Correlation of DME Pulse Trains for Use in Multilateration

ICNS Conference

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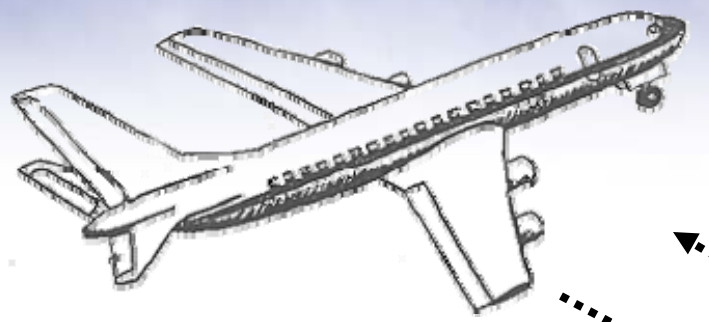
DME = Distance Measuring Equipment



Interrogator onboard aircraft

Transponder @ 978-1213 MHz

Interrogator @ 1041-1150 MHz

DME health monitor antenna

- Interrogator broadcasts dual-pulse trains.
- Ground based transponder re-broadcasts the pulse train after a fixed time delay (50 μs).
- **Slant-range distance** is calculated *by aircraft* based on two-way travel time

Transponder on the ground, usually colocated with VOR

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DME pulses

DME pulse pair

Interrogator varies this interval so it can identify replies intended for it

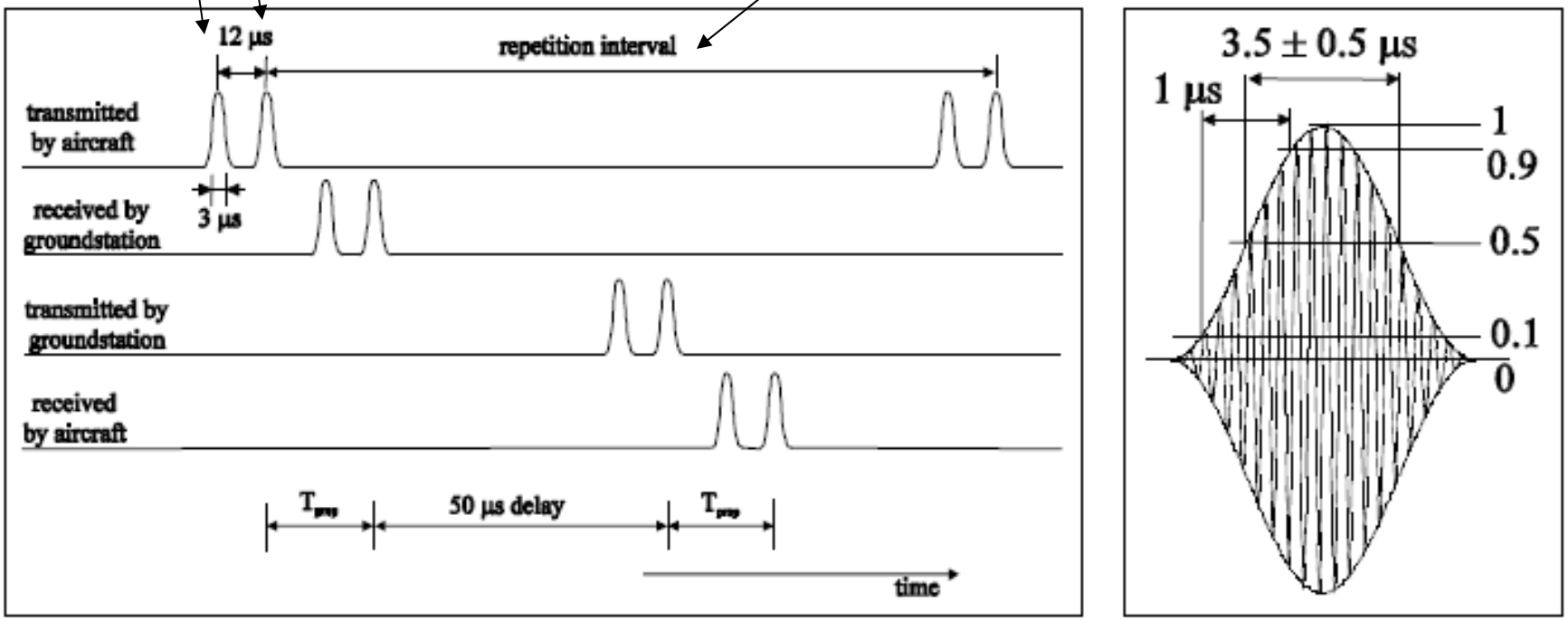
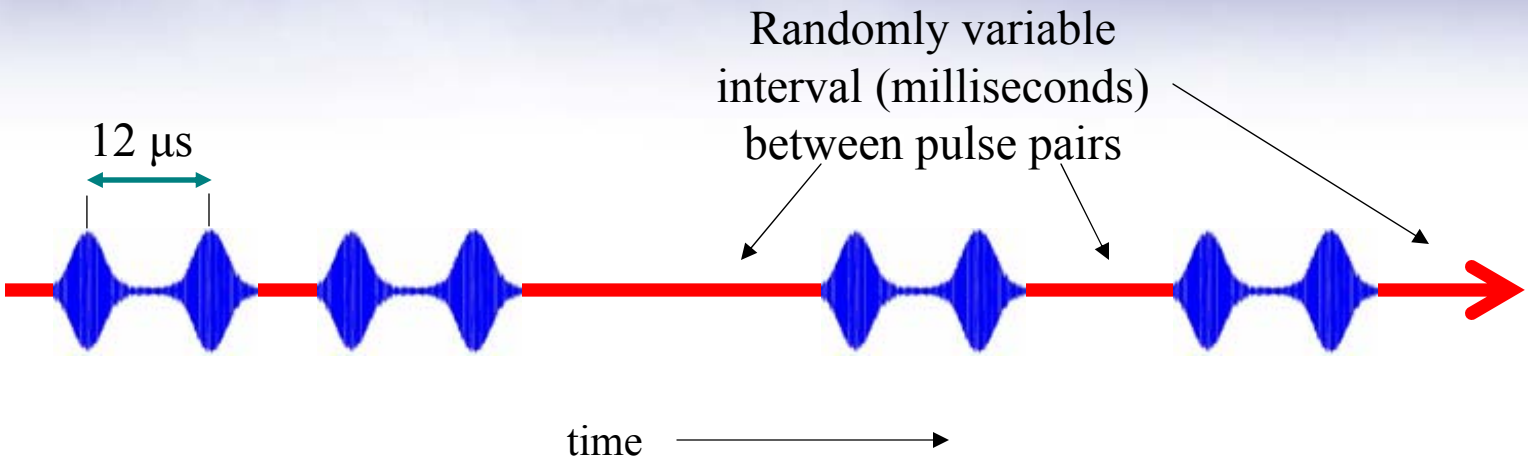


Figure 7-7 Principle of the DME pulse structure (left) and DME pulse shape(right).

http://www.pn.ewi.tudelft.nl/education/et4-022/notes/h7.pdf

DME pulse streams



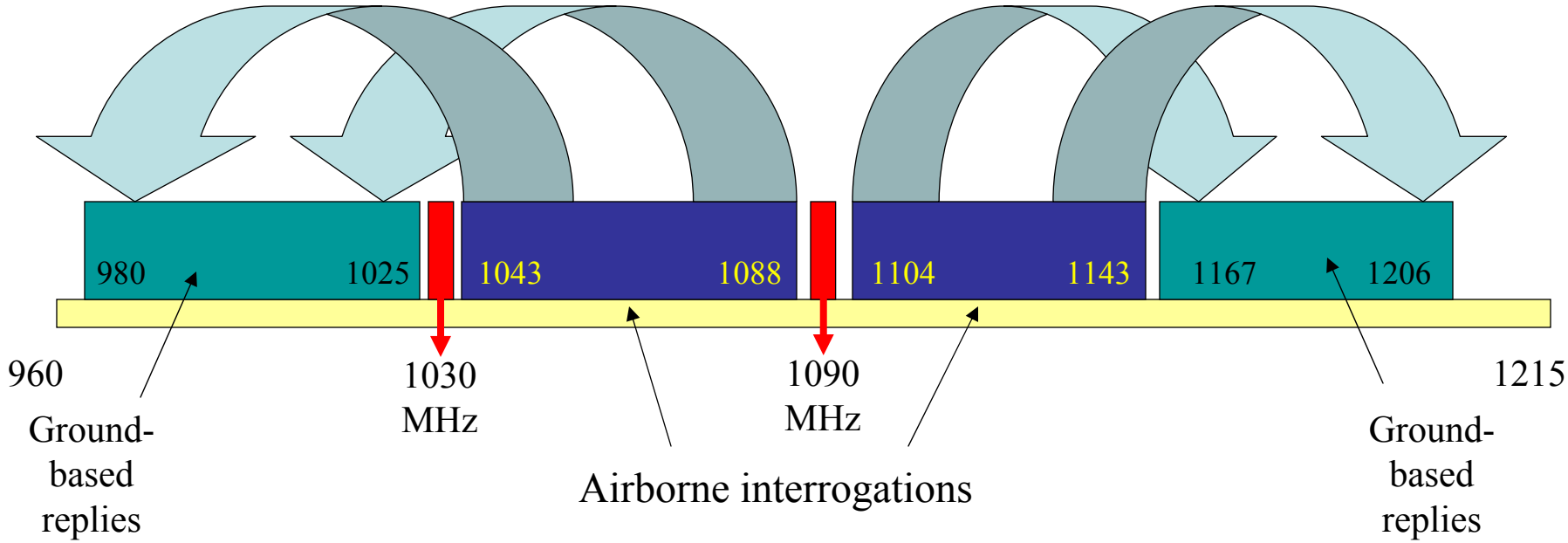
An airborne DME interrogator transmits a stream of pulse pairs with a fixed time interval (12 µs or [rarely] 36 µs) between pulses. The interrogator randomly varies the time interval *between pulse pairs*.

Pulse Repetition Rate

- 100-150 Pulse pairs/sec in "search mode"
- 25 pp/sec in "locked" mode.

DME bandplan

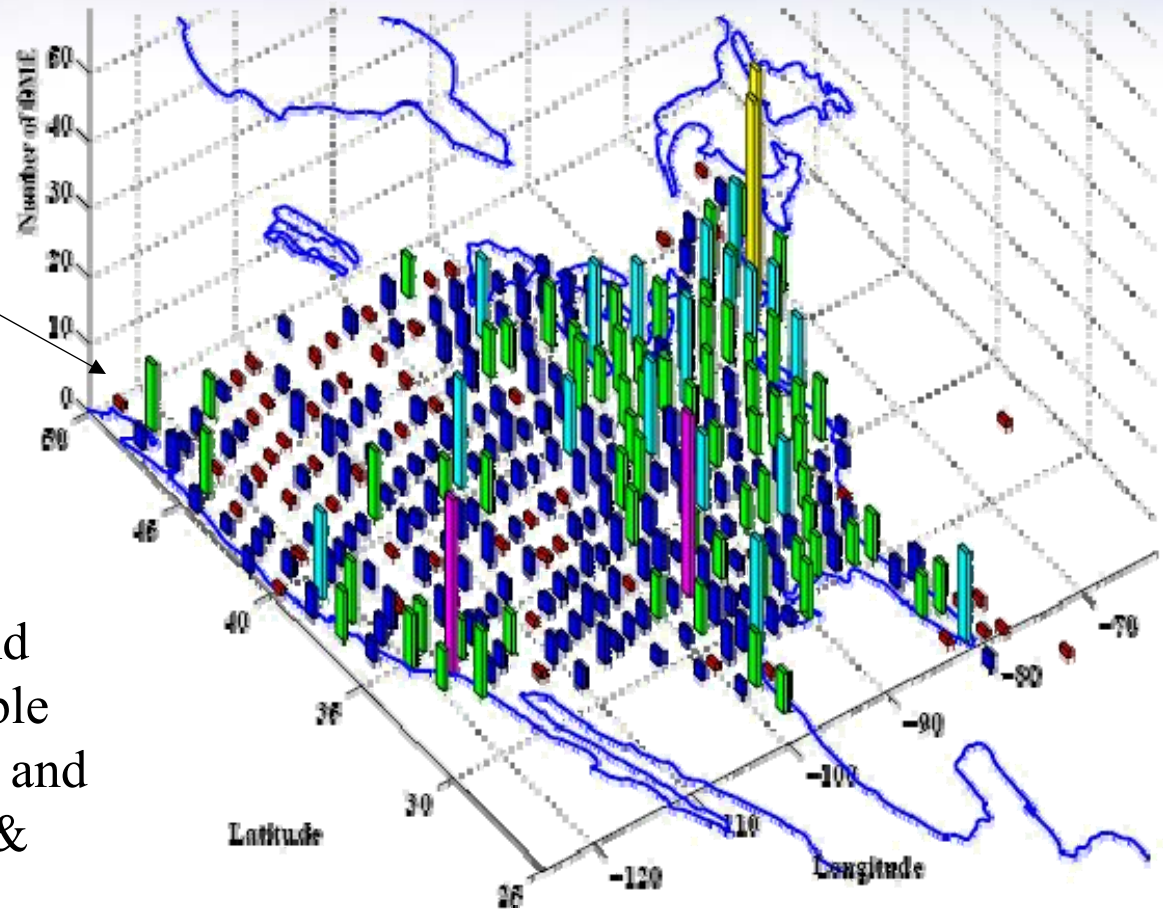
$$f_{reply} = f_{interrogator} \pm 63 \text{ MHz}$$



