

Principles of Geolocation Techniques

A CRFS White Paper

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Geolocation of RF signals can appear to be a complex field, with an alphabet soup of available techniques (AoA, TDOA, FDOA & POA). In this White Paper, we will seek to unpick some of this complexity by describing the underlying principles of these geolocation techniques and giving an outline of their applications.

Contents

1	ANGLE OF ARRIVAL	3
1.1	PRINCIPLES OF OPERATION	3
1.2	STRENGTHS AND WEAKNESSES	4
1.3	EXAMPLE APPLICATION – LOCATING GPS JAMMERS	6
2	TIME DIFFERENCE OF ARRIVAL	7
2.1	PRINCIPLES OF OPERATION	7
2.2	STRENGTHS AND WEAKNESSES	9
2.3	EXAMPLE APPLICATION – ADS-B SPOOFING DETECTION	10
3	FREQUENCY DIFFERENCE OF ARRIVAL	12
3.1	PRINCIPLES OF OPERATION	12
3.2	STRENGTHS AND WEAKNESSES	15
3.3	EXAMPLE APPLICATION – LOCATING ILLEGAL BOATS	15
4	POWER OF ARRIVAL	16
4.1	PRINCIPLES OF OPERATION	16
4.1.1	<i>The Friis Equation</i>	16
4.1.2	<i>Two-Ray Model</i>	17
4.1.3	<i>PoA Geolocation</i>	19
4.2	STRENGTHS AND WEAKNESSES	22
4.3	EXAMPLE APPLICATION — TSCM	23
5	GEOLOCATION TECHNIQUES SUMMARY	24

1 Angle of Arrival

1.1 Principles of Operation

Angle of Arrival (AoA) 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. So how do we find out what direction a signal is coming from? 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:

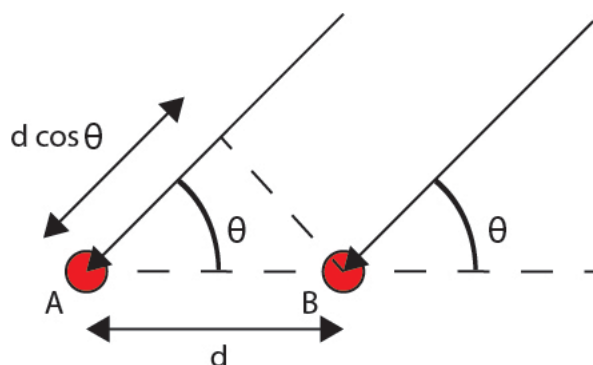


Figure 1 – Additional path length traveled

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 $d \cos \theta$. If the wavelength of the signal is λ , then the phase difference, ϕ , over that distance will be

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

(assuming that $d < \lambda$).

Rearranging to put this in terms of θ , we have

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

so if we know the phase difference, wavelength and antenna separation, we can determine the angle of arrival.

Alternatively, we can determine the angle of arrival by using two directional antennas, set up with an angle (most likely 90°) between them. Taking the measured amplitude of the received signal at each antenna, we can calculate the ratio of the signal strengths at each. This can then be compared with measured calibration values for that particular antenna setup, or with values calculated using the known antenna gain values. The antenna patterns are typically both complicated and frequency-dependent.

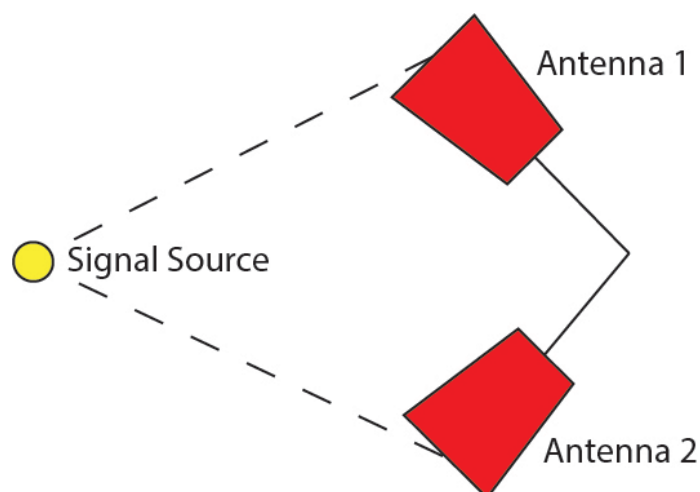


Figure 2 - Directional antennas used for AoA

1.2 Strengths and Weaknesses

As a geolocation technique, AoA's primary advantage is its simplicity, both conceptually and in terms of the equipment required. A LOB to a target can be generated using a single array, and target location can be determined using just two arrays. Even more usefully, a single receiver can be used for target location if it is mobile, and the target is stationary, by taking a series of AoA measurements at different locations.

The primary weaknesses of AoA come from the fact that it requires an antenna array, rather than a single antenna, to perform measurements. Arrays are generally physically large, especially if low frequency coverage (low VHF and HF bands) is required, and bandwidth-limited. In addition, the requirement that $d < \lambda$ means that as frequency is increased, antenna separation must correspondingly decrease, further limiting the operational bandwidth.

AoA measurements are also susceptible to multipath effects. 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 3 below, a spurious LOB will be generated.

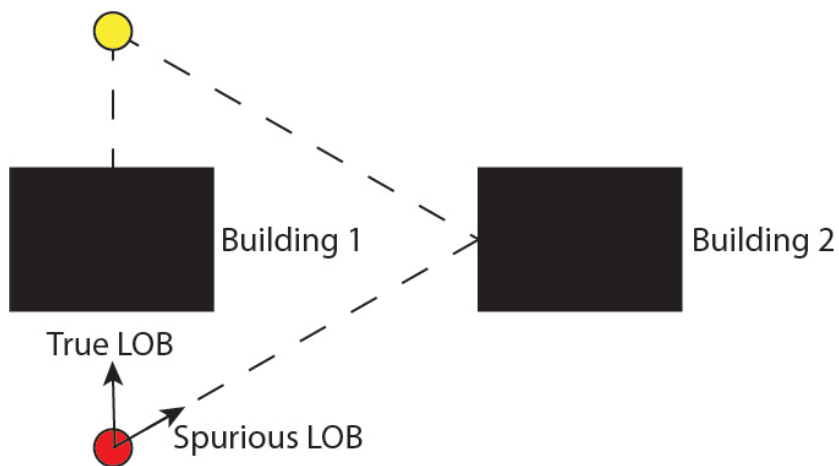


Figure 3 – Aerial view of spurious LOB generated by multipath effects

This effect can be mitigated using the kind of mobile cumulative tracking setup described above, which allows many LOBs to be taken, 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.



