

WHITE PAPER

ADVANCED GEOLOCATION CAPABILITIES



In this paper, we are going to look at how standard AOA (Angle of Arrival), TDoA (Time Difference on Arrival) and PoA (Power on Arrival) geolocation techniques can be improved upon by using advanced signal processing techniques as implemented by RFeye® software and hardware.





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1. Advanced Geolocation Capabilities

In this paper, we are going to look at how standard AOA (Angle of Arrival), TDOA (Time Difference on Arrival) and POA (Power on Arrival) geolocation techniques can be improved upon by using advanced signal processing techniques as implemented by RFeye® software and hardware. We will start by reviewing each of these three methods of geolocation in their standard form before seeing how RFeye functionalities such as combining geolocation techniques in Multi Geolocation, Cumulative AOA and Multitarget Tracking can improve the ease and accuracy of locating signal sources. We will then see how the ability to geolocate on recorded spectrum data as well as real-time data, offers a more flexible geolocation solution.



2. AoA

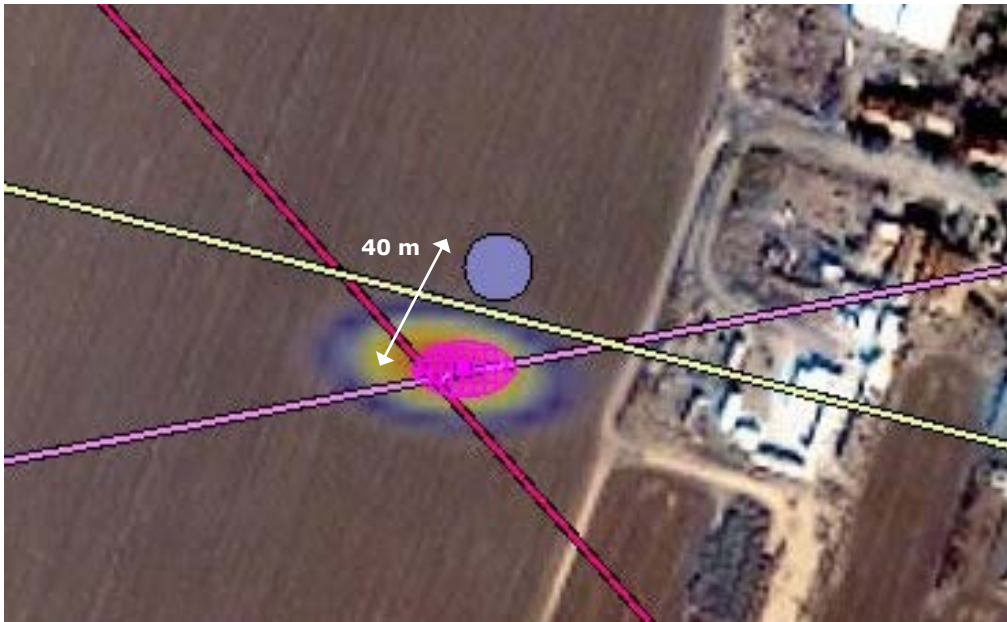
AoA uses the amplitude variation across an antenna array to calculate location from the intersection of LOBs (Lines of Bearing); it is therefore possible to geolocate using AoA with just two arrays. AoA works well for most signal types and distances and does not require antennas to be synchronized but is difficult to use in a multipath environment. Determining location using AoA may also not be possible if all receivers and the target transmitter lie on a straight line. (Silvus Technologies) (Sector), 2014)

Figure 1 shows a setup of receivers in an approximate 2 km by 3 km area with a 1 GHz 40 dBm CW (Continuous Wave) transmitter located outside of the receiver network boundary, while Figures 2 to 4 show the resulting geolocation using AoA, TDOA and POA respectively. We can see that AoA performs much better for this application based on the positioning and size of the pink 50% confidence ellipse. Note that TDOA does not work on CW signals.



<< Figure 1:
Receiver network
setup with CW
transmitter located
outside of area
surrounded by
receivers.

$w = \approx 3 \text{ km}$
 $h = \approx 2 \text{ km}$



<< Figure 2:
AOA performance
for distant CW Tx,
only 40 m error –
good for this range



<< Figure 3:
TDOA performance
for distant CW
Tx, unable to
geolocate



<< Figure 4:
POA performance
for distant CW Tx, large
geolocation error with
unstable reading

3. TDoA

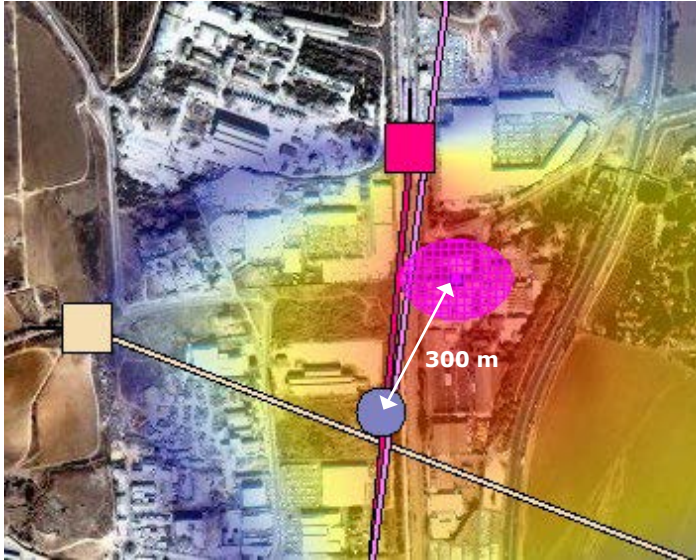
Standard TDOA, based on maximization of the correlation between signals at two different receivers, requires at least 3 receivers to locate a signal and requires these receivers to be well-synchronized, using GPS for example. TDOA works better for wideband and long pulsed signals for which the correlation function will have a narrower peak. TDOA works well over wide areas, is good for resolving multipath effects and can even locate signals below the noise floor. (Silvus Technologies) (Sector), 2014)

Figure 5 shows the network setup with a transmitter emitting a pulsed 1 GHz 40 dBm PSK signal. Two of the receivers are on a straight line with the transmitter making AOA more difficult. Figures 6 to 8 show that TDOA works best for this case, note that both the AOA and the POA geolocations were very unstable with the graphic jumping across (and off) the screen.

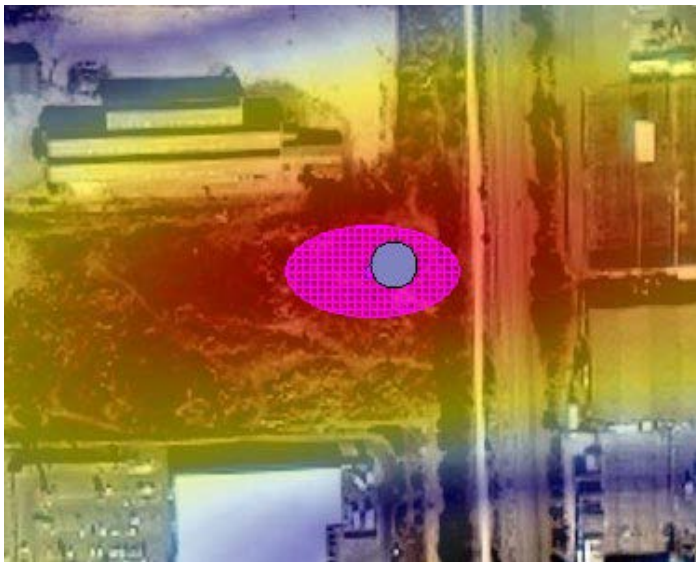


<< Figure 5:
Receiver setup
with pulsed PSK
transmission.

