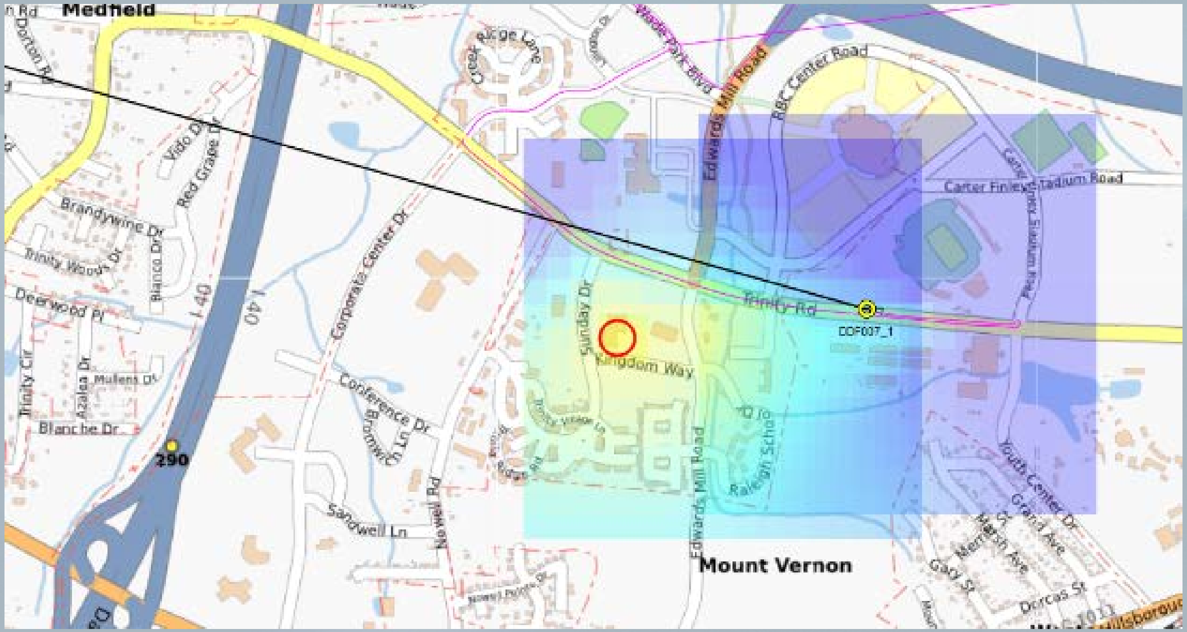
# An Introduction to Radio Direction Finding Methodologies





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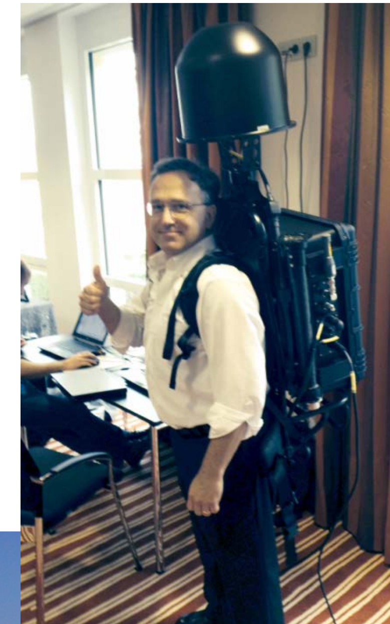
# Workshop Outline

- Part I
  - What is direction finding?
  - Who does direction finding?
  - Overview of direction finding
  - General introduction to direction finding
- Part II
  - Direction finding methodologies
    - Manual
    - Doppler
    - Angle of Arrival
    - Watson-Watt
    - TDOA
    - Correlative Interferometry
- Additional topics
- Discussion / Q&A

# About the presenter

- Paul Denisowski, Applications Engineer, Rohde & Schwarz (paul.denisowski@rsa.rohde-schwarz.com).
- Specialties include direction finding / radiolocation, interference hunting, and radar applications.
- MS in Electrical Engineering from NC State University.
- Over 20 years of both R&D and field experience in test and measurement.
- Extensive and on-going field work in direction-finding with both military / government and commercial customers.



# Part I – Introduction to Direction Finding

# What is direction finding?

- Direction finding refers to the use of specialized instruments, antennas, and methodologies to determine the physical location of a source of RF energy or “targets”
- Accuracy requirements vary depending on application, but typically on the order of 100 meters or less.
- Targets may be stationary or moving (at various rates of speed)
- Targets are usually non-cooperative, but not always (e.g. search and rescue)

# Who does direction finding?

- Government (civilian)
  - Spectrum enforcement
  - Search and rescue
- Military
  - Location of hostile forces / EOB
  - Spectrum deconfliction
- Law enforcement and security
  - Clandestine transmitter location
  - Tracking of individuals or vehicles
- Spectrum license holders
  - Cellular network operators
  - Venue operators
  - Usually interference issues

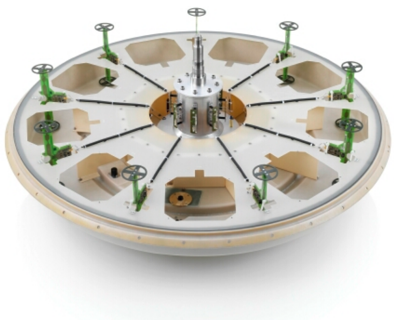
# What are we looking for?

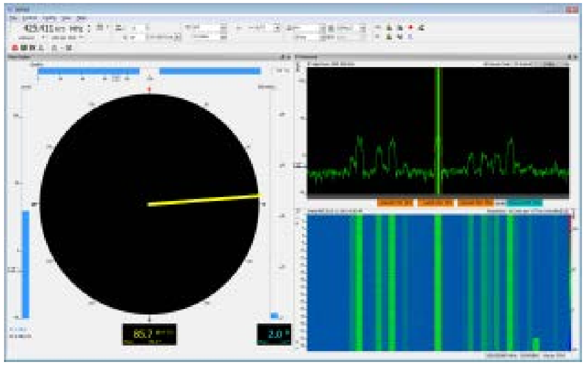
- Normally DF is used to locate uncooperative targets.
- Targets in direction-finding vary by application
- Most common types of targets overall are:
  - Communications transmissions
  - Broadcasters (including radar)
  - Malicious interference (e.g. jammers)
  - Unintentional interference (e.g. spurious emissions)
  - Transponders (ELTs, EPIRB, etc.)

# How do we locate the source of a signal?

- Possible sources of variation in the received signal:
  - Amplitude
  - Frequency
  - Phase / Time
- Variations can be used to determine the direction towards the signal source.
- Most DF methodologies use a single type of variation (amplitude, frequency, or phase/time)
- The modulation (or lack of modulation) on the target signal is usually unimportant for direction-finding.

# Typical direction-finding systems



DF antenna ↔ Receiver(s) ↔ Processing unit ↔ Display and control

## Antenna

- Design usually specific to a given DF methodology

## Receiver(s) and processing unit

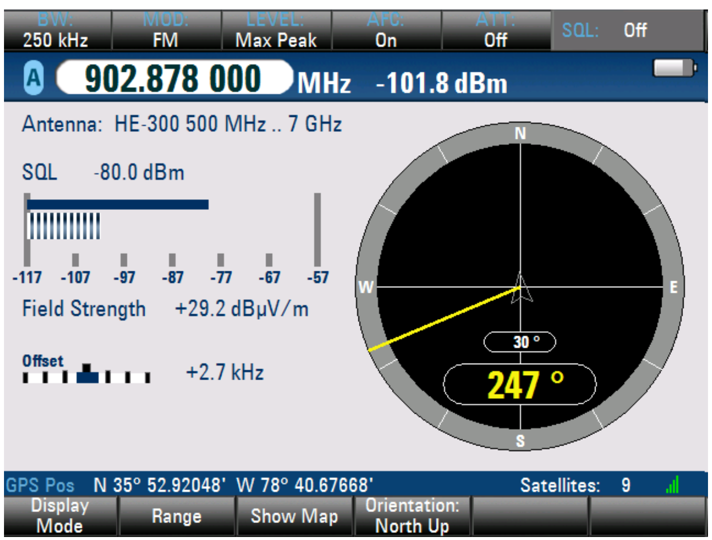
- One or more receive channels with analog-to-digital conversion
- Integrated or separate digital signal processing

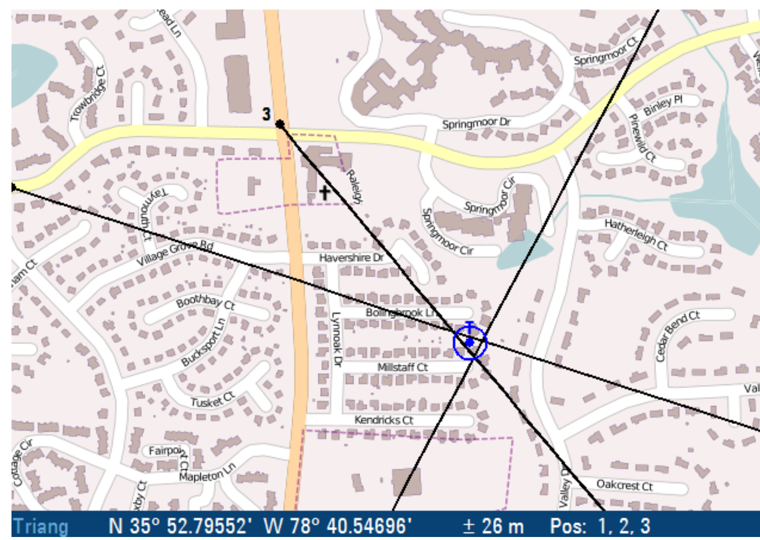
## User interface

- Software for display and control
- Position fix and map display software

# Radiolocation vs. Direction Finding

- Although the terms are often used interchangeably, there are (strictly speaking) differences between “radiolocation” and “direction finding”
- “Radiolocation” more generally refers to the process of determining the location of a source of radio frequency energy
- “Direction finding” usually implies the use of one or more <u>bearings</u> to determine the direction (azimuth and potentially elevation) towards a source of RF energy.



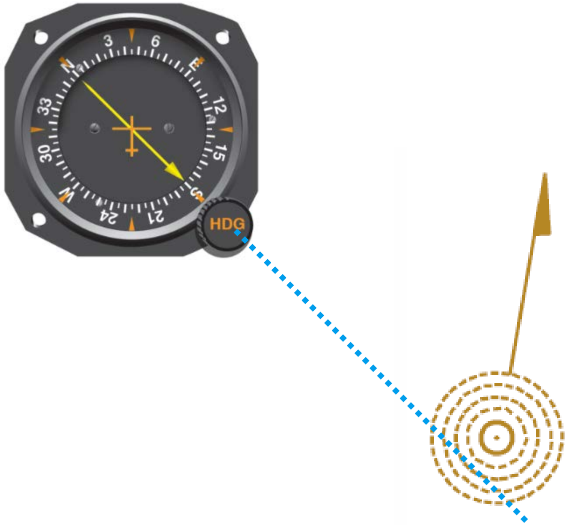



# Radiolocation, not Direction Finding

- Examples of radiolocation methodologies that do not produce bearings
  - Manual handheld antenna sweeps (as opposed to taking bearings)
  - Non-directional amplitude comparison / heat maps
  - Time difference of arrival

# Radiolocation vs. radionavigation

- “Radiolocation” normally refers to finding the location of a source of radio frequency energy.
- Sources of RF energy can also be used to determine one’s **own** location – this is more properly referred to as radio**navigation** as opposed to radio**location**.
- For example, aircraft use navigational aids such as VOR, DME, and ADF to determine their **own** location.
- Sometimes the same methodologies are used for both radionavigation and radiolocation (e.g. crossed loops in ADF).

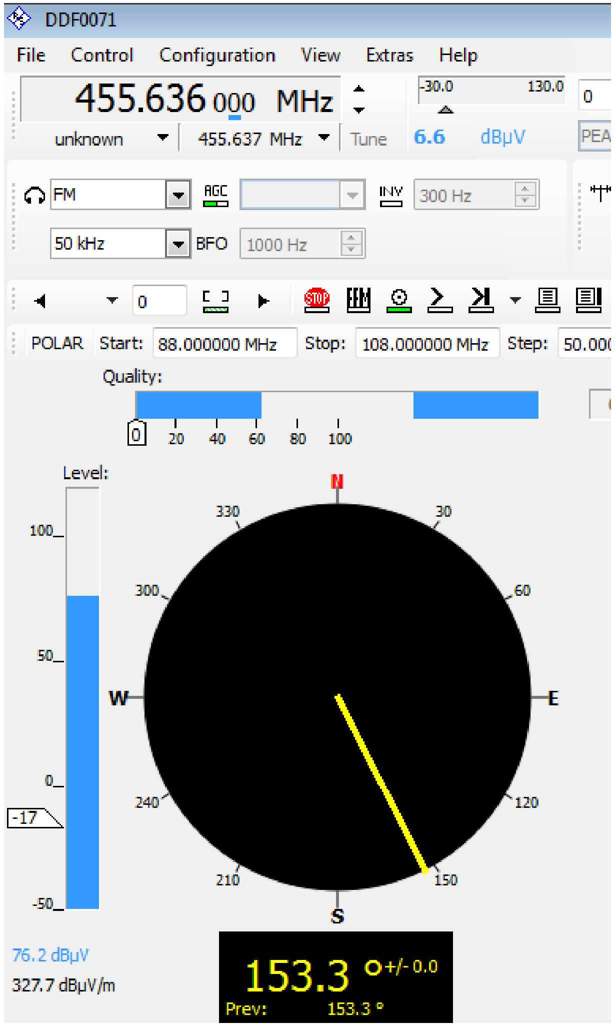



# Bearings

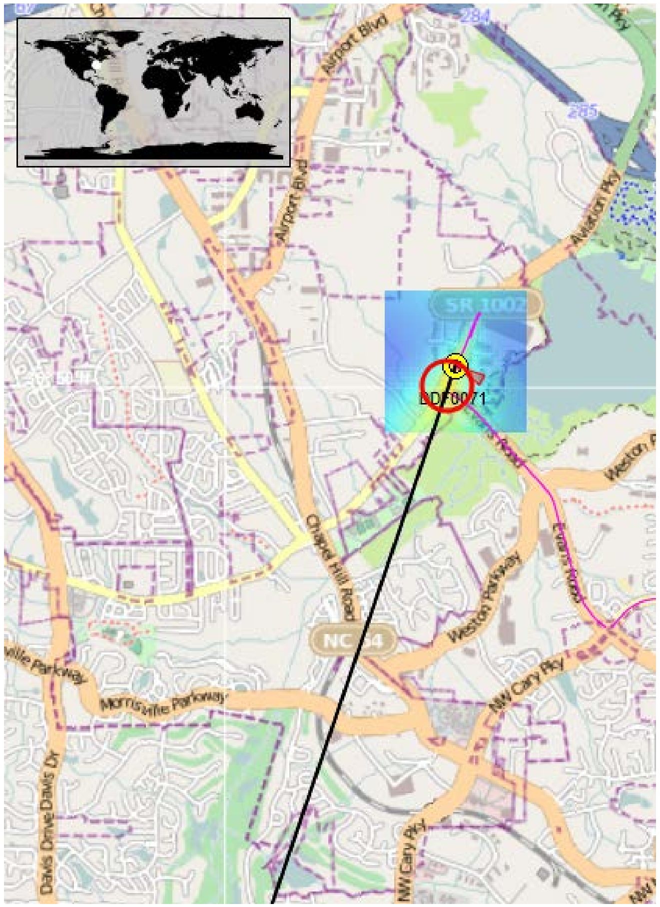
- Direction-finding systems generate **bearings** (sometimes called “lines of bearing” or LOBs) that point towards a target.
- Two ways of using bearings:
  - A single bearing can also be used when homing towards a target.
  - Multiple bearings taken from different locations can be used to compute the most probably location of a target.
- Accuracy in direction finding is primarily a function of the accuracy of the bearings, which in turn depends on the methodology used to produce the bearings as well as the operator / configuration.
- The algorithms used to process multiple bearings and compute a target location also play a non-trivial role in accuracy.

# What is a bearing?

- A **bearing** (or **azimuth**) simply indicates a direction, usually the direction towards a signal.
- Given in degrees, relative to our current position (whether stationary or moving).
- For bearings to be useful in calculating a location, we need to know **both** the bearing and the location from which the bearing was taking.
- In homing mode, current location may not be necessary
- It is sometimes also helpful to measure the elevation.



# Two methods of getting bearings




- **Manual** – the operator manually points the antenna until the strongest signal level is obtained.
- **Automatic** – the instrument automatically computes the bearing line based on a radiolocation methodology (Doppler, Watson-Watt, Correlative Interferometry, etc.).
- Manual bearings are typically more “operator-sensitive.”
- Note however that automatic bearings (especially those without bearing quality information) are not necessarily superior to manual bearings.