Figure 4 – Cumulative tracking with a single mobile array

1.3 Example Application – Locating GPS Jammers

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 Airport¹.

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.

¹ <https://www.cnet.com/news/truck-driver-has-gps-jammer-accidentally-jams-newark-airport/>

2 Time Difference of Arrival

2.1 Principles of Operation

Time Difference of Arrival (TDOA) uses the time difference between receipt of signals at spatially separated receivers to determine the location of the source. The signals received at each of the two receivers are compared using a cross-correlation function to work out the time difference of receipt of the signals. If we take two receivers, R_1 and R_2 , and have a signal arriving at R_1 a time T later than at R_2 , we can say that the source is a distance δ_1 further from R_1 than R_2 , where

$$\delta_1 = cT$$

(Assuming that the RF signal travels at the speed of light).

So what can we say about the location of the source based on this information? If we have two receivers separated by a distance $2D$, and an emitter at an arbitrary point (x, y) , then we will have a setup as in Figure 5 below.

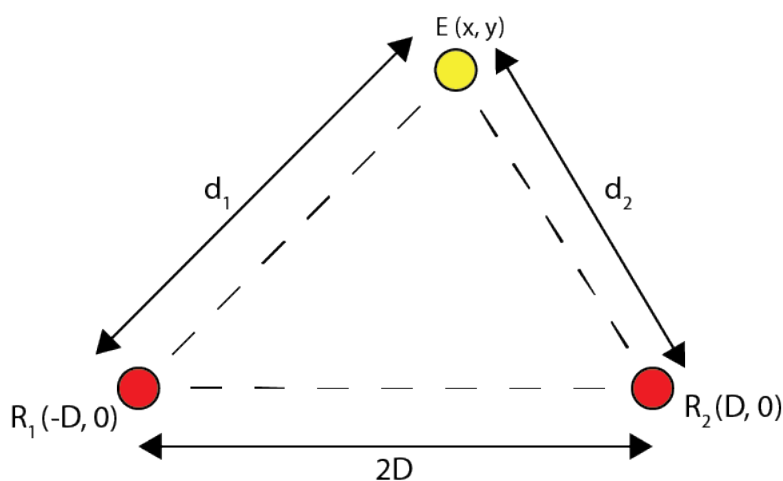


Figure 5 – Distances from two receivers to an arbitrary point

The distances d_1 and d_2 , from R_1 and R_2 to the emitter are

$$d_1 = \sqrt{(x + D)^2 + y^2}$$

$$d_2 = \sqrt{(x - D)^2 + y^2}$$

If we know that the emitter is δ_1 further from R_1 than R_2 , then we have

$$d_1 - d_2 = \delta_1$$

and therefore

$$\sqrt{(x + D)^2 + y^2} - \sqrt{(x - D)^2 + y^2} = \delta_1$$

This can be rearranged to

$$\frac{4x^2}{\delta_1^2} - \frac{4y^2}{(4D^2 - \delta_1^2)} = 1$$

For any given value of δ_1 , this equation can be satisfied by a continuous line of points constituting a hyperbola. Figure 6 illustrates this, with hyperbolas plotting out given differences in distance from the two receivers.

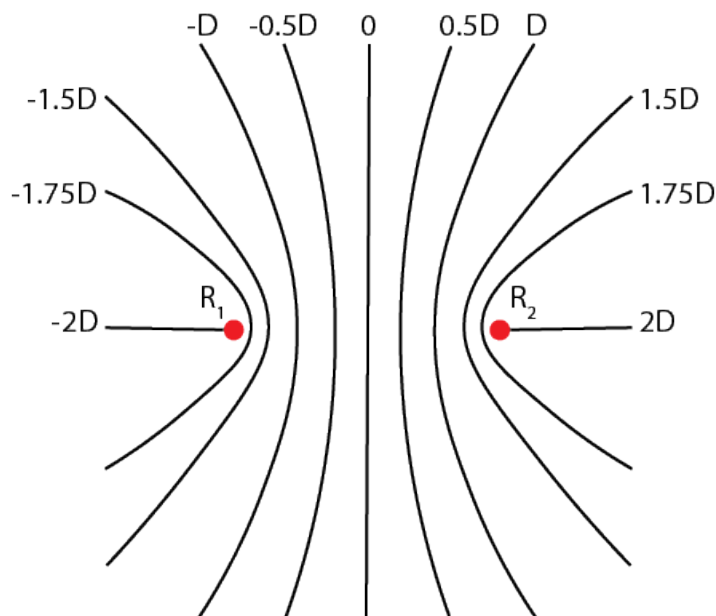


Figure 6 - Curves indicating possible transmitter locations that correspond to various values of δ_1

So if we have just two receivers, we can only say that the source lies somewhere along the relevant hyperbola. A third receiver, R_3 , is required, with a time difference T' between receipt of the signal at R_3 and R_2 . We then know that the source is a distance

$$\delta_2 = cT'$$

closer to R_3 than R_2 . The set of points located δ_2 farther from R_3 than R_2 also traces out a hyperbola, and the source will be located at the point where the two hyperbolas intersect. The time difference

between arrival at R_3 and R_1 can also be used in the same way, and will result in a third hyperbola that intersects the other two at the same point.

