doppler systems, although, as indicated above, this will usually be over a narrower range of frequencies. This will correspond to lower bearing errors, with low single figures of degrees RMS achievable.

The Adcock antennas used for Watson Watt incorporate omnidirectional antennas spaced a fraction of a wavelength apart, producing a figure of eight gain pattern (by subtracting the output of one from the other). The presence of the omnidirectional antennas means that the systems can be used for non-DF purposes, including spectrum monitoring and time difference of arrival geolocation.

1.3 CORRELATIVE INTERFEROMETRY

If we have more than one antenna in an array, we can use the phase difference of the signal received at the antennas to determine the incident angle as follows:



<< ***Figure 5***
Additional path length traveled

If two adjacent antennas are separated by a distance d, then the additional path length that the signal needs to travel to reach antenna A compared to antenna B is d cosθ. If the wavelength of the signal is λ, then the phase difference, φ, over that distance will be

$$\phi = \frac{2\pi}{\lambda} d \cos \theta$$

Rearranging to put this in terms of θ, we have

$$\phi = \cos^{-1}\left(\frac{\phi\lambda}{2\pi d}\right)$$

so if we know the phase difference, wavelength and antenna separation, we can determine the angle of arrival. However, this only gives an unambiguous answer if the antenna separation is less than half a wavelength.

To deal with this ambiguity, we can extend the idea of measuring phase differences between elements to a multi-element setup (where the elements will not generally be in a single line). The phase differences between the all pairs of elements can be measured simultaneously, and the results compared with patterns generated by known signals from known incident angles. The direction that generates the strongest correlation with the recorded values is taken to be the angle of arrival, hence correlative interferometry.

Correlative interferometry systems are capable of producing angular resolution superior to either of the previously considered techniques. However, the requirement for multiple elements in the antenna array means that the systems will generally be significantly larger and more expensive than either Watson-Watt or pseudo-Doppler systems.

2. SOURCES OF ERROR IN AOA

The first thing to note when discussing sources of error in direction finding techniques is the relationship between the angular error at the receiver and the spatial error in the position of the source.

