# An Introduction to Direction Finding Methodologies

White Paper

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White Paper
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# 1 Basic concepts

## 1.1 What is Direction Finding?

In the radio-frequency world, the term "direction finding" (DF) refers to the use of specialized instruments, antennas, and methodologies to determine the physical or geographical location of an emitter; that is, a source of radio-frequency energy. Although these methodologies differ substantially in terms of how they estimate an emitter's location, they all share the common goal of the highest possible accuracy. Accuracy requirements do however vary between applications. For example, finding a ship in distress on the open water only requires an accuracy of several hundred meters, particularly in good weather. On the other hand, eliminating sources of radio-frequency interference often requires accuracy of several meters or less. Note too that in some cases, direction finding targets are “non-cooperative.” In other words, not only do they not want to be found, but they may also take steps to hide their location or otherwise complicate the direction finding process.

This whitepaper discusses the basic principles behind radio direction finding and the most commonly-used direction finding methodologies: manual angle of arrival (AOA), Doppler, Watson-Watt, correlative interferometry (CI), time difference of arrival (TDOA), and hybrid methodologies. A general technical introduction is provided for each of these methodologies, including an overview of how they are implemented and the relative strengths and weaknesses of each.

## 1.2 Power of Arrival vs. Angle of Arrival

Before discussing individual methodologies, it would be helpful to define some terms that are often a source of confusion when discussing direction finding: namely, the difference between “power of arrival” and “angle of arrival." There are various competing definitions for these terms, but in this whitepaper "power of arrival" will be used to describe measuring the **level** of received radio-frequency energy at a given location. In this sense, power of arrival could be used to locate an emitter by simply moving our receiver and measuring the received RF level to create a "heat map" (Figure 1) of power versus location. The points at which the highest power levels were measured are the closest to the emitter location. This

**Figure 1 - Heat map (power of arrival)**

procedure, strictly speaking, is not direction finding since we are not finding the direction towards the source, but rather a more general case of radiolocation.

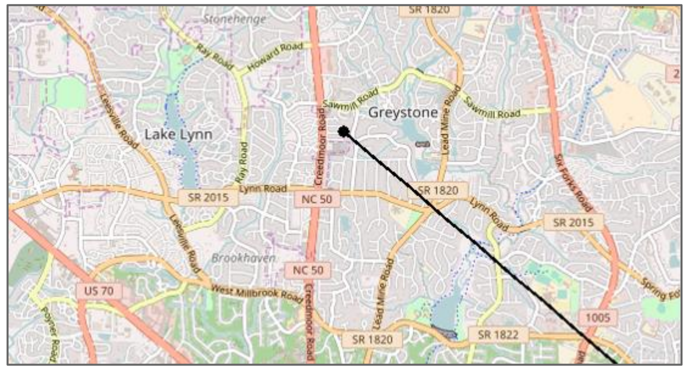

**Figure 2 - Bearing (angle of arrival)**

"Angle of arrival," on the other hand, determines the angle, that is, the bearing (or azimuth) towards the source of RF energy. This is true direction finding in the sense that we determine the **direction** from which the signal is arriving (Figure 2).

This distinction is important because the vast majority of direction finding methodologies are based on angle of arrival, not power of arrival. Angle of arrival allows the use of a wide variety of methodologies, all of which are faster, more efficient, and more much more accurate than approaches based on power of arrival.

## 1.3 Determining bearings

Angle of arrival based direction finding methodologies all share one common task: determining the direction (angle, bearing) from which a signal is arriving. Recall that there are three things that can potentially change as a radio-frequency signal propagates through space: its amplitude, its frequency, and/or its phase. Since these changes are primarily a function of the path between transmitter and receiver, direction finding methodologies can calculate bearings using these location-dependent variations in the received signal. Direction finding methodologies based on angle of arrival use one of these variations to compute bearings: changes in amplitude, frequency, or phase.

## 1.4 Using bearings

These bearings, which represent the direction towards the emitter, can be used in two main ways. The first of these involves a single bearing. A single bearing provides direction but not distance information, so the main application of a single bearing is homing towards a target – we simply follow the bearing until it leads us to the source. The second case involves multiple bearings. If we are able to take bearings from multiple locations, these can be plotted together to compute the most probable location of the target – a process often called **triangulation** (Figure 3). Triangulation is a simple mathematical calculation whose accuracy is entirely a function of the accuracy of the bearings used to produce it: accurate bearings yield accurate triangulation results.

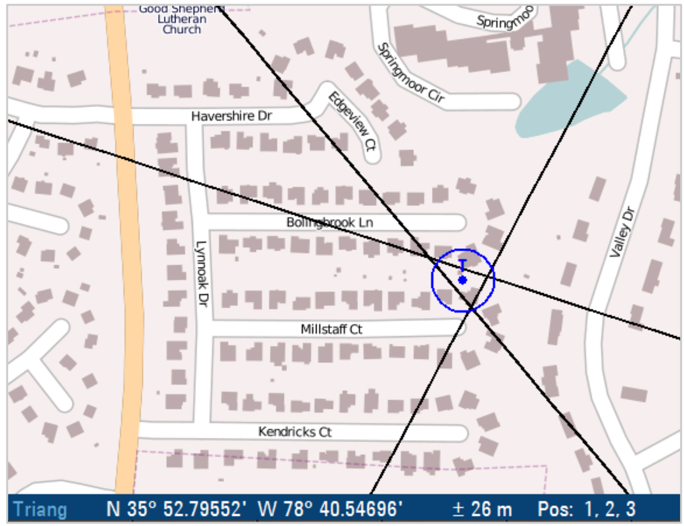


**Figure 3 - Triangulation**

In most cases, three or four good bearings are sufficient for obtaining a good triangulation result. Further increasing the number of bearings used in the triangulation calculation above more than five or six does not typically yield additional accuracy. It's also worth noting that “real-word” bearing results taken from multiple locations will rarely all intersect precisely at the same point. In some cases, it's also necessary to discard obvious fliers or so-called “junk bearings” that clearly are not pointing towards the true source of the signal. These can be caused by multipath or reflections of the RF signal, which will be discussed later.