# Bearings and bearing location

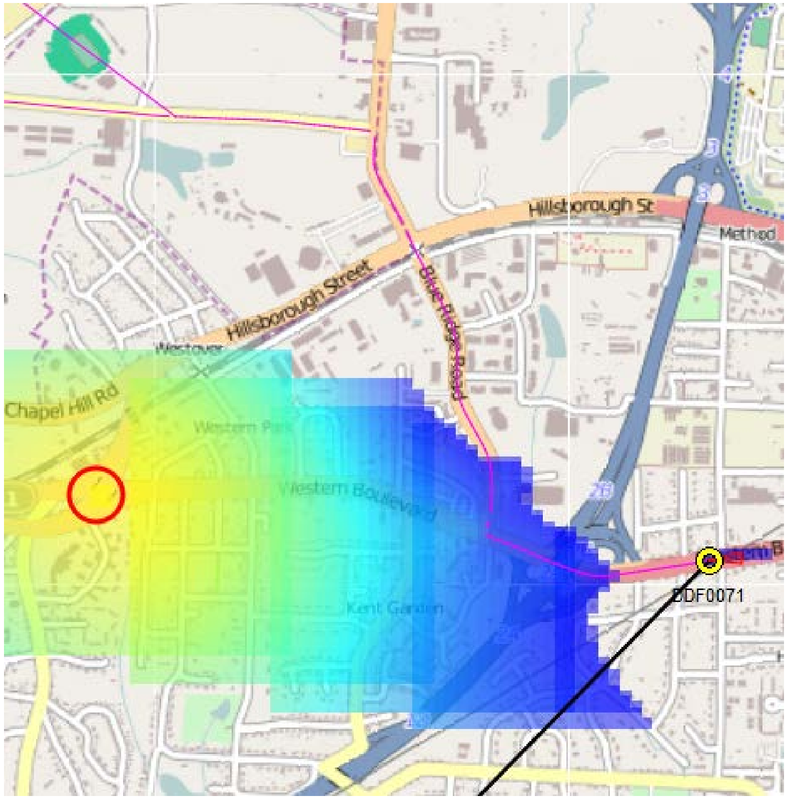
- When using bearings to compute a target location, the location at which the bearing is made is also needed.
- The easiest and most accurate way to obtain position information is using GNSS (single or multiple – e.g. GPS + GLONASS).
- The more satellites the GNSS receiver can see, the better the accuracy (improved DOP). Augmentation systems such as WAAS or GBAS improve accuracy.
- GNSS normally requires a clear view of the sky.  This normally is only an issue when performing DF in “urban canyons”
- Errors in location can adversely impact DF accuracy.

# Bearing errors


- A certain percentage of bearings typically will be so-called “junk bearings” or “fliers”
- Bearing errors can be caused by the operator, instrumentation and/or the environment.
- Environmental factors include things such as:
  - Multipath
  - Noise
  - Co-channel signal sources
- Proper methodology, a good understanding of propagation, and careful selection of measurement locations can reduce or eliminate these errors.
- There are some locations from which it is impossible to obtain accurate bearings towards a given target.

# Effects of bearing errors

- Note that distance increases the effect of bearing errors, e.g.
  - 5º error = ~ 8.7 meters @ 100 meters
  - 5º error = ~ 437 meters @ 5 kilometers
- Generally speaking, the closer you are to the transmitter (up to a point), the lower the impact of bearing errors.
- Bearings errors are most critical when employing direction finding methodologies that process small numbers of bearings.
- Note that some direction finding methodologies can (partially) compensate for bearing errors and/or discard obvious "fliers"

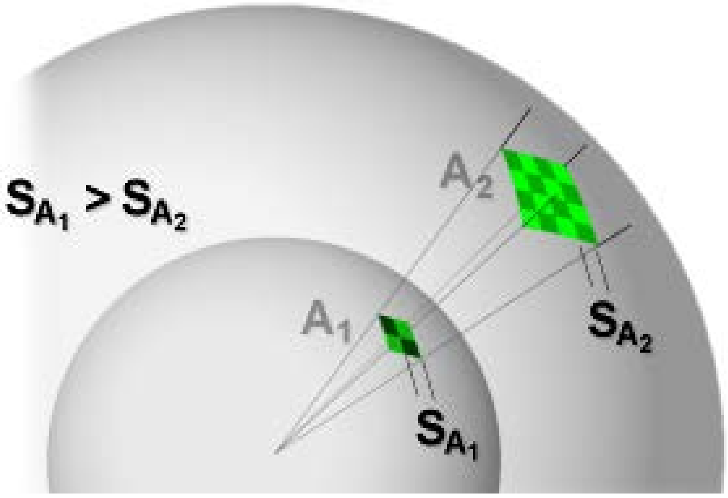


# Bearings and propagation / noise

- Understanding the impact of propagation effects is very important in direction finding.  This includes:
  - Free space path loss (FSPL)
  - Absorption / attenuation
  - Reflections
  - Multipath
  - Noise
- Note that propagation characteristics are very frequency-dependent.
- With regards to direction finding, the greatest differences in propagation are between HF and non-HF frequencies.  We will be concentrating primarily on non-HF direction finding in this workshop

# Free space path loss

- Free space path loss (FSPL) calculates loss of signal strength (attenuation) as a function of distance and frequency.
- Assumes an unobstructed path and copolarized antennas.
- Free space path loss is a calculation, not a measurement.
- Formulas can be found in ITU-R P.525-2 “Calculation of Free Space Attenuation”
- Important for direction finding as it determines the (absolute) maximum distance at which a target can be located given the DF receiver sensitivity or settings.



# FSPL equations

- Free space path loss (attenuation, A) is computed between isotropic antennas using

$$A = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

- This can be rewritten in decibel form as

$$A = 32.4 + 20\log d + 20\log f$$

*Ref : ITU-R P.525-2*

where f = frequency in MHz and d = distance in kilometers

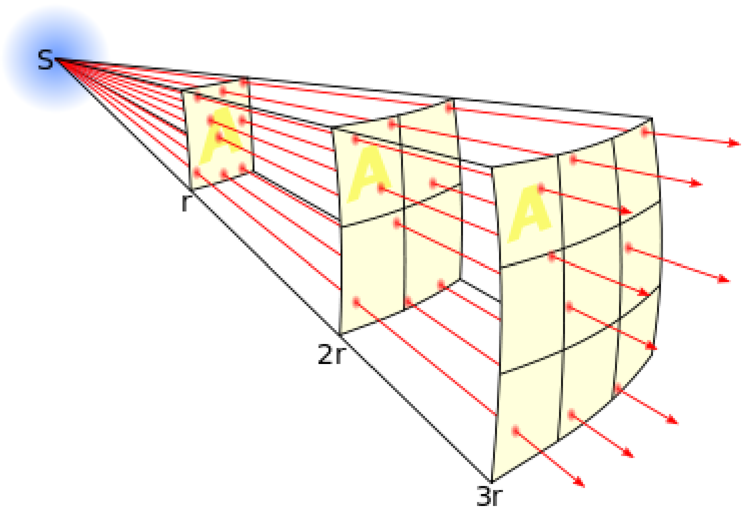
- Notice that FSPL is a function of **distance** (*d*) and **frequency** (*f*)

# FSPL and distance

- A signal transmitted by an isotropic radiator into free space will propagate outwards in the form of a sphere ($A = 4\pi d^2$).
- As the sphere expands, the intensity of the signal over the surface area of the sphere decreases as per the *inverse square law.*
- Thus, FSPL increases with increasing distance.

$$S = P_{tx} \frac{1}{4\pi d^2}$$

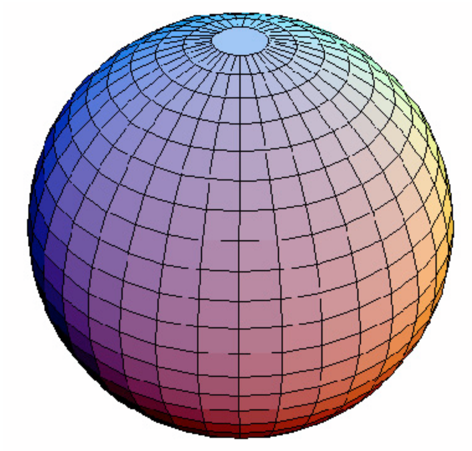
S = power density, $P_{tx}$ = total radiated power,
d = distance from antenna (radius of sphere)



# FSPL and frequency

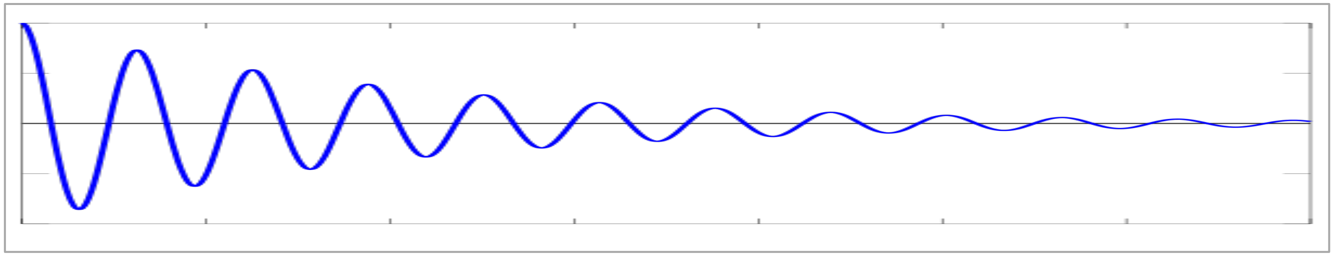
- Since FSPL increases with frequency, a common misconception is that free space attenuation is frequency-dependent.
- Although physical objects often exhibit frequency-dependent attenuation, FSPL is a **free space** calculation (i.e. no objects).
- FSPL is frequency-dependent because the effective aperture ($A_e$) of the receiving isotropic antenna changes with frequency.
- As frequency increases, effective aperture decreases. This is why path loss increases with increasing frequency.

$$A_e = \frac{\lambda^2}{4\pi}$$



# Absorption / attenuation

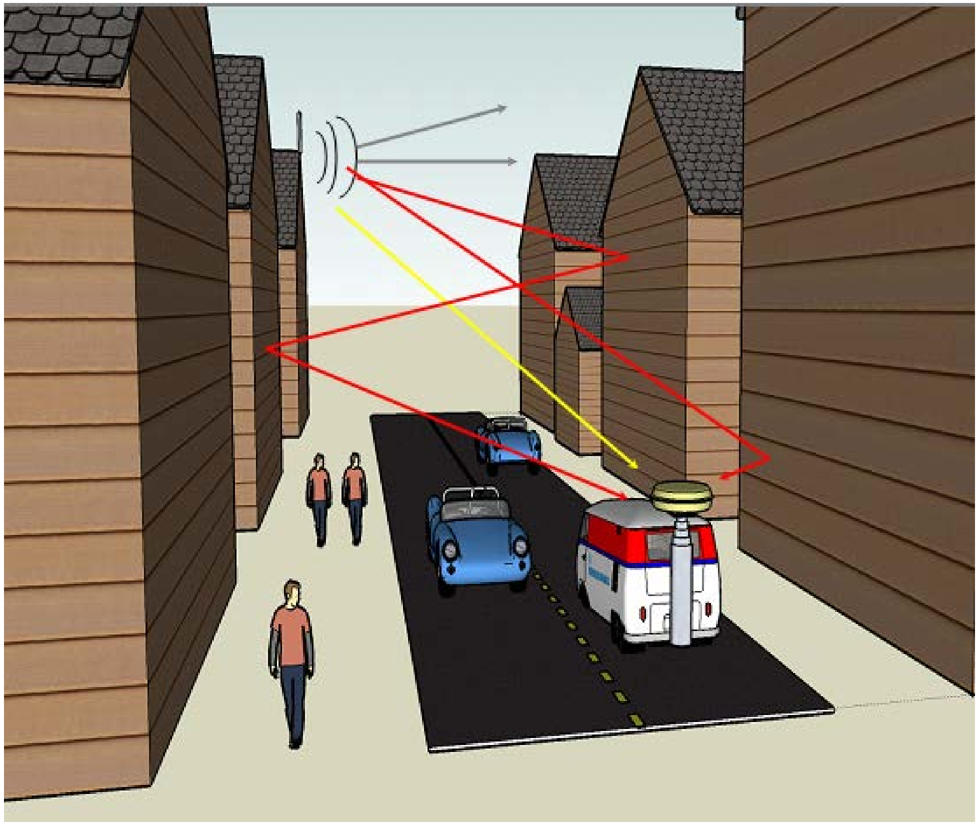
- FSPL assumes line of sight with no intervening obstructions.  This is almost never the case in normal direction finding scenarios.
- Intervening objects will absorb (or attenuate) RF, further reducing the range at which a target signal can be detected.
- Absorption depends on the frequency of the signal and object composition:
  - Wood, plastic, (non-tinted) glass  : low attenuation.
  - Bricks, organic material, liquids : medium attenuation.
  - Concrete, metal, tinted glass, soil : high attenuation.
- As a practical matter, higher received target signal strength tends to yield better results, so line of sight is preferred whenever possible.



# Reflections

- Highly radio-opaque objects such as concrete and metal will also reflect RF signals.
- This can create multipath interference and complicates radiolocation.
- Signals may appear to be coming from concrete buildings, tinted windows, vehicles, etc. when, in fact these signals are simply being reflected.
- The best way to avoid erroneous bearings due to reflections is to maintain an adequate distance from reflective objects.

# Multipath



- Multipath means receiving a signal from different directions simultaneously.
- Caused by single or multiple reflections, most commonly in an urban environment.
- The severity of multipath is also a function of the frequencies involved.
- **Multipath is the single biggest issue in direction finding**.
- Measuring the level of or effect of multipath on bearing accuracy is sometimes possible.

# Effect of multipath on direction finding

- Multipoint is somewhat of a statistical issue – in high multipath environments we can't trust any single bearing
- However, the majority bearings taken *from different locations* in a multipath environment typically end up pointing in roughly the correct direction, albeit with varying degrees of accuracy.
- In the extreme case of multipath, the signal could take two different paths and arrive 180° out of phase, cancelling each other out. In reality, this is not a practical concern, especially as the number of bearings taken from multiple locations increases.

# Practical tips for minimizing bearing errors

- Since multipath has the greatest adverse effect on bearing accuracy take bearings from multiple locations with low multipath and a clear line of sight to the target.
- Note however, that in many cases we have fixed DF sites and/or limited geographical freedom in terms of DF measurement locations.
- To minimize bearing errors with static DF locations:
  - Avoid obstructions
    - Increasing height
    - Use open locations (fields, etc.)
  - Avoid reflective structures (including vehicles)

# Effect of noise on direction finding

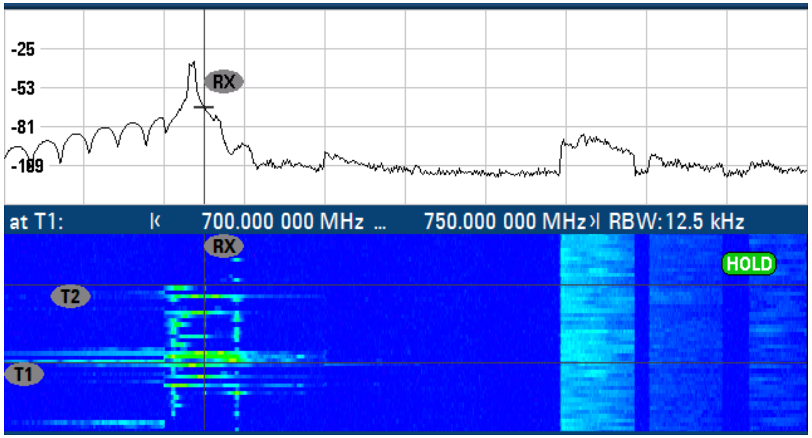
- The level of ambient noise (the “noise floor”) at a given measurement location can affect DF results in two main areas:
  - High levels of noise can potentially mask the target signal (unable to detect and / or generate bearings)
  - Constant or intermittent noise may be mistaken for the target signals – bearings taken on noise
- *Uncorrelated* noise is noise whose location and spectral characteristics are essentially random – approximately the same level and spectral composition at all locations.
- Some DF methodologies have the ability to specify a minimum target signal threshold and/or the ability to take bearings on signals below the (uncorrelated) noise floor.

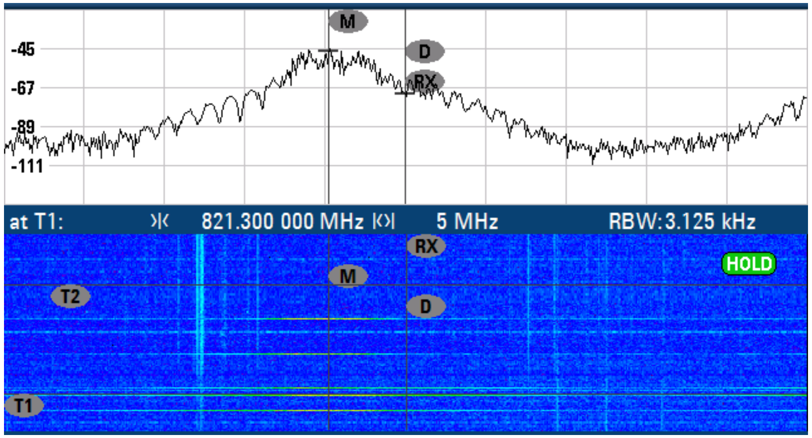
# Additional general DF considerations

- The behavior or characteristics of the target may have a substantial influence on the accuracy of our DF results or the time required to obtain accurate results.
- The three most important characteristics are:
  - Target duty cycle
  - Target frequency agility
  - Target motion
- As mentioned previously, the specific type of modulation (or lack of modulation) on a target signal does not normally affect DF results.