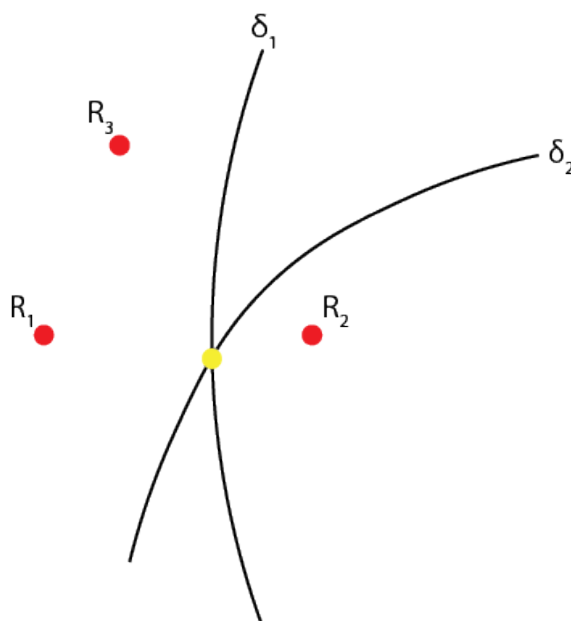


Figure 7 – Two hyperbolas intersect at the source location

TDOA can also be used to determine the position of a source in three dimensions. The set of points in 3D that are a given distance further from one receiver than another is not a curve, but is instead a surface – the three-dimensional extension of a hyperbola known as a hyperboloid. Adding a third receiver will define a second hyperboloid, which will overlap with the first one along a curve. That means that we need a fourth receiver, and the third hyperboloid that it defines, if we are to determine a point location for the source. More detail on 3D TDOA can be found in the [“Passive Geolocation with 3D TDOA” White Paper](#).

2.2 Strengths and Weaknesses

TDOA has a number of significant advantages, particularly when contrasted with AoA. The simpler antenna requirements (i.e. a single antenna, rather than an array) allow the system to be smaller, and therefore much easier to install and transport. It is also more robust against multipath effects (as the direct route between emitter and receiver will be the shortest, so the first signal received will be the one required). TDOA works best for wider-modulation bandwidths with better signal correlation properties and therefore localization to a narrower area. A significant advantage of TDOA is that the processing gain of correlations allows successful geolocation of signals that are

close to, or even below the receiver noise floor. It works particularly well for pulsed transmissions and can resolve multipath effects.

TDOA is unable to perform geolocation on narrowband signals (as obtainable accuracy is inversely proportional to bandwidth) or periodic signals (because if a signal is periodic with period P , it will be impossible to tell if the time difference of arrival at two receivers is t , or $t+P$, or $t+nP$ where n is any integer). It is not possible to perform TDOA geolocation with fewer than three receivers, or 3D TDOA with fewer than four receivers. An accurate synchronization method (usually GPS-based) is required in order to work out the time difference of arrival at the different receivers, and communications link with a high data rate is needed to allow comparison of the signals received using a cross-correlation function, to work out when the same signal is received at different receivers. This also means that performing multiple simultaneous geolocations can be problematic, as the data rate requirement scales accordingly (although this can be mitigated by performing data processing at the receiver location, rather than sending raw data).

2.3 Example Application – ADS-B Spoofing Detection

Automatic dependent surveillance-broadcast (ADS-B) is a surveillance technology currently being introduced in the US (as part of the Next Generation Air Transportation System), Europe (as part of the Single European Sky ATM Research project) and across the globe. It requires aircraft to determine their current position using GPS, and then to broadcast the details of this position (ADS-B OUT). Aircraft may also carry an onboard receiver (ADS-B IN), which allows them to receive the ADS-B OUT transmissions of other planes in the vicinity.

Because ADS-B is unencrypted, anyone receiving a transmission can determine the location of the aircraft sending that transmission. This capability is used in a harmless (and, indeed, useful) way by websites such as FlightAware, which plot (almost) live position updates of commercial aircraft. A more concerning possibility is that because ADS-B transmissions are unauthenticated, spoofed ADS-B signals can be generated. By creating a signal that matches the required messaging protocol, details of a non-existent 'ghost' aircraft can be sent either to ATC ground stations or to other planes. This could cause major disruption if flights need to be diverted to avoid the ghost aircraft. Moreover, it is possible to create multiple ghost signals simultaneously, greatly increasing the possible disruption.

3D TDOA offers a means to mitigate the harm caused by ADS-B spoofing. By analyzing the signal time of arrival at TDOA stations, we can determine whether the signal actually originates from the

location it purports to, based on the ADS-B encoded information. In cases where there is a disparity between the two geolocation determination methods, air traffic controllers can be alerted, and investigation of the signal source can be carried out.