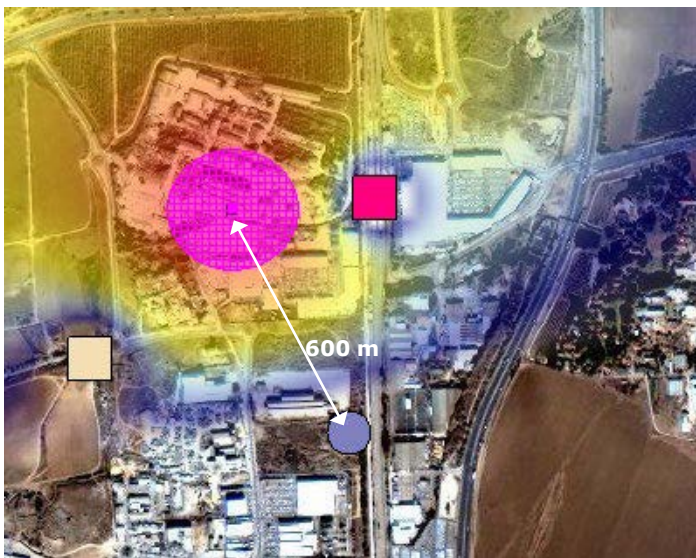
$w = \approx 1.5 \text{ km}$
 $h = \approx 1 \text{ km}$



<< Figure 6:
AOA performance
for pulsed PSK,
inaccurate and
unstable



<< Figure 7:
TDOA performance for
pulsed PSK, 110 m by
40 m area with 50%
confidence but centered
on true location



<< Figure 8:
POA performance for
pulsed PSK, inaccurate
and unstable

4. PoA

Similarly to TDOA, POA uses differential signals at three synchronized receivers to locate signals, but POA relies on differential received powers rather than differential arrival times. Owing to the $\frac{1}{r^2}$ relation between received power and distance r from the signal source, the differential power between receivers is relatively small over large distances making accurate geolocation unrealistic for POA, see Figure 9. POA over short distances, such as in-building applications, gives very high precision, however. POA can be used with all signal types. (Silvus Technologies)

<< **Figure 9:**
 $\frac{1}{r^2}$ distance
relationship for
received power

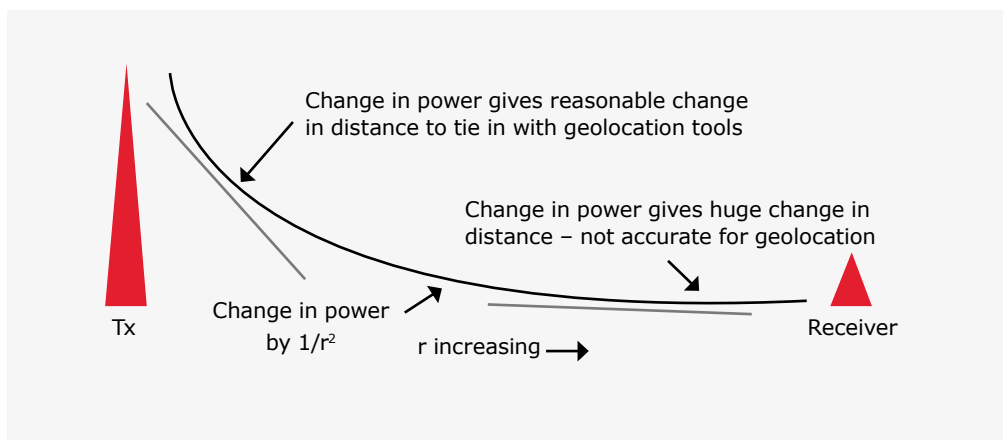
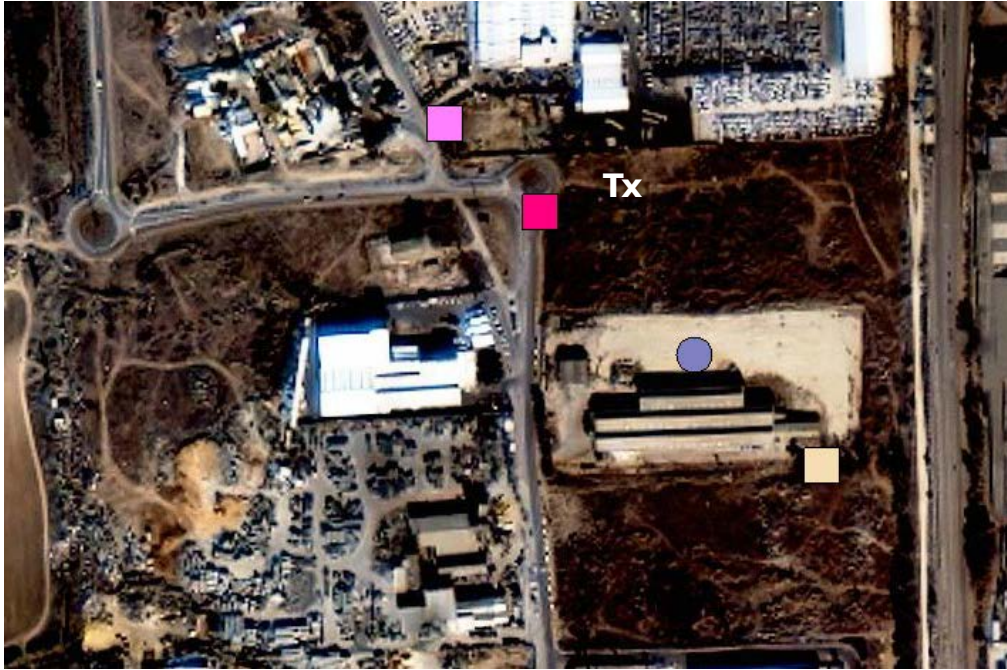
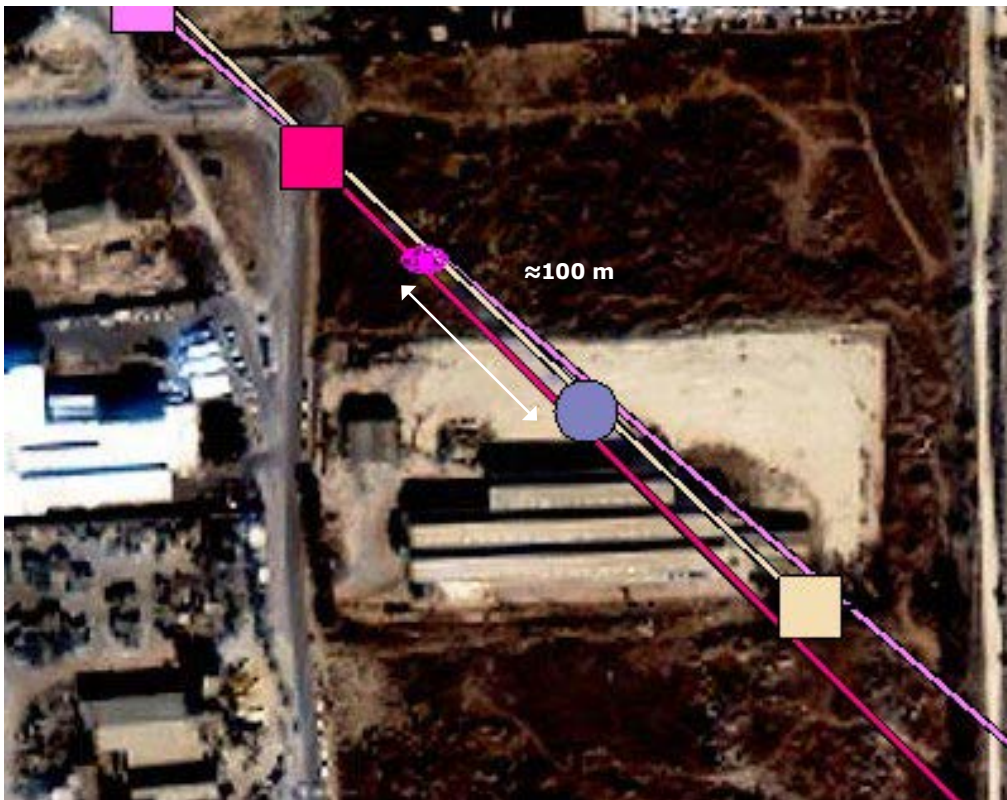


Figure 10 shows a setup which is conducive to good POA geolocation, we have a continuous wave at short range with the three receivers lying on close to a straight line with the transmitter such that AOA is highly inaccurate. As we can see in Figures 11 to 13, POA is clearly the best choice in this case.