# Target duty cycle

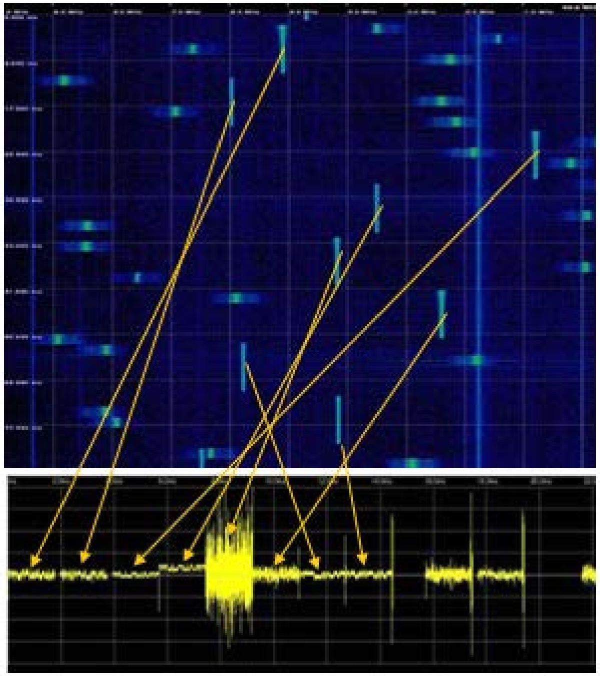
- Targets with a constant or very high duty cycle are much easier to locate than targets with a very low duty cycle.
- Obtaining manual bearings on very short duration signals are extremely difficult.
- Many automatic direction finding systems can take measurements on signals with very short transmit times (< 1 second).
- However, short duty cycle reduces the number of bearings that can be taken per unit time, increasing overall time required to obtain a fix.



# Target frequency agility

- Most DF systems are designed to locate signals at single frequencies (single-channel)
- Frequency-agile targets can greatly complicate direction-finding, since the transmit frequency will change.
- Frequency change can vary in the following ways:
  - Speed of frequency change (e.g. slow drifters, medium oscillator, fast hopper)
  - Continuous or discrete states
  - Random or predictable / known transitions.
- Common approaches:
  - DF only at a single known frequency state (slow)
  - Multiple channels / fast-scanning DF system (expensive)



# Target motion

- Bearings taken on moving targets are no different or less accurate than bearings taken on stationary targets.
- Complications result if target is assumed to be stationary – has target moved or were previous bearings inaccurate?  How can we tell?
- Homing is an excellent way of tracking down moving targets, but this is not always possible (geographical constraints).
- Shorter DF periods and periodic calculation of location / clearing of saved bearings can help determine if target is in motion and track changing locations.

# Summary of general introduction

- In this section we've looked at
  - Who does direction finding and why
  - What are bearings
  - Factors influencing bearing accuracy
  - Propagation and its effects on direction finding
- In the next section we will cover the main direction finding methodologies
  - Manual
  - Doppler
  - Angle of Arrival
  - TDOA (time difference of arrival)
  - Watson-Watt
  - Correlative Interferometry
- Advanced topics / future directions

# Part II – Direction Finding Methodologies

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# Direction finding methodologies

- Although there are many different direction finding / radiolocation methodologies, the most commonly used are:
  - Manual
  - Doppler
  - TDOA (time difference of arrival)
  - Watson-Watt
  - Angle of Arrival
  - Correlative Interferometry
- We will cover each of these methodologies, including technical information, areas of application, and relative strengths and weaknesses

# Manual Direction Finding

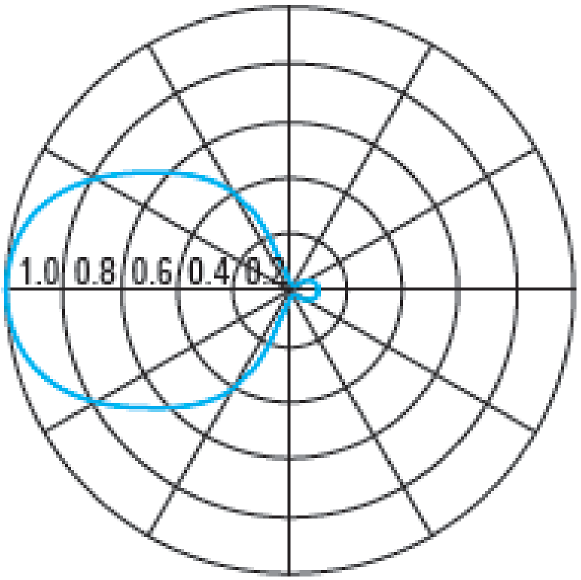
# Manual direction finding

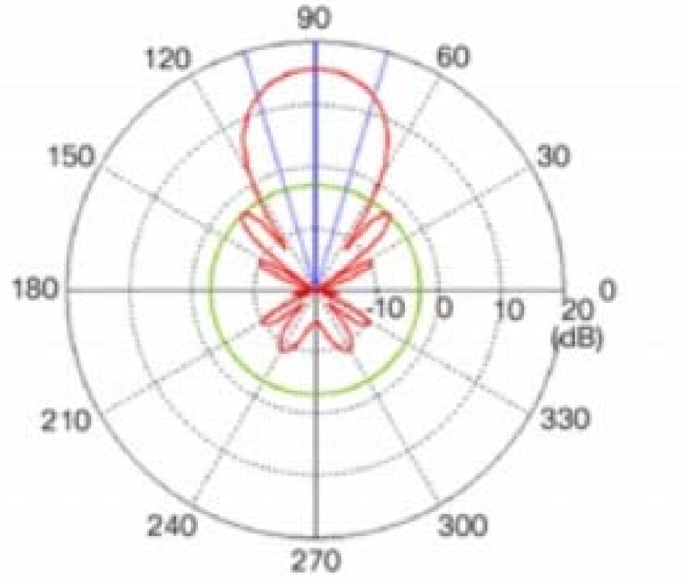
- Manual direction finding involves the use of a receiver and hand-held directional antenna : usually some type of yagi / log-periodic.
- The antenna is moved / rotated until the point of maximum signal strength is determined.
- Rotation can also be performed using an antenna mounted on a rotor or swivel.
- Accuracy decreases rapidly as distance to source increases.

# Handheld antenna characteristics

- Although antennas parameters are important for all types of direction-finding, they are particularly important in manual direction finding
- Handheld antennas used in manual direction-finding should
  - Be reasonably directional
  - Have very-low / no sidelobes
  - Be portable and rugged
- Typical handheld directional antennas trade off:
  - Higher gain = narrower bandwidth = more sidelobes

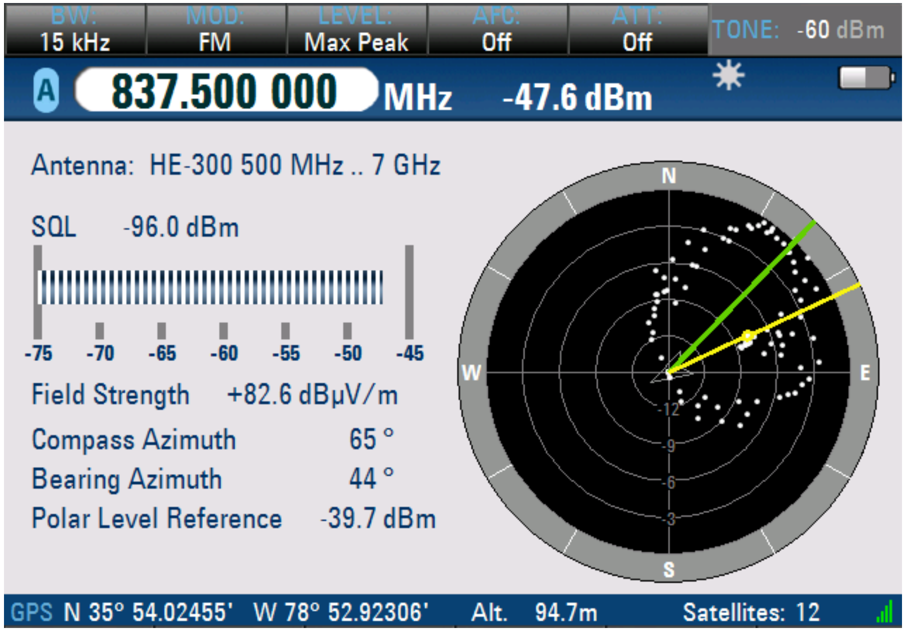
# Handheld antenna pattern examples



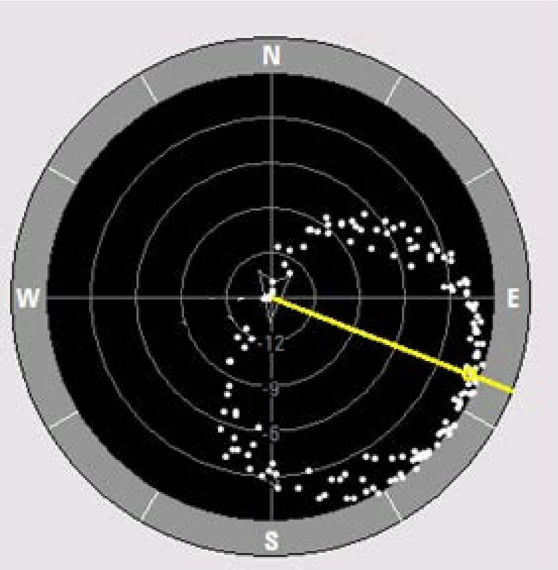




# Understanding handheld antenna patterns

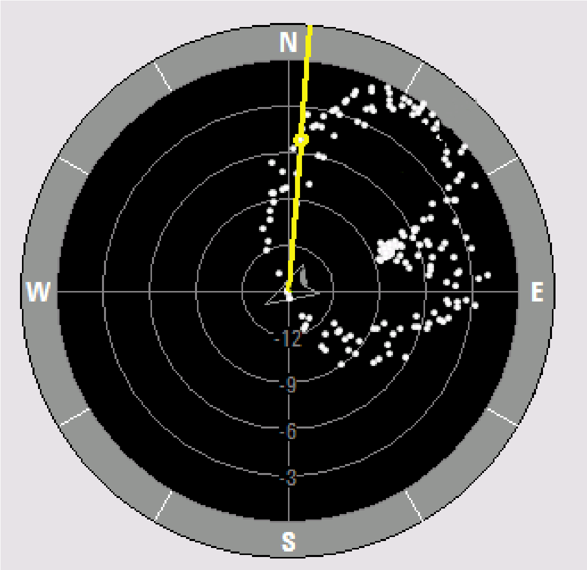
- Important to remember that the nominal antenna pattern was measured in a reflection-free environment.
- Distortion in or deviation from the nominal pattern of a handheld antenna is a good indicator of multipath or other (undesirable) interactions, typically with nearby objects such as structures, vehicles, etc.



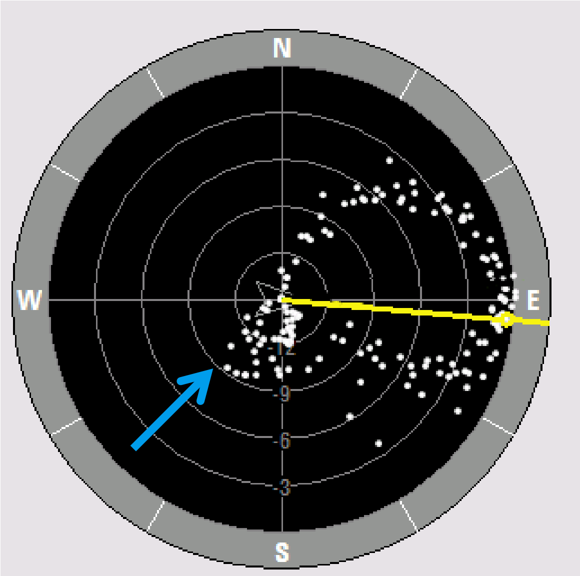
# Handheld antenna patterns – field measurements




Ideal pattern



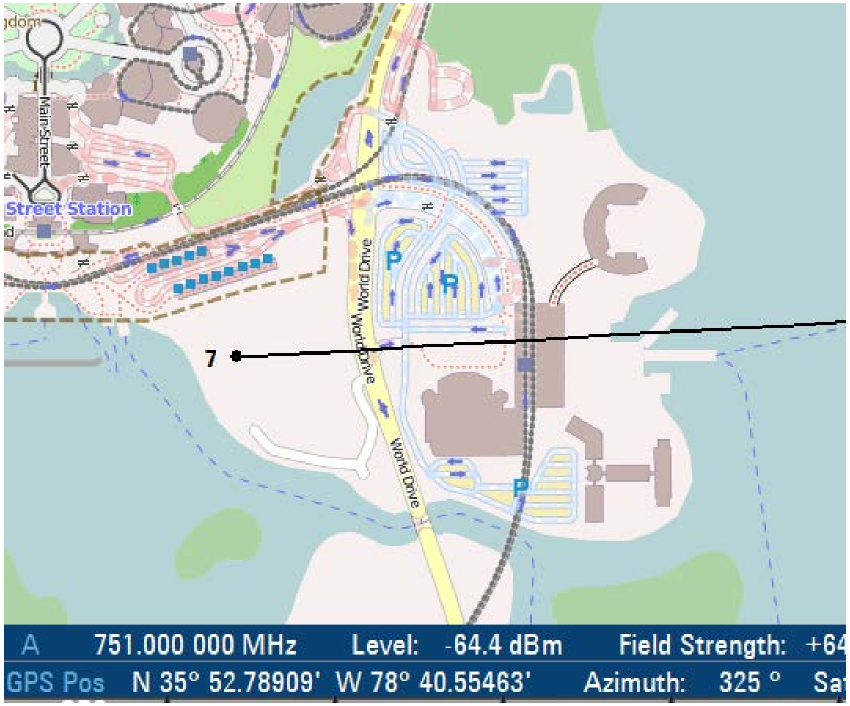

Distorted pattern




Unexpected lobe

# Manual bearing determination

- Given that we have a suitable directional antenna and an instrument capable of measuring RF signals, how do we (manually) determine a bearing towards the source?
- Most common approaches are
  - Level (numeric)
  - Level (waterfall / spectrogram)
  - Audio output

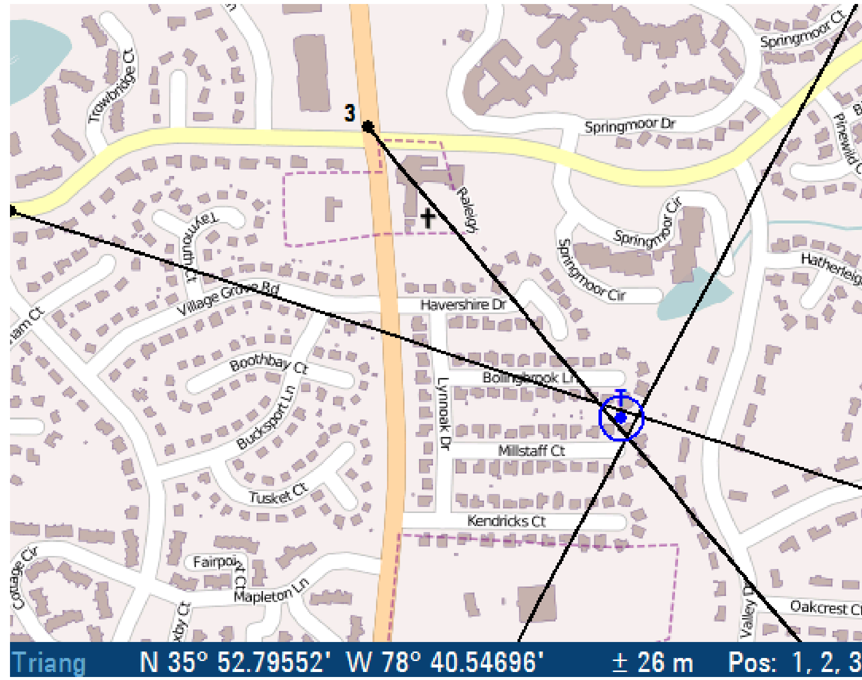


# Application of manual DF results

- Two main ways in which manual DF is used
  - Bearing lines
    - Antenna is used to determine a line of bearing to the signal source.
    - Multiple lines are plotted and used to triangulate the transmitter's location
  - Homing / Sweeping
    - Homing : bearing is used as direction of travel
    - Sweeping : when a the source has been narrowed down to ~100 meters, manual DF is often the only way to find the precise location. Antenna is used to sweep or test possible locations in the suspect area.