Simplified diagram (not to scale) of DME bandplan. DME channels are allocated adjacent to the 1030 & 1090 MHz SSR frequencies. Airborne DME interrogations are answered by ground-based replies at ±63 MHz.

DME availability in N. America

Bins = 100 mi^2 area



>900 DME ground stations are available throughout the USA and adjacent Canada & Mexico.

Source: Demoz Gebre-Egziabher, J. David Powell and Per Enge, 2000, A DME-based area navigation Systems [sic] for GPS/WAAS interference mitigation in General Aviation Applications: http://waas.stanford.edu/~wwu/papers/gps/PDF/**demozdme**.pdf

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DME transponders in Europe

Source: Eurocontrol

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The Problem

- In order to use DME for multilateration, we need to know:
  - What pulses are coming from each target?
  - What is the Time Difference of Arrival (TDOA) of pulses between our ground-based receiver units (RUs)?
- **The problem**: DME pulses are *anonymous*… no identifying information is encoded in them;
- Only the aircraft knows the pattern of random time intervals that it inserted between pulses;
- Ground-based receivers hear a torrent of anonymous pulses… how can they discern which pulses come from which aircraft?

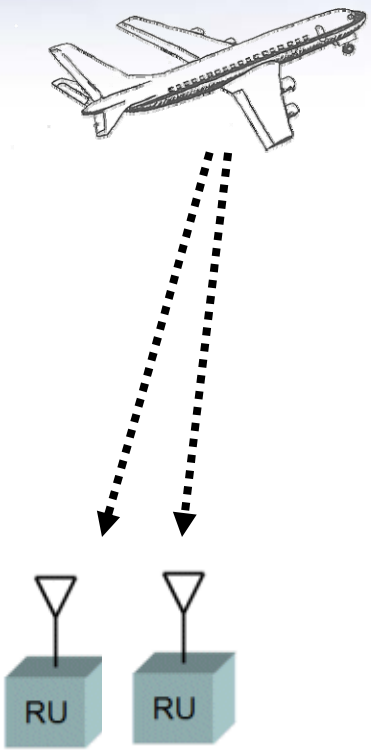
A solution: correlation between RUs

- The technique described here answers both questions simultaneously:
  - What signals are coming from each target?
  - What is the TDOA between pairs of receivers (RUs)?
- The technique is based on correlation of pulse* streams
- The technique begins with the following observation:

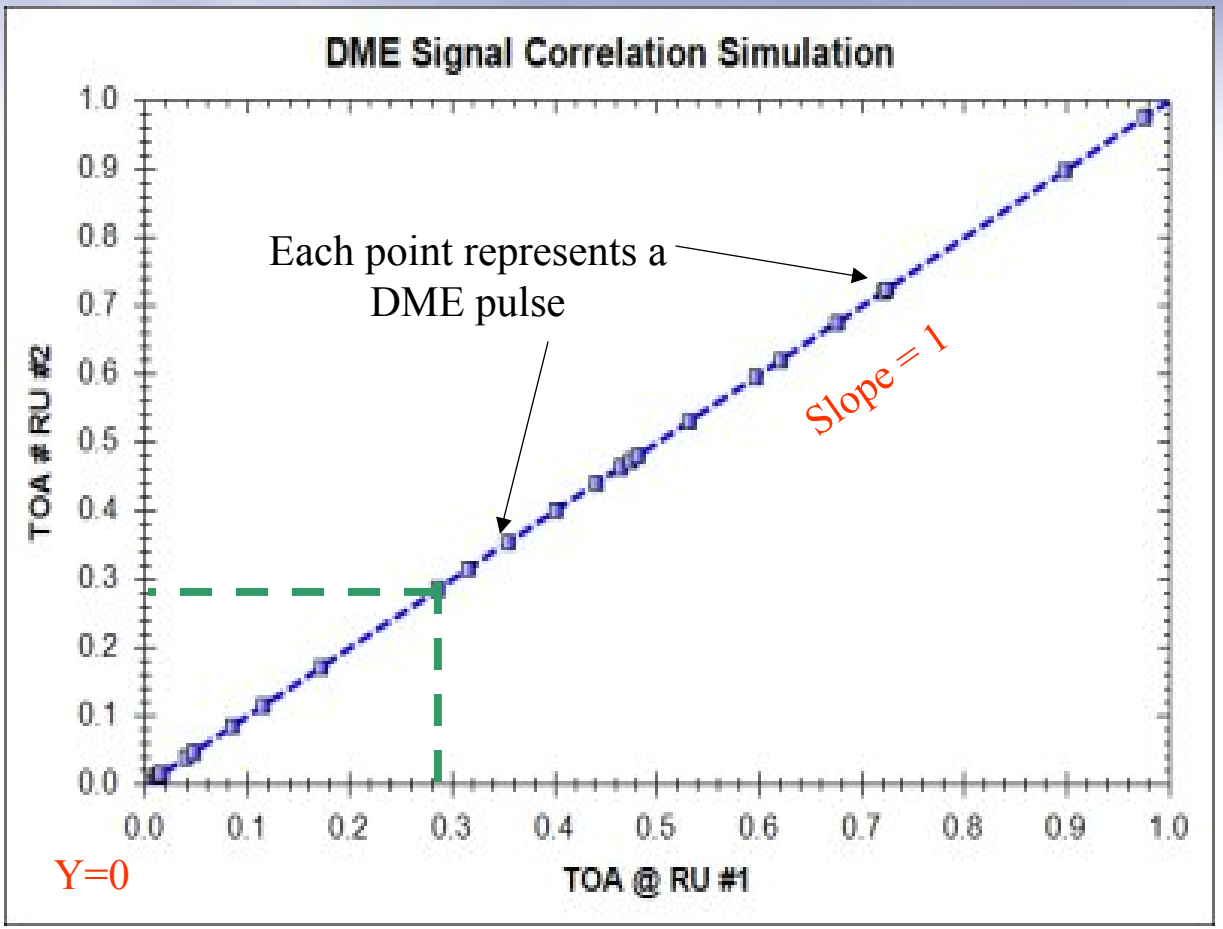
Time interval between pulses in a pulse stream is not affected by aircraft-RU distance.

*"Pulse" is actually a pulse-pair. The 2nd pulse of the pair is ignored here for simplicity.