## 1.5 Manual vs. Automatic Bearings

The methods used to obtain bearings can be divided into two general categories. The first method involves some type of manual process. In almost all case, this manual methodology means that the operator manually moves or points the antenna until the strongest signal level is observed. Note the use of the word “observed” – in most cases, a human operator that makes the determination as to when the antenna is pointed in the “right” direction. This means that manually-obtained bearings tend to be somewhat “operator-sensitive,” which can be either good or bad, depending on the operator’s skill level and experience. In the proper environment and when performed by a skilled operator, manually-obtained bearings can be highly accurate. The other method of obtaining bearings involves the use of automatic direction finding methodologies. Here, a system *automatically* determines bearings based on one or more changes in the signal characteristics (amplitude, frequency or phase) at a given location. One of the main advantages of automatic direction-finding methodologies is that they do not depend as strongly on the operator's skill level. Another important advantage is that these automated methodologies can produce accurate results even in challenging propagation environments, particularly in the presence of multipath.

## 1.6 Multipath

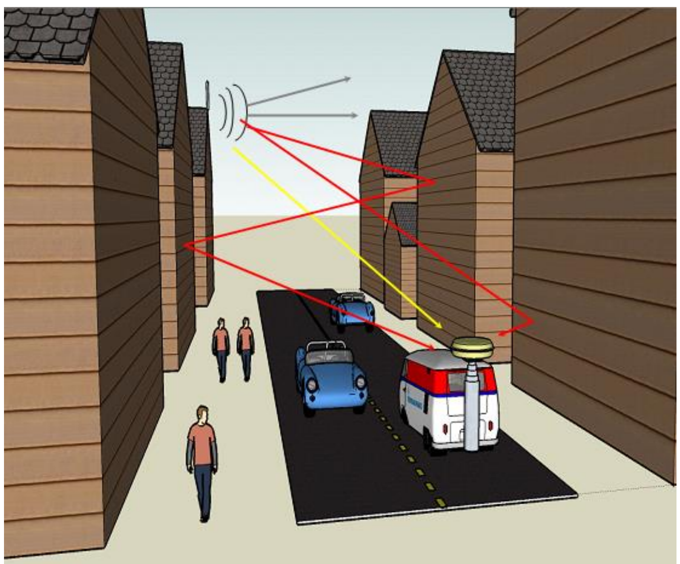

**Figure 4 - Multipath**

As the name implies multipath means receiving a signal from multiple directions simultaneously (Figure 4). Radio frequency signals can be reflected from radio-opaque objects, such as concrete, metal, etc. and this means that the signal may appear to be coming from the reflection point, rather than from the source itself. This is a particularly significant issue in urban or mountainous areas. Most people have experienced multipath in their everyday lives: when sitting at a stop light or stop sign, an FM radio station signal may get stronger or weaker as the car is inched forwards. The change in the signal strength and quality are due to the multipath profile at that particular point - moving the car a few inches can dramatically change the nature of the received signal. In direction finding, having a signal that appears to come from multiple locations or which changes level due to constructive or destructive interference is a significant problem, and therefore multipath is usually the single biggest challenge in direction finding. In many cases, a “good” direction finding system or methodology is primarily dependent on its ability to obtain good bearing results even in the presence of substantial multipath.

# 2 Manual direction finding

## 2.1 About manual direction finding

Manual direction finding is the most basic direction finding methodology. Recall that all direction finding methodologies based on angle or arrival use a change in amplitude, frequency, or phase to determine the direction towards a signal. Manual determination of angle of arrival is based on **amplitude** comparison. In manual direction finding, a directional antenna is physically moved or rotated until the maximum received signal strength is obtained, usually via visual inspection by the system operator. This direction, or bearing, is then used either for homing or for triangulation. The directional antenna can be either handheld or mounted on a tripod, mast, or vehicle.

## 2.2 Antennas used in manual direction finding

**Figure 5 - Log-periodic antenna used in manual DF**

Although a directional antenna is a requirement for direction finding using manual angle of arrival , the type of directional antenna will vary based on the application. Some antennas, such as Yagi antennas, may have very good directionality (narrow beamwidth), but also numerous sidelobes and a limited usable frequency range. Log-periodic antennas (Figure 5) can cover wide frequency ranges with minimal or no sidelobes, but the main lobe is often quite wide. Horn antennas are excellent (and sometimes the only choice) at very high frequencies, but can be challenging to work with. Interaction between the antenna and the mounting hardware, including the arm and body of a human operator, can also affect results in a non-trivial manner.

In most cases, the angle or bearing is normally determined and/or recorded using a manual or electronic compass, relative to magnetic north, since this facilitates the use of these bearings in mapping and triangulation.

## 2.3 Practical considerations in manual direction finding

The biggest advantage of manual angle of arrival is that it is low-cost and portable, especially when done using handheld antennas and portable receivers. Even when using a tripod or other mounting device (Figure 6), manual systems are almost always man-portable and can be quickly deployed in almost any location with minimal setup time. Vehicle-mounted systems can range from the simple "Yagi-on-the-roof" to more elaborate magnetic mounts and elevating masts.

**Figure 6 - Tripod mounted manual DF antenna**

Manual angle of arrival based approaches can often yield acceptable results, depending on the type and nature of the target signal and the ambient propagation environment. That said, there are a number of limitations when it comes to manual direction finding approach. As mentioned early, the effectiveness of this methodology can be strongly dependent on the operator's skill level and experience since the antenna is usually being manually manipulated and the bearing determination is being manually made by a human operator,. Accuracy can be poor for distant targets due to the human aspect as well – even with a tripod and a very narrow antenna pattern, the amount of human introduced bearing error can lead to substantial location errors at distances of more than a few hundred meters. Antenna choice can be problematic, especially when it comes to balancing narrow bandwidth and narrow beamwidth. And lastly, manual angle of arrival techniques don't work well when trying to locate short-duration signals. A signal that only appears for a few seconds at a time can be "there and gone" before the operator has time to rotate the antenna and determine and/or record a bearing. These limitations are one of the reasons for the development of automatic direction finding methodologies.