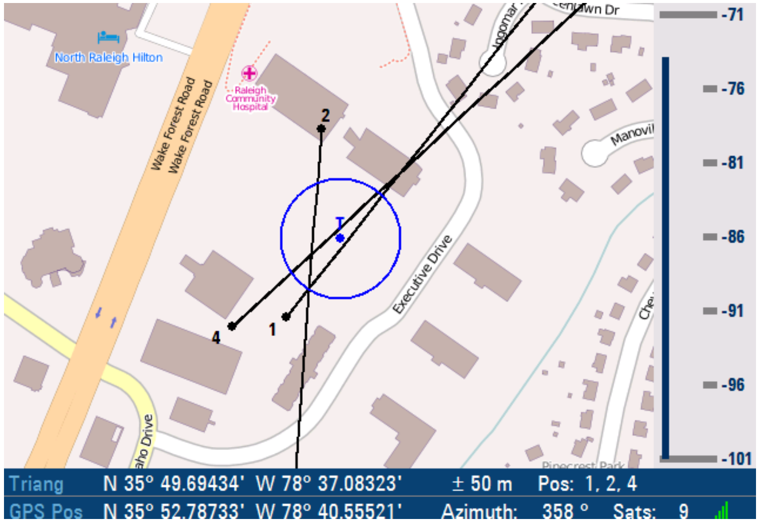
# Bearings and Triangulation

- The main reason for taking and storing bearings in manual DF is for performing **triangulation**.
- Bearings are plotted (manually or automatically) on a map, and the estimated transmitter location is at the intersection of the lines.
- Generally done over shorter geographic distances, so altitude differences and earth curvature are not normally considered.
- Process may be iterative



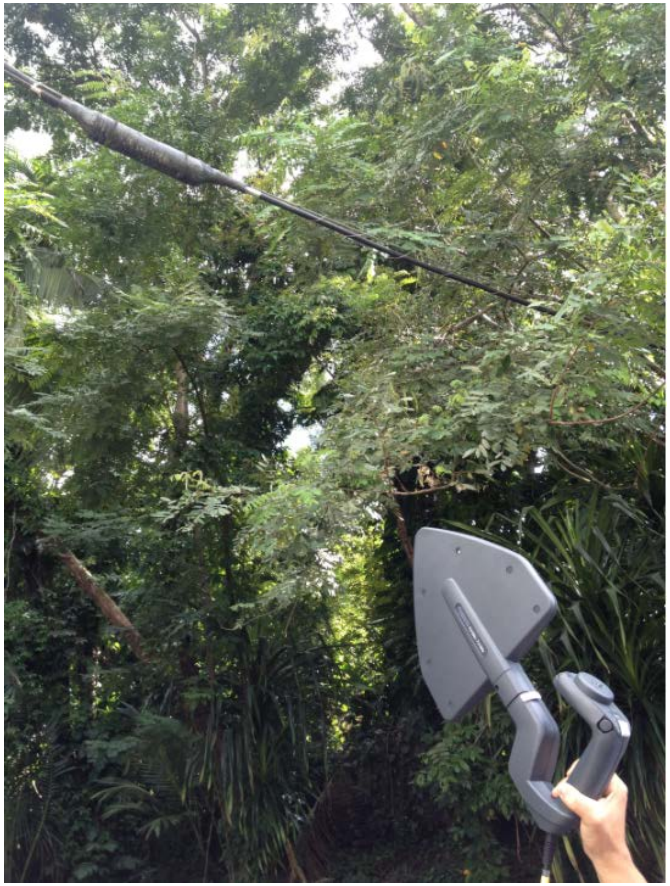
# Triangulation considerations

- How many bearings do we need to take to compute a triangulation point?
  - At least three (why not two?)
  - More than 5-6 (good) bearings does not improve accuracy
  - Triangulation accuracy is limited by bearing accuracy
- Selection of DF sites is critical : good bearings = good triangulation
- To keep yourself honest, best to mask previous bearings



# Homing / Sweeping

- Manual bearings are used for both homing and sweeping
- In **homing** mode
  - We simply want a single (reliable) bearing towards the target.
  - Used to travel towards / pursue the source.
  - Result is azimuth, often computed using an electronic compass
  - Two-dimensional
- In **sweeping** mode
  - We examine structures, objects, etc. to determine precise location
  - Result is the physical orientation of the antenna
  - Sometimes three-dimensional



# Manual DF - practical considerations

- Low-cost, no need for dedicated DF receiver or complex antennas
- Portable – can be done in almost any location (rooftops, in buildings, etc.) with minimal setup time.
- Effectiveness depends strongly on the skill level of the operator.
- Difficult when dealing with short duration or frequency-agile signals.
- Accuracy may be poor for objects more than several hundred meters away.
- Important to have an antenna with both sufficient directivity and acceptable bandwidth.

# Doppler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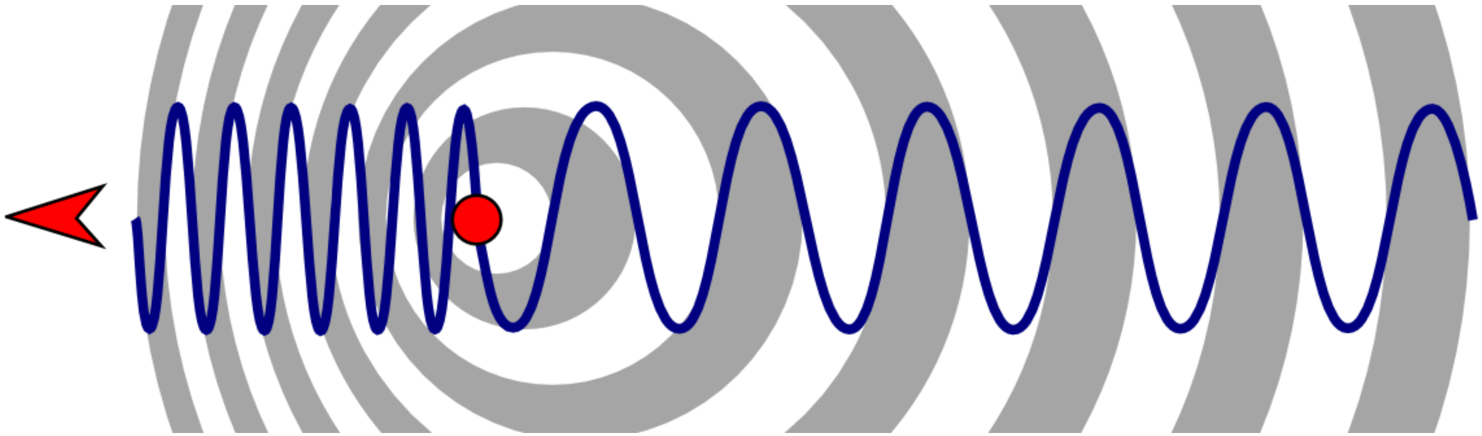
# A Doppler Shift refresher

***Christian Doppler (1803-1853)***

- The Doppler effect is named after Christian Doppler, who described it in 1842.
- Doppler shift is a type of frequency modulation.
- Relative motion of objects towards each other causes the observed frequency to increase. Relative motion away from each other causes a decrease in frequency.
- Doppler shift can be observed in the audio frequency domain (a passing train) and the visible energy domain (red shift of stars moving away from Earth).
- In the radio frequency domain it can be used for direction finding.

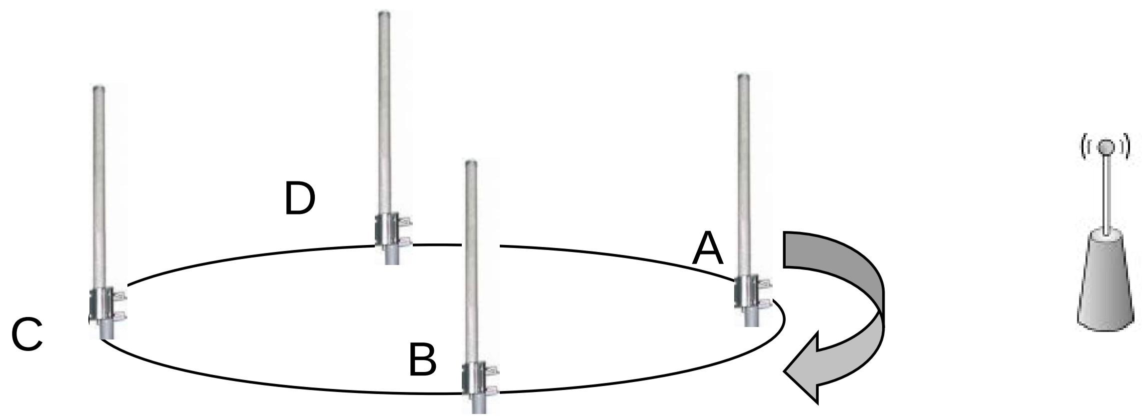
# Using Doppler shift for DF

- As we move closer to a signal, the received frequency will shift upwards (or vice-versa). This shift can be detected and used to determine if we are moving in the right direction.
- What we want is a method for moving the DF receiver relative to the transmitter so that we can measure the Doppler shift.
- But how do we do this if the DF receiver is not in motion?



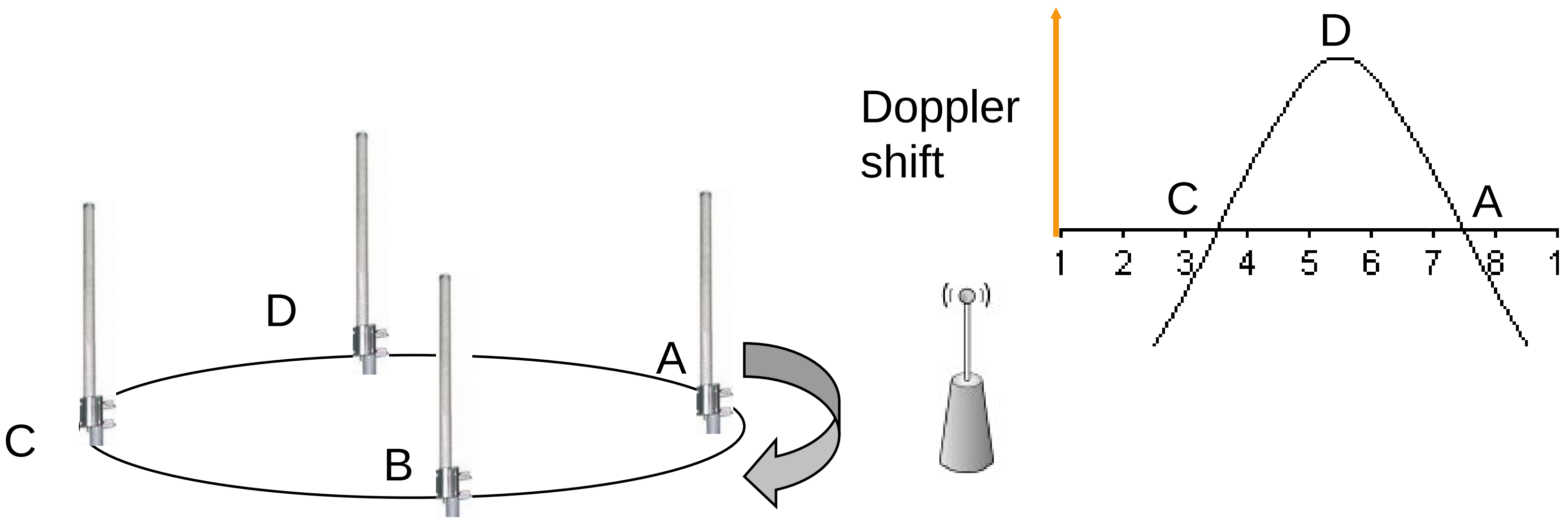
# Simple rotating antenna

- Imagine we have a single antenna mounted on a rotating disk.
- As this disk is rotated, the antenna will move closer to and then further away from the transmitter.
- At positions A and C, the antenna is stationary relative to the transmitter, so Doppler shift = 0
- At position B (moving away) and D (moving towards), Doppler shift will be maximum.
- Continuous measurements of Doppler shift will yield a so-called Doppler sine-wave



# Doppler sine wave

- By making frequency shift measurements as we go around the wheel (so to speak), we get a Doppler sine wave with two zero crossings at A and C, i.e. where there is no Doppler shift.
- The second zero crossing (downwards slope) is the point closest to the transmitter.
- This sine wave has the same frequency as the rotational frequency (ω) of the antenna.

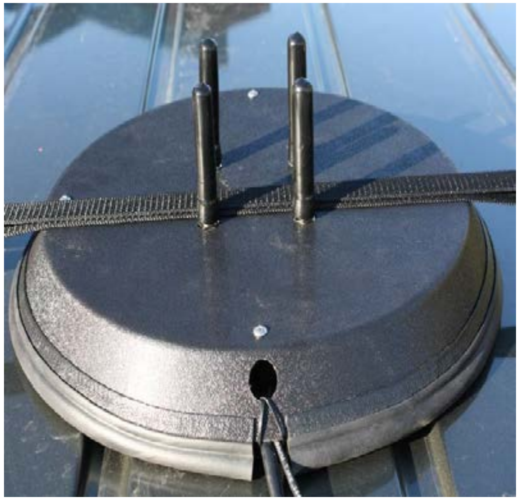


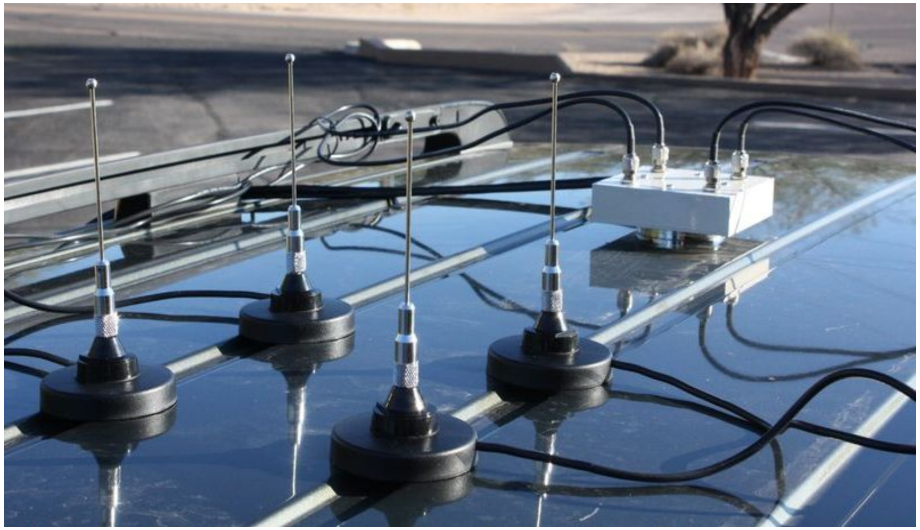
# Implementing the antenna

- An antenna on a rotating disk is not practical (required rotational speed is far too high).
- To simulate a rotating disk, Doppler DF switches sequentially between a set of (usually) 4 antennas
- Each antenna generates a series of Doppler pulses and the system uses them to synthesize the Doppler sine wave.
- To produce sufficient Doppler shift, the switching between the antennas must be very fast.

# Antenna element placement

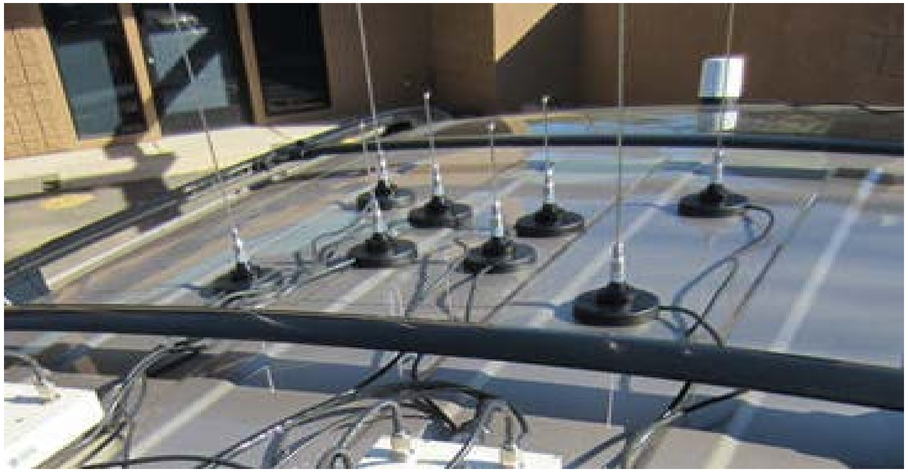
- The placement / spacing of antennas used in Doppler DF can influence bearing accuracy – ideal situation is single mounting vs. individual mounting.
- However, practical Doppler accuracy and bearing presentation is usually so low that minor antenna placement imperfections are not the limiting factor with regards to accuracy.





# Number of Doppler antenna elements

- Most Doppler antenna arrays contain four antennas.
- Implementations with larger numbers of antennas exist, but this only improves results if the diameter of the array is increased.
- Note that some Doppler systems have multiple sets of elements for different frequency ranges (4 for VHF, 4 for UHF, etc.)