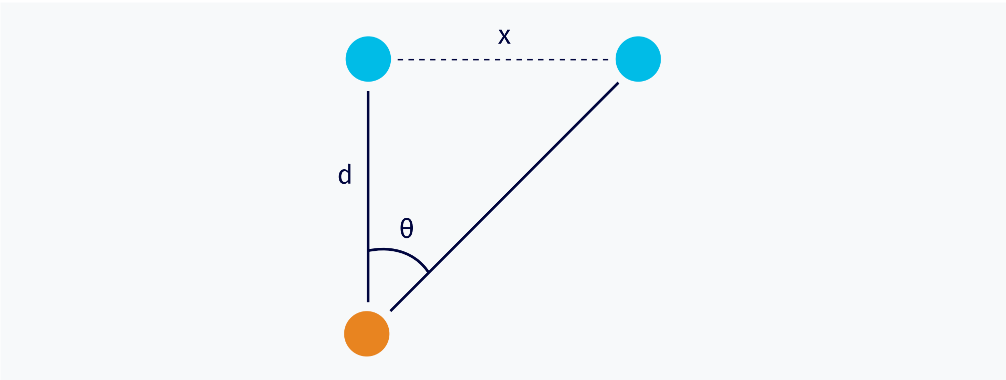


Figure 6
Actual and determined positions of a signal source

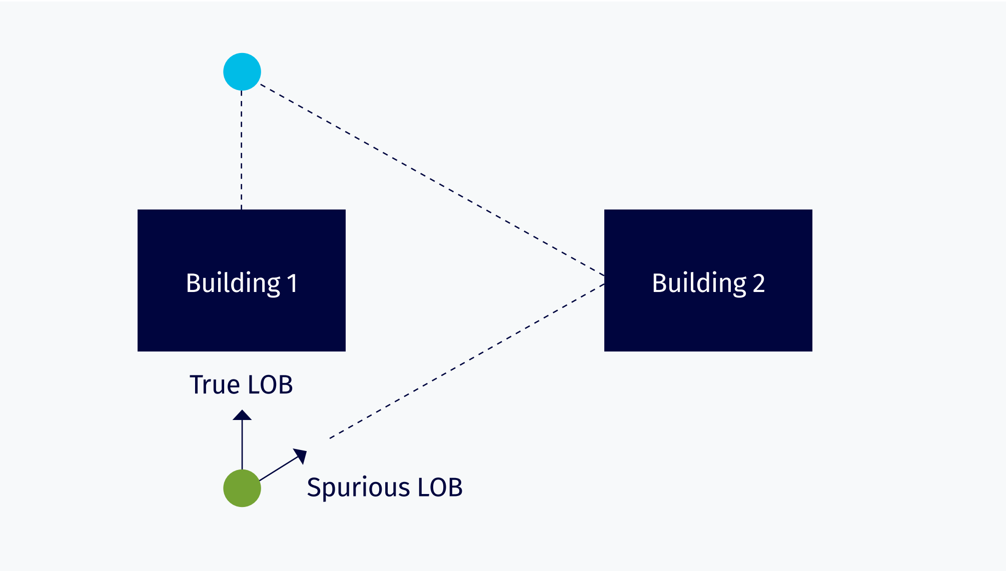
For a given angular error θ, the error, x, in the position of the source is related to the distance, d, between the receiver and source by

$$x = d \tan \theta$$

that is, there is a direct linear relationship between the two. That means that even small errors in the determination of the incoming angle can project out into large discrepancies at sufficiently large distances.

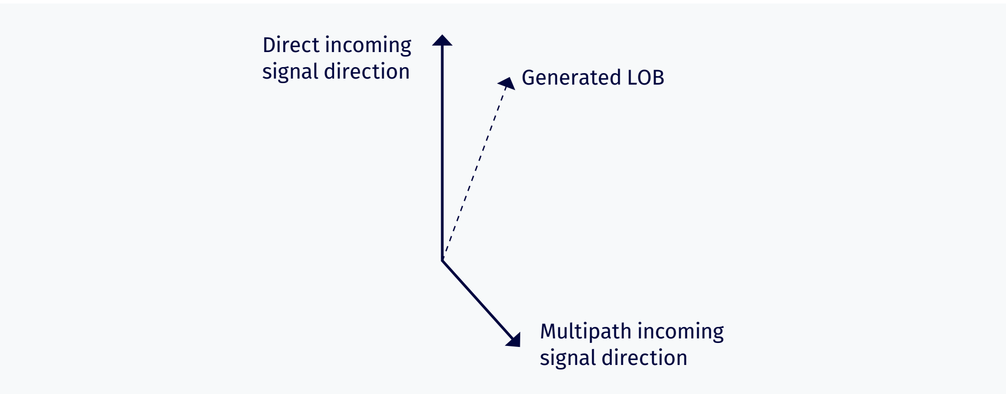
2.1 MULTIPATH REFLECTIONS OF SIGNAL

AoA measurements are susceptible to multipath effects, where the initial signal reaches the receiver via one or many indirect paths, in addition to the direct one. Consider the simplest version of this, where the direct line of sight to the RF source is blocked by one building, but there is a strong reflected signal from another building. As shown in Figure 7 below, a spurious LOB will be generated.



<< ***Figure 7*** *Aerial view of spurious LOB generated by multipath effects*

In general, the effect will not be nearly as pronounced as this. The initial signal will almost always be the strongest signal at the receiver, while multipath signals, having been reflected many times, will be weaker.[1] This will still have an effect on the accuracy of the LOB though, as it will be generated by measuring the total power at a given frequency coming in from any angle, and then taking a weighted average. The result will be a bearing slightly offset from the true direction.