# 3 Doppler

## 3.1 About Doppler direction finding

The first automatic direct finding methodology we will discuss is called "Doppler" direction finding because it is based on the Doppler effect. The Doppler effect, or Doppler shift, is named after Christian Doppler, who first described it in 1842. Doppler shift is a type of frequency modulation caused by relative motion. If an objects is moving towards an observer, the frequency of waves emitted by an object will appear to increase. Similarly, if the object is moving away from the observer, a downward shift in frequency occurs. Doppler shift applies to many different domains. Most people are familiar with Doppler shift in the audio frequency domain, such as the change in pitch in the whistle of a passing train. Doppler shift also occurs in the visible energy domain, such as the red shift of stars moving away from Earth. In the radio frequency domain, Doppler shift can be used for the purposes of direction finding.

As we move towards a signal source, the received frequency of the signal will shift upwards. If we move away from a signal source, the received frequency will move downwards. If we are able to detect and measure this shift, we could then determine whether we are moving towards or away from the signal source, that is, we could get a direction. Thus, in order to use Doppler shift for direction finding, the receiver, or more precisely, the antenna, needs to be moved in such a way that a measurable Doppler shift is created.

There are, however, a couple of challenges with regard to this approach. First, if the target may be stationary, the receiver would have to be moved to create a Doppler shift. There is also the question as to whether it is possible or practical to move the receiver fast enough to create a measurable Doppler shift.

## 3.2 Creating a Doppler shift

Fortunately, it's not the receiver but rather the antenna that needs to be moved, so the problem now becomes: how do we move an antenna in such a way as to create Doppler shift? We'll begin with a single antenna mounted on a rotating disk (Figure 7).

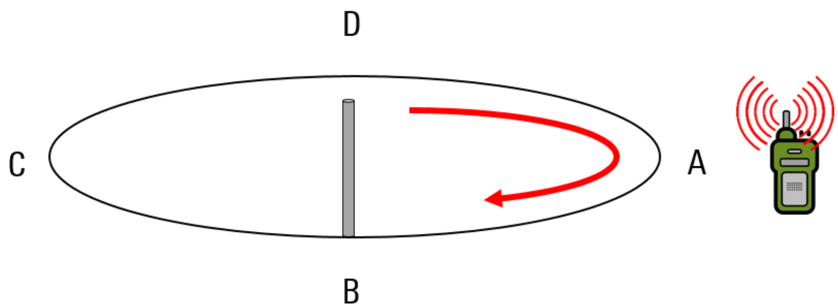


**Figure 7 - Rotating disk concept**

As this disk is rotated, the antenna will move closer to and then further away from the transmitter. At positions A and C (Figure 8), the antenna is stationary relative to the transmitter – that is, the antenna is neither moving towards nor moving away from the transmitter. This means that the Doppler shift is zero at positions A and C. At position B, we have the maximum speed moving away from the transmitter and at position D, we have maximum speed moving towards the transmitter. The varying Doppler shift creates a so-called Doppler sine wave, which is a maximum when the antenna is at position D, with zero crossings at positions C and A. The second zero crossing at point A represents the position or angle that points towards the transmitter.

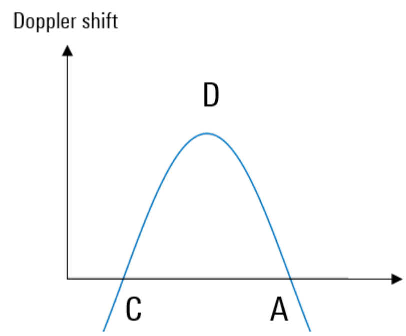


**Figure 8 - Doppler Sine Wave**

## 3.3 Implementing Doppler antennas

The problem with this implementation as described is that an antenna on a rotating disk is not practical. The rotational speed required to create a measurable Doppler shift is much too high to be implemented as a vertical antenna on a physically spinning disk. However, we can simulate a rotating disk by using an array of antennas, usually four, and then rapidly switching between them. Each of the antennas is used to generate a series of Doppler pulses, and the system uses this information to synthesize the Doppler sine wave. Although the switching between the antennas must be very fast in order to accurately synthesize the Doppler sine wave using inputs from four discrete antennas, this is not a technological challenge.

As mentioned above, most Doppler DF antennas have four elements, equally spaced, with vertical polarization (Figure 9). In many cases, Doppler antennas are vehicle-mounted, but Doppler antennas can also be fixed-mounted or configured in a man-portable package. It is possible to have Doppler DF antenna arrays with much more than four antenna elements. The hypothesis here is that the synthesized Doppler sine wave will be more accurate if more measurement points are used. While it is in fact true that a larger number of antennas improves Doppler DF results, this only applies if we also increase the diameter of the antenna array. It's also worth noting that some Doppler systems have multiple sets of antenna elements to cover wider frequency ranges. For example, a Doppler DF array with eight elements may simply be two arrays of four elements each – a set of four longer antennas for VHF and four shorter antennas for UHF.

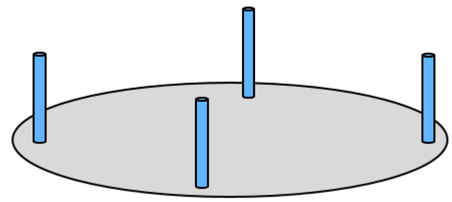

**Figure 9 - Doppler antenna with four elements**

## 3.4 Practical Considerations in Doppler DF

Doppler DF is relatively low cost compared to other automatic DF methodologies. Part of the reason why Doppler is so low cost is that it's possible to build a Doppler system using simple vertical antennas and an off-the-shelf receiver, although commercial Doppler DF systems usually have a specialized DF receiver for better performance. There are however a few limitations inherent to Doppler DF. First, Doppler DF systems more or less require that the target signal be a constant, CW or similar type signal. Doppler doesn't work well for locating intermittent, that is, on and off signals, or very broadband or noise-like signals. The antennas or antenna elements in most Doppler systems also limit the useful frequency range for Doppler DF. Almost all Doppler systems are designed to work at VHF or (low) UHF frequencies, so Doppler isn't a good choice for direction finding at either HF or microwave frequencies. And because Doppler antenna arrays are made up of vertical elements, these arrays don't work well when trying to locate horizontally polarized signals – the loss from cross-polarization limits can easily be 20 to 30 dB. A Doppler-based automatic direction finding systems is something of an "entry level" DF system that can be a good choice for certain applications, particularly when cost is a consideration.