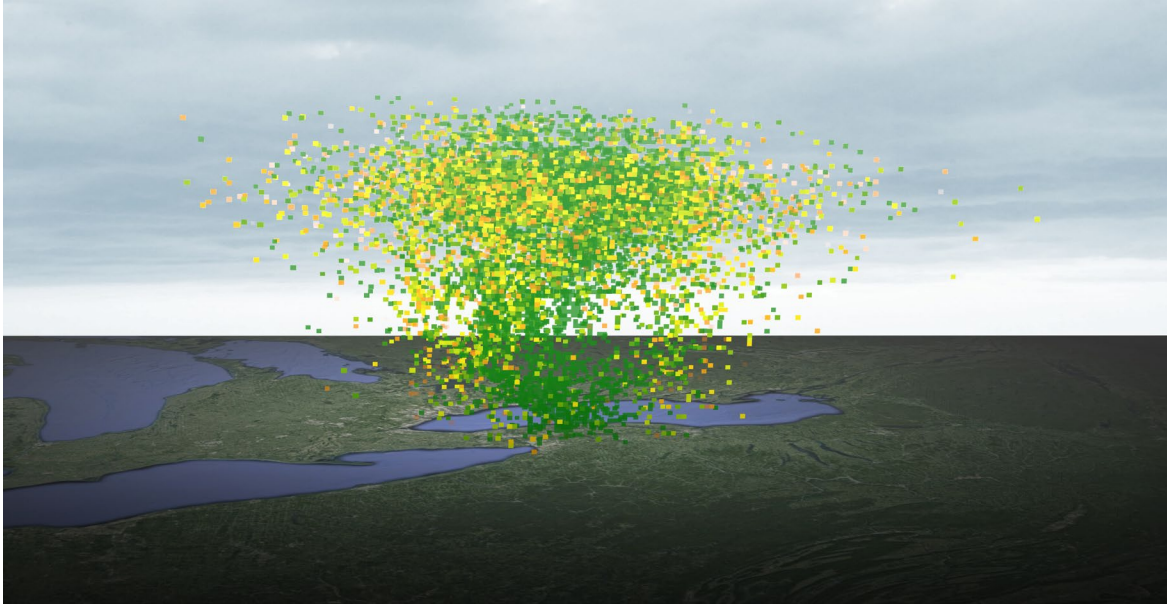


Figure 8 – Plane locations plotted in 3D

3 Frequency Difference of Arrival

3.1 Principles of Operation

Frequency Difference of Arrival (FDOA), sometimes also known as Differential Doppler, uses moving receivers to geolocate signals. It works by measuring the Doppler shift in the frequency of incoming radiation due to the relative motion of the receiver and source. So how does this frequency shift relate to the position of the emitter? Let's consider a situation where our receiver is traveling at a velocity, v_1 , in a direction relative to the emitter given by the angle θ , as shown in Figure 9 below.

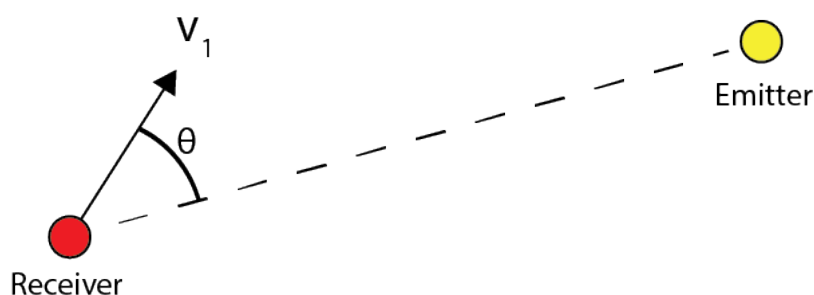


Figure 9 – FDOA initial geometry

The Doppler shift, δ , of a signal of frequency, f_0 , is given by

$$\delta = f_0 \frac{v}{c}$$

where v is the instantaneous velocity of the receiver toward or away from the emitter, and c is the speed of light.

In Figure 9, the receiver is not moving directly toward the emitter, so we need to resolve the component in that direction to find out the expected Doppler shift. This will be $v_R \cos\theta$. We then have a Doppler shift of

$$\delta_R = f_0 \frac{v_1 \cos\theta}{c}$$

So if we receive a signal shifted by δ_R , we can determine the line of bearing to the source by using

$$\theta = \cos^{-1} \left(\frac{\delta_R c}{f_0 v_1} \right)$$

There will be two values of θ consistent with this (if $\theta=x$ is a solution, then $\theta=-x$ is also a solution), so given one receiver, and a known Doppler shift, we will be able to determine that the source is located along one of the bearings shown in Figure 10.

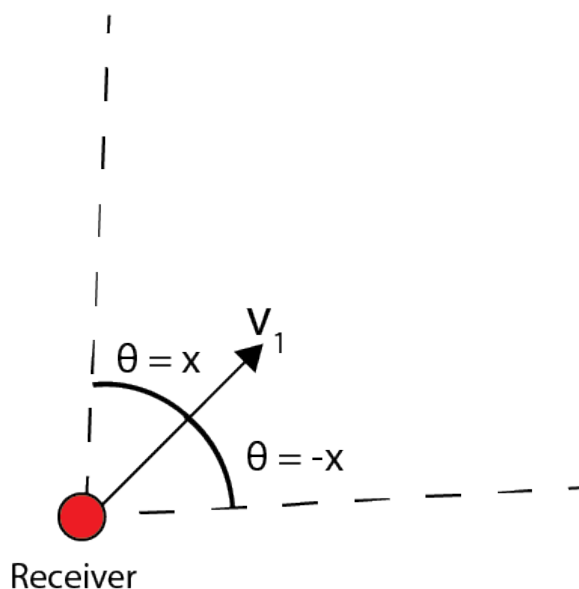


Figure 10 – Lines of bearing from one receiver

As with the previous geolocation methods, we require additional receivers, or additional measurements at different locations using the same receivers, if we are to pinpoint the source location. Given that our receiver is moving, the latter option will often be employed with FDOA. Our second measurement will give two further lines of bearing, which will intersect with the LOBs generated by the first measurement, giving two possible source locations.

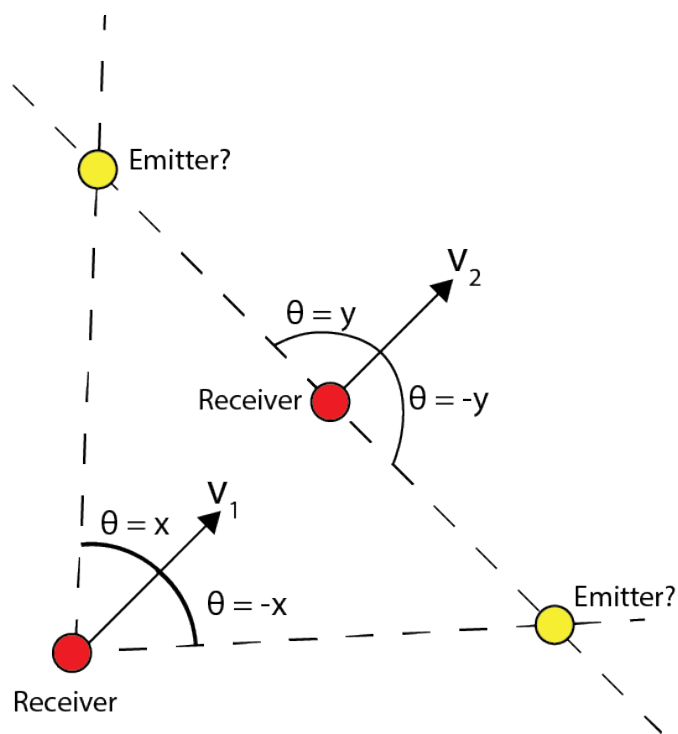


Figure 11 – Two possible locations for the emitter from two receiver measurements

A third measurement, giving us two further LOBs, will allow us to find a unique location for the emitter.