DME Signal Correlation

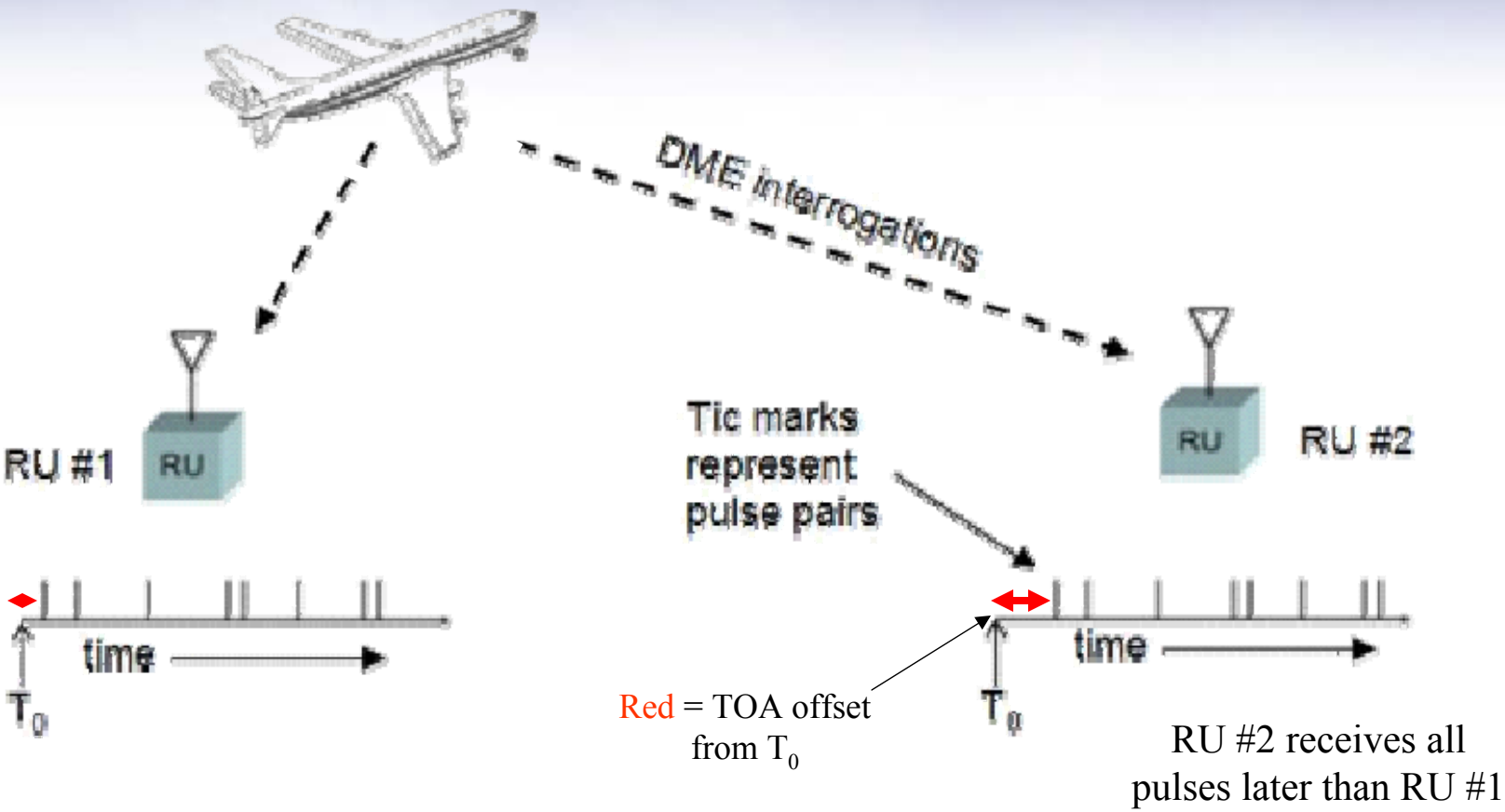


Colocated RUs receive the DME interrogation simultaneously



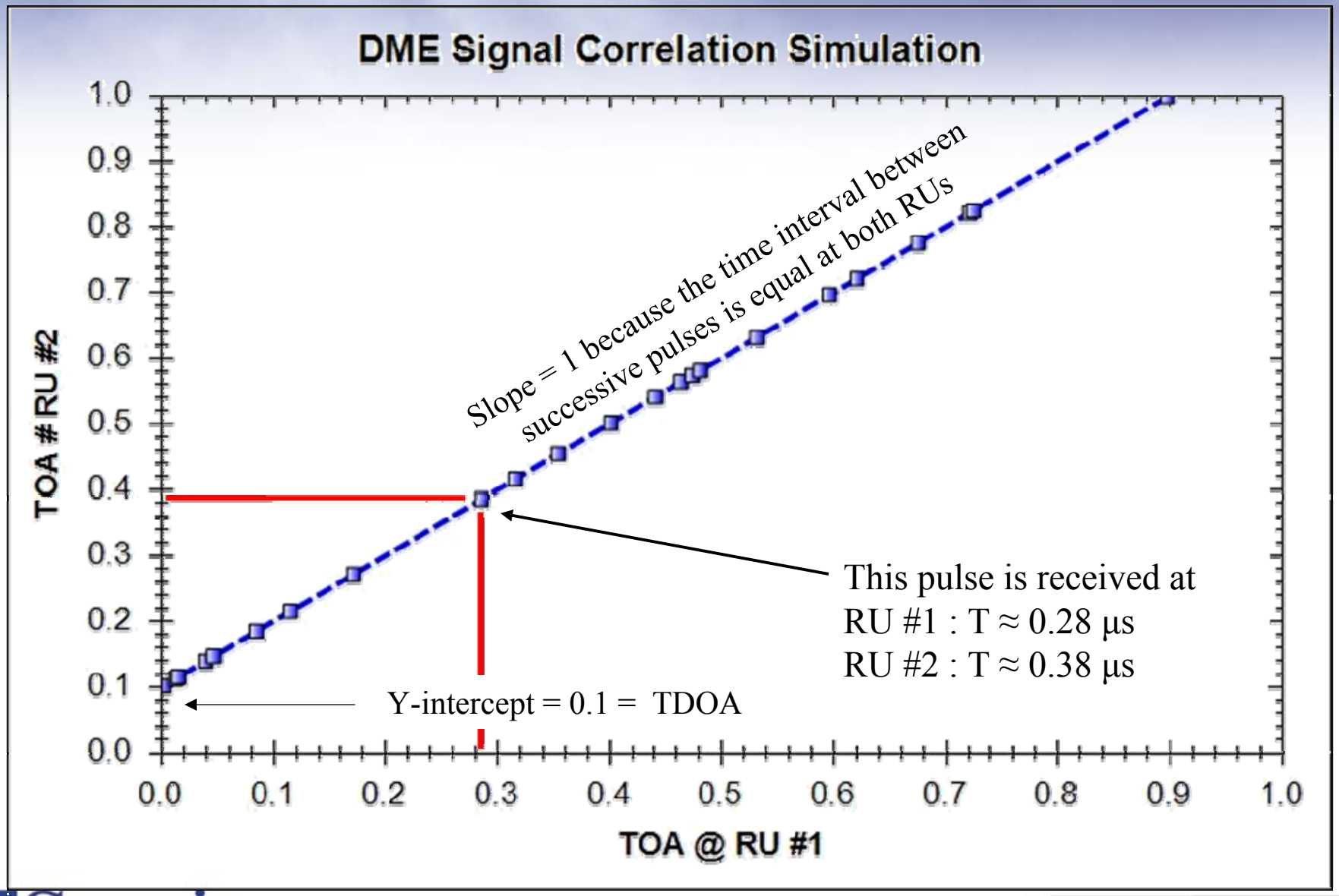
Because RUs are colocated, a plot of their (simultaneous) reception timestamps has slope = 1 and Y intercept = 0

Separated RUs



Pulses received by RU #1 and RU #2 differ in their time of arrival (TOA) but ***not*** the intervals between correlated pulses.

Simple Case #2: correlation graph



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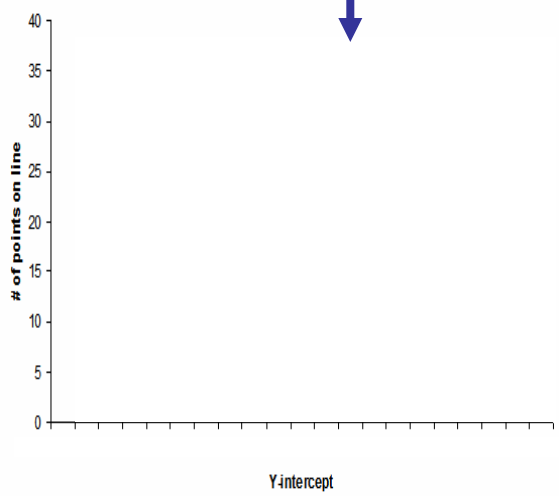
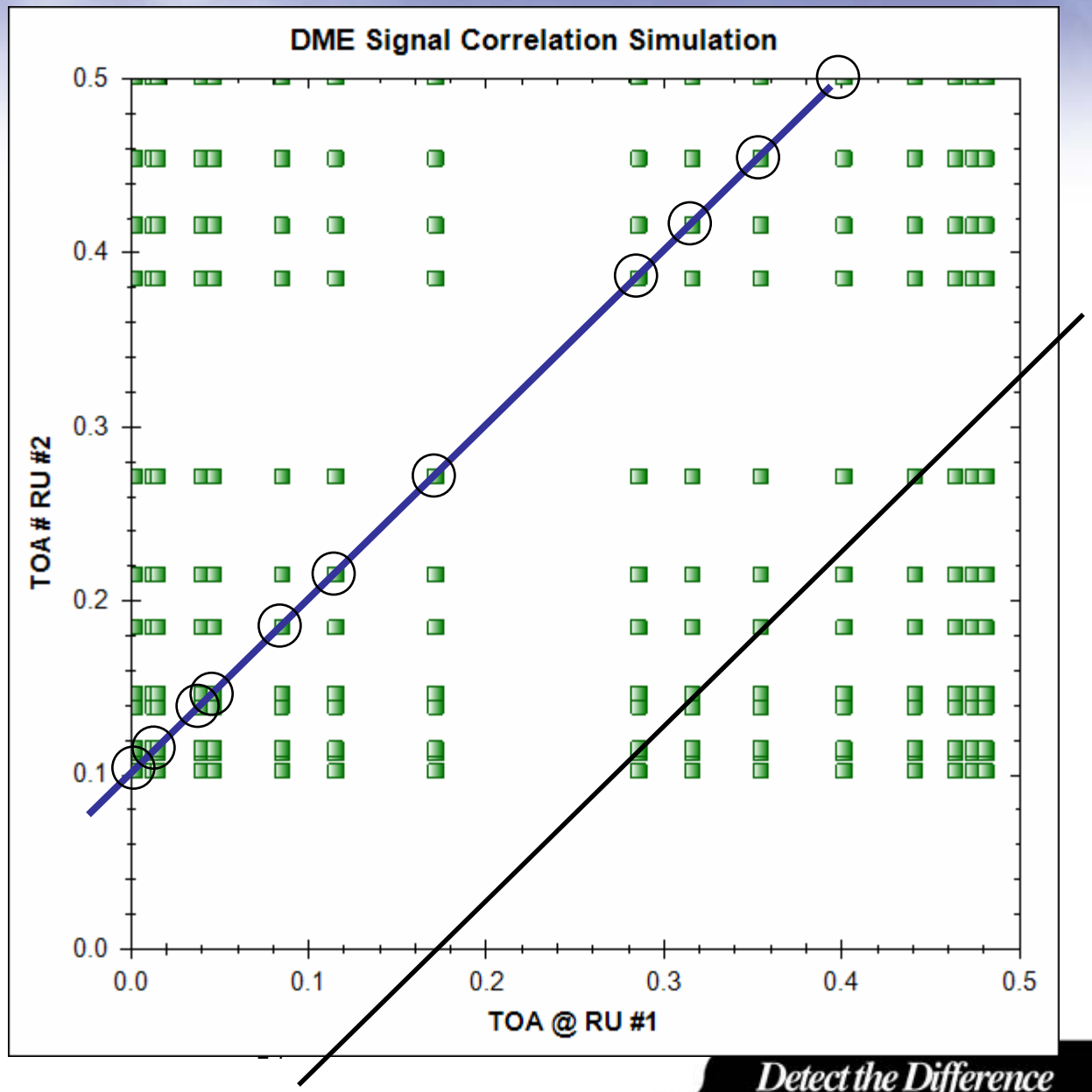
Therefore…

- A pulse stream received at two RUs will *always* generate a correlation graph with unity slope.
- Stated differently, a valid correlation line represents a collection of pulses whose inter-pulse intervals at the two RUs are consistently equal.
- By isolating collections of points along a line with unity slope, we will be finding correlated pulse streams.
- **A strong maximum in points along a proposed correlation line represents a valid correlation of pulses from a single target.**
- **The Y-intercept of this line represents the TDOA for all correlating pulses.**

A graphical approach

Given that unity slope is required for a valid correlation line, find a line with unity slope that intersects the maximum number of points.





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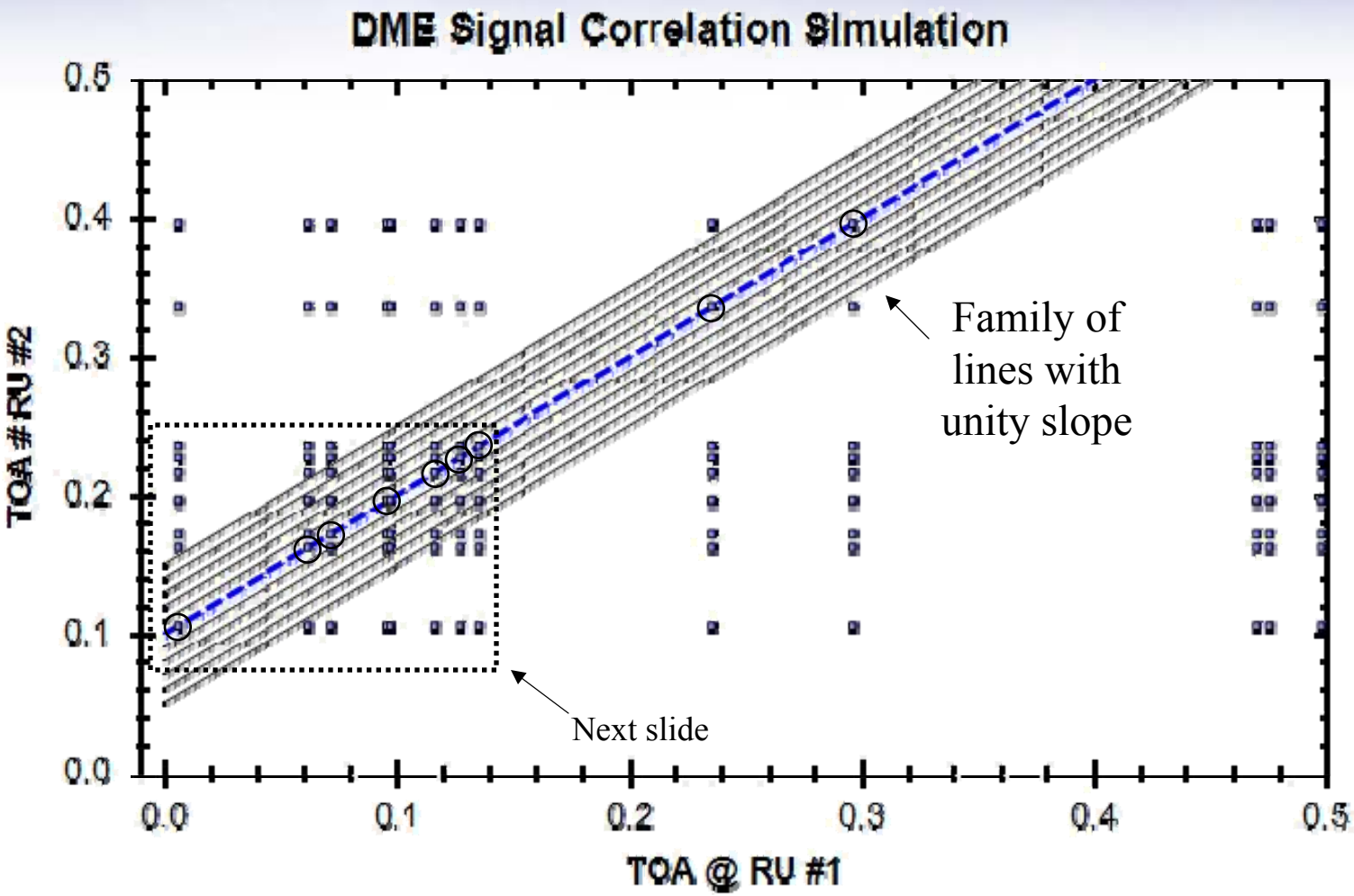
Plot of every pulse received at RU #1 against every pulse received at RU #2