# 4 Watson-Watt

## 4.1 About Doppler direction finding

Doppler can be classified as a frequency-based direction finding methodology: changes in frequency are used to determine the direction or bearing towards the emitter. Watson-Watt, on the other hand, is an amplitude-based DF system.

More precisely, Watson-Watt is an amplitude comparison system. It's one of the older DF methodologies, having been developed shortly after the First World War, and is named after its inventor, Sir Robert Alexander Watson-Watt, one of the pioneers in the field of radar. The Watson-Watt direction-finding methodology is based on the properties of a special type of antenna, commonly referred to as an Adcock antenna.

## 4.2 About Adcock Antennas

The classic Adcock antenna consists of four equally-spaced vertical elements arranged in pairs. This creates an antenna pattern consisting of two figure-eight shaped lobes. Each of the two figure-eight shaped patterns has maximum sensitivity along the axis running through both antennas and nulls perpendicular to this axis. This arrangement yields a unique set of magnitudes for every incoming signal direction (Figure 10).

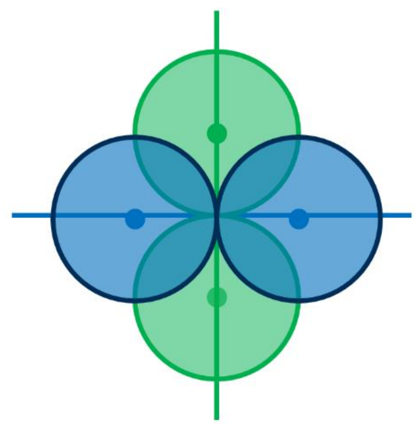

**Figure 10 - Basic Adcock antenna pattern**

An example might be helpful: we'll define two axes, the North-South axis, for our green antennas and the East-West Axis, for our blue antennas. Note that the nulls in these two patterns are orthogonal, or at right angles to each other. A signal originating due North, or with an azimuth of zero degrees, is sensed very strongly on the North-South axis, but almost not at all on the East-West axis (Figure 11). A signal that arrives from the northeast would, ideally, result in equal measured amplitudes for both antenna pairs In a similar way, any arbitrary direction can be sensed by comparing the amplitudes on the two axis. There is, however, the possibility of a 180 degree ambiguity: a signal arriving from the west and one arriving from the east will create the same set of magnitudes on the East-West axis. This ambiguity is however easily dealt with using a simple sense antenna that is usually placed at the center of the array.

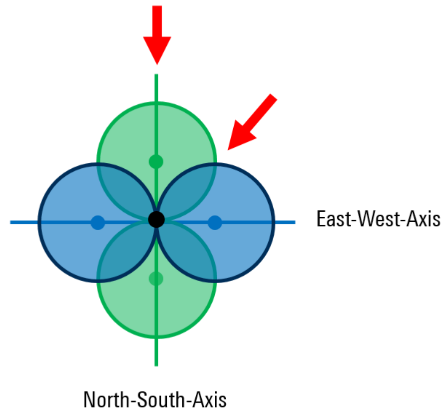


**Figure 11 - Bearings from an Adcock antenna**

## 4.3 Implementation of Adcock Antennas

There are quite a few ways to physically implement Adcock antennas. Most typically, the individual antenna elements are implemented as monopoles when there is a ground plane to work against, or as dipoles in pole-based or tower-mounted applications. The same type of pattern and behavior can be obtained using a pair of crossed loops as well. With regards to the arrangement of the elements, the biggest question is how far apart to space the elements. This spacing is a compromise between accuracy and sensitivity – placing the elements closer together gives higher accuracy, but sensitivity is better when the elements are spaced further apart. Note that is some cases, additional pairs of Adcock antennas can be used to overcome these constraints, but this is uncommon in practice.

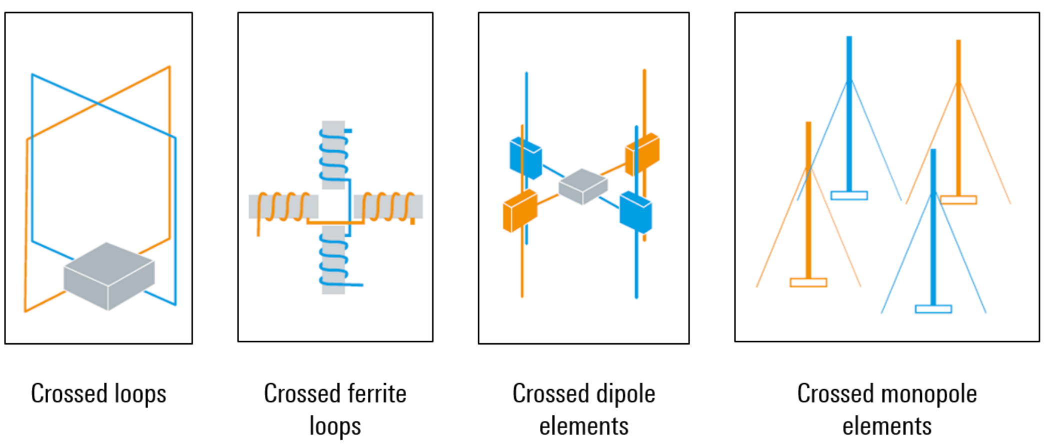


**Figure 12 - Adcock antenna implementations**

## 4.4 Practical Considerations in Watson-Watt DF

Like all other direction finding methodologies, Watson-Watt has its own particular set of advantages, disadvantages, and practical considerations. One of the ways in which Watson-Watt distinguishes itself from other direction finding methodologies is that it's well suited to HF direction finding, mostly due to the ease with which smaller antennas can be implemented at these frequencies. Compare this to Doppler, which usually is limited to only VHF and UHF. Watson-Watt is also very fast.  There is very little “calculation” of results required before obtaining a bearing, since the system simply compares amplitude on two different antenna pairs.  Watson-Watt has good accuracy and sensitivity, with the accuracy depending primarily on the circularity of the antenna patterns – something that is not difficult to control. The main drawback to Watson-Watt is that it can’t measure elevation in addition to azimuth, and if the target is significantly higher or lower than the plane of the antenna, accuracy can suffer.