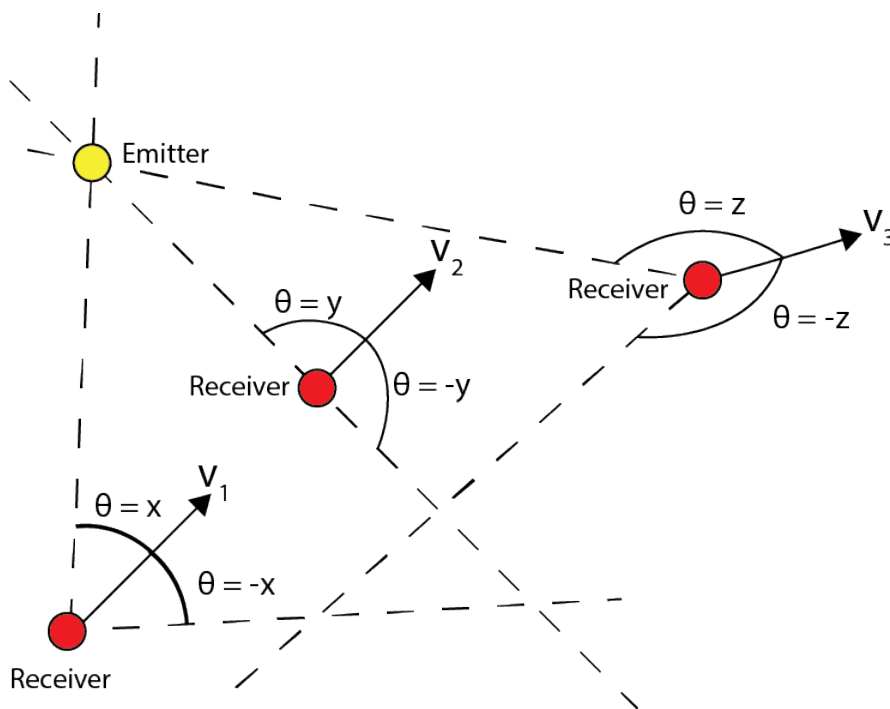


Figure 12 – Three measurements allow the emitter location to be pinpointed

Of course, all of these calculations assume that we know the initial frequency of the emitted signal, and that the emitter itself is stationary.

3.2 Strengths and Weaknesses

The key weakness of FDOA is also the most obvious, namely that it requires relative motion between the source and the receiver, and thus can only be deployed for moving targets (with known velocities), or from a moving receiver (e.g., one situated on a plane).

In situations where there is relative motion between source and receiver, FDOA can be combined with TDOA, allowing a geolocation to be carried out using just two receivers.

3.3 Example Application – Locating Illegal Boats

The setup described above can be used in practice by customs officials to monitor illegal boat movements off the coast. By mounting a receiver on a drone, measurements can be taken while traveling at a known velocity. After three measurements, an approximate location of the source can be determined, and in a similar way to the AoA application described in section 1.3, the drone can be piloted toward the source, allowing additional measurements, and an increasingly accurate determination of the location of the source.

4 Power of Arrival

4.1 Principles of Operation

Power of Arrival (POA) works in a conceptually similar way to TDOA, but instead of using the time it takes for signals to reach receivers, it uses the reduction in signal power as it travels to the receiver. The relationship between distance traveled and signal strength is not as straightforward as that between distance traveled and time taken, so if we are to understand this technique fully, we will need to examine this relationship more closely.

4.1.1 The Friis Equation

Let's begin by considering a signal of power, P_t . If we assume that the signal radiates in all directions evenly, then at a distance, d , from the source, the signal power will be distributed evenly over the surface of a sphere of radius d . The surface area of this sphere is $4\pi d^2$, so the power density on the surface will be $\frac{P_t}{4\pi d^2}$. The power received, P_r , by an isotropic receiving antenna will be given by multiplying this density by the antenna area, $\frac{\lambda^2}{4\pi}$. We then have

$$P_r = \frac{P_t}{4\pi d^2} \cdot \frac{\lambda^2}{4\pi} = P_t \left(\frac{\lambda}{4\pi d} \right)^2$$

and we can see that the power falls off as the square of the distance traveled.

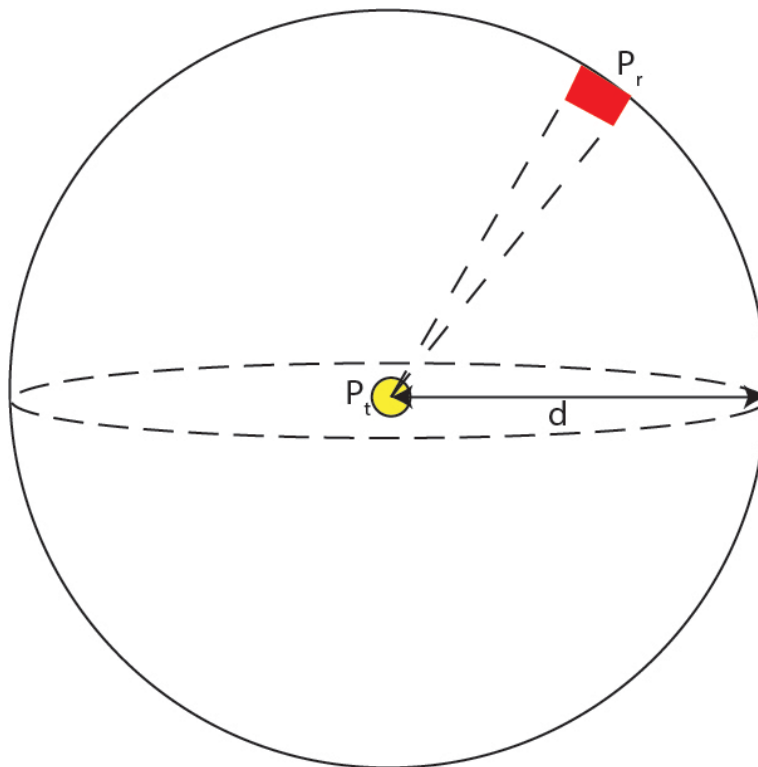


Figure 13 – Power received on the surface of a sphere

In practice, no antenna will be perfectly isotropic, so we add in terms for the receiver and transmitter gains, G_r and G_t , to give

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

4.1.2 Two-Ray Model

We can move beyond the free-space model to something slightly closer to reality by considering the two-ray model. Here, we assume that the RF signal received in a certain location is made up of two components: one traveling from source to receiver, and the other reflected from the ground as in Figure 14.