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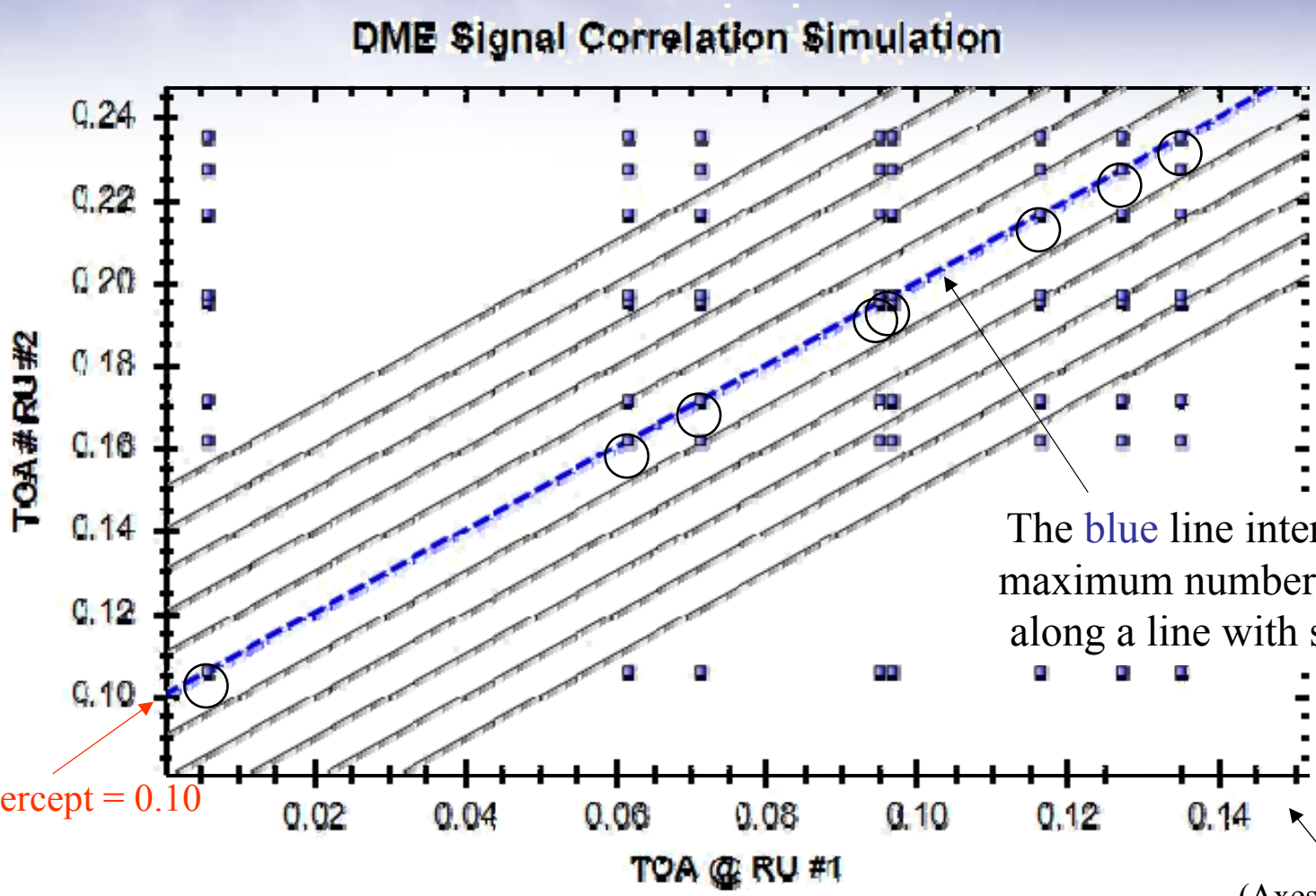
Enlarged area



The blue line intersects the maximum number of points along a line with slope = 1

Y-intercept = 0.10

(Axes aren't the same scale)

The Y-intercept of a line with slope = 1 represents TDOA for the collection of points making up the line

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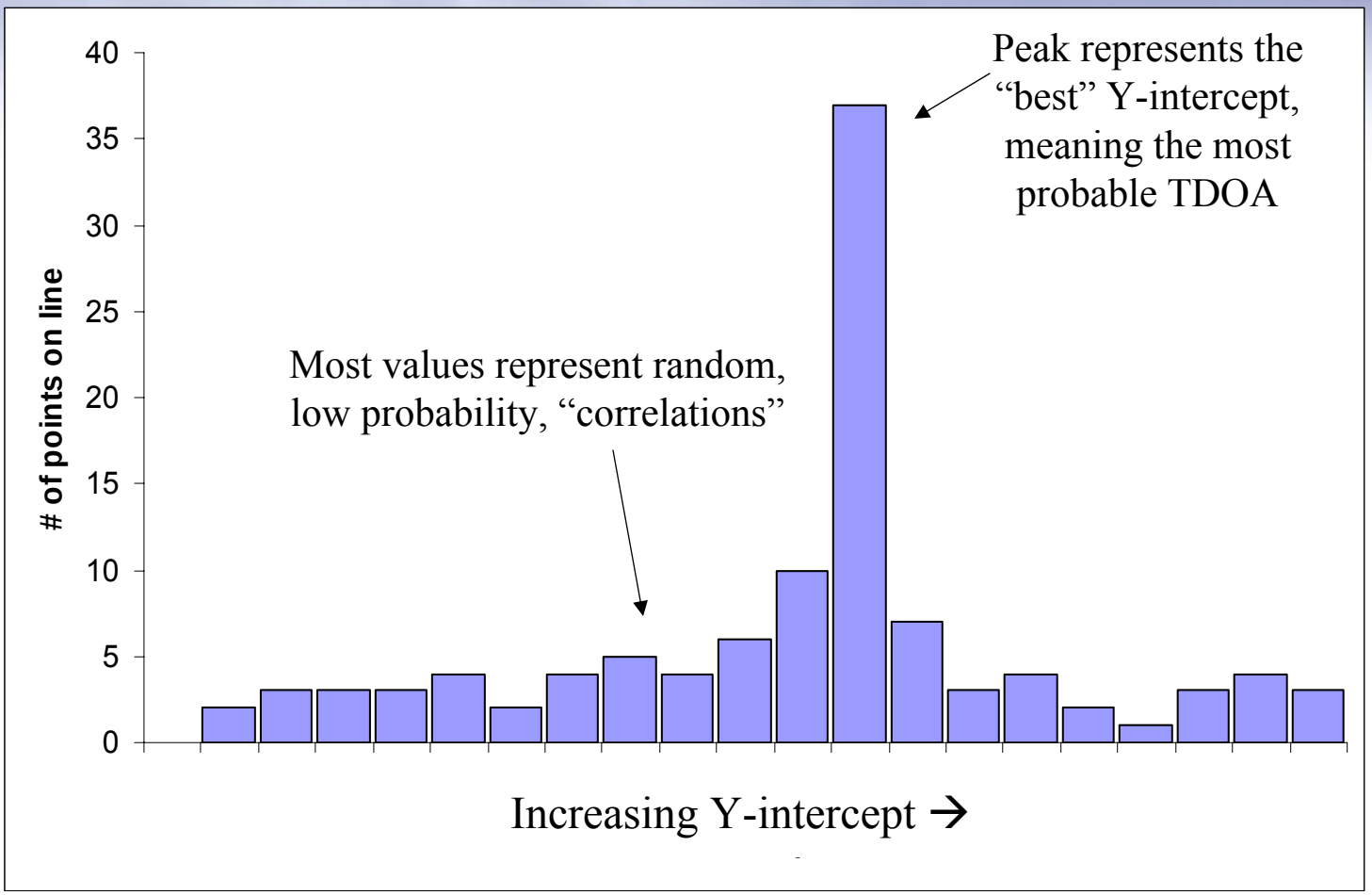
Histogram view



Schematic histogram representing the number of data points (derived from DME pulses) intersected by lines with unity slope as Y-intercept is increased