# 5 Correlative Interferometry

## 5.1 About Correlative Interferometry

Manual angle of arrival and Watson-Watt are both amplitude-based direction finding methodologies, and Doppler DF is based on changes in the frequency of the received signal. Correlative interferometry (CI) is different from all of the previously-discussed methodologies in that it is based on changes in the **phase** of the received signal.

Like many other direction finding methodologies, correlative interferometry was derived from another application, in this case, radio astronomy. Correlative interferometry determines bearings by calculating differences in the received signals' phase as seen at multiple collocated antenna elements. CI antennas generally use an odd number of antenna elements arranged in a circular pattern.

## 5.2 Determining bearings using correlative interferometry

In order to explain the principles behind correlative interferometry, we'll use a five-element antenna as an example. Five antennas are placed in a circular pattern, with one of the antennas, here antenna 1, being designated as the reference channel. When a signal arrives at the array on a given angle, for example, 45 degrees, the measured signal will be phase offset at each of the five antenna elements. A calibration process is performed done for each reference angle, 0 to 360 degrees, in increments of one degree. The result is a table that contains phase offsets for all incoming signal angles. Measuring phase differences is the "interferometry" part of the this methodology's name (Figure 13).

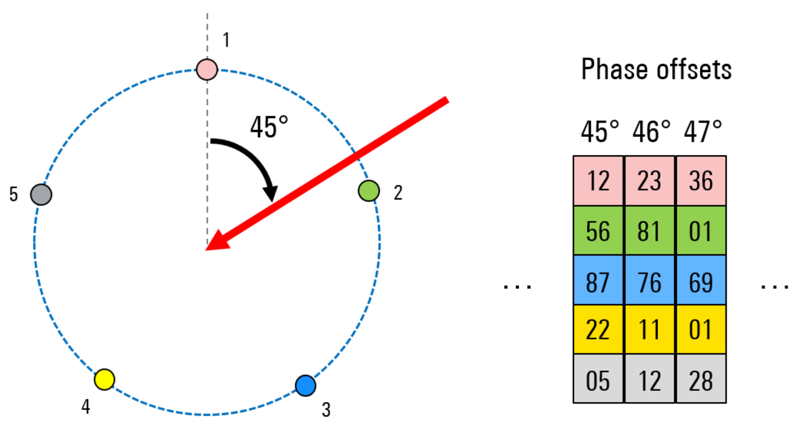


**Figure 13 - Measuring phase offsets with an interferometer**

When a target signal arrives at the antenna array, the received phase offsets are measured at each antenna. The correlation between the measured phase offsets and the calibrated or ideal phase offsets is calculated for each arrival angle. This process should yield a clear correlation peak from which the bearing or arrival angle can be derived (Figure 14).

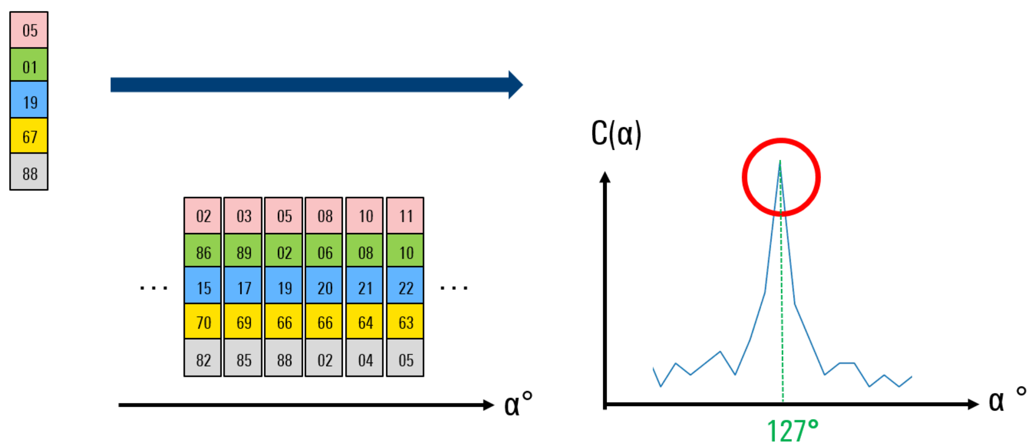


**Figure 14 - Deriving bearings from correlation with reference phase values**

In addition to delivering a bearing result, correlative interferometry also provides a bearing quality. Both of these correlation graphs in Figure 15 yield a peak that corresponds to a bearing of 127 degrees. However, the graph on the left shows much stronger correlation at this angle than the graph on the right. So while both sets of results produce the same bearing, we would have a higher degree of confidence in one of the results than the other one. This type of “bearing quality” result is unique to correlative interferometry.

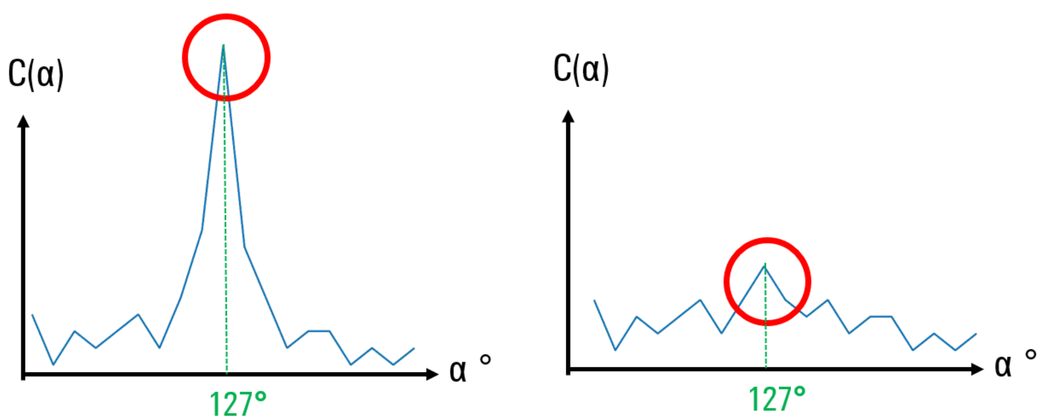


**Figure 15 - Quality of correlation**

## 5.3 Implementation of CI antennas

Figure 16 - Nine element CI antenna (radome removed)

Antennas designed for use in correlative interferometry usually have an odd number of elements, typically 5 to 9, and these are enclosed within a radome (Figure 17). Depending on the characteristics and placement of the antennas, a carefully-designed CI array can cover very wide frequency ranges, up to and above 1 GHz.