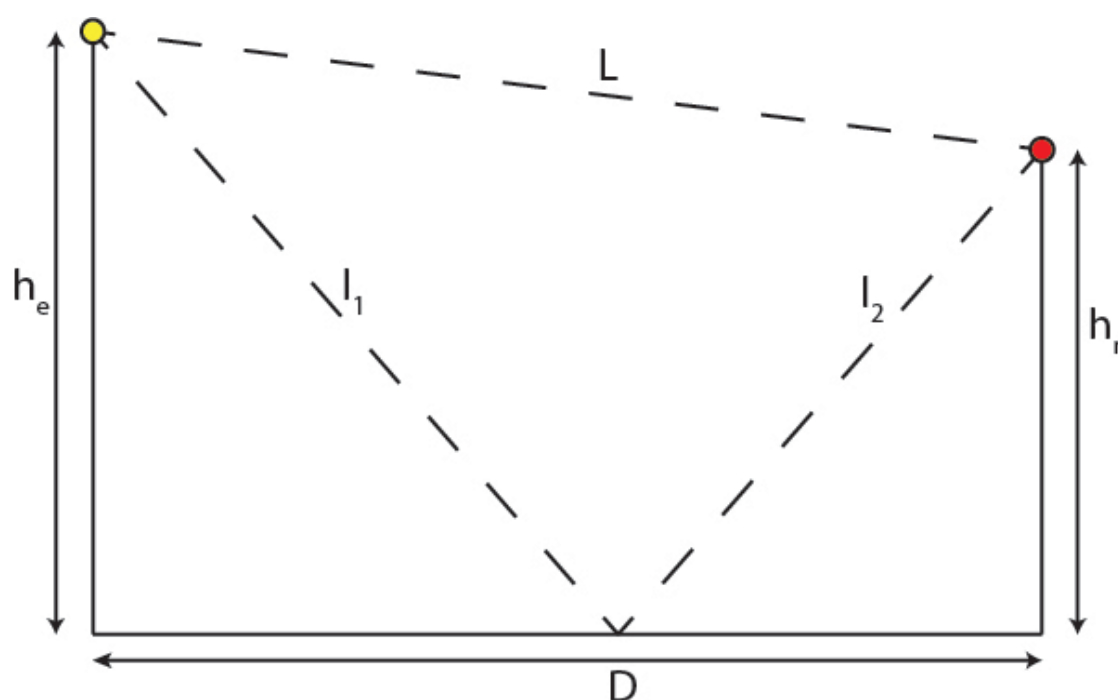


Figure 14 – Two-ray model geometry

The reflected ray travels a distance $\Delta L = (l_1 + l_2 - L)$ further than the one taking a direct path from emitter to receiver. Working from the Pythagorean theorem, we can see that

$$L = \sqrt{D^2 + (h_e - h_r)^2} \text{ and}$$

$$l_1 + l_2 = \sqrt{D^2 + (h_e + h_r)^2}$$

and the corresponding phase difference between the two signals is

$$\Delta\phi = \frac{2\pi\Delta L}{\lambda}$$

When taken individually, and using the expression from the free-space model, the received power levels from the signals traveling the two possible paths are

$$P_L = P_t G_t G_r \left(\frac{\lambda}{4\pi L} \right)^2$$

$$P_{l_1+l_2} = P_t G_t G_r R_G \left(\frac{\lambda}{4\pi d(l_1 + l_2)} \right)^2$$

where R_G is the ground-reflection coefficient, which we will take to be -1.

But when combining the two contributions, we need to take the phase difference into consideration as well:

$$\begin{aligned}
 P_r &= P_L + R_G P_{l_1+l_2} e^{-i\Delta\phi} \\
 &= P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \left[\frac{1}{L} - \frac{e^{-i\Delta\phi}}{l_1 + l_2} \right]^2
 \end{aligned}$$

If $D \gg h_e + h_r$, then $D \approx L \approx (l_1+l_2)$

$$= P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \left[\frac{1}{D} - \frac{e^{-i\Delta\phi}}{D} \right]^2$$

Using Taylor series for e^x , $e^{-i\Delta\phi} \approx 1 - i\Delta\phi$

$$\begin{aligned}
 P_r &= P_t G_t G_r \left(\frac{\lambda}{4\pi D}\right)^2 \Delta\phi^2 \\
 &= P_t G_t G_r \left(\frac{\lambda}{4\pi D}\right)^2 \left(\frac{2\pi\Delta L}{\lambda}\right)^2 \\
 &= P_t G_t G_r \left(\frac{\Delta L}{2D}\right)^2
 \end{aligned}$$

Given that $D \gg h_e + h_r$, and using the Taylor series for $\sqrt{1+x} = (1+x/2+\dots)$

$$\Delta L \approx \frac{D}{2} \left[\frac{((h_e + h_r)^2)}{D^2} - \frac{((h_e - h_r)^2)}{D^2} \right] = \frac{2h_e h_r}{D}$$

Substituting this back in, we have

$$P_r = P_t G_t G_r \frac{h_e^2 h_r^2}{D^4}$$

The key point to note here is that the dependence on distance is now $\frac{1}{d^4}$, as opposed to $\frac{1}{d^2}$ in the free-space case.

4.1.3 PoA Geolocation

In real-world applications, signal power will generally drop off at between $\frac{1}{d^2}$ and $\frac{1}{d^6}$, with the exact rate dependent on environmental conditions. We can give a general formula for the received power in any situation:

$$P_r = C \frac{P_t}{d^\alpha}$$

where C comprises all of the constants relevant to the situation (e.g. $P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2$ for the free-space case).