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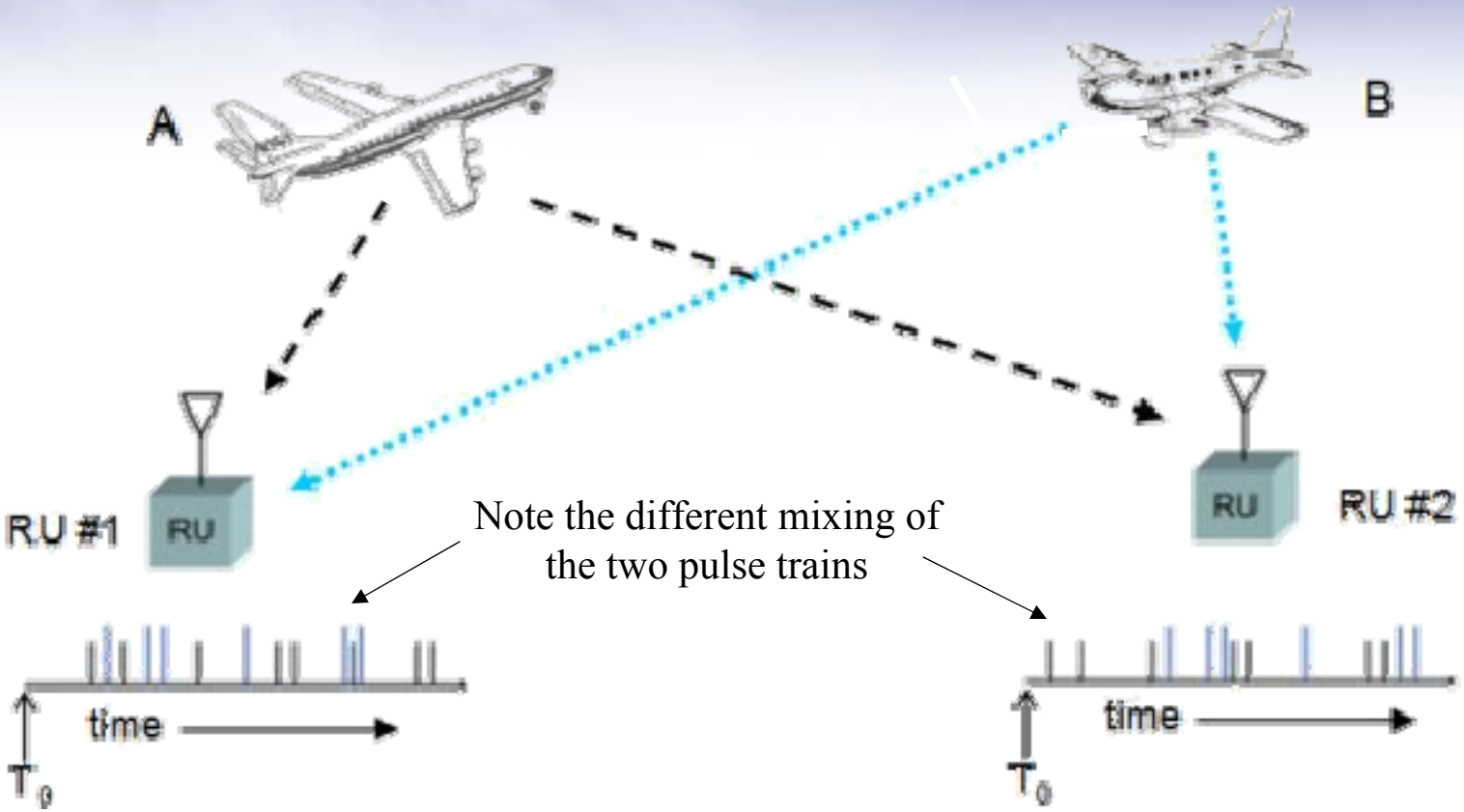
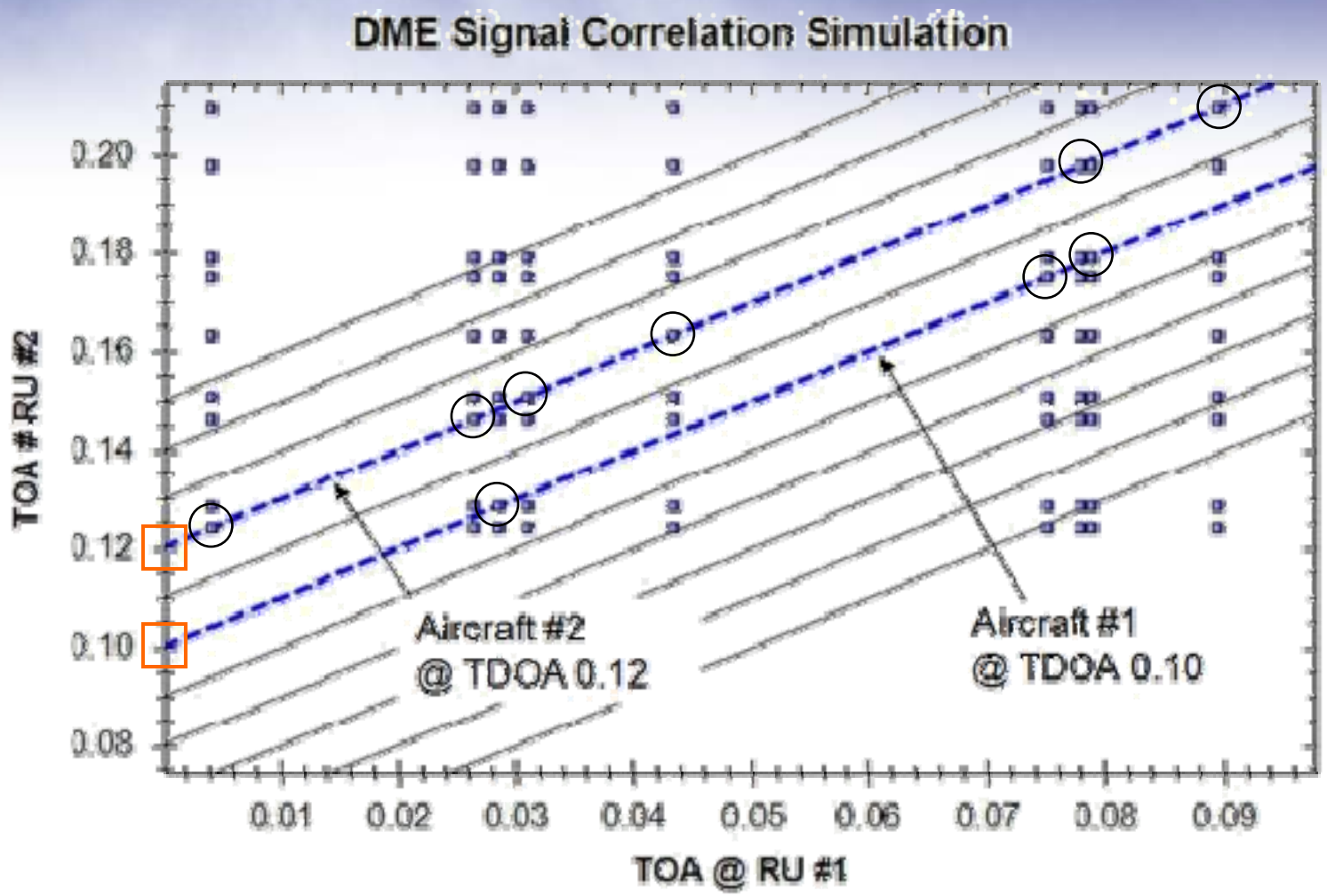
Case #3: Two aircraft



Two aircraft emit pulse trains that are received differently at two RUs. As before, *the time interval between pulses for a particular aircraft remains the same when received at each RU*.

Two-aircraft correlation



Correlation of pulse trains from two targets with TDOAs at 0.10μs & 0.12μs

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Non-graphical correlation algorithm

Graphical representation is conceptually useful but not satisfactory for computation. Here is a much faster approach:

1. **Timestamp** the leading edge of each pulse received at each RU. Time can be UTC or an offset from any arbitrary T_0
2. **Accumulate** data and send them to a central Target Processor (TP) at a regular interval (0.25 to 0.5 second)
3. In the TP, **initialize** a 2-D matrix of pulse train times, RU #1 on one axis, RU #2 on the other
4. **Fill** the matrix with calculated time differences between every X and every Y. Most of these values are meaningless.
5. Using narrow bins, **tally** the frequency of occurrences of time differences from Step 4.
6. **Identify** statistically significant peaks in the frequency distribution
7. **Retrieve** TDOA values from identified pulse correlations for MLAT
8. **Repeat** steps 3-7 for remaining pairings of RUs (1-3, 2-3, etc.)

Example matrix

Pulse arrival times at RU #2

	4.8622	4.8624	4.9281	4.9479	5.09564	5.14530	5.17500	5.18225	5.18401	5.20389	. . .
5.01222	-0.15	-0.14973	-0.08403	-0.06424	0.083425	0.133082	0.162784	0.170028	0.17179	0.191666	
5.01249	-0.15027	-0.15	-0.0843	-0.06452	0.083151	0.132809	0.162511	0.169754	0.171517	0.191393	
5.04564	-0.18342	-0.18315	-0.11745	-0.09767	0.05	0.099658	0.12936	0.136603	0.138366	0.158242	
5.07819	-0.21597	-0.2157	-0.15	-0.13021	0.017452	0.06711	0.096812	0.104055	0.105817	0.125693	
5.09798	-0.23576	-0.23548	-0.16979	-0.15	-0.00233	0.047325	0.077026	0.08427	0.086032	0.105908	
5.16510	-0.30288	-0.30261	-0.23691	-0.21713	-0.06946	-0.0198	0.009901	0.017145	0.018907	0.038783	
5.29530	-0.43308	-0.43281	-0.36711	-0.34732	-0.19966	-0.15	-0.1203	-0.11305	-0.11129	-0.09142	
5.29625	-0.434			.34828	-0.20061	-0.15095	-0.12125	-0.11401	-0.11224	-0.09237	
5.30297	-0.4			5499	-0.20732	-0.15767	-0.12796	-0.12072	-0.11896	-0.09908	
5.32500	-0.462			.37703	-0.22936	-0.1797	-0.15	-0.14276	-0.14099	-0.12112	
5.33225	-0.47003		0.40405	-0.38427	-0.2366	-0.18695	-0.15724	-0.15	-0.14824	-0.12836	
5.33401	-0.47179	-0.47152	-0.40582	-0.38603	-0.23837	-0.18871	-0.15901	-0.15176	-0.15	-0.13012	
5.35389	-0.49167	-0.49139	-0.42569	-0.40591	-0.25824	-0.20858	-0.17888	-0.17164	-0.16988	-0.15	
5.37442	-0.5122	-0.51193	-0.44623	-0.42644	-0.27877	-0.22912	-0.19941	-0.19217	-0.19041	-0.17053	
5.37466	-0.51244	-0.51217	-0.44647	-0.42668	-0.27902	-0.22936	-0.19966	-0.19241	-0.19065	-0.17077	

Interior cells contain calculated <u>time differences</u> between pulse arrival times at each RU

Pulse arrival times at RU #1

Partial matrix, arbitrary time units

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Evaluating the matrix

	4.8622	4.8624	4.9281	4.9479	5.09564	5.14530	5.17500	5.18225	5.18401	5.20389
5.01222	-0.15	-0.14973	-0.08403	-0.06424	0.083425	0.133		70028	0.17179	0.191666
5.01249	-0.15027	-0.15	-0.0843	-0.06452	0.083151	0			0.171517	0.191393
5.04564	-0.18342	-0.18315	-0.11745	-0.09767	0.05	0.0		3	0.138366	0.158242
5.07819	-0.21597	-0.2157	-0.15	-0.13021	0.017452	0.06711	0.096812	0.104055	0.105817	0.125693
5.09798	-0.23576		0.16979	-0.15	-0.00233	0.047325	0.077026	0.08427	0.086032	0.105908
5.16510				-0.21713	-0.06946	-0.0198	0.009901	0.017145	0.018907	0.038783
5.29530				34732	-0.19966	-0.15	-0.1203	-0.11305	-0.11129	-0.09142
5.29625				.34828	-0.20061	-0.15095	-0.12125	-0.11401	-0.11224	-0.09237
5.30297				-0.35499	-0.20732	-0.15767	-0.12796	-0.12072	-0.11896	-0.09908
5.32500	-0.46278				-0.22936	-0.1797	-0.15	-0.14276	-0.14099	-0.12112
5.33225	-0.47003				-0.2366	-0.18695	-0.15724	-0.15	-0.14824	-0.12836
5.33401	-0.47179				0.23837	-0.18871	-0.15901	-0.15176	-0.15	-0.13012
5.35389	-0.49167					0.20858	-0.17888	-0.17164	-0.16988	-0.15
5.37442	-0.5122	-0.51199				12	-0.19941	-0.19217	-0.19041	-0.17053
5.37466	-0.51244	-0.51217	-0.4			5	-0.19966	-0.19241	-0.19065	-0.17077

Note the recurrent value -0.15

Do any time differences occur significantly more frequently than others?

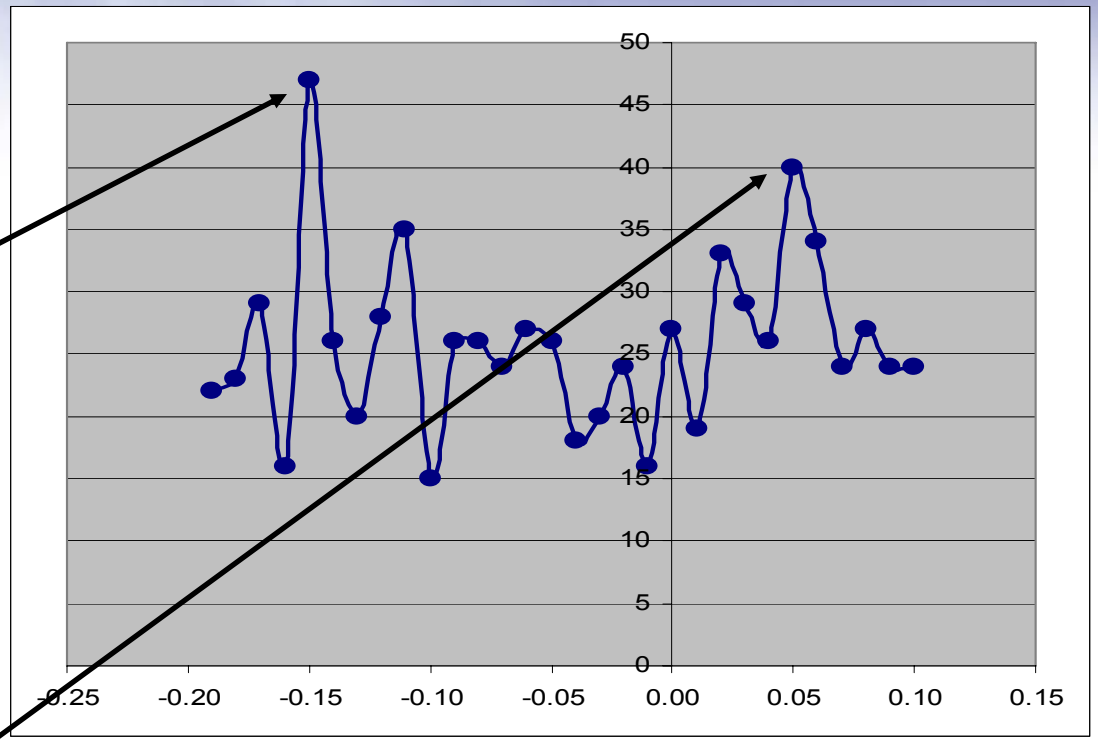
If so, then they represent aircraft

Multiple peaks in abundance represent multiple aircraft.