CI antennas can also be implemented in very small packages with good accuracy, but the array's immunity to things such as reflections and multipath increases as the diameter of the antenna increases. Reflections and multipath cause variations in the phase of the received signal. Increasing the aperture (diameter divided by wavelength) of a CI antenna to a value greater than one improves accuracy since the effect of these "bent" isophase lines is decreased (Figure 17).

However, compared to the other the DF methodologies discussed so far, correlative interferometry places fairly strict requirements on the antenna in terms of design and manufacturing tolerance. One can “home-brew” antennas for manual DF, Doppler, and Watson-Watt and get reasonably acceptable results, but CI antennas require very specialized engineering and production resources due to highly demanding design and manufacturing tolerances

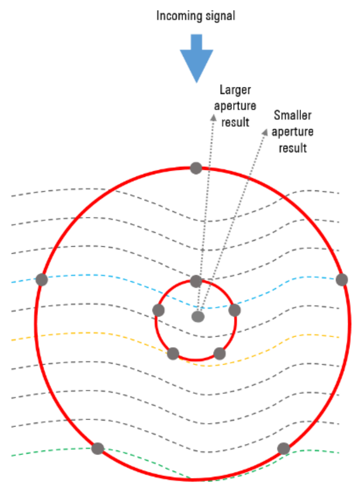


Figure 17 - Effect of bent isophase lines on smaller versus larger apertures

## 5.4 Practical considerations in correlative interferometry

Despite the added complexity and cost required to produce a CI antenna, correlative interferometry has several significant advantages over other DF methodologies. The first is very high accuracy – usually one degree or less in an ideal environment. No other direction finding methodology can produce bearings with a similar level of accuracy. Because CI compares phase differences on multiple elements simultaneously, it offers very high immunity to multipath compared to other DF methodologies. Signal polarization does not affect the accuracy of CI-based systems – this was one of the main drawbacks of Doppler DF – and CI-based systems do not suffer from the elevation issues found in Watson-Watt direction finding.

# 6 Time Difference of Arrival

## 6.1 About time difference of arrival

Time difference of arrival (TDOA) is neither a power of arrival nor a time of arrival direction finding methodology, but rather a **time**-based methodology that determines the location of an emitter based on the time when a signal is received at multiple locations.

The basic principle of time difference of arrival is as follows: three or more receivers are placed in different locations, and all of these receivers receive a signal. In most cases the distances between the transmitter and each receiver are different, and so the time at which the signal arrives at each receiver will also be different. We can represent these time differences as curves, or hyperbolae, and the location of the transmitter will be at the intersection of these hyperbolae. In fact, time difference of arrival is sometimes also referred to as “hyperbolic” direction finding because we determine the location of the transmitter using these hyperbolae.

## 6.2 Using hyperbolae

To create a hyperbola, two receivers are needed, and the time delta between the receive times at both receivers is measured. If the time delta is zero, then the hyperbola will be a straight line between the two receivers because every point on this line is the same distance from both receivers. On the other hand, the hyperbola will be curved if the difference in the time of arrival at the two receivers is non-zero (Figure 18).

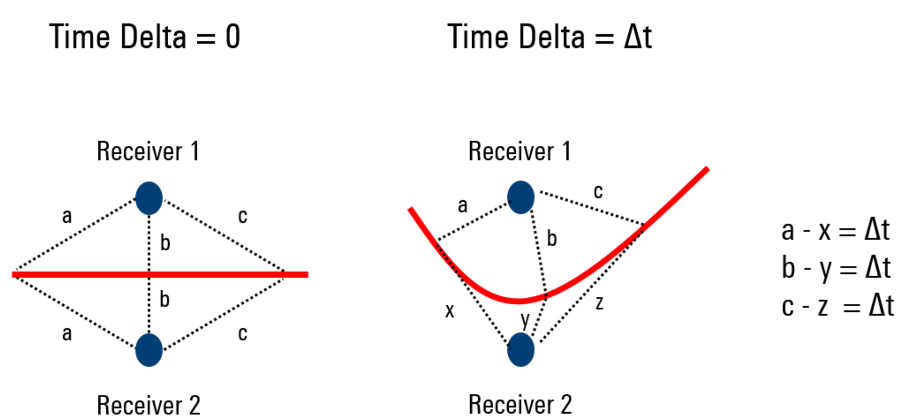


**Figure 18 - Creating hyperbolae based on time differences**

If there are three receivers, there will be three hyperbolae – one between receivers 1 and 2, another between receivers 2 and 3, and a third between receivers 1 and 3. The emitter location is at the intersection of these three curves (Figure 19). It is possible to have more than three stations, but a minimum of three stations is needed to obtain an unambiguous position fix.

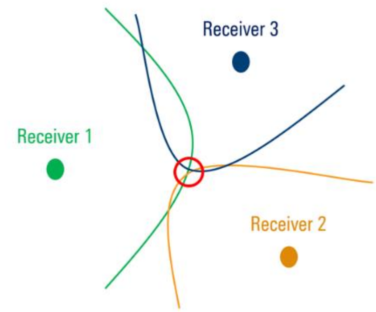


**Figure 19 - Emitter location based on TDOA**

## 6.3 Implementation of TDOA

A TDOA-based direction finding system is made up of a network of interconnected sensors and a master station. Received signals of interest are digitized, that is, are converted to IQ data, and then transferred to the master station over a data link. Note that TDOA requires this data to be very precisely timestamped using a shared clock – usually, this precise shared clock is provided by GPS. The master station then calculates cross-correlations using the data from each station, and the results of this calculation provide the time difference, which is then used to draw the hyperbolae.