So how do we use this knowledge of how power reduces with distance to geolocate the source of a signal? And in particular, how do we do this when the initial power of the signal is unknown?

Consider two spatially separated receivers, R_1 and R_2 , that measure received signals of power P_{r1} and P_{r2} . We know that

$$P_{r1} = C \frac{P_t}{d_1^\alpha} \quad \text{and} \quad P_{r2} = C \frac{P_t}{d_2^\alpha}$$

where d_1 and d_2 are the distances from the emitter to R_1 and R_2 respectively.

Taking the ratio of these, we find

$$\frac{P_{r1}}{P_{r2}} = \frac{d_2^\alpha}{d_1^\alpha}$$

The distances d_1 and d_2 are fixed, which means that the ratio of their values is a constant

$$d_2 = k d_1$$

$$\text{and} \quad \frac{P_{r1}}{P_{r2}} = k^\alpha$$

So the set of possible transmitter locations is the set of points that are k times further from R_1 than R_2 . If R_1 is located at coordinates (a, b) and R_2 at (c, d) , then

$$(x - a)^2 + (y - b)^2 = d_1^2$$

$$(x - c)^2 + (y - d)^2 = d_2^2 = k^2 d_1^2$$

and therefore

$$(x - a)^2 + (y - b)^2 = \frac{1}{k^2} [(x - c)^2 + (y - d)^2]$$

This can be rearranged to make an equation for a circle

$$(x - u)^2 + (y - v)^2 = w$$

where

$$u = \frac{ak^2 - c}{k^2 - 1}$$

$$v = \frac{bk^2 - d}{k^2 - 1}$$

$$w = u^2 + v^2 - \frac{k^2(a^2 + b^2) - c^2 - d^2}{k^2 - 1}$$

The set of points satisfying this equation are the possible locations for the emitter

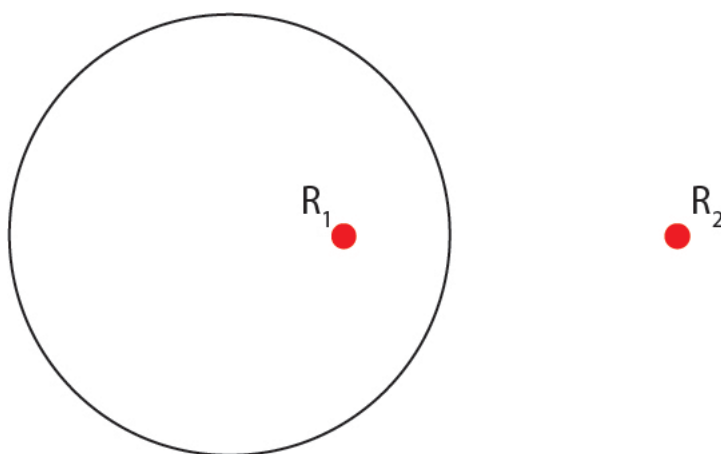


Figure 15 – Set of possible emitter locations

As was the case with TDOA, we need a third receiver if we are to determine the exact location of the emitter. The power difference between R₁ and R₃ will give a second circle of possible locations that will intersect with the first at two points, giving two possible locations. The power difference between R₂ and R₃ can then be used to produce a third circle, which will allow us to work out which of these is the true location.

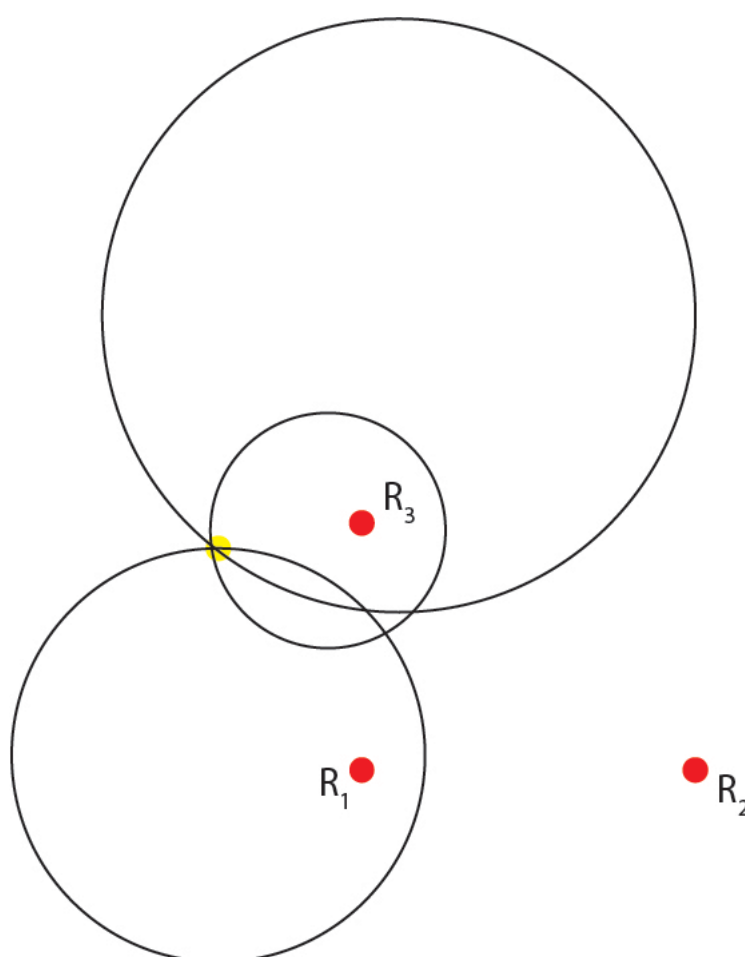


Figure 16 – Circles from three pairs of receivers determine the source location

4.2 Strengths and Weaknesses

In a number of important ways, POA can be considered the most generally applicable geolocation technique. The required hardware is simple, and any RF transmission type, from unmodulated carrier wave signals to narrow-band or short-burst pulsed transmissions, can be geolocated. However, POA also has several important drawbacks associated with it. Because it relies on statistical modeling of signal propagation, the achievable accuracy is usually lower than can be achieved with TDOA. This modeling is particularly problematic in urban environments, where power loss is highly variable, and multipath effects from buildings, trees and similar structures can further complicate modeling. POA is also best suited to geolocating over short distances (e.g., within an office). The rapid ($\frac{1}{d^2} - \frac{1}{d^6}$) drop-off in signal power means that accuracy falls very rapidly as distance increases.