Tally (bin) frequencies of differences

Ranges	Count
<-0.20	-
-0.19	22
-0.18	23
-0.17	29
-0.16	16
-0.15	47
-0.14	26
-0.13	20
-0.12	28
-0.11	35
-0.10	15
0.01	19
0.02	33
0.03	29
0.04	26
0.05	40
0.06	34
0.07	24
0.08	27
0.09	24
0.10	24

Data omitted



Graph of binned frequencies of time offsets derived from table to the left. Note peaks at -0.15 and +0.05

Binned counts of time offsets of the full data set. Note discontinuity. Highlighted time differences are >2σ from mean

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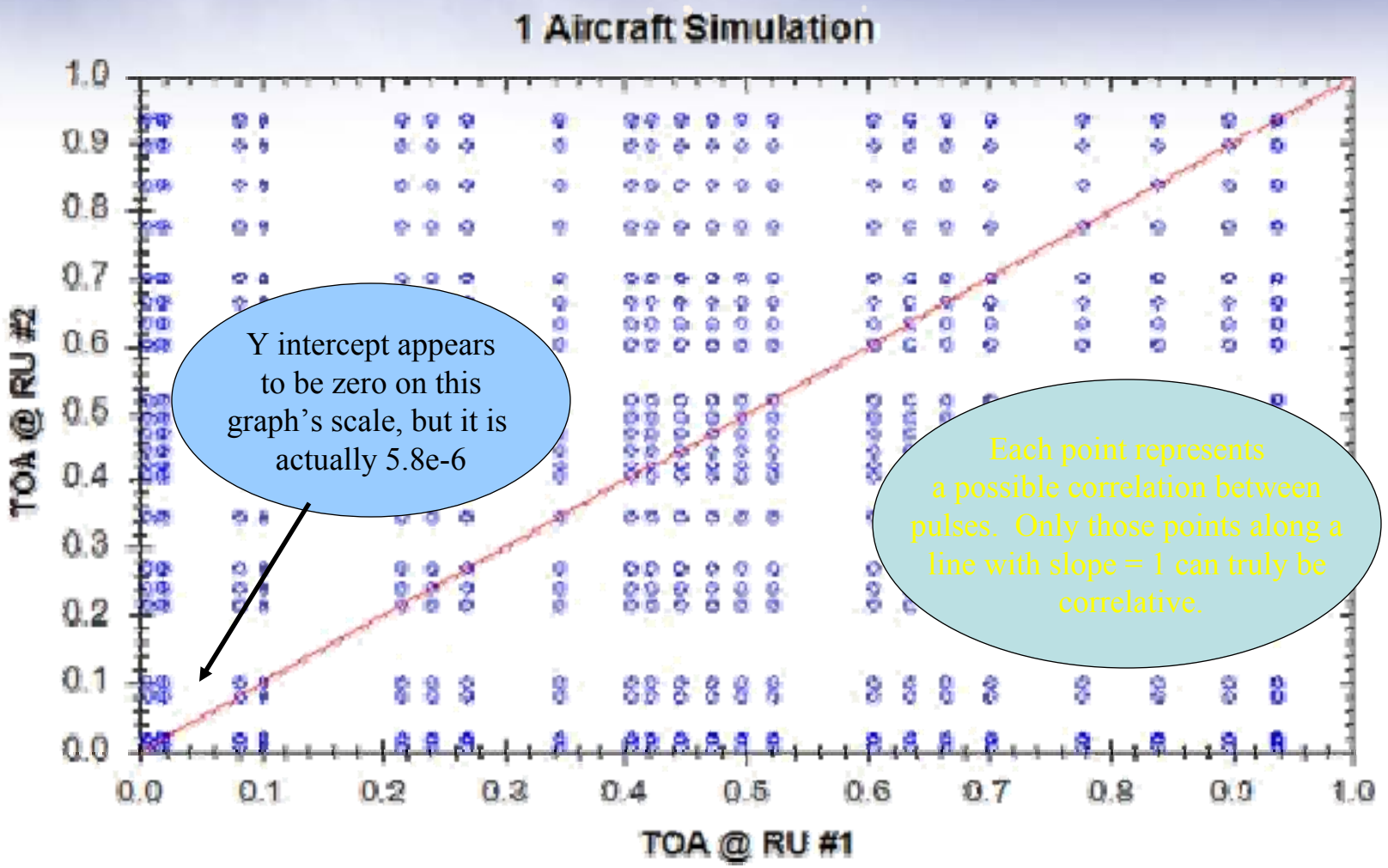
Simulation: one aircraft, 25 pulses/sec



Correlation diagram of 25 pulses received at each of two RUs during one second.

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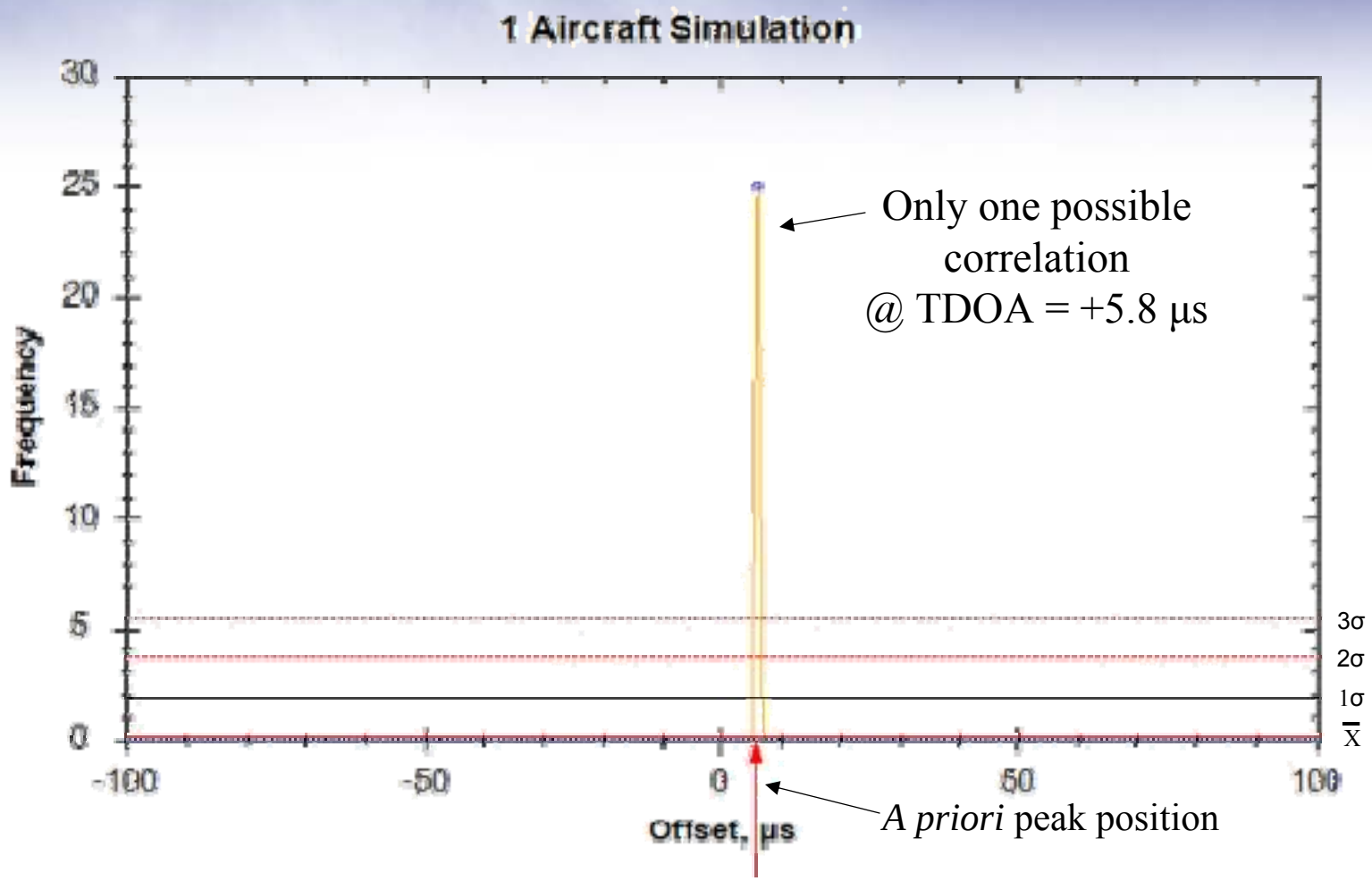
Identical data plotted as a histogram



Histogram, 1 µs bin width.

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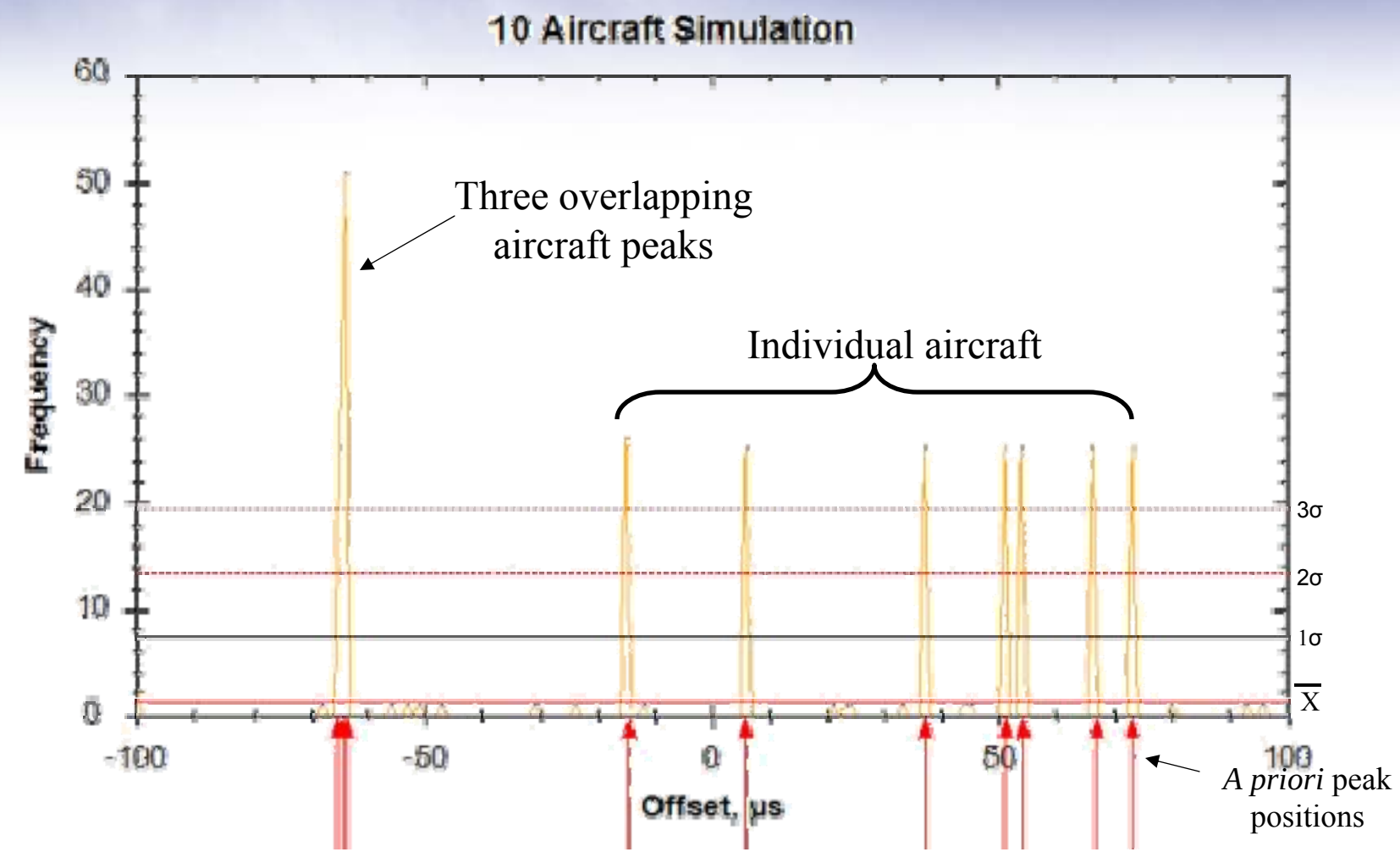
Simulation: ten aircraft, 25 pulses/sec



Simulation with ten aircraft emitting 25 pulses/sec, received at two RUs.
1 µs bin width. All ten aircraft peaks exceed 3σ from the mean.