<< ***Figure 8*** *Multipath effects on the generated LOB*

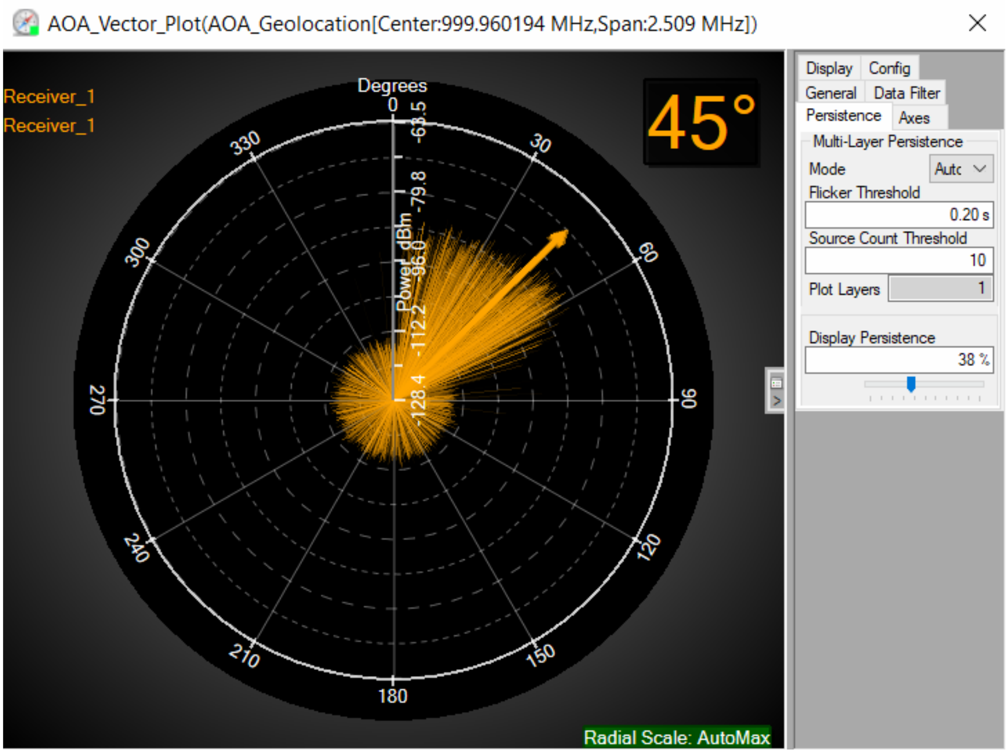
Multipath effects can be mitigated using a mobile cumulative tracking setup, which allows many LOBs to be taken from different positions, and anomalous results such as this to be discarded.

Multipath effects caused by reflections in the immediate vicinity of the array can also present significant problems for AoA, particularly when using phase difference to determine angle of arrival.

1. *For an idea of what this would look like, see "Understanding Multipath RF for Direction Finding"*

2.2 CO-CHANNEL EFFECTS OF OTHER SIGNALS ON SAME FREQUENCY

A similar problem can occur with other signals of the same frequency as the target signal - the LOB is generated by taking an average of all incoming signals at that frequency, weighted by the power of the signal. This problem will not occur as frequently as multipath errors, because while there will almost always be multipath generated signals, there will not always be other signals at the same frequency. However, when other signals are present, it will not necessarily be the case that they are weaker than the signal of interest, as was the case for multipath. In these circumstances, the generated LOB may likely be significantly offset from the true direction, aligning more closely towards the strongest signal. To improve situational awareness, CRFS software can display all incoming signals, as well as the LOB generated from them.



<< ***Figure 9***
LOB and the signals used to generate it

2.3 EQUIPMENT BEARING OFFSET

To translate the bearings generated by an AoA system into directions in the real world, it is necessary to align 0º in the system settings with external North. Any small offset here will produce a systematic error in all of the results produced by the system.

2.4 SIGNAL MODULATION COMPONENTS

Errors in AoA can also be caused by modulations of the signal that is being located. Consider, for example, an amplitude modulated signal. If we are using an amplitude comparison technique such as Watson-Watt, and the amplitude changes between measuring the N-S and E-W components, the calculated bearing will be offset from the true one.

3. FIXED VS MOBILE SYSTEMS

As we discussed right back in the introduction, with a single receiver it is only possible to get a line of bearing towards a target. This shows which direction it is in, but not where it is exactly. To determine its location, a second, spatially-separated receiver is required. However, this is not quite the whole story. If the signal source is static, then a single receiver can be used to locate it, as long as that receiver is mobile. By generating a LOB from one position, moving to another, and then generating a further LOB, the source location can be determined.

Mobile systems also have an additional advantage. As discussed in section 2, the accuracy of the determined location is affected by the distance between source and receiver, with a given angular resolution corresponding to a wider spread of actual positions as the distance increases. With a mobile system, the receiver can be transported towards the source once an initial position determination has taken place. This means that the accuracy of the geolocation can be repeatedly improved, until the precise location is found.