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# Displaying the results

- A Doppler DF display usually consists of a circle of LED's which show the relative bearing to the signal source.  It may also output a numeric bearing.
- Can also be integrated with PC-based mapping systems

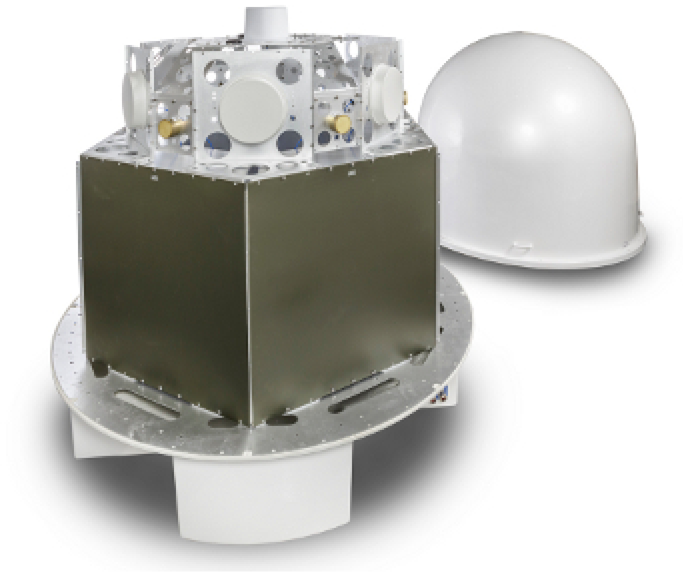

# Doppler example : Lojack

- After a vehicle is reported stolen, the Lojack network sends out a signal that activates the installed vehicle locator unit.  Ground and air based police units with installed (Doppler-based) Lojack systems can then track the VLU signal.
- Since type / appearance of stolen vehicle is known, homing mode and (relatively) low accuracy is sufficient for locating vehicles.

# Practical considerations in Doppler DF

- Low cost compared to other DF systems.
- May use either commercial, off-the-shelf receivers (hobbyist level) or specialized DF receivers (commercial systems).
- Require a constant (CW) type signal.  Not suitable for intermittent signals or broadband noise.
- Works while stationary or when moving.
- Antenna-based factors impact useful range:
  - Normally works best on VHF/UHF frequencies (< 1 GHz).
  - Doesn’t work well for horizontally polarized signals (Doppler antennas usually vertically polarized)

# Angle of Arrival



# What (exactly) do we mean by “Angle of Arrival”?

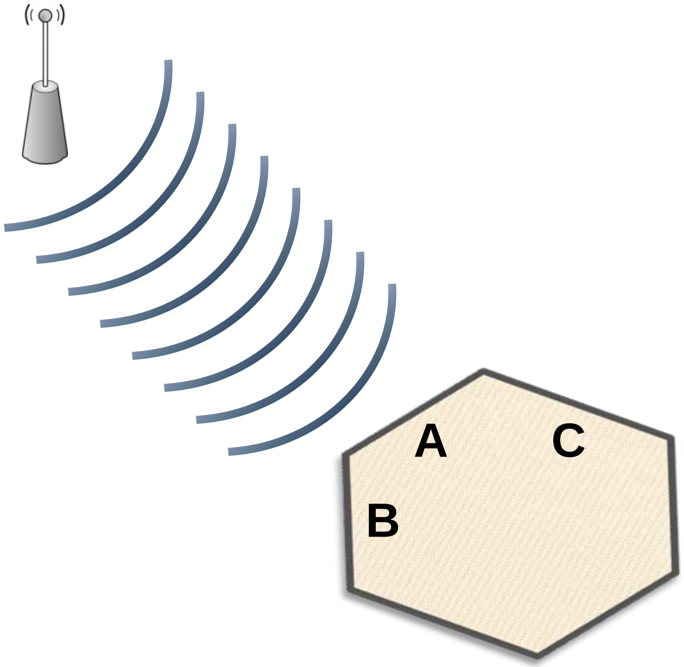
- The term “Angle of Arrival” means different things to different people.
- ALL true DF systems generate bearings, which are “angles of arrival”
- In the strictest sense, AOA simply measures the **angle(s)** at which a signal **arrives** at an antenna array : not the phase or time differences of the signal at different elements.
- To determine if a signal is “arriving” at an antenna, we make a determination of the power of the incoming signal at one or more antennas, so AOA is sometimes also called “power of arrival” (POA).

# Potential sources of confusion regarding AOA

- Confusion results because:
  - **All** true DF systems generate bearings ("angles") towards targets
  - AOA shares some characteristics with other DF methodologies
  - Some DF products use a combination of AOA and other methodologies
- Note that a heatmap-based "DF" system is NOT using AOA
- We will discuss AOA in the strictest sense : an DF methodology that determines a bearing based on relative power (**only**) at different elements.

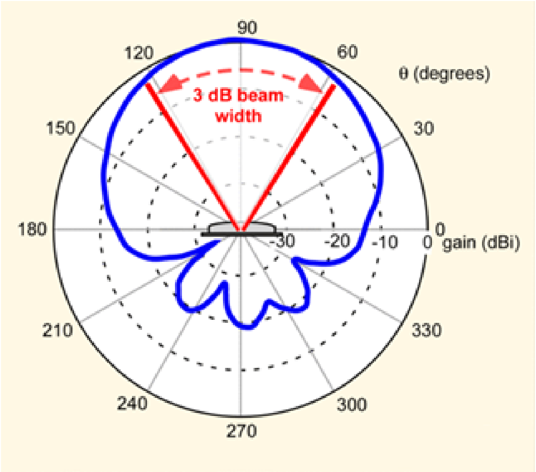
# Simple example of AOA (narrow sense)

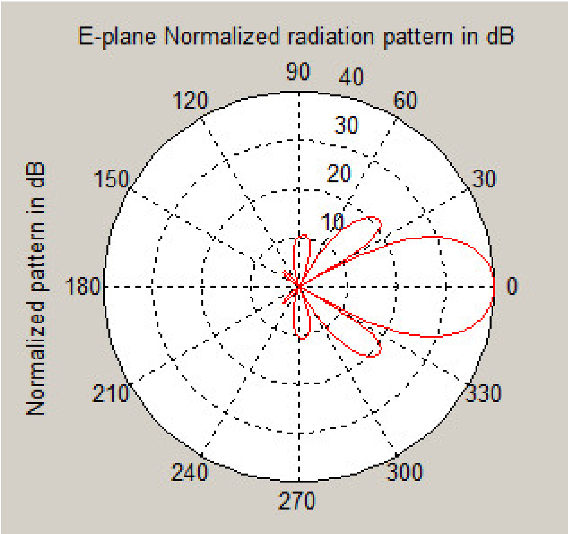
- Consider an array of six antennas with approximately uniform frequency response across each face.
- Power received at antenna A > B > C.
- No power received on other faces.
- The power (and only the power) received at the target frequencies is measured at each antenna.  This is used are used to produce a bearing.
- Again, no measurement of phase / time difference – bearing obtained purely based on received power.



# AOA antennas

- AOA antennas are typically circular array of (somewhat) directional antennas.
- Antenna patterns assumed to be wide and flat – panel-type antenna patterns.
- Number of antennas can vary – typically between four and 8.
- Resolution / bearing accuracy is increased with an increasing number of antenna faces.
- Conversely, a single directional antenna (e.g. a horn) can be used and rotated. This is similar to manual DF with a handheld antenna.  In this case, narrow beamwidth is desirable

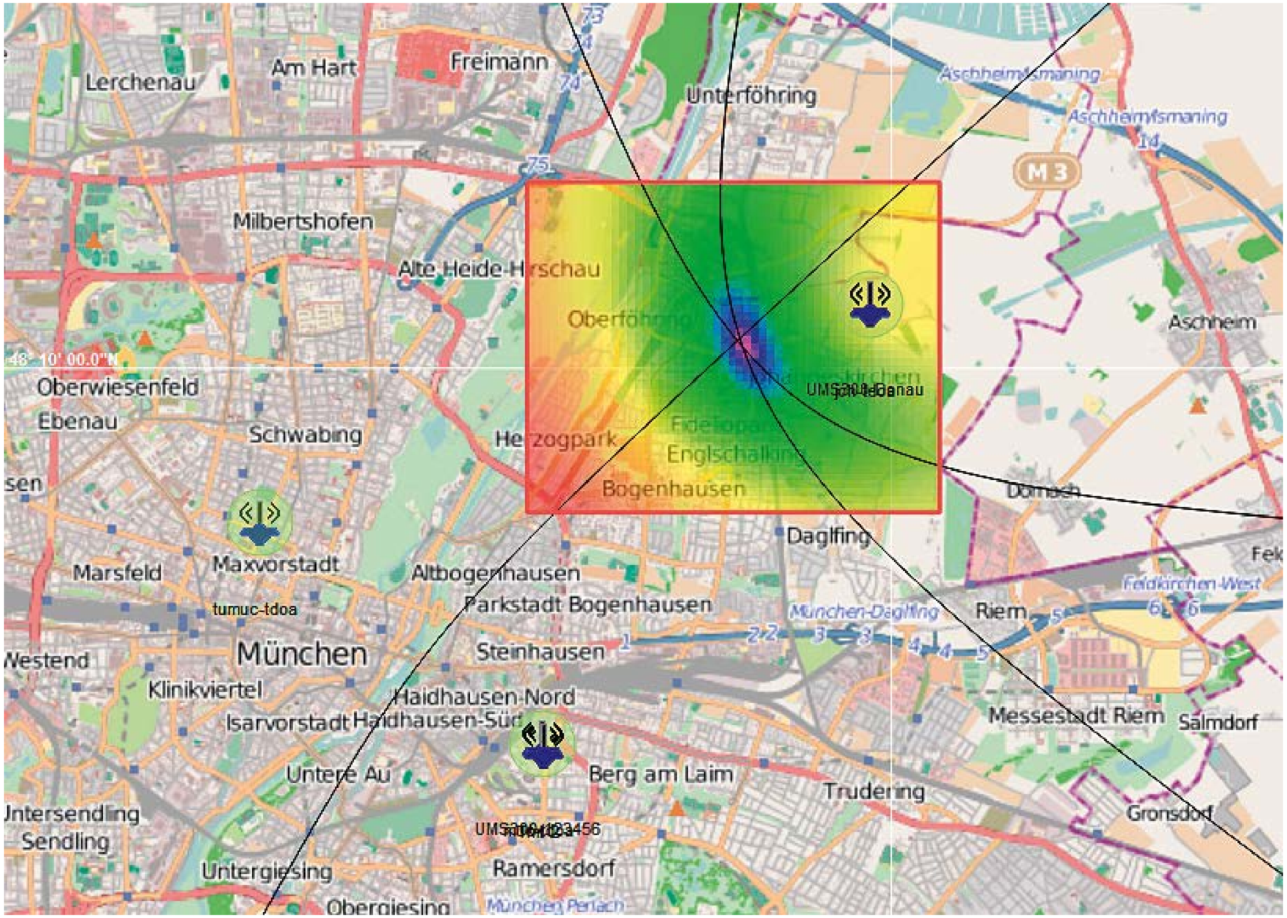


# Practical considerations regarding AOA

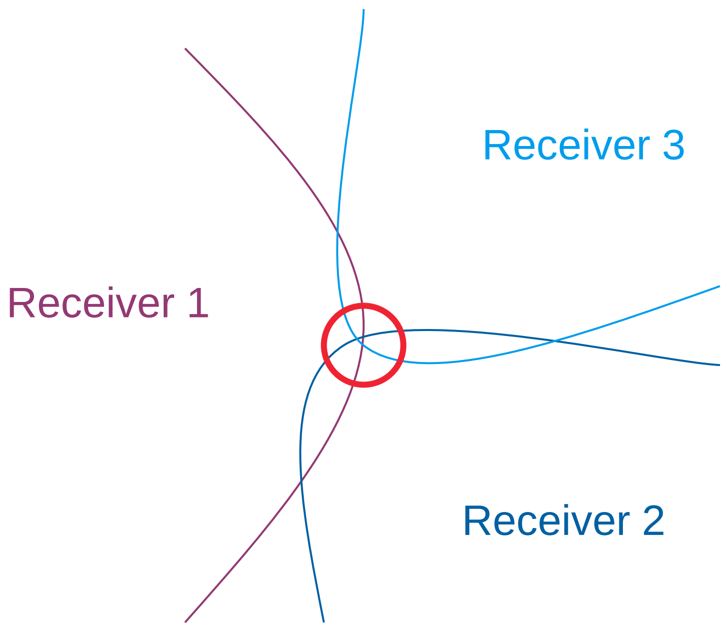
- AOA is a very straightforward DF methodology – no requirement for time / phase alignment, frequency comparison, etc. Receivers very simple. Calculation of bearing not complex or time/processor intensive.
- Accuracy increases with number of antennas for multi-element antennas. For rotating antennas, narrow beamwidth and slow rotation time increase accuracy.
- Works on all types of signals, but highly susceptible to multipath – clear line of sight often required for satisfactory results.

# TDOA (Time Difference of Arrival)



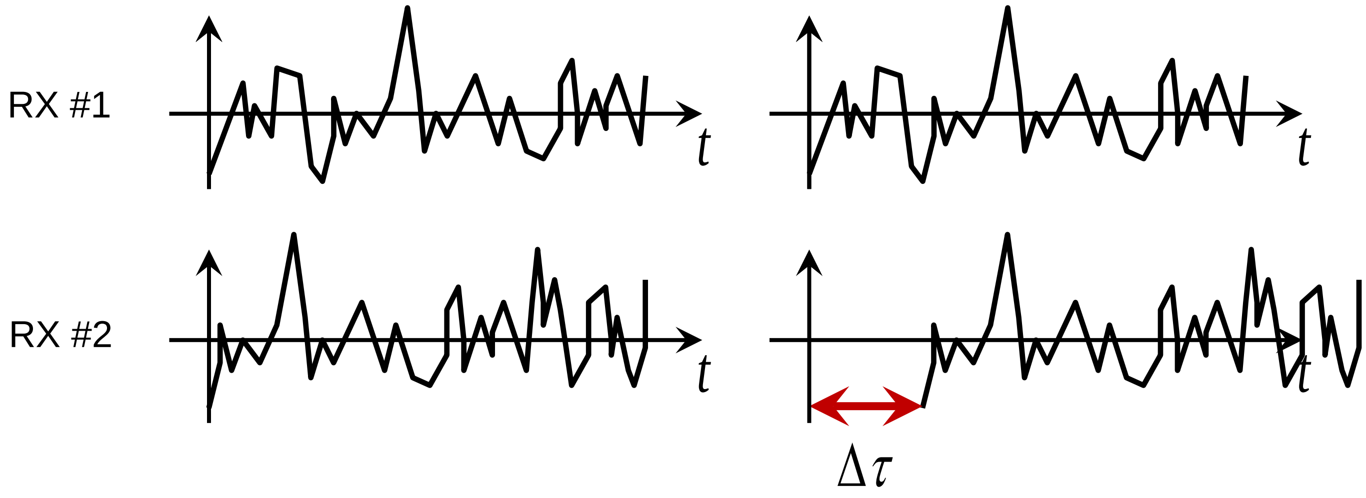
# Time Difference of Arrival (TDOA)

- Three or more receivers at different locations receive a signal from the target.
- Usually the paths between the transmitter and the receivers are of different length, so there are **differences** in the time of **time of arrival** at the different receiver locations.
- The time differences can be represented as hyperbolae which cross at the location of the transmitter of interest.
- Sometimes also referred to as “hyperbolic” direction finding because the location is the intersection of several hyperbolae.



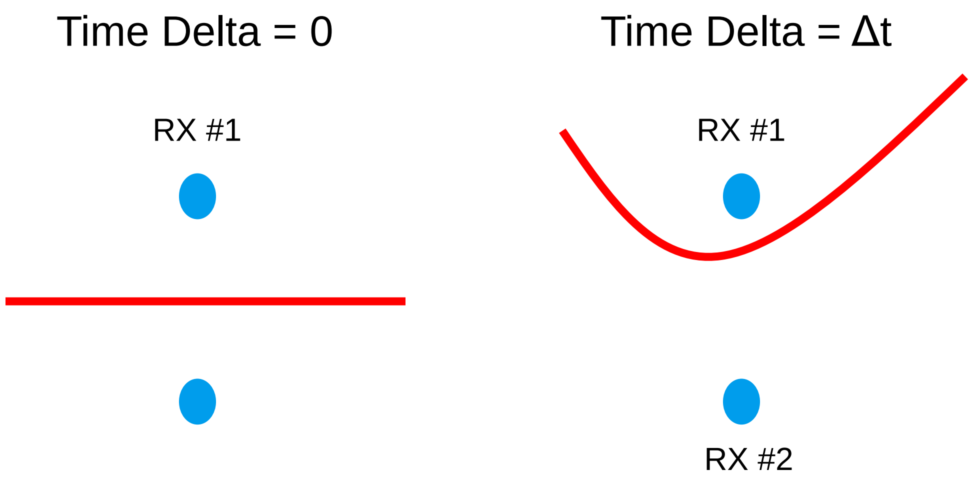
# Implementation of TDOA

- Time-stamped digitized IF (IQ data) from all receive stations is transferred over data links to a master station (computer/processor).
- Once the master station receives IF data from all receive stations a cross-correlation function for all stations is calculated.
- This calculation yields the time difference, which is then used to generate the hyperbolae.