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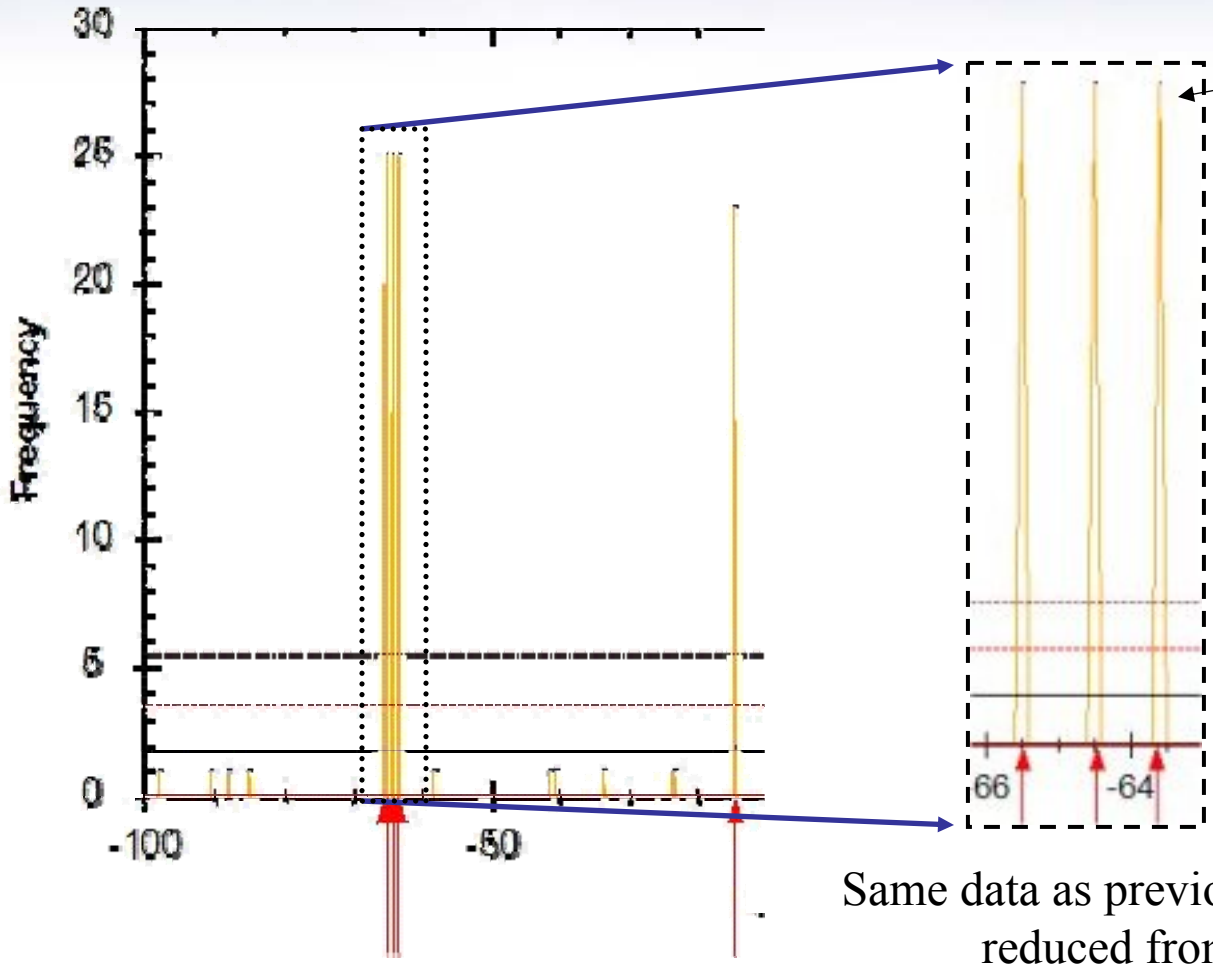
Narrower bin width separates overlapping peaks



"Overlapping" peaks are discernable but at the expense of longer computation time

Same data as previous graph but bin width reduced from 1 μs → 0.1 μs

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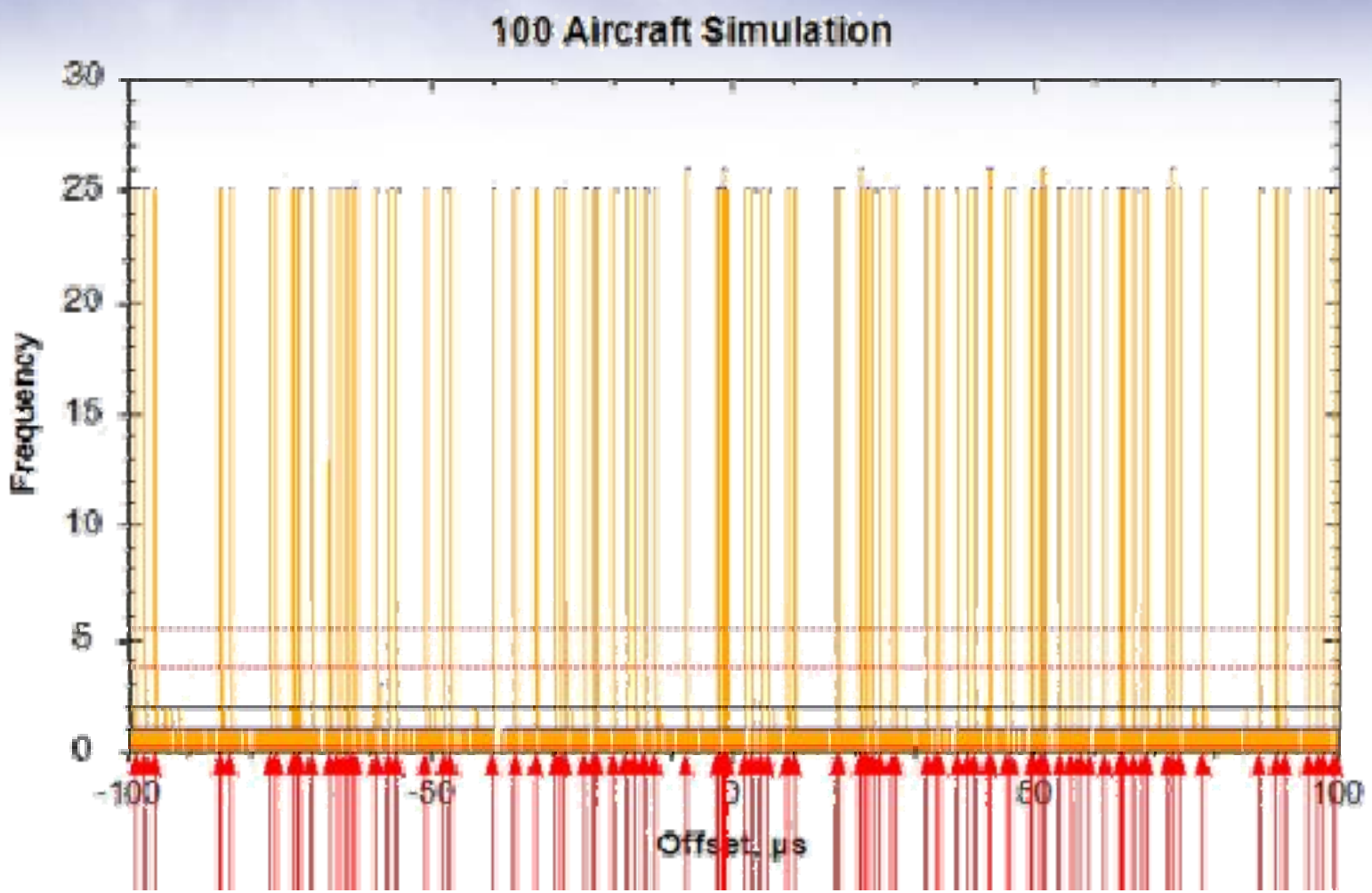
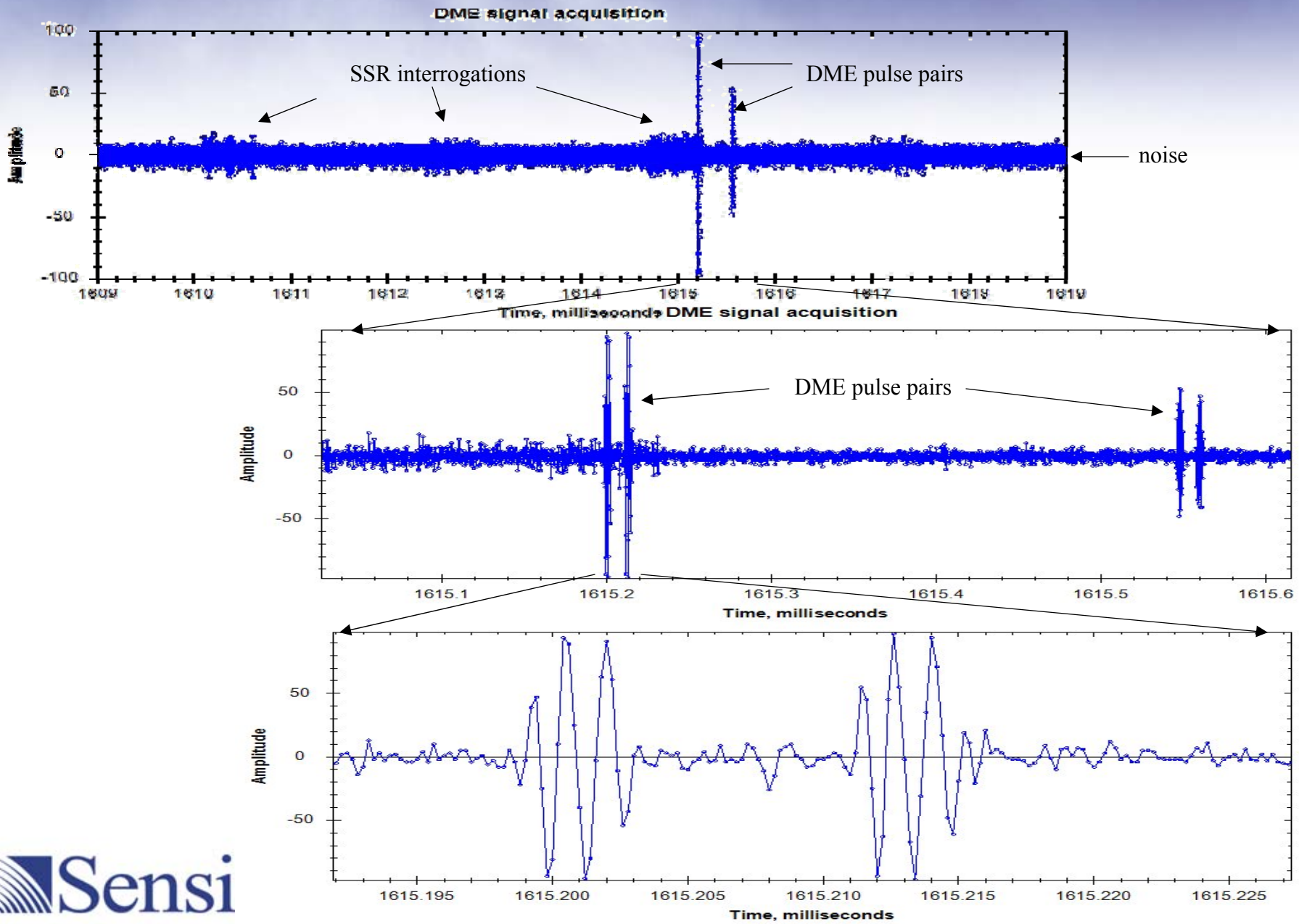
Simulation: 100 aircraft, 25 pulses/sec