<< *Figure 10*
Cumulative tracking with a single mobile array

The main disadvantage of mobile systems is that in order to make them mobile, their size, weight and power must be reduced, which comes with associated reductions in their performance. In situations as described above, where the target can be incrementally approached, this reduction in performance can be offset. However, there are many applications (see section 4.2 below for instance) where getting closer and closer to the target would not be feasible.

4. APPLICATIONS

4.1 GPS JAMMER LOCATION

GPS location tracking is an almost ubiquitous feature of modern life, with applications including tracking the locations of company vehicles. Employees unhappy about being tracked in this way have deployed GPS jammers to block the GPS signal being received by their vehicles. As well as being illegal, this can also lead to unexpected side effects. Perhaps most notably, in the case of an employee of the engineering company Tilcon, these side effects included interfering with the GPS guidance system of Newark Liberty Airport.

In situations like this, it is vital to be able to quickly identify the source of the interference, so that airport operations are not interrupted for any longer than necessary. Using a mobile AoA system, multiple LOBs can be generated, with the GPS jammer located at the intersection of these lines. The mobile system has the additional advantage that further LOBs can be generated as the system closes in on the jammer location, allowing it to be determined with increasing precision.

4.2 SIGINT

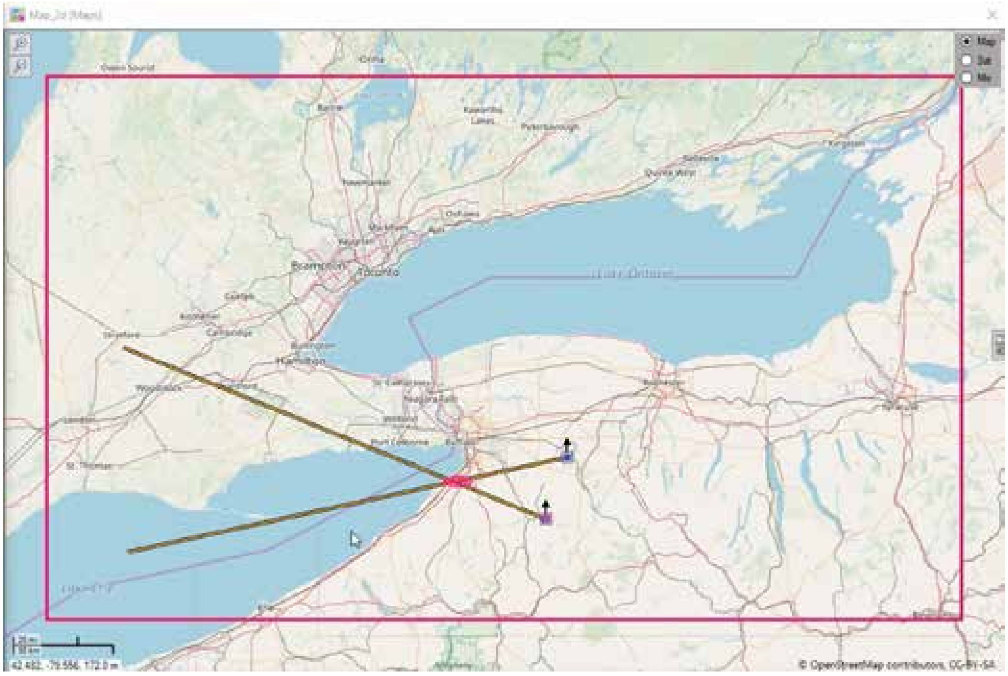
The use of direction finding systems for signals intelligence (SIGINT) purposes has a long and distinguished history, going back as far as 2nd World War "huff-duff" systems that were used to locate Nazi U-boats. In the 21st century, the requirement to be able to capture and locate the source of enemy transmissions remains, and DF systems are a key component of systems designed to do so. One significant improvement over 2nd world war systems is the widespread use of small, portable DF systems that can be mounted on vehicles or even hand carried by military personnel, allowing troops in the field to continue to collect and utilize information about the disposition of enemy forces by collecting electronic transmissions. This information can also form the basis for more active electronic warfare measures, such as allowing jamming systems to be targeted against enemy positions.

4.3 EMERGENCY SERVICES

For walkers and skiers in avalanche-prone areas, an avalanche transceiver is a potentially life-saving piece of equipment. Transmitting a signal at a standard frequency of 457 kHz, they can be activated when the carrier is trapped and unable to move. Emergency services then need to be able to locate the source of the signal as rapidly as possible in order to rescue them. Portable DF systems, which give a line of bearing to the transmitter, can be used by search teams to zero in on the trapped person.