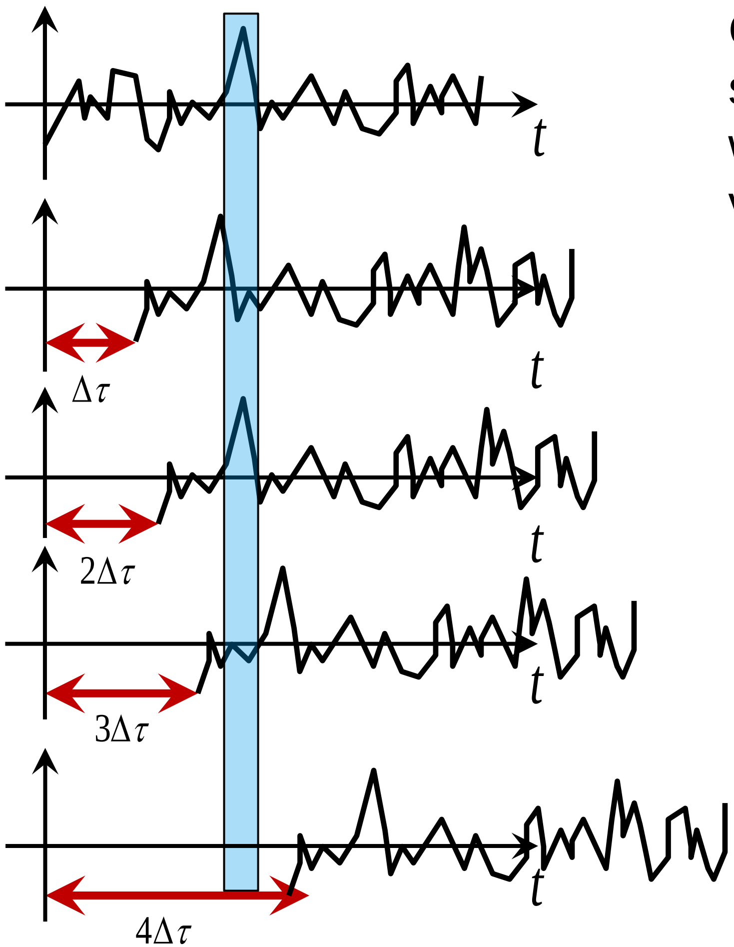


# Time differences / hyperbolae

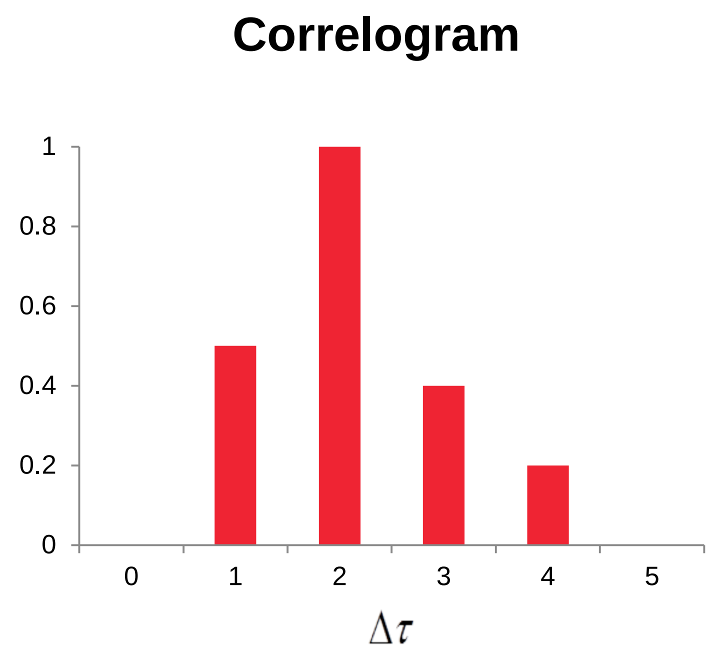
- Once we have computed the time difference, Δt, between the times the signal was received at two stations, we can then compute / plot a hyperbola representing this distance between them.
- The intersection of multiple hyperbolae yields the estimated target location.
- The term “iso-chrone” is sometimes used instead of “hyperbola”



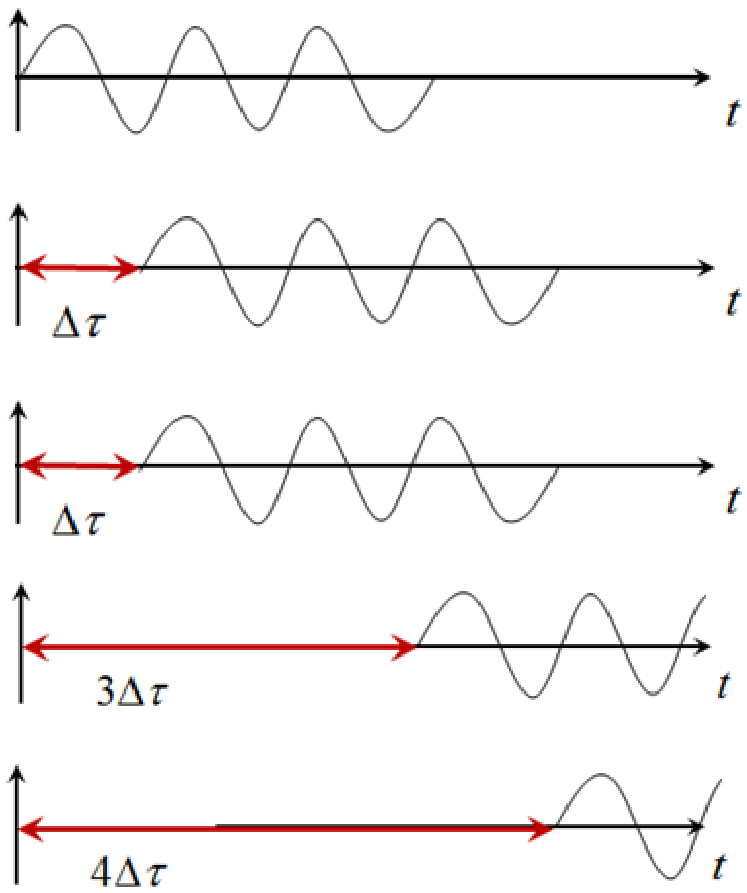
# TDOA correlogram



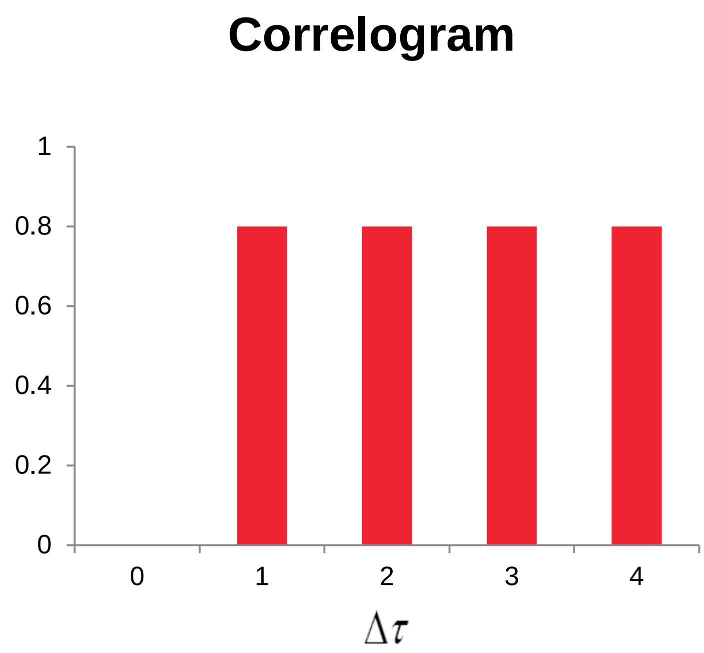

Computing correlation for non-periodic signals can be done using a correlogram, which should yield a clear peak at some value of Δt.



# TDOA correlogram for CW-type signals



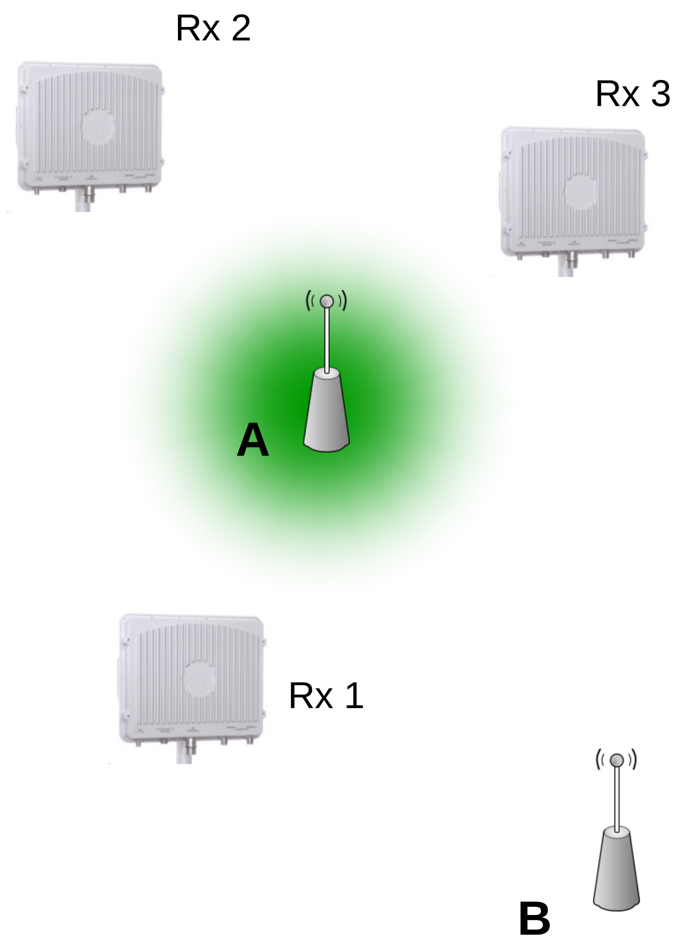

Computing correlation for narrowband signals (here, an unmodulated CW carrier) is more difficult, since the correlogram may not have a clear peak.



# TDOA sensors

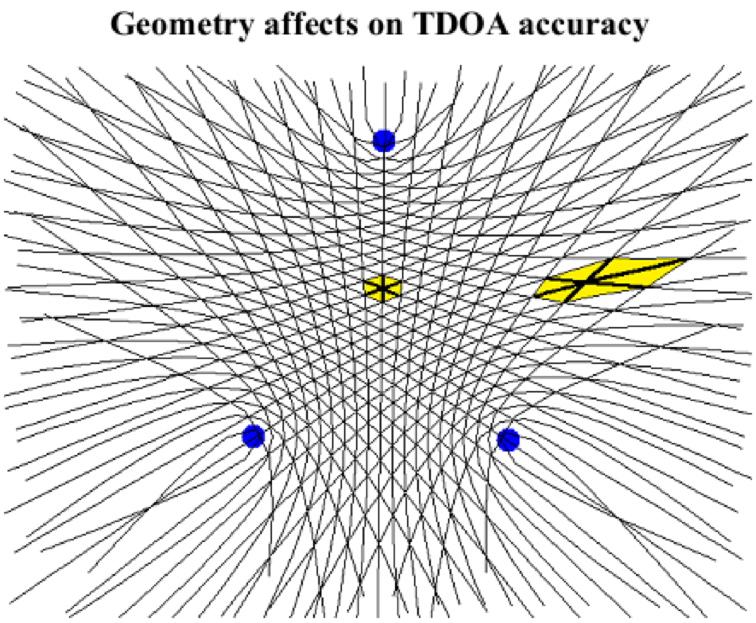
- Sensors can be used in a fixed (more common) or movable configuration.
- TDOA sensors are normally purpose-built devices : cannot normally be used as stand-alone receivers without the control computer.
- Sensors require network, power and GPS connections.  Typically weatherized.
- Good accuracy over a larger area requires large number of TDOA sensors.  Therefore, TDOA sensors tend to be inexpensive, which means lower RF performance.

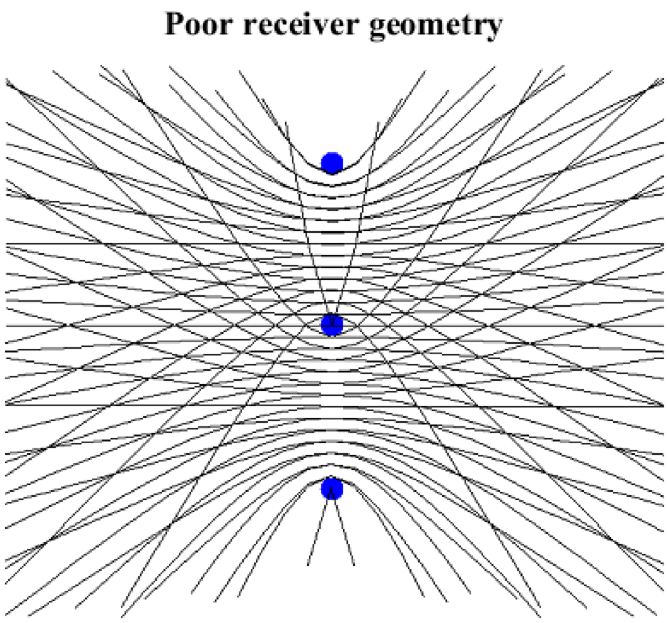
# Location coverage and accuracy




- In practice good TDOA results typically are accurate to within several hundred meters.
- Outside the area surrounded by the TDOA receive stations the location accuracy can be poor.
- In the diagram to the left, transmitter A is within the covered area of sensors Rx 1-3, whereas transmitter B is not within the covered area.
- Some pre-knowledge of the transmitter location is therefore essential when positioning TDOA sensors.

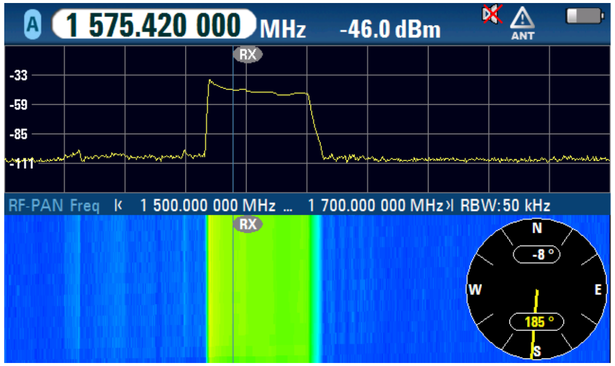
# Sensor geometry and TDOA accuracy




Source: ITU Spectrum Monitoring Handbook 2012

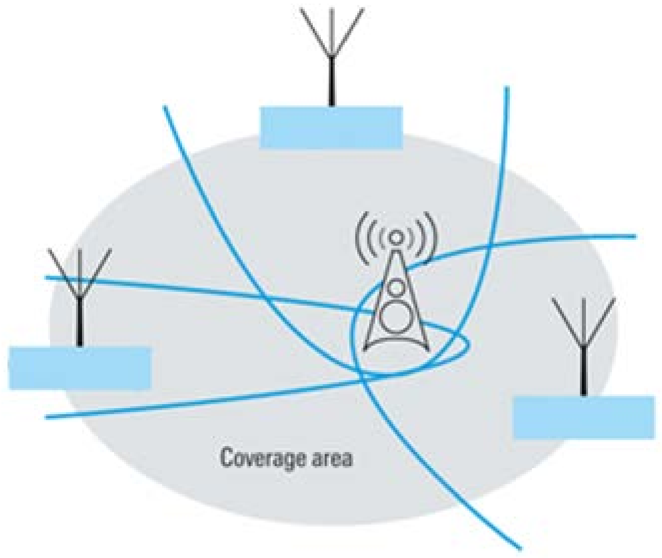
# Importance of GPS / GNSS in TDOA




- TDOA requires both precise location information and precise timing information.
- In modern TDOA systems, GPS (or, generically, a GNSS) provides both location and time information
- GNSS timing accuracy is important for getting accurate results. Location accuracy is less important, especially for fixed, pre-surveyed sites.
- Note that TDOA-based direction finding systems are vulnerable to denial of service attacks based on GNSS jamming. Very hard to use TDOA to find GNSS jammers.