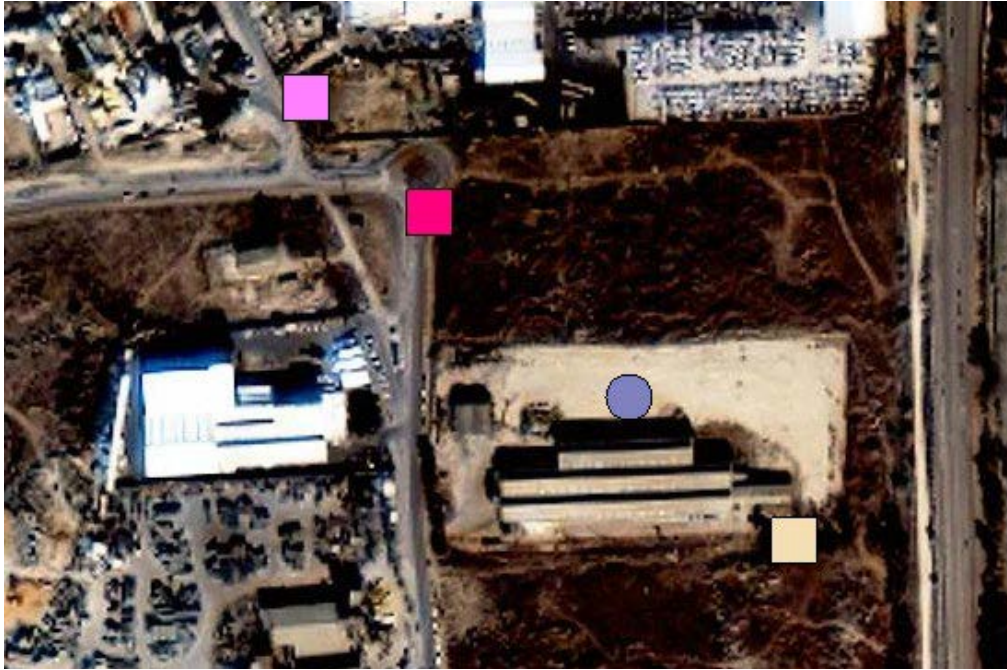


<< Figure 10:
Receiver setup for
CW at close range,
all Rx and TX lie on
a straight line.

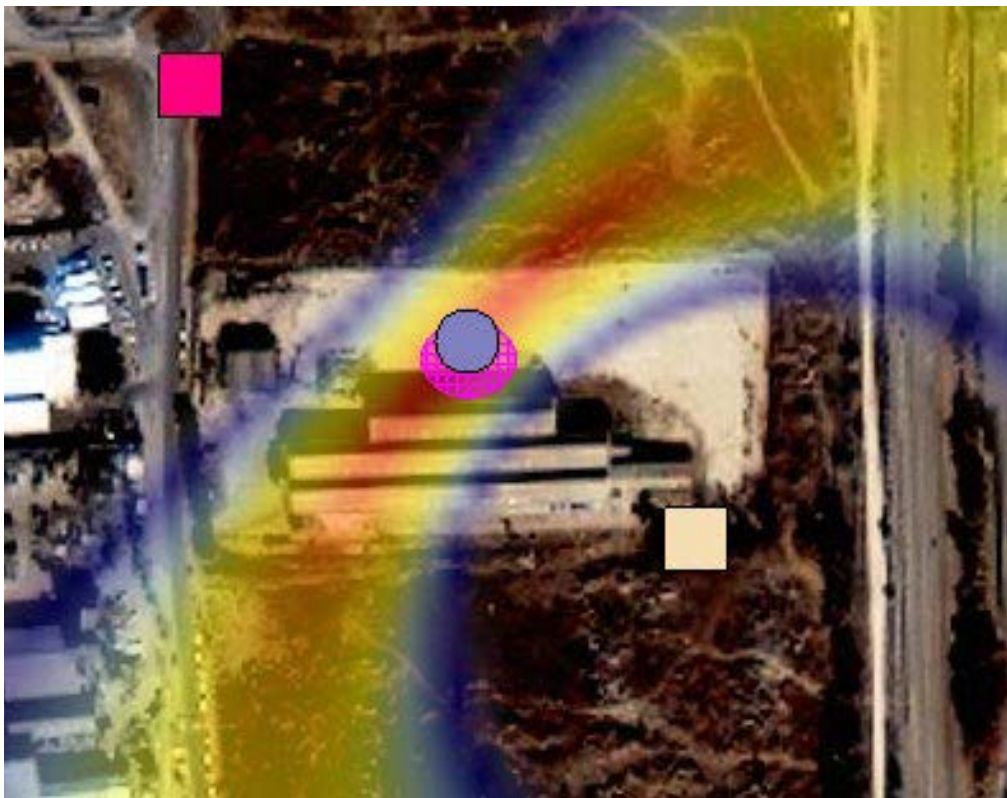
$w = \approx 1 \text{ km}$
 $h = \approx 500 \text{ m}$



<< Figure 11:
AOA performance
for close range CW
with all Rx and Tx
on a straight line.
Error of 100 m with
spurious 9 m by 5 m
uncertainty.



<< Figure 12:
TDOA performance
for close range CW
with all Rx and Tx
on a straight line,
no location data.

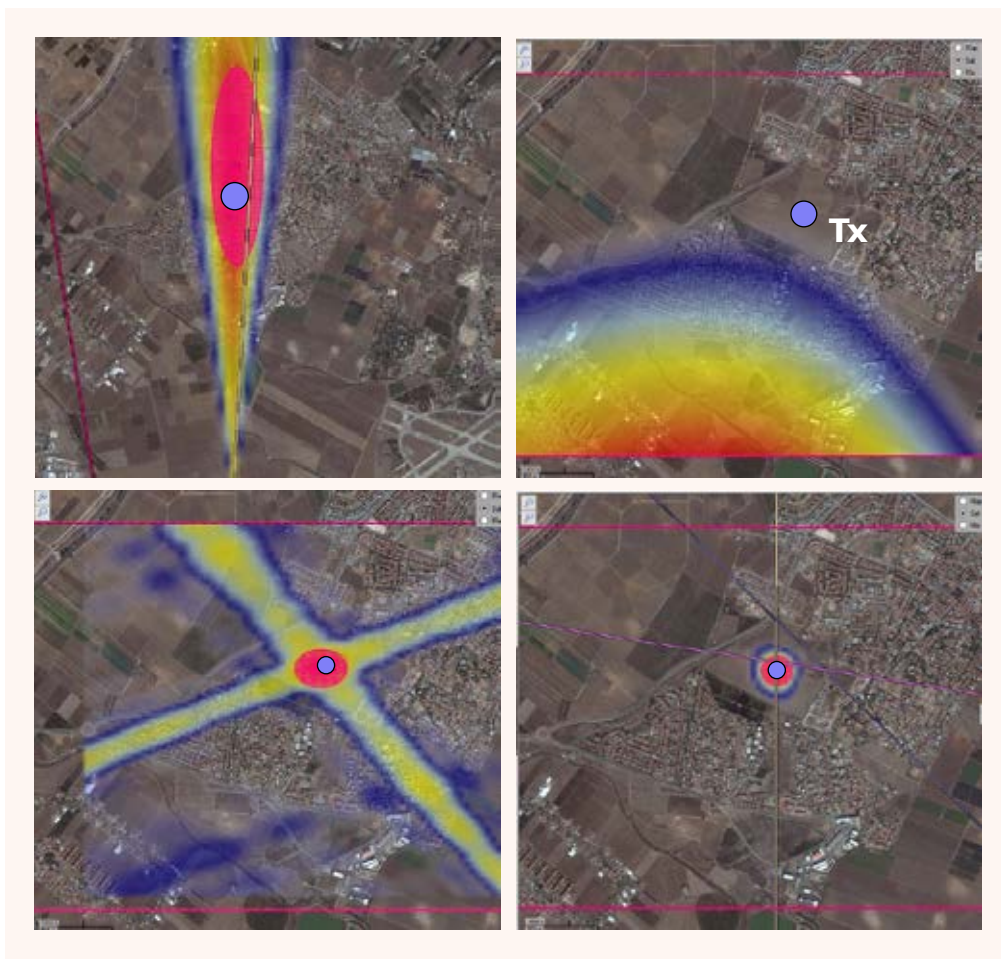


<< Figure 13:
POA performance
for close range
CW with all Rx and
Tx on a straight
line, high accuracy
with 20 m by 15 m
uncertainty.