5. **PROOF OF CONCEPT**

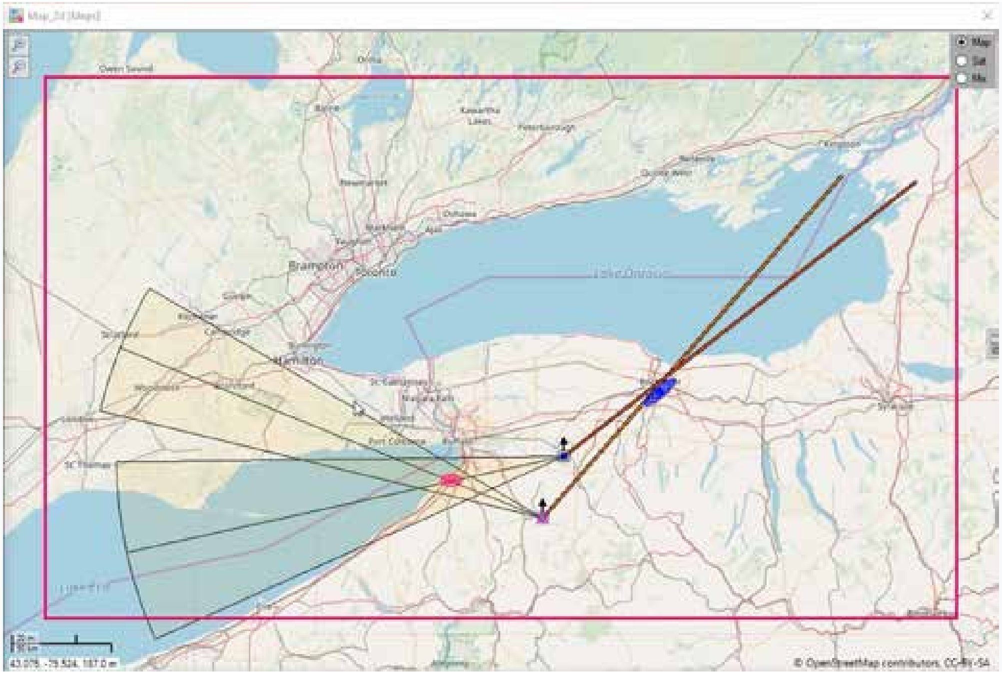
To showcase the real-world performance of our AoA systems, we conducted a live demonstration during our direction-finding webinar by connecting to two CRFS arrays located around 50 miles outside of Buffalo, NY. We began by choosing a frequency that appeared to have a signal on to apply the AoA processor to. The arrays then generate LOBs based on that signal, which can be displayed either as a single line, or as a wedge showing the range of angles that that frequency is being received from. The pink ellipse shows the spread of possible locations of the transmitter based on the intersection of the LOB's of the two arrays.



*<< **Figure 11** Live AoA determination*

The LOBs can also be color-coded to intuitively display different aspects of the geolocation. Each LOB can be colored according to which array is generating it, or according to which signal it is locating (useful when multiple missions are being conducted simultaneously). Perhaps most usefully, the LOBs can be colored to indicate the quality of the signal received (amount of multipath etc), which determines the accuracy and reliability of the geolocation being performed.

We then moved on to perform geolocation of a pulsed signal around 60 miles from the arrays. This can be done using the pulsed signals setting in the RFeye Site software. To improve the accuracy in this case, multiple instances of the pulsed signal can be combined and processed simultaneously.