## 6.4 Correlating signals

TDOA requires the difference in the time of arrival (delta t), and this is time difference is determined using correlation. A reference time is defined and correlation is calculated at various time offsets. The results of the correlation yield a correlogram, whose peak value corresponds to the time offset that produces the strongest correlation (Figure 20).

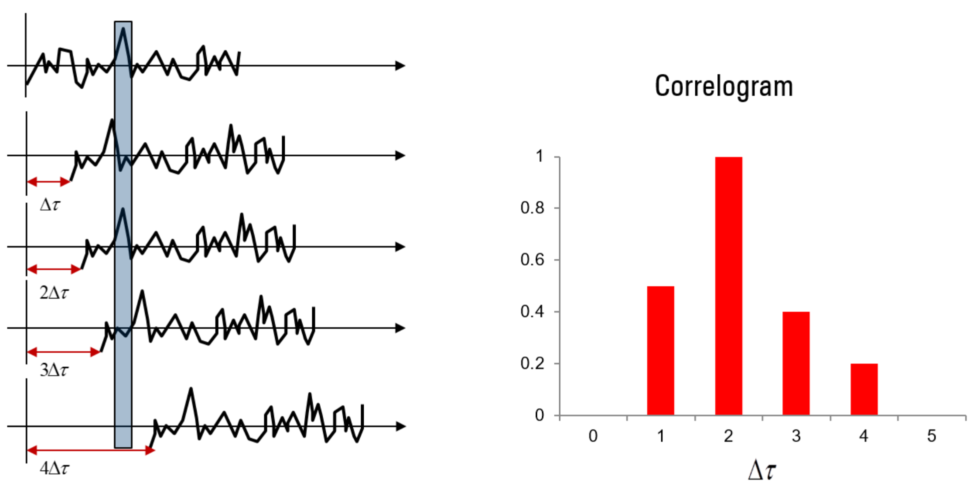


**Figure 20 - Determining delta t using a TDOA correlogram**

When the signal is wideband, it's usually not difficult to find a clear correlation peak for use in TDOA. However, if the signal is narrowband or CW (unmodulated), it becomes much more difficult to find a clear correlation peak in the correlogram (Figure 21). Without a clear peak to provide difference in time of arrival, it is difficult to generate an accurate hyperbola. It's important to remember that TDOA-based direction finding system yield more accurate results when trying to locate wideband signals.

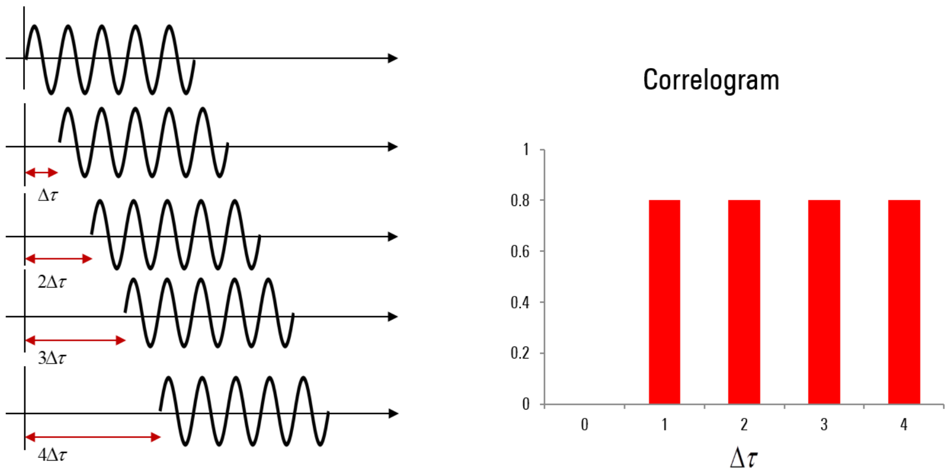


**Figure 21 - Ambiguity when calculating delta t for an unmodulated signal**

## 6.5 TDOA sensors

All of the previous direction finding methodologies discussed so far, such as Doppler, Watson-Watt, or correlative interferometry each required a special type of directional antenna or antenna array. TDOA, on the other hand, is concerned with the **time** at which a signal arrives rather than the direction or angle from which that signal arrives and requires collection and timestamping of data at multiple points simultaneously. Therefore, TDOA-based direction finding typically is implemented in the form of purpose-built sensors that contain a receiver and a non-directional antenna. These sensors can be more or less permanently fixed in a location or can be movable. Sensors digitize received radio frequency signals in the form of IQ (in-phase and quadrature) data, and timestamp this data, most commonly obtaining timing from GPS or another satellite navigation system. This timestamped data is then sent to the master data station over some type of data link. Good accuracy over a larger area requires a large number of these sensors, so dedicated TDOA sensors tend to be relatively inexpensive with lower RF performance than the receivers used in other direction finding methodologies.

## 6.6 Location coverage and accuracy

In general, TDOA results are accurate to about several hundred meters, this being both a function of the methodology and sensors themselves, as well as the target signal type, that is, broadband versus narrowband. Note too that best accuracy is obtained when the target is more or less “surrounded” by sensors, but that outside of this area, location accuracy can be poor. For example, if a target has sensors on all sides, accuracy will usually be good. On the other hand, if the target is outside of the sensor network, results are often poor (Figure 22). So often one needs to have some idea of where the target is or will be before sensors are deployed. This isn’t a problem when trying to cover a given area, but limits the usefulness of TDOA in ad hoc direction finding applications.