5. Multi Geolocation

Given that no single geolocation technique is perfect for all signal types and locations, it is best to make use of a hybrid system such as RFeye Site's Multi Geolocation to ensure the system is robust in all scenarios.

The screenshots above (Figures 1-8 and 10-13) are obtained using RFeye Site's Multi Geolocation tool, with AOA, TDOA and POA enabled or disabled as desired. With multiple techniques enabled, the heatmaps displayed and the underlying probability functions for each geolocation technique will be combined to maximize geolocation performance. Figure 14 shows an example of all three geolocation techniques being combined.



<< Figure 13:
Top left: AOA heat map
Top right:
TDOA heat map
Bottom left:
POA heat map
Bottom right:
Corresponding Multi
Geolocation heat map



6. Additional Geolocation Enhancements

Having demonstrated the benefit of combining geolocation techniques, we can now look in depth at some of the additional functionality which can be implemented to locate transmissions in some specific scenarios.

6.1 CUMULATIVE TRACKING

On some occasions, it may not be possible to set up a physical network of fixed monitoring and geolocation sites, especially if the target area is only known as a situation is developing, in an anti-terror operation for example or if the area to be surveyed is large, such as checking for misuse of spectrum across a country. In these cases, it is possible to achieve AOA geolocation using just one antenna array by varying its position, most commonly by using a direction-finding vehicle.

The example of Figure 15 illustrates this with a mobile antenna array moving along a road at 100 km/h, successfully locating a transmitter approximately 1.5 km away to a precision of a 117 m by 78 m area at 50% confidence after just a few seconds of driving.



<< Figure 15:
Cumulative AOA tracking, 1 GHz PSK transmitter located to a precision of 117 m by 78 m using a single moving antenna array.

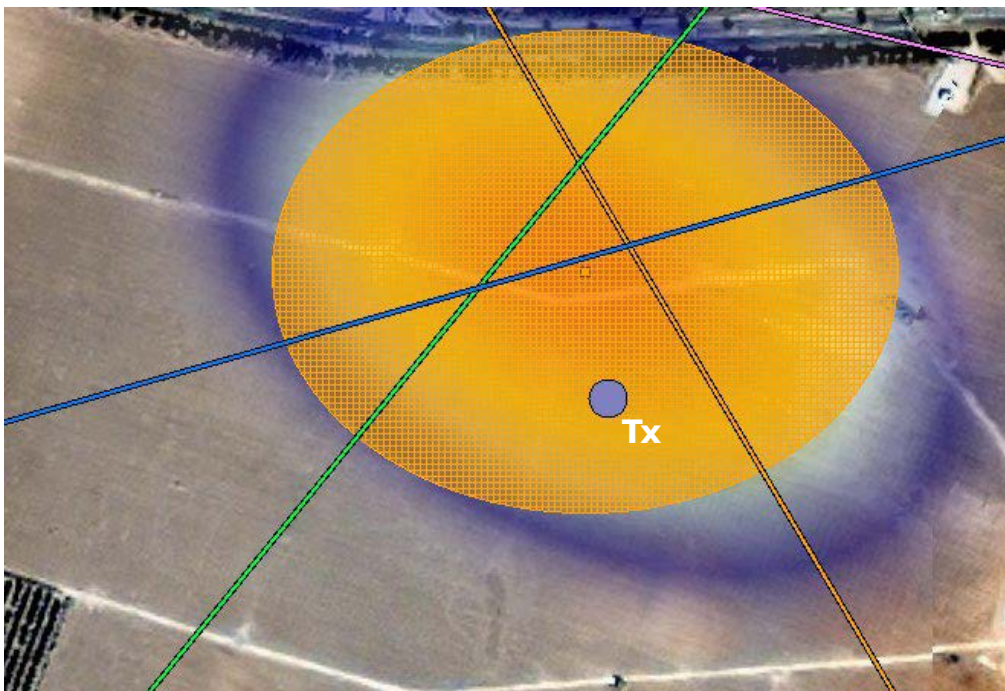
Having obtained this information, it is then possible to narrow down the location further by getting closer to the candidate area of 117 m by 78 m such that a more precise estimate, less affected by multipath effects can be acquired.

6.2 QUALITY AND POWER THRESHOLDING

Where AOA measurements are inaccurate and unstable, whether in a static receiver setup or using a moving receiver as in the cumulative tracking example above, it is also possible to improve this by placing quality and power limits on the received measurements. The quality threshold allows one to ignore all signals below a given percentage quality; this will filter out signals at frequencies with a lot of multipath effects, leaving only those frequencies dominated by line of sight paths which give a smaller uncertainty in bearing.

Power thresholds can also be used to filter out noise by setting lower and upper limits on the power values of signals to be included in AOA calculations. While filtering noise is the most common and obvious application for this feature, it could also be used to filter out high power signals.

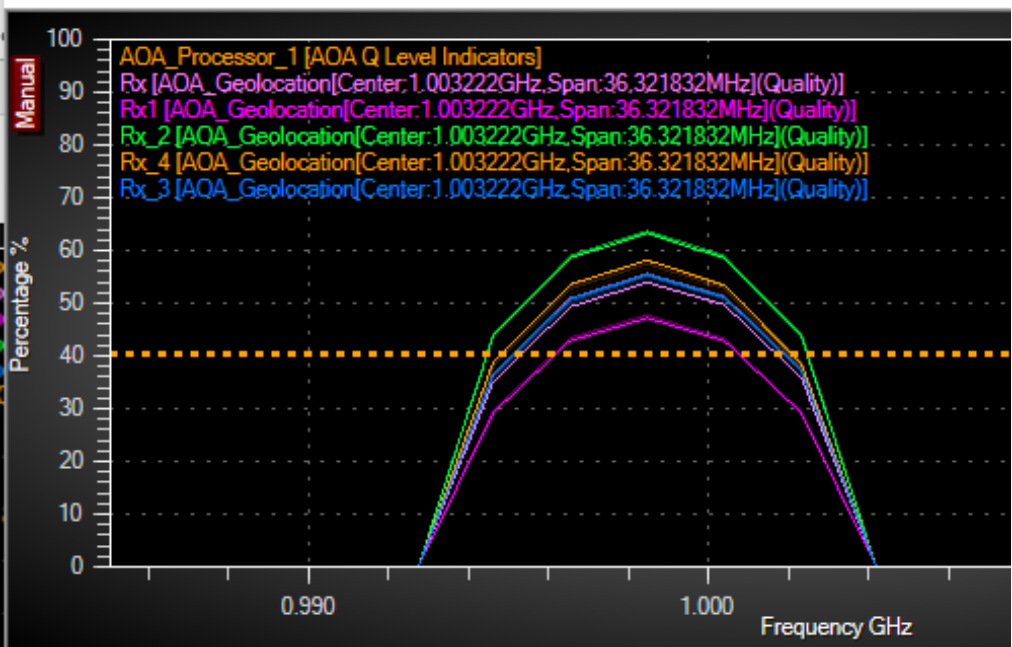
Figure 16 shows the inaccurate geolocation measurement without quality or power thresholding when AOA is implemented in an obstacle dense multipath environment. The 95% confidence probability ellipse is not very well centered on the true transmitter location and the reading is also very unstable giving a larger effective uncertainty than the 300 m by 200 m indicated.