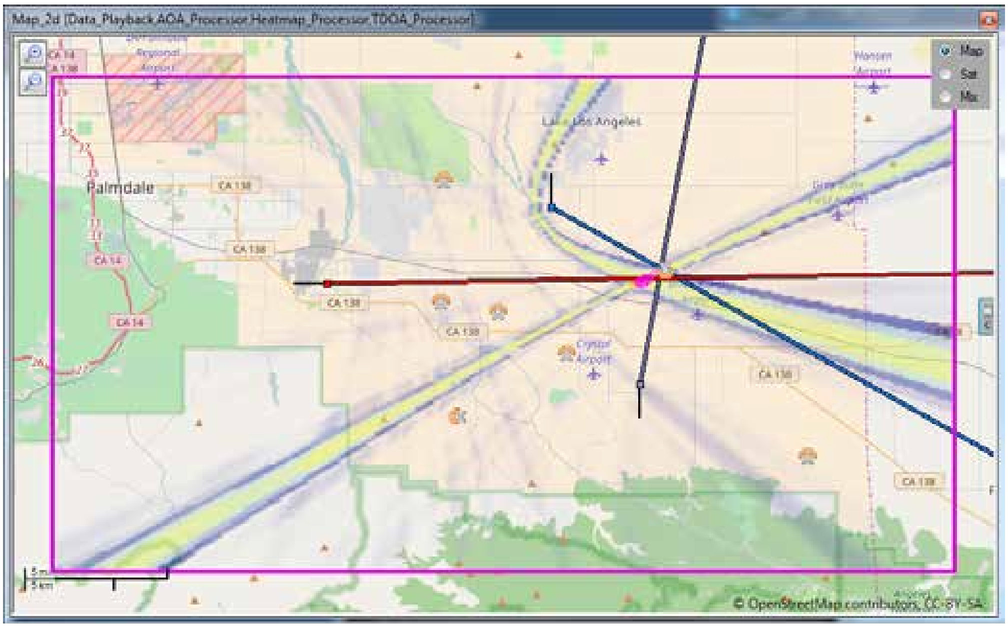


<< *Figure 12*
AoA geolocation of a pulsed signal (blue ellipse)

All of these geolocations can be seen in real time in the webinar “AoA Accuracy – Myths and Legends”.

6. **HYBRID AOA/ TDOA TECHNIQUES**

If we have a receiver system like the CRFS RFeye Array, which can record both the time a signal is received, and the direction from which it came, it is possible to use a combined Angle of Arrival and Time Difference of Arrival (AoA/TDOA) approach to locating signals. We will not cover the theory of how TDOA works in this white paper (see Passive Geolocation with 3D TDOA and Principles of Geolocation Techniques for more details), but will simply note here that with two receivers, the signal source can be located along a hyperbola, as in Figure 13.



<< ***Figure 13***
Combined AoA and TDOA geolocation

By combining the two techniques, we can confine the possible source locations more tightly than could be achieved with either technique alone. TDOA is also largely unaffected by multipath error, as any signal arriving via a multipath route will arrive both later and at lower power than the direct signal, allowing it to be relatively easily discarded.

7. SUMMARY

In this white paper, we have outlined the main AoA/DF techniques, looked at some applications, and discussed how it can be combined with other techniques. As an introductory paper, though, we have barely scratched the surface of potential uses of DF, so if you have a particular RF geolocation scenario in mind, and want to know whether AoA (or perhaps another geolocation technique) could be suitable, then contact us on enquiries@crfs.com, and we'll be happy to help.

LEGAL INFORMATION

CRFS Limited reserves the right to make changes to the specifications of the products detailed in this document at any time without notice and obligation to notify any person of such changes.

RFeye, CRFS and the CRFS logo are trademarks of CRFS Limited. All other trademarks are acknowledged and observed. Mention of third-party products does not constitute an endorsement or a recommendation.

All figures, data and specifications contained in this document are typical and must be specifically confirmed in writing by CRFS Limited before they apply to any tender, order or contract. CRFS takes every precaution to ensure that all information contained in this publication is factually correct but accepts no liability for any error or omission. No freedom to use patents or other property rights is implied by this document.

DISCLAIMER

The information contained in this document is not intended to amount to advice on which reliance should be placed. Although we take reasonable steps to ensure the accuracy of the information provided, we provide it without any guarantees, conditions or warranties as to its accuracy or reliability. To the extent permitted by law, we expressly exclude all conditions, warranties and other terms which might otherwise be implied by law. This document is subject to change without notice.

CRFS | EXTRAORDINARY **RF TECHNOLOGY**

CRFS is an RF technology specialist for the defense industry, national security agencies, and systems integration partners. We provide advanced capabilities for real-time spectrum monitoring, situational awareness, and electronic warfare support to help our customers understand and exploit the electromagnetic environment.

CRFS Inc
Chantilly,
VA, USA
+1 571 321 5470

CRFS Ltd
Cambridge,
United Kingdom
+44 (0) 1223 859 500