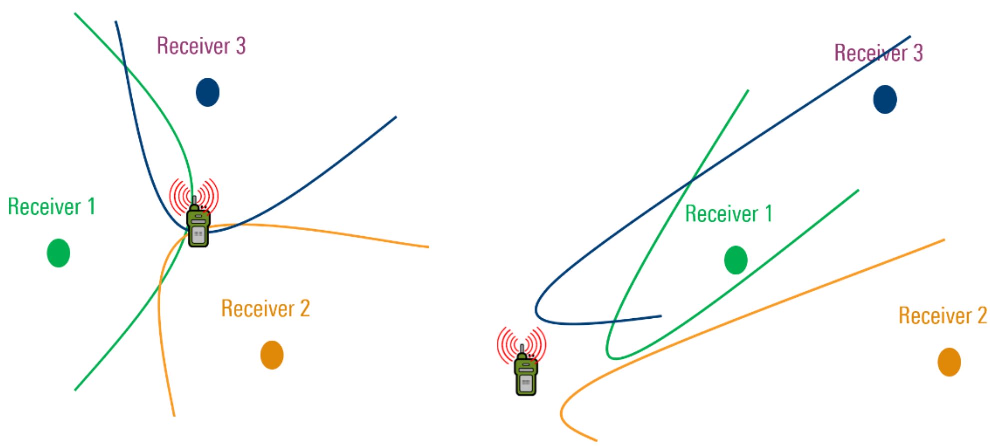


**Figure 22 - Influence of sensor geometry in TDOA**

## 6.7 Practical considerations in TDOA

As shown above, TDOA location accuracy is usually good inside the receiver coverage area, that is, when the target is “surrounded” by as many sensors as possible. TDOA accuracy tends to be much better for wideband than narrowband signals, mostly due to the difficulty in getting a strong correlation peak and thus a time offset for narrowband signals. Adding additional TDOA sensors to the network offers better accuracy, but at some point (typically about six sensors), there is no additional improvement and calculation time increases dramatically. TDOA also offers something called "proximity gain," which means that a system is more likely to receive weaker signals if there are many sensors in an area – the odds of one of the sensors being physically “close” to the source is higher. And finally, some TDOA algorithms can detect and process out the effect of multipath to various degrees.

# 7 Hybrid Methodologies

## 7.1 What is a hybrid methodology?

A recent advancement in direction finding is something called “hybrid methodologies.” One possible definition of a “hybrid” methodology is something that is actually quite common in many direction finding applications, namely using an automatic direction finding system to obtain the general location of a target, e.g. within about a hundred meters and then switching to manual or hand-held direction finding to narrow down the location to the meter level. In a sense this is a “hybrid” methodology, but normally what is meant by the term “hybrid” methodology is the combination of two different automatic direction finding methodologies: in particular, the combination of an angle of arrival methodology and a time difference of arrival methodology.

## 7.2 Combining angle of arrival and time difference of arrival

As we known, there are two different methods of using bearings. The first of these is homing, which gives a direction or bearing towards the target. This is most often used in mobile applications where one can “follow the bearing” to the target. The other method of using bearings is triangulation, where bearings are taken from multiple locations, either using multiple direction finders, or by moving the direction finder from place to place.

In time difference of arrival, the receivers or stations are usually fixed, and location information is derived from the differences in the time when the target signal appears at each station, represented in the form of hyperbolae. Note that in angle of arrival, one could use a single mobile DF system to take bearings from different locations one after another and then later combine them. A TDOA based DF system, on the other hand, requires a minimum of three stations operating *simultaneously* to produce unambiguous results.

A hybrid scenario uses one or more TDOA sensors and one or more angle of arrival stations (Figure 23). In this example, two TDOA sensors create a hyperbola, with the target lying somewhere along this line. Rather than using an additional TDOA station to locate the target, an AOA station generates a bearing, which provides the information needed to make an unambiguous position determination.

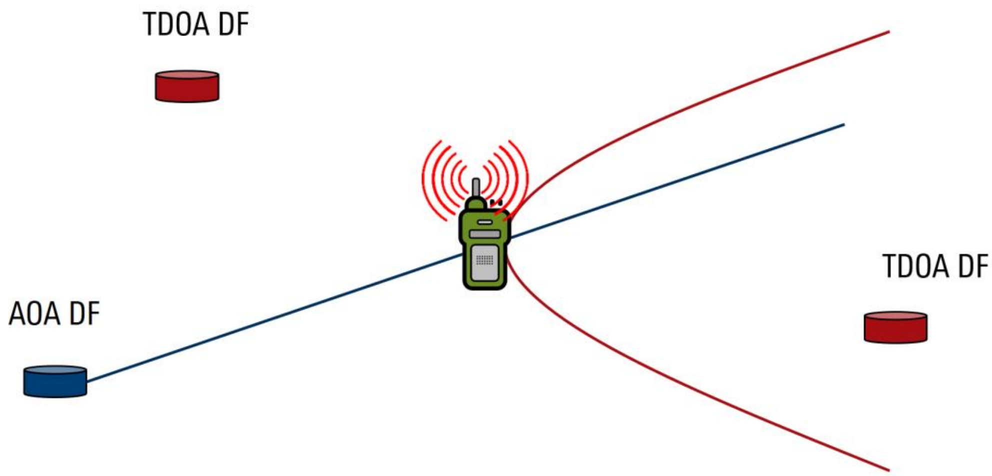


Figure 23 - Hybrid DF using both AOA and TDOA

## 7.3 Advantages of hybrid methodologies

Additional flexibility can be gained by integrating TDOA and angle of arrival functionality into a **hybrid station**. For example, when trying to locate a narrowband source in a relatively low multipath environment, the stations operate in angle of arrival mode. If trying to located a wideband signal source or when operating in a high multipath environment, switching two or more of these stations to TDOA may yield better results. The benefit of a hybrid approach is that the operator can try different combinations of stations and methodologies to see if the results are consistent, or which set of stations yields the highest accuracy.

# 8 Conclusion

All direction finding methodologies have the same goal:  determining the physical or geographical location of a source of radio frequency energy.  Angle of arrival based methodologies create bearings, or directions towards the target, by examining changes in the received signal's frequency, amplitude, or phase, whereas time difference of arrival compares the relative receive time of a target signal at geographically separated stations. The choice of an appropriate direction finding methodology to use for a given application is largely a function of the target signal's characteristics, such as frequency and modulation, but is also influenced by the propagation environment (multipath) as well as cost / complexity.  Recent advances in the development of hybrid direction finding methodologies attempt to overcome some of these restrictions and increase accuracy by using a combination of methodologies.

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