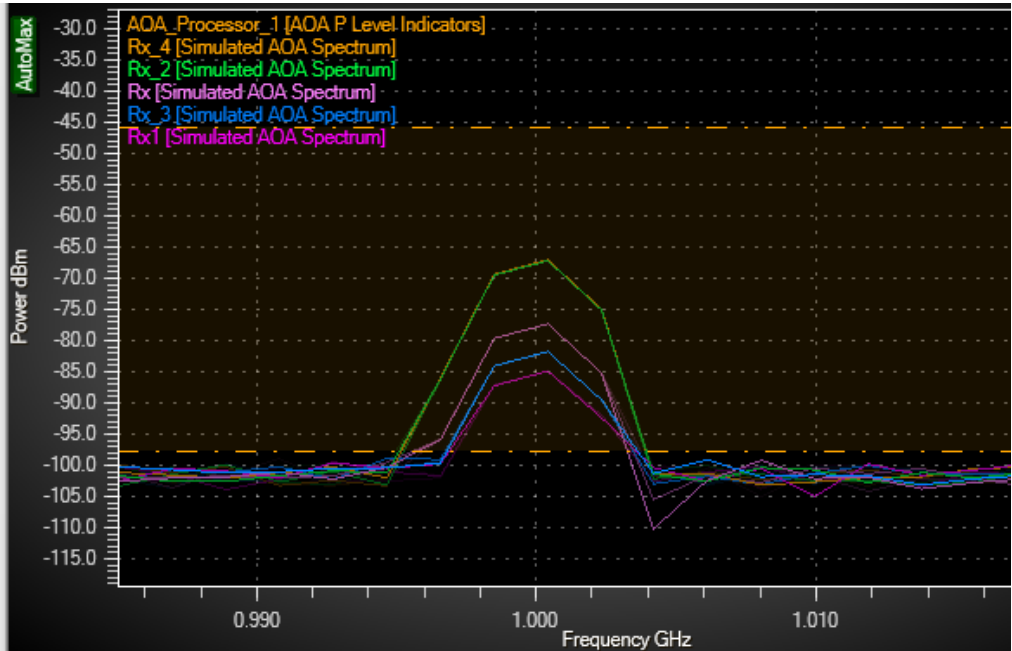
<< Figure 16:
Long distance
geolocation with
no quality or power
thresholding:
Approximately 300 m
by 200 m uncertainty,
very unstable and not
centered on transmitter
for 95% confidence level.



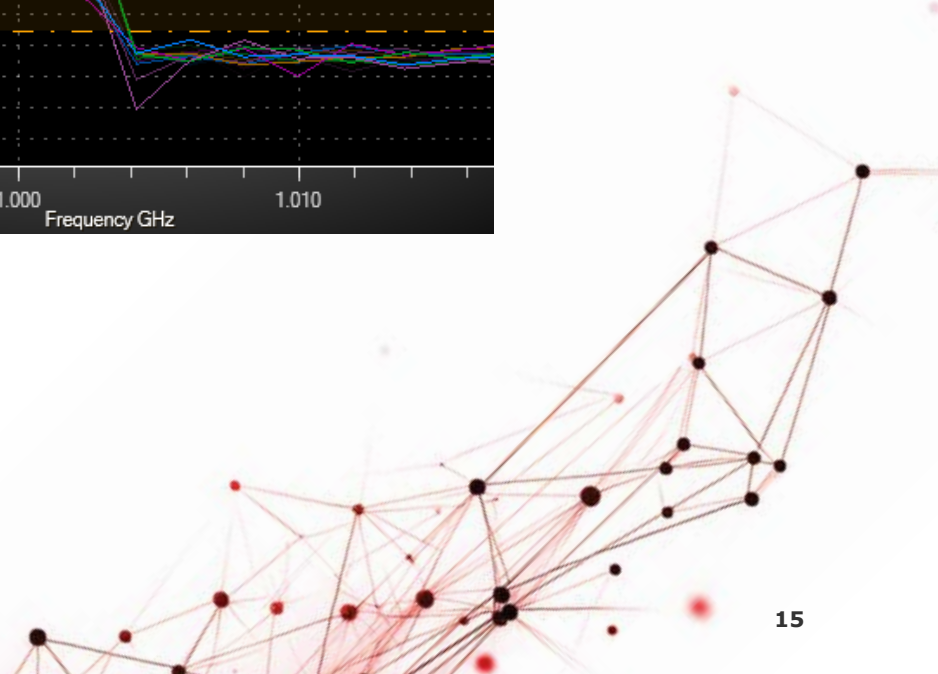
Using quality and power thresholds, as well as some averaging techniques that are part of the RFeye Site package of tools, we obtain a 95% confidence probability ellipse which is much better centered on the true location, has a smaller uncertainty (100 m by 80 m) and is more stable. Figures 17 and 18 show the quality and power threshold settings used, with Figure 19 showing the resulting heat map.

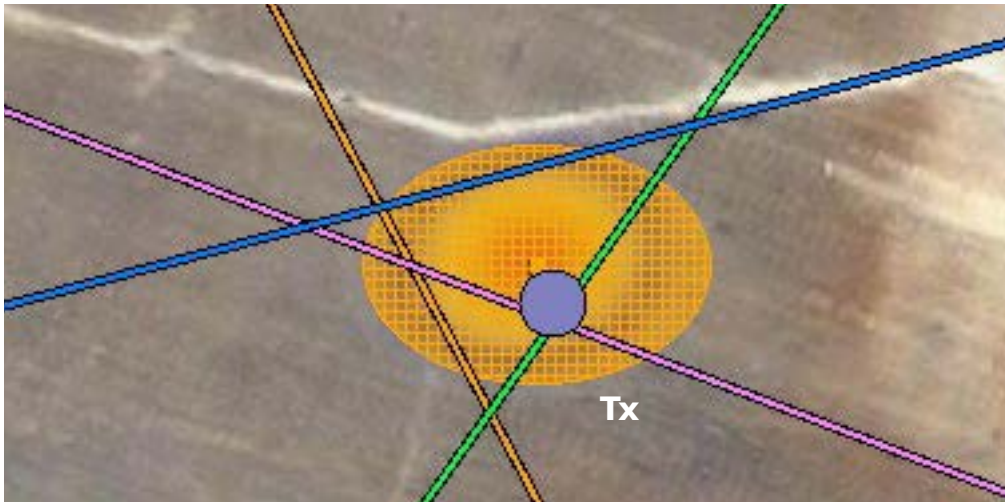


<< **Figure 17:**
Quality threshold
of 40%.



<< **Figure 18:**
Power thresholds
set to filter out
background noise.





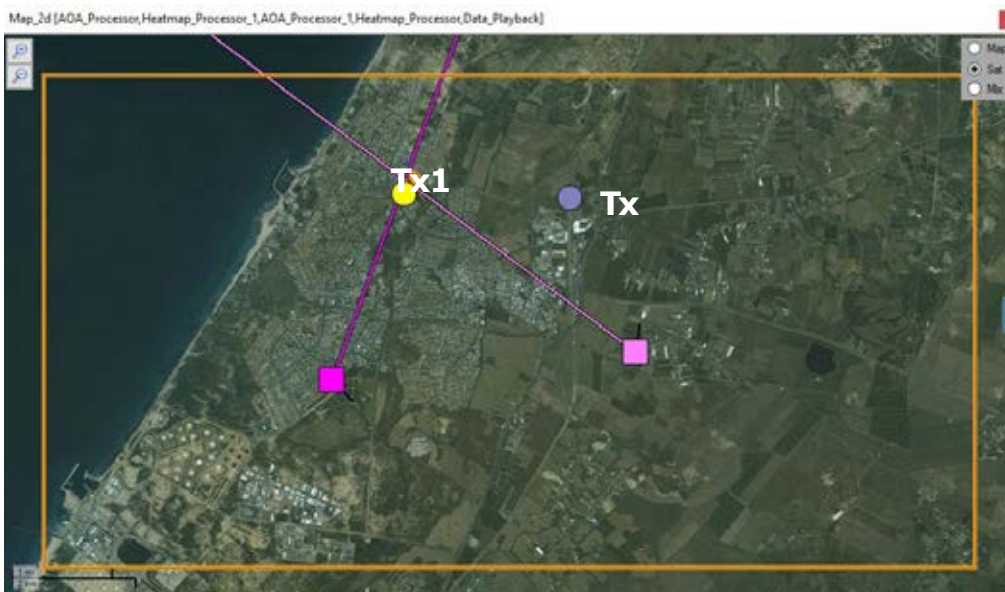
<< Figure 19:
Approximate 100m by 80 m uncertainty with 95% confidence with addition of quality and power thresholds, ellipse is now better centered and more stable.