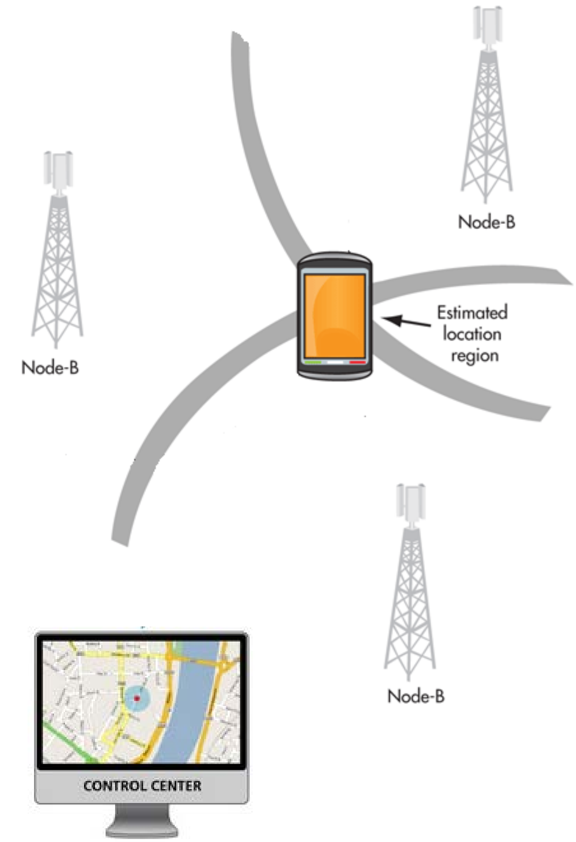
# TDOA practical considerations

- Unobtrusive RF sensors - usually easy installation on roof tops or wall panels.
- Robust location results (only) within receiver geometry. Better results for wideband than narrowband signals.
- Accuracy increases with number of receivers, but at some point (usually > 6 receivers), there is no improvement (but calculation time increases dramatically).
- Reception of weak signals possible if sensors nearby (proximity gain).
- TDOA algorithms allow to process out some multipath effects.



# Practical Example : locating cell phones with TDOA

- Numerous requirements for radiolocation of cellular phones / mobiles.
- Mobiles are usually within the coverage range of numerous base stations simultaneously.
- Uplink signals are measured and information is processed in central location.
- Difficulties with this approach include the need for base stations to be time-synchronized as multipath and other propagation issues (indoor mobiles).
- In many cases, radiolocation of mobiles is performed using (pseudo-) cooperative techniques using the mobile's integrated GPS receiver.



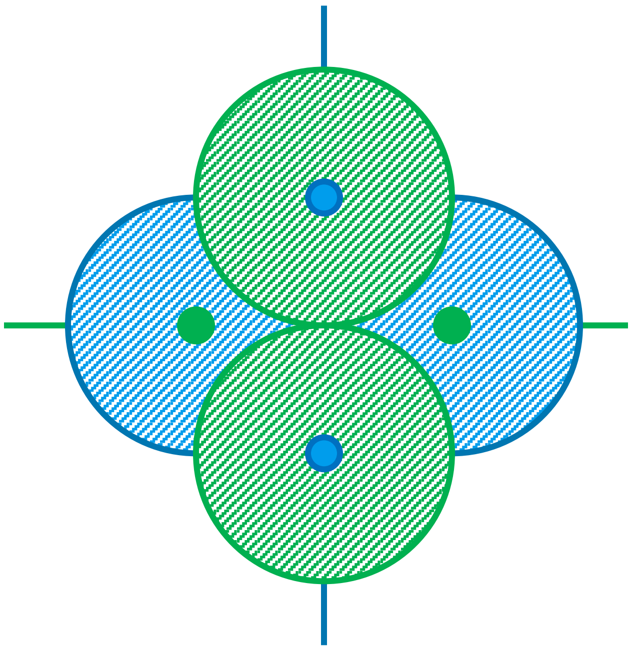
# Watson-Watt

# Overview of Watson-Watt

- Originally developed shortly after World War I and named after Sir Robert Alexander Watson-Watt, one of the inventors of radar.
- Watson-Watt is an amplitude comparison DF system.  It uses Adcock (or crossed loop) antennas to compare the level of the signal received at each antenna.  It then computes bearing based on the differences between them.
- Note that **Watson-Watt** is the name of the method used to process information obtained from an **Adcock** antenna.

# Adcock antenna basics

- An Adcock antenna has four equally-spaced vertical elements. These four antennas are arranged in pairs : a North-South axis and the East-West axis
- The results is two figure-eight shaped lobes, with maximum sensitivity along the axis and nulls perpendicular to the axis
- This creates a unique set of magnitudes for every direction due to the antenna pattern.
- An omnidirectional sense antenna is used to resolve 180º ambiguities

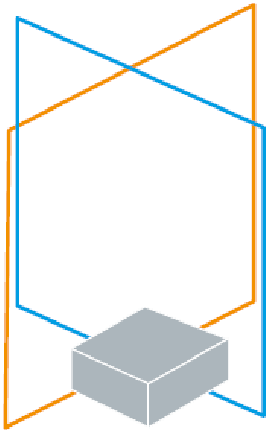


# About Adcock antennas

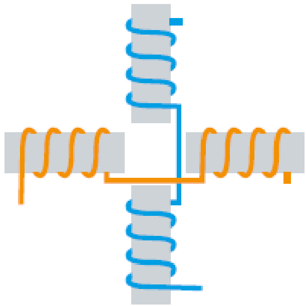
- Adcock antennas are typically be monopoles (where a ground plane is present, e.g. a vehicle roof) or dipoles (for pole/tower mounted applications).
- They can also be implemented as a crossed loop.
- Spacing between aerials is a compromise between accuracy (closer together is better) and sensitivity (farther apart is better).
- In some cases, additional Adcock pairs can be used to lessen the effect of these constraints.

# Implementing Adcock antennas

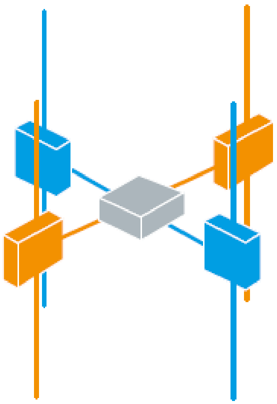
- Depending on size and frequency requirements, the Adcock pairs may be implemented in a variety of ways.



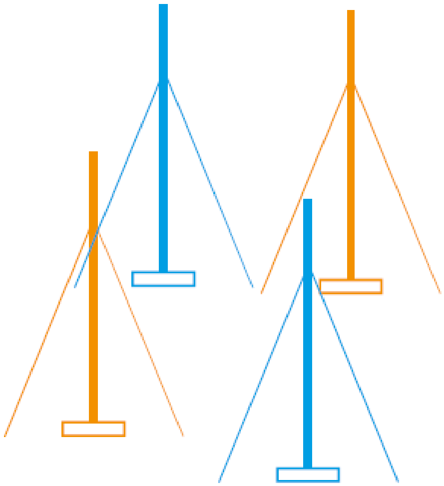
*Crossed loops*



*Crossed ferrite loops*



*Crossed dipole elements*



*Crossed monopole elements*

# Adcock antenna examples

*Crossed loops*

*Crossed monopole*

*Crossed dipole*

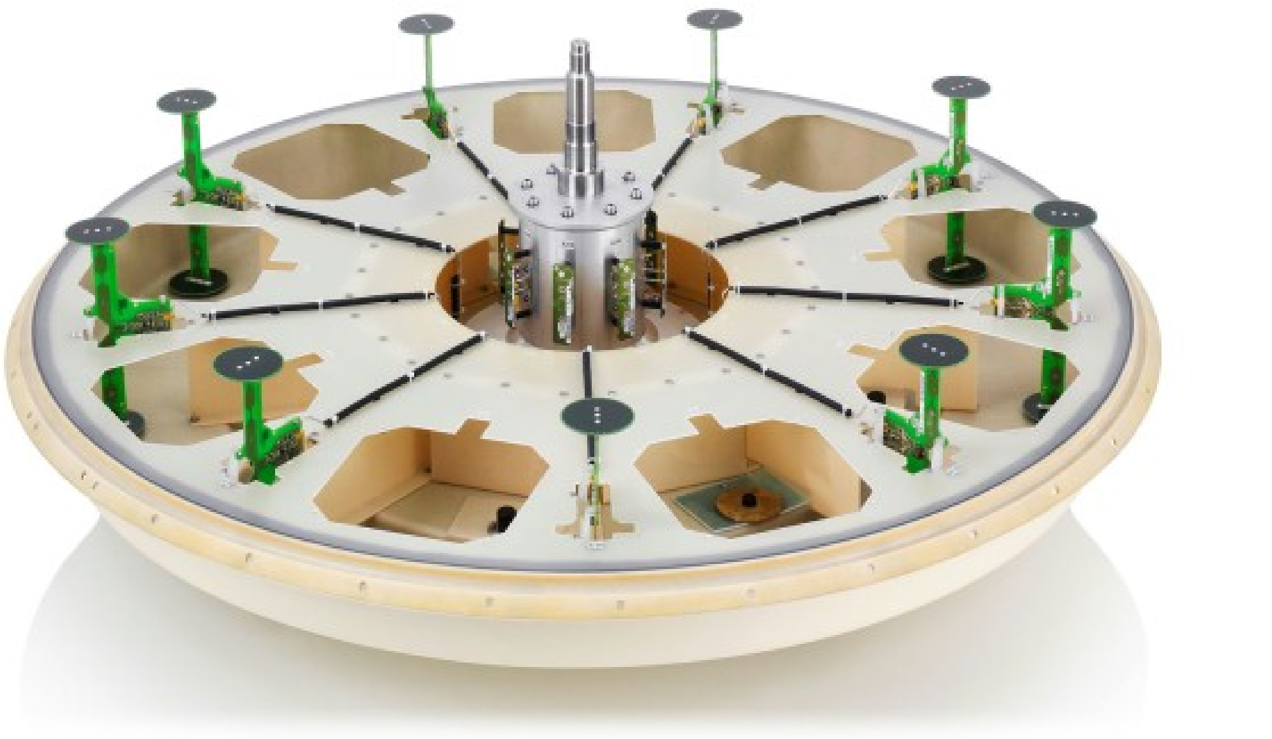
# Practical considerations for Watson-Watt DF

- Watson-Watt is the method of choice for HF direction finding due to ease of implementing small antennas at these frequencies.
- Accuracy depends on the circularity of the antenna pattern.
- Fast response time – minimal "calculations" required to obtain bearings
- Accuracy and sensitivity are usually both very good.
- No measurement of elevation possible, and decreasing azimuth accuracy as transmitter elevation increases.

# Watson-Watt practical example – Rescue 21

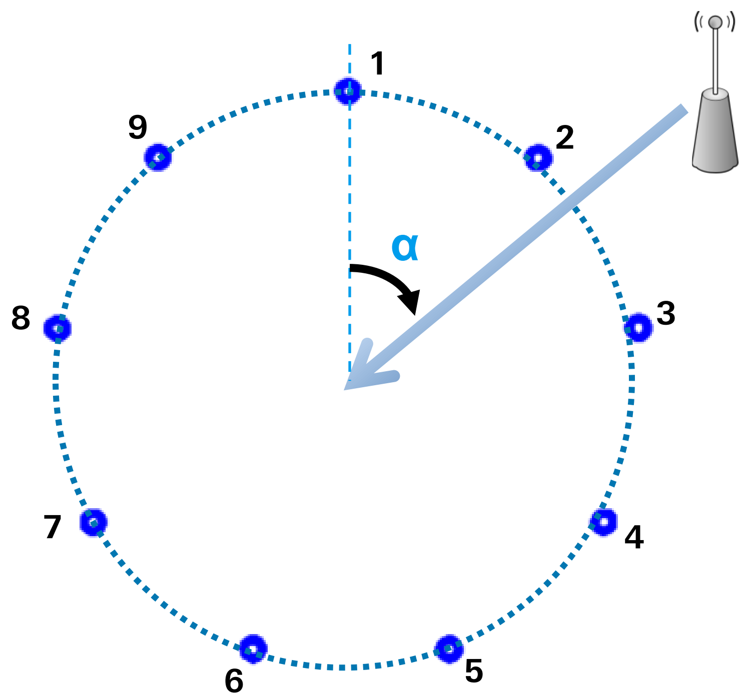
- The US Coast Guard system Rescue 21 system uses over 225 Watson-Watt based DF sites to radiolocate stations across over 40,000 miles of coastline.
- Watson-Watt ideal for the common maritime HF / VHF frequencies.


# Correlative Interferometry



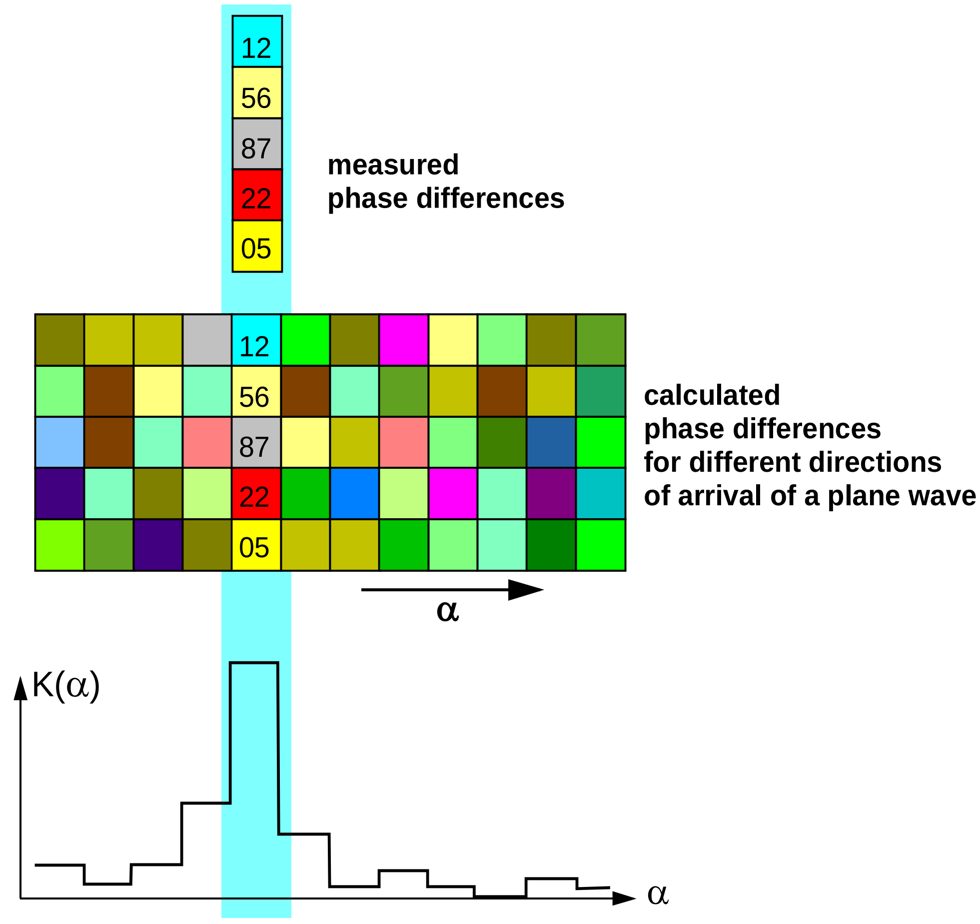
# Correlative Interferometry

- First used in radio astronomy.
- Interferometers calculate bearings based on phase differences of the signal received at multiple co-located antenna elements.
- These antennas are normally arranged in a circular pattern with one antenna element serving as a reference channel.
- For each antenna element the phase difference relative to a reference element is calculated. This is typically done for each reference angle (0º to 360º) in increments of 1º.



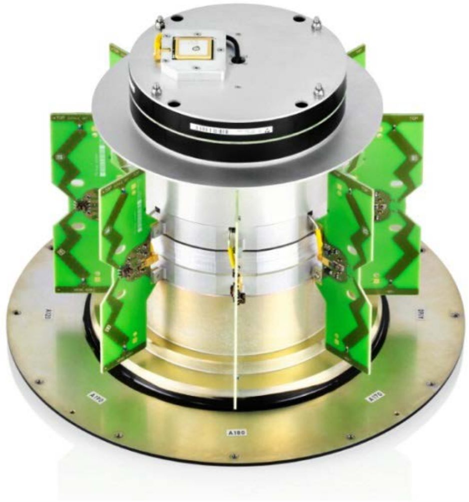
# Measuring and calculating correlation

- In correlative interferometry we compare the *measured* phase differences with *reference* phase differences for the DF antenna at each wave angle.
- We move our column of measured phase angles through our matrix of reference phase angles and look for the value at which maximum correlation occurs.
- This value corresponds to the angle (α) of the incoming signal.