4.3 Example Application – TSCM

Covert surveillance by hostile parties poses a significant threat to government departments, law enforcement agencies and private corporations. Using a tiny, easily deployable bugging device to carry out RF surveillance and data transmission, these hostile parties could potentially gain access to companies' trade secrets, governments' confidential plans or law enforcement agencies' operational details. Traditional TSCM (Technical Surveillance Countermeasures) involve dedicated teams conducting sweeps for unauthorized RF transmissions. However, because these sweeps are conducted over a short period of time, bugging devices can avoid detection by simply not transmitting during this time.

POA systems, such as CRFS's [RFeye Guard](#), offer a more effective means of detecting surveillance devices by carrying out 24/7 monitoring. POA is well-suited to operating in these kinds of environments: conditions within a building are much more consistent than those outdoors, allowing accurate modeling of signal power loss with distance, and the RF emitters that need to be located will necessarily be near to the system.

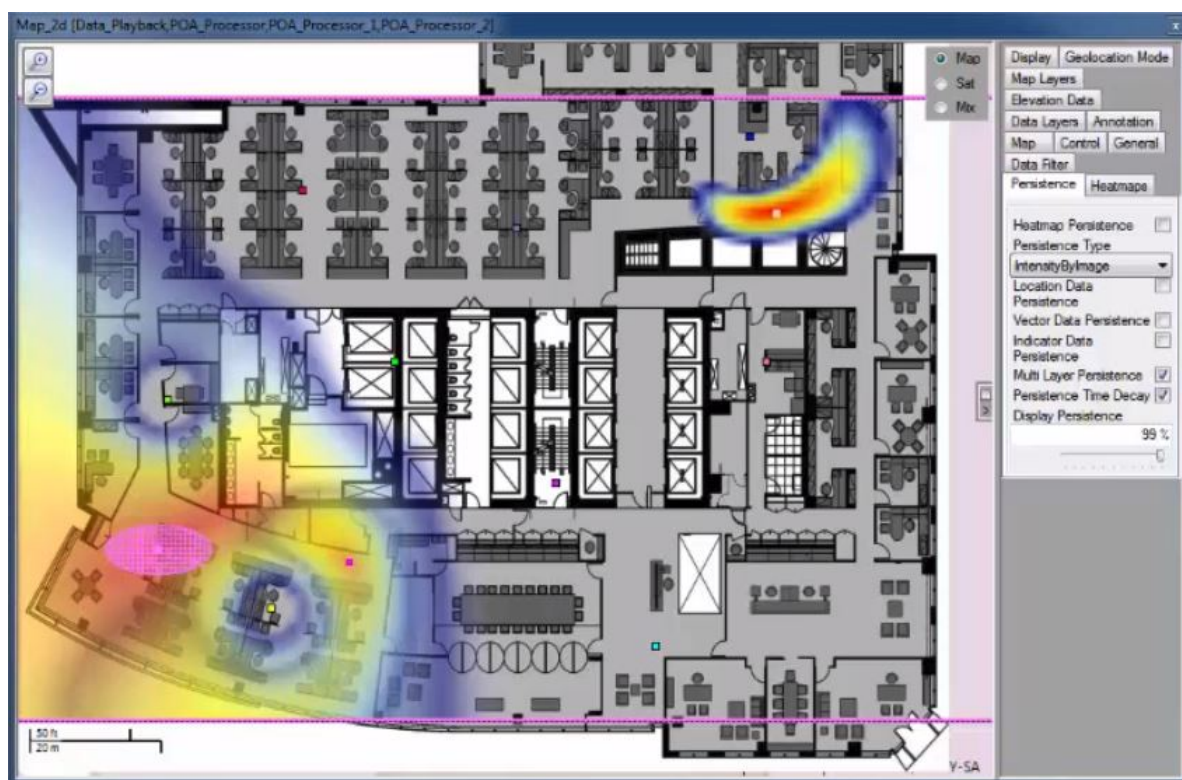


Figure 17 – In-building geolocation with POA

5 Geolocation Techniques Summary

Technique	Strengths	Weaknesses
AoA	<ul style="list-style-type: none"> • Conceptually simple • Can geolocate with just two measurements • Narrowband signals (e.g. sweeping radar) 	<ul style="list-style-type: none"> • Requires (often very large) antenna array, which is bandwidth-limited • Multipath effects can lead to spurious LOBs • Complicated calibration requirements
TDOA	<ul style="list-style-type: none"> • Simpler antenna requirements • Wideband, low-SNR signals and short-duration signals • Rejection of uncorrelated noise and interference • Mitigates multipath effects 	<ul style="list-style-type: none"> • Narrowband signals • Geolocation requires 3 (or 4) receivers • Requires communication links with higher data rates • Requires accurate time synchronization across receivers • Ambiguous location from periodic signals • May be difficult to perform multiple simultaneous geolocations
FDOA	<ul style="list-style-type: none"> • Can be paired with TDOA to allow geolocation with two receivers 	<ul style="list-style-type: none"> • Requires relative movement between source and receiver • Requires communication links with higher data rates
POA	<ul style="list-style-type: none"> • Simplicity of hardware • Works with any kind of RF transmission 	<ul style="list-style-type: none"> • Rapid drop-off in signal power means only useful for short-range applications • Relies on modeling path loss, which may greatly vary (esp. in urban environment), so accuracy is affected

- *Further discussion of geolocation techniques can be found in CRFS's "[Advanced Geolocation Capabilities](#)" white paper.*
- *If you have a specific geolocation requirement, and would like to know which technique would be best suited, then [contact our specialist team](#), and we will be happy to discuss your requirements in detail.*

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