A further example of the usefulness of quality and power thresholding is shown in the frequency hopping example on page 18.

6.3 FREQUENCY EXCLUSION ZONES: INTERFERING TRANSMITTER PROBLEM

Similarly to our quality and power-based exclusion above, we can ignore certain frequency bands in our AOA sweeps, this can allow us to exclude known transmitters from our search.

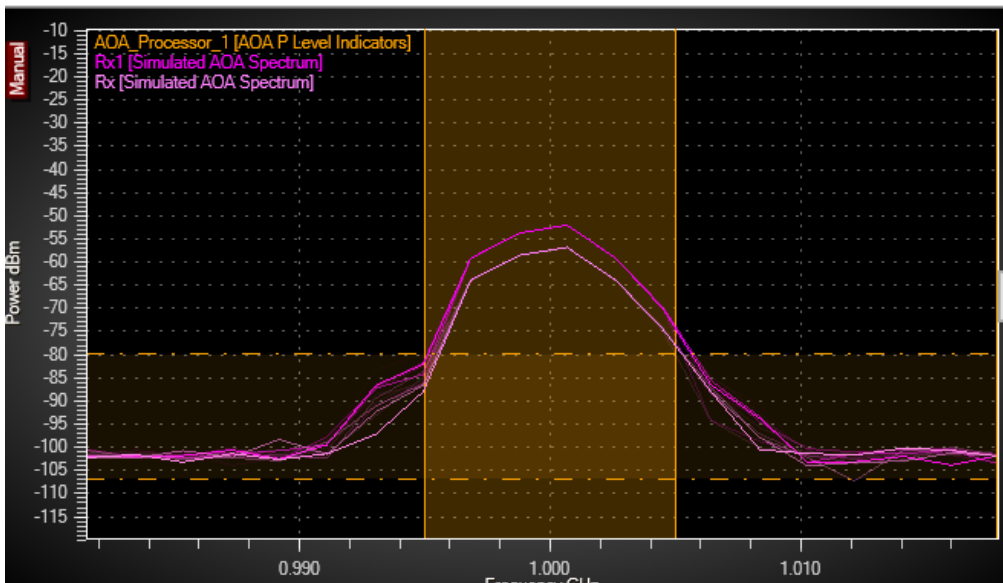
Figure 20 shows a setup with two receivers and two transmitters. Both transmitters are centered on 1 GHz, with Tx transmitting at a symbol rate of 11 MHz with 40 dB power while Tx1 transmits just a 10 kHz symbol rate at 60 dB; we wish to locate Tx, but as we can see, the greater power of Tx1 is interfering causing us to locate the wrong transmitter.



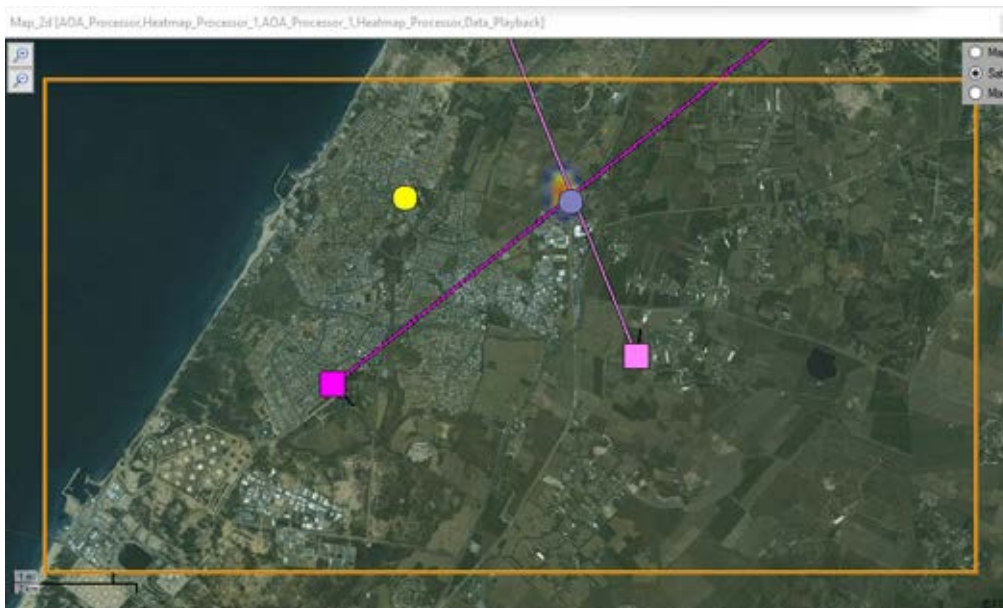
<< Figure 20:
Interfering transmitter Tx1, prevents AOA geolocation of Tx.

We can however, take advantage of the larger bandwidth of Tx by creating a narrow exclusion zone centered on 1 GHz which will remove any signal from the narrowband Tx1, leaving us to locate Tx, Figure 21 shows our excluded frequency band with the resulting new heat map shown in Figure 22. The interfering transmitter has forced us to filter out the central part of our target transmitter too however, resulting in compromised geolocation precision. Tx is placed within an approximate 200 m by 100 m area with 50% confidence and this is also quite an unstable reading. Since we are however at least now locating the correct transmitter, this will enable us to move closer such that a more precise estimate can be obtained. This can be used to geolocate wideband jammers causing interference to other transmissions for example.

AOA_Analysis(AOA_Geolocation[Center:999.687526MHz,Span:36.321832MHz])



<< **Figure 21:**
Narrowband Tx1
excluded using
a frequency
exclusion zone.



<< **Figure 22:**
Tx now successfully
located within a
200 m by 100 m
area with 50%
confidence.

6.4 FREQUENCY EXCLUSION ZONES: FREQUENCY HOPPING

A particularly noteworthy example of the usefulness of exclusion zones is detection of frequency hopping signals. Since we do not know the exact frequency of the carrier at any given time, we cannot restrict our geolocation on a narrow frequency band. The more feasible solution is to have a very wide sweep in which we use exclusion zones to remove interference from other transmitters in this band. Figures 23 and 24 are for a setup of three receivers and four transmitters including a frequency hopping transmitter; Figure 23 shows the resulting spectrum with display persistence set to 100% to allow the multiple channels of the frequency hopping signal to be visible.



<< Figure 23:
*Spectrum with frequency
hopping signal*



<< Figure 24:
*Receiver and transmitter
setup including a
frequency hopping
transmitter*

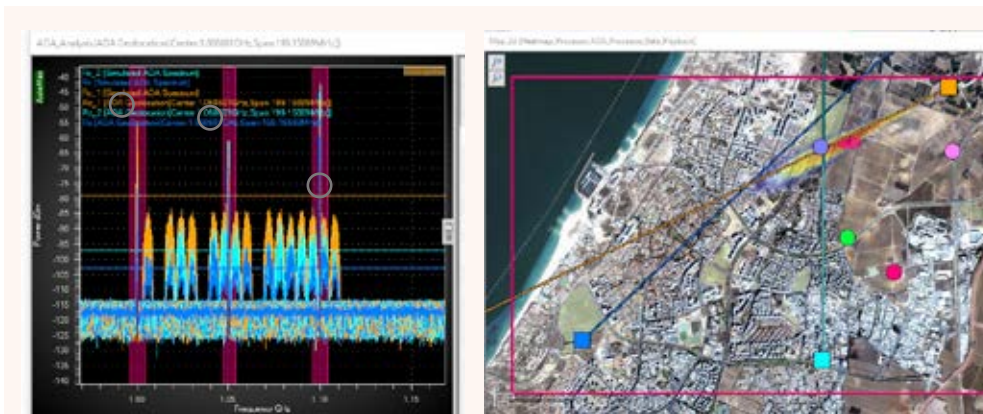
The three non-hopping transmitters of Figure 24 are shown matched to the corresponding parts of the spectrum in Figure 23 with the remaining hopping signal corresponding to Tx clearly visible.