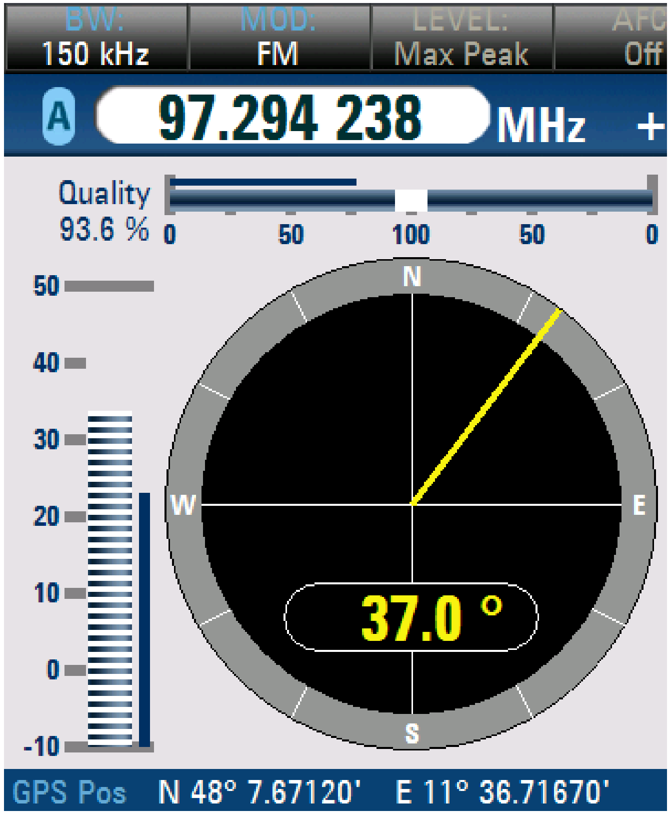
# Implementation of CI antennas

- Typical CI antennas have 5-9 elements enclosed in a radome.
- Circular arrays can cover very large frequency ranges (> 1 GHz). In addition, the larger the diameter of the CI antenna, the better immunity to reflections / multipath.
- Accuracy independent of azimuth due to circular array
- Design and manufacturing tolerances are very tight.



# Advantages of correlative interferometry

- Very high accuracy : less than 1º is typical.
- Provides both a bearing and a **quality** (strength of correlation) value for the bearing.
- Higher immunity to reflections and multipath compared to other DF techniques.
- Measurement of elevation is also possible.
- Cross-polarization does not decrease accuracy, only sensitivity.



# Advanced topics in direction finding

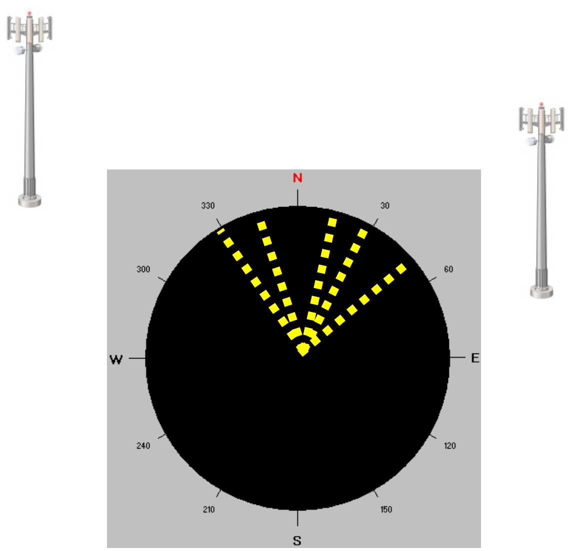
- Some additional advanced topics in modern direction finding include:
  - Location of co-channel sources / super-resolution
  - Computation enhancement of bearing results

# Location of co-channel sources

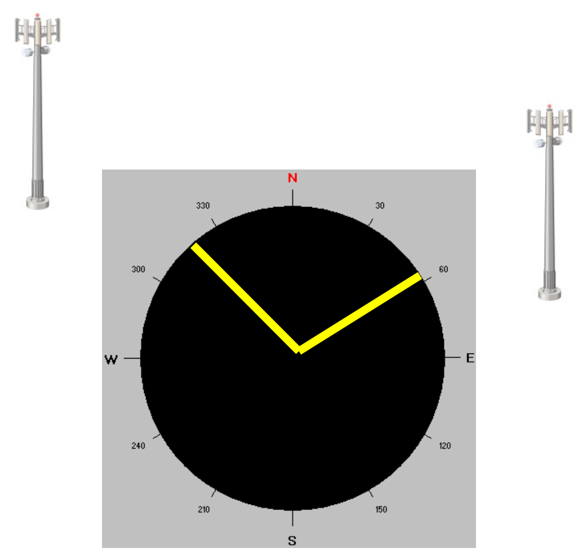
- Typically in direction finding we discuss methods to locate a single transmitter on a given frequency.
- In some situations, there may be multiple (co-channel) transmitters on the frequency of interest.  Examples:
  - Simplex communications channels
  - Broadcast transmitters / cell sites
  - Spurious emissions from common devices
  - Jammers / malicious interference
- This can present a serious issue for direction finding, especially when the co-channel transmitters have a non-constant duty cycle.

# What is super-resolution?

- Super-resolution is a DF methodology that uses various techniques to obtain separate lines of bearings towards co-channel sources.
- Two main methods : likelihood modeling and principle component analysis.



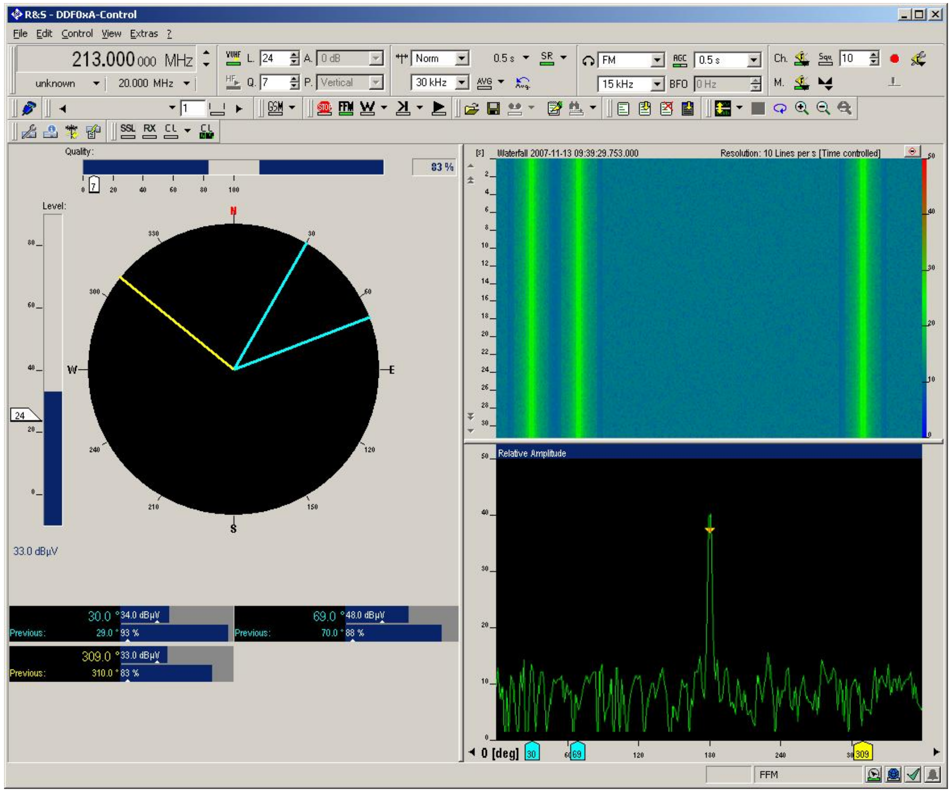

Normal direction finding




Super-resolution

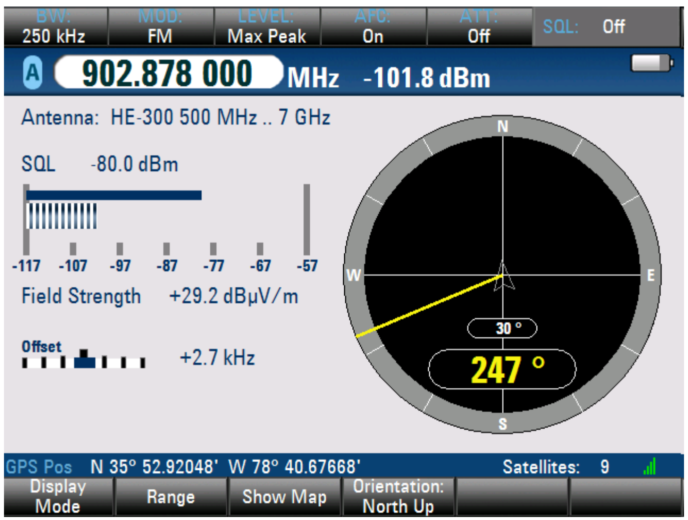
# Super-resolution results

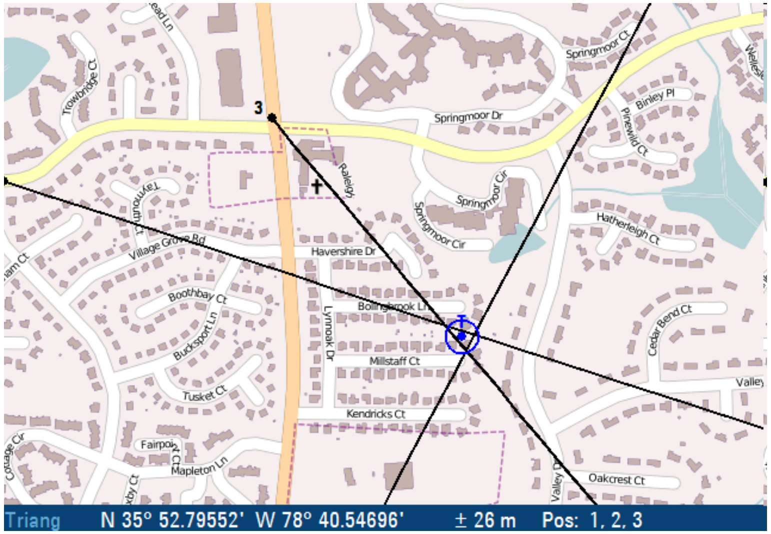
- Super-resolution systems can normally autodetect the number of co-channel signals.
- A DF result with additional information (level, quality) is calculated and displayed for each co-channel signal



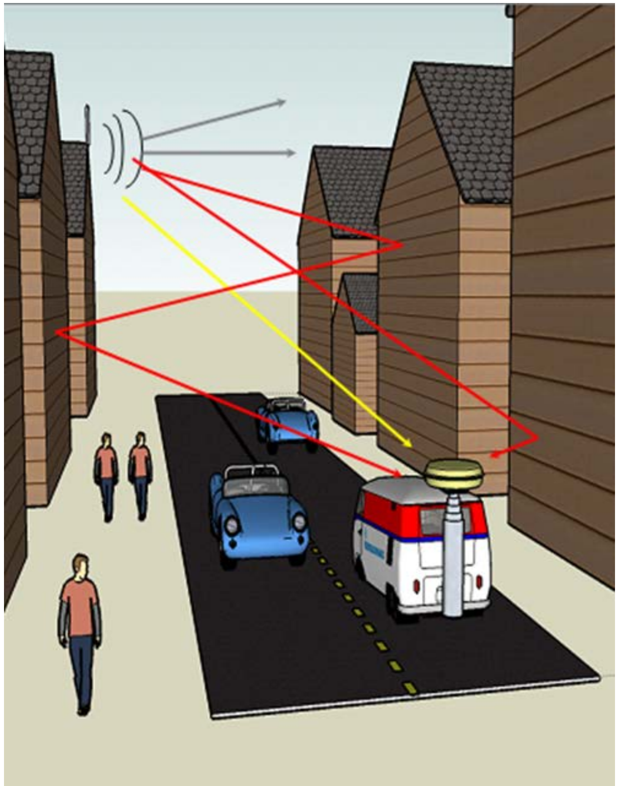
# Computational bearing enhancements

- The “raw” output of a most radiolocation systems consists of bearings. These bearings are usually combined to produce an estimated target location.
- The algorithms used to combine these bearings have traditionally been relatively unsophisticated (triangulation) and are based on processing relatively low numbers of bearings.



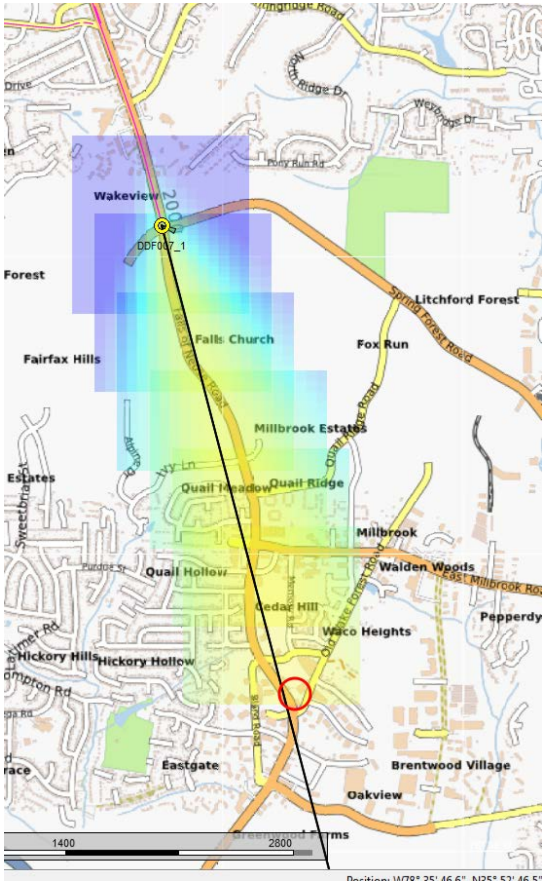
# Overcoming multipath



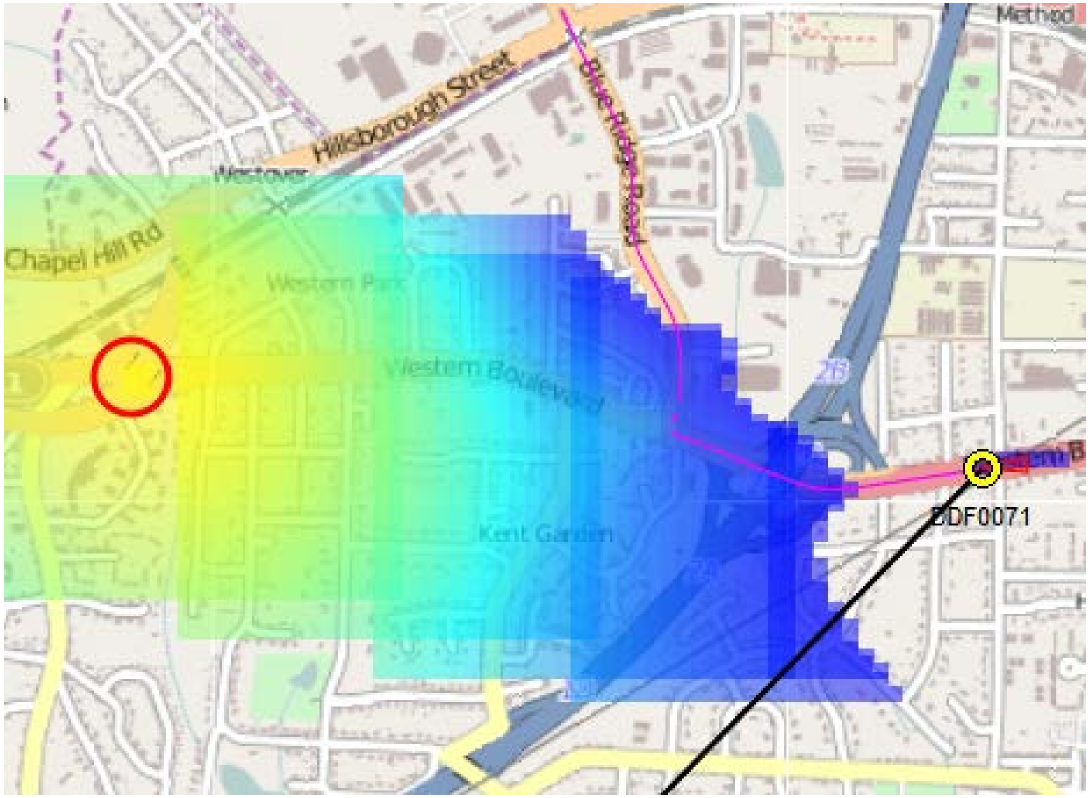
- Targets (i.e. transmitters) are found more frequently in areas of higher multipath (e.g. cities) than in areas of lower multipath (e.g. fields, deserts, oceans). This makes multipath the primary issue affecting bearing accuracy in many scenarios.
- One of the best ways to overcome multipath is to take many bearings from many unique locations : "many" being on the order of hundreds to tens of thousands. This creates two challenges:
  - Motion : we want to avoid taking the same bearing more than once
  - Computation : triangulation does not benefit from extremely large number of bearings.

# Mobile locator

- An example of a computational enhancement system uses a combination of a small, vehicle-mounted interferometry-based antenna and a specialized receiver / software to process several hundred bearings per minute.
- Bearings are only taken while system is in motion to maximize the number of unique bearings obtained.
- Complex (and proprietary) algorithms are used to generate a running calculation of probable target location, represented as probability “clouds”.
- After sufficient bearing information is obtained and processed, a specific target location is plotted (circle). Additional bearing information is used to continue to refine the location estimate.



# Video demonstration



# Discussion / Q&A