Bin width 0.01 µs. This graph represents 2,500 DME pulses

Off-the-air signals (1073 MHz)



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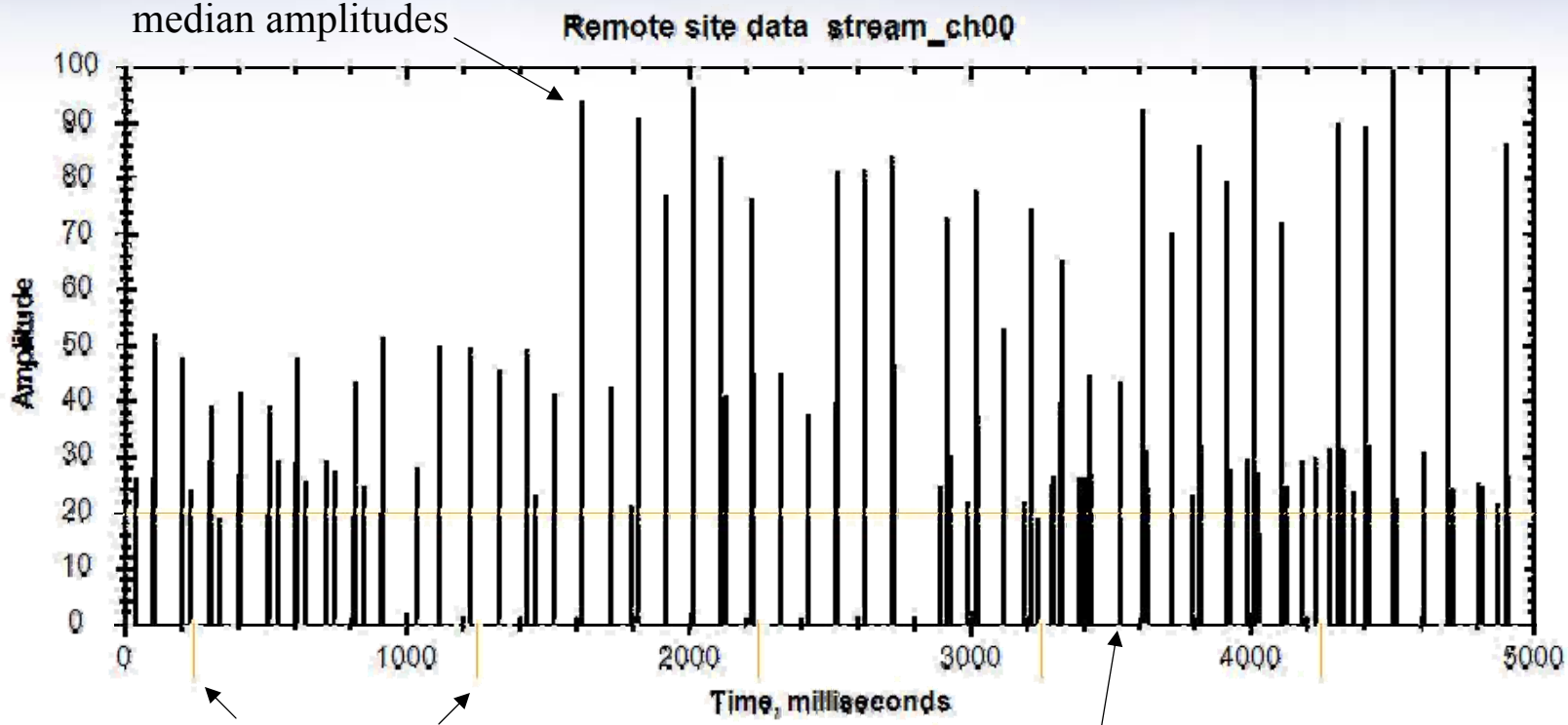
5 seconds of processed DME data

Pulse amplitude is the mean of the two pulse median amplitudes



GPS 1 PPS markers

Each vertical line represents the center of the pulse pair

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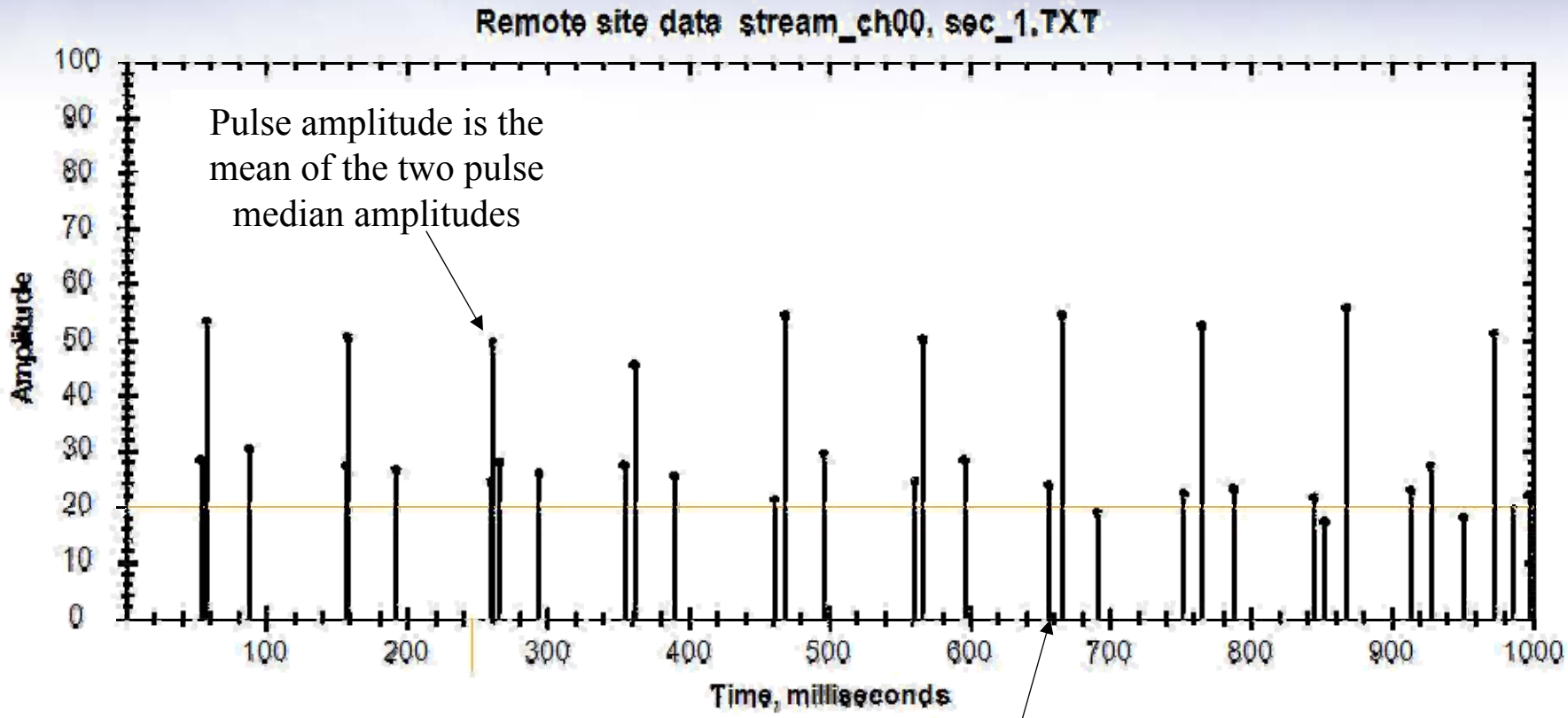
1 second of processed DME data



Pulse amplitude is the mean of the two pulse median amplitudes

Each vertical line represents the center of a pulse pair

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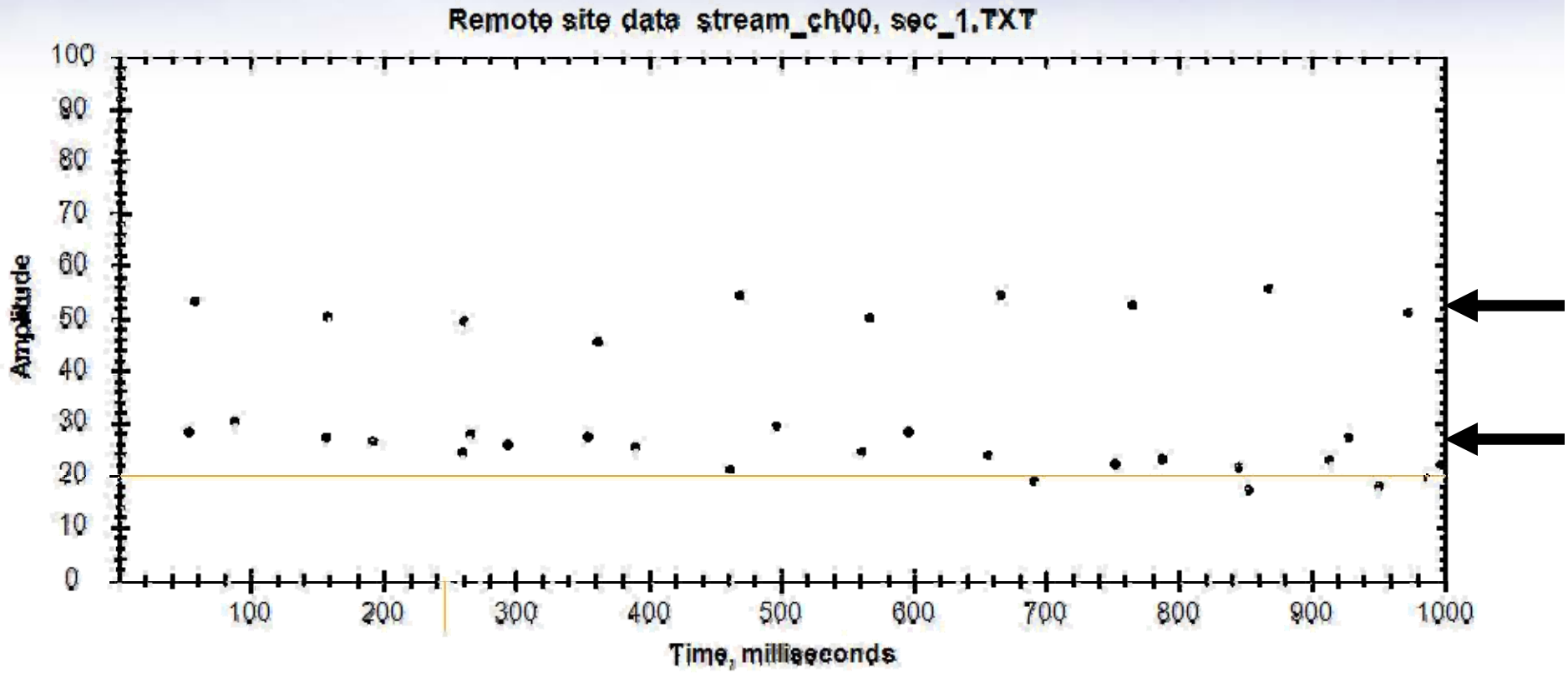