Without intervention, AOA geolocation with a sweep between 1 GHz and 1.15 GHz (covering the frequencies spanned by the hopping signal) will just locate the strongest signal i.e. the 1.1 GHz transmitter - this is shown in Figure 25.



<< Figure 25:
By default, the strongest received signal is located

The addition of exclusion zones, as in Figures 26 and 27, allow the frequency hopping transmitter to be detected, but the heat map is rather unstable with a large uncertainty.

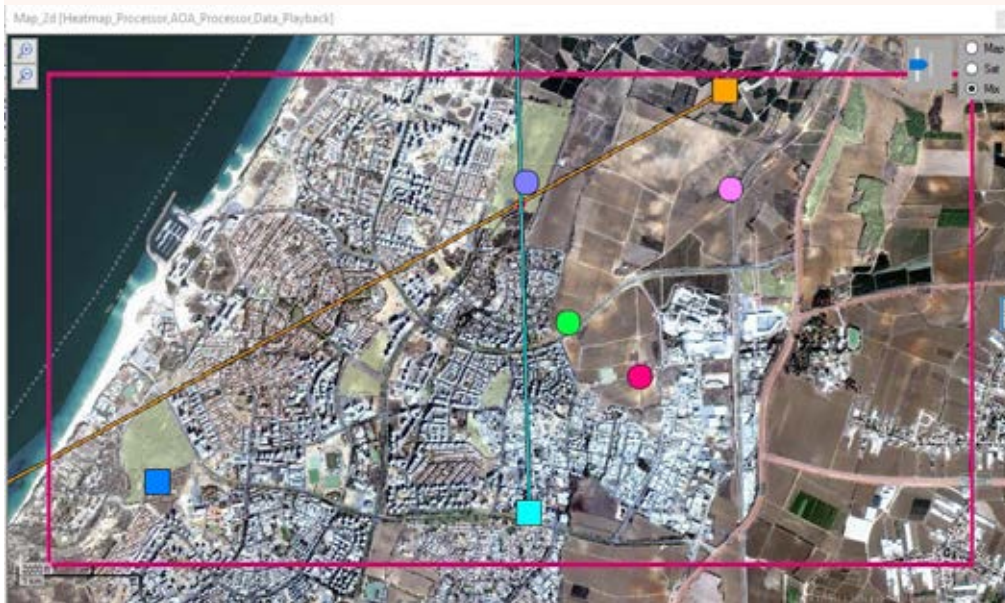


○ 1, 1.05 and 1.1 GHz fixed

<< Figure 26 (left):
Addition of exclusion zones to ignore all but the frequency hopping signal

Figure 27 (right):
Attempted geolocation of frequency hopping signal following addition of exclusion zones

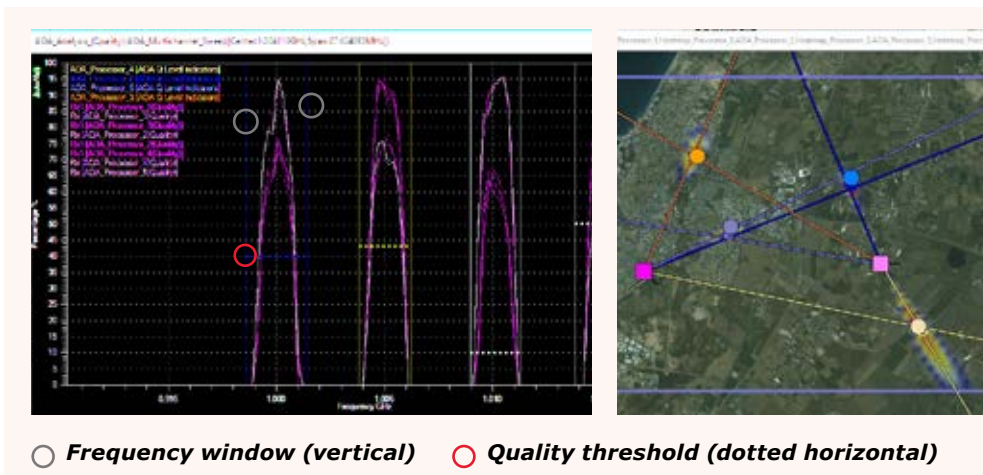
Taking this further by adding a quality threshold of 50% and a power window around the frequency hopping signal results in a reasonable and stable location measurement as in Figure 28.



<< Figure 28:
Geolocating a
frequency hopping
signal by use of
exclusion zones,
quality threshold
and power window.

6.5 MULTITARGET TRACKING

RFeye's Multitarget tracking capabilities allow the user to set up multiple AOA processors, each with their own frequency band of interest, quality thresholds and power windows to geolocate multiple targets. Figure 29 shows the frequency windows used by each AOA processor along with quality thresholds, while Figure 30 shows the resulting heat map.



<< Figure 29 (left):
Frequency windows
and quality thresholds
for Multitarget tracking

Figure 30 (right):
Multitarget tracking
heatmap

Multitarget Tracking could also be implemented with appropriate selection of frequency windows and exclusion zones to deal with the interfering transmitter and frequency hopping problems above in Figures 20 to 28 which would allow us to simultaneously geolocate signals with overlapping frequency spectra.

6.6 SYNCLINC

TDOA and POA geolocation techniques require the receivers in the network to be highly synchronized, usually GPS is sufficient with its typical RMS error of 30 ns. (Elliott Kaplan, 2006) For highly precise in-building applications (generally using POA) however, we will usually want as small a timing error as possible. Since GPS performance will be worse not better for indoor applications, owing to the severe attenuation of signals, we are motivated to look for an alternative (K. Pahlavan, 1998). The RFeye SyncLinc system uses a reliable wired network to give a typical RMS error of less than 10 ns. SyncLinc can be implemented for any sensibly scaled network but is most common for in-building applications where a wired network is most feasible and offers the most benefit.

6.6 GEOLOCATION IN POST-PROCESSING

Geolocation on recorded spectrum data

It is not always desirable or necessary to have a human user sat at a screen monitoring spectrum and location data in real-time. RFeye Site removes the need for real-time human monitoring without any loss of information with its post-processing TDOA geolocation feature to geolocate on recorded spectrum data. This retrospective geolocation is also key where receivers are running in standalone mode in remote locations without network access such that data packets cannot be sent over IP for real-time geolocation.

Another simple but vital application is the ability to have multiple chances to geolocate using data playback in cases where a transmission is very brief and the chosen geolocation setup at the time was not optimal for that signal type.

Recorded data for geolocation in post-processing can also be recorded selectively using the Triggered Record functionality such that data will only be recorded when a signal meeting particular frequency and power requirements is detected.

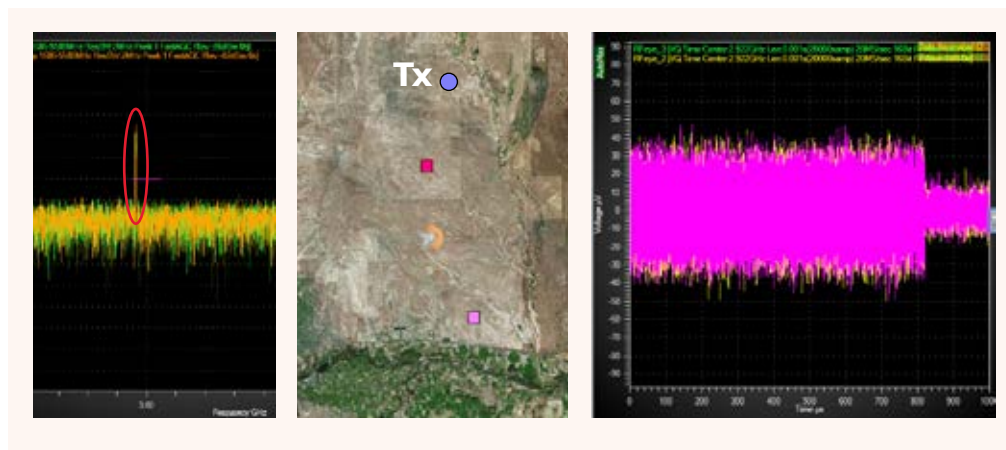
Setting up masks for recording data

Suppose a military user wishes to gather intelligence on RF activity in a remote location in anticipation of a planned operation requiring use of particular frequency bands. They want to ensure the frequencies of interest are not congested with other activity to prevent congestion and interference issues. For this purpose, data over several weeks will be gathered using a remote setup of receivers, after this time the data will be downloaded to a PC for analysis.

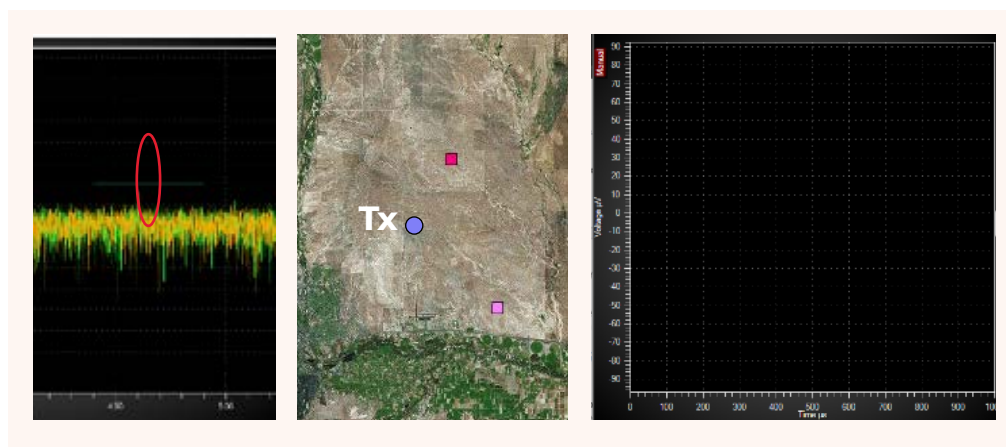
As only certain frequency bands are of interest and it is only important if a transmission above a certain power is detected, the user can set up a mask to only record the relevant data. In this way, both memory usage and time spent analyzing data is minimized.

For example, radar surveillance operations typically use the 2900-3100 MHz band and a UAS video link may use the 4400-4900 MHz band, in the US both of these are shared bands, not restricted for government use, and so may be subject to congestion and interference.

Figures 31 to 32 show two masks setup across these bands with power thresholds of -95 dB. Figure 31 shows the data capture for a signal within the corresponding frequency and above -95 dB, while Figure 32 shows the lack of data capture when the signal is in a relevant band but below the power threshold.



<< Figure 31:
Left to right - Mask broken by 2925 MHz signal, Receiver and transmitter setup, Data capture in response to mask breakage



<< Figure 32:
Left to right - Low power 4600 MHz signal doesn't break mask, Receiver and transmitter setup, No data capture when mask unbroken

With a complete set of data recorded and downloaded to a PC, the user can then geolocate signals of interest in post-processing, this might enable them to request that the disruptive transmissions are paused during the planned operation or to select different frequency bands for the operation which are less congested.

Note that if the signals of interest are not known prior to the installation of the receiver network, it is also possible to capture all data and apply masks as needed in post-processing rather than in advance.

Real-time triggered geolocation

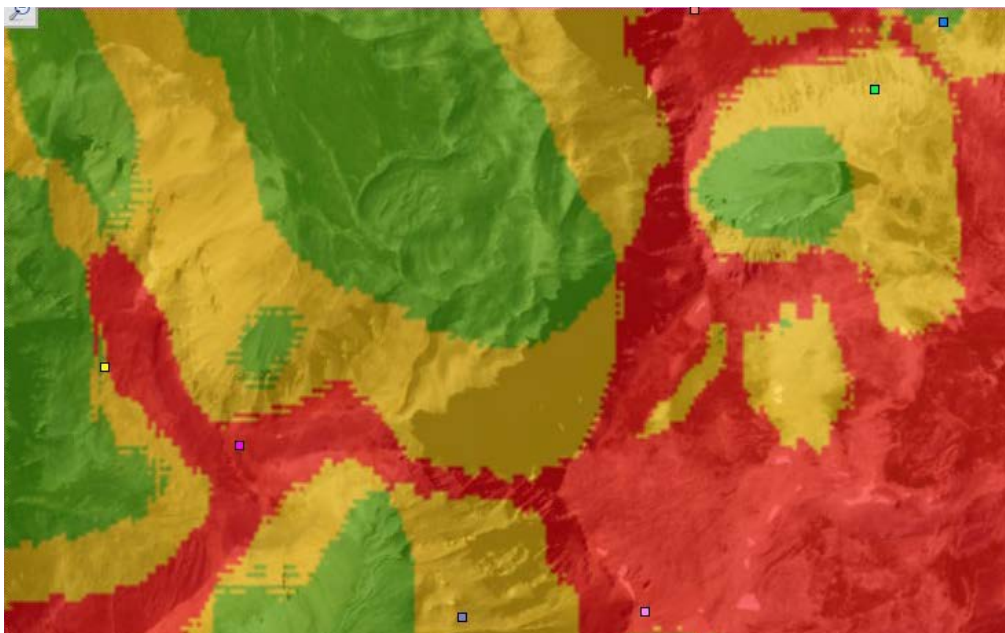
One can also take advantage of mask breakage triggers in real-time, by setting up a geolocation task to trigger only on the detection of particular signals. This works in the same way as the triggered record functionality described above, but with the resulting event being geolocation rather than recording of data. In this way, the user can respond to threats in real-time while ignoring innocuous transmissions. This can also be integrated with triggered alarms and notifications, such that on detection of a suspect signal an SMS message is sent to an operative alerting them and specifying the location of the detected transmitter.

7. Predicting Geolocation Performance

RFeye Site, in addition to real-world spectrum monitoring, allows creation of a network of simulated transmitters and receivers to test geolocation performance before real-world installation. However, if we are looking to ensure that a planned network of receivers is sufficient for geolocation purposes, we might not wish to test the geolocation performance of a receiver setup for every possible transmitter position in the target region.

What we can do instead is check TDOA, POA and AOA performance for the signal(s) of interest by using the Propagation Analysis plugin.

Propagation Analysis indicates how many receivers will 'see' a transmitter placed at each location in the target analysis region. In the mountainous area of national forest in Colorado shown in Figure 33 for example, transparent, green, yellow and red mean 0, 1, 2 and 3+ receivers respectively would be able to see a transmitter placed at those locations. Using this information, and our knowledge of the receiver requirements for AOA, TDOA and POA techniques we can ensure our planned network will geolocate effectively e.g. TDOA geolocation will be possible in all red areas as it requires 3 receivers. The user can also adjust the power and LOS (Line of Sight) requirements to meet the threshold of being able to 'see' a transmitter. The accuracy of this modeling is however limited by the use of low-precision SRTM (Shuttle Radar Topography Mapping) elevation data, more precise LIDAR (Light Detection and Ranging) data will provide better models (USGS - Shuttle Radar Topography Mission (SRTM), n.d.) (UK government data - LIDAR, n.d.).



<< Figure 33:
Propagation Analysis indicating the number of receivers able to detect a transmitter at each location

8. Conclusion

We have seen how Silvus Technologies's RFeye hardware and software can provide more advanced geolocation with the use of tools such as Multi Geolocation and Cumulative Tracking. The ability to geolocate in both real-time and post-processing and use triggered record and geolocation gives the user full flexibility in choosing how, what and when to geolocate.

Contact Silvus Technologies to arrange a demo or get further details on our geolocation capabilities.



9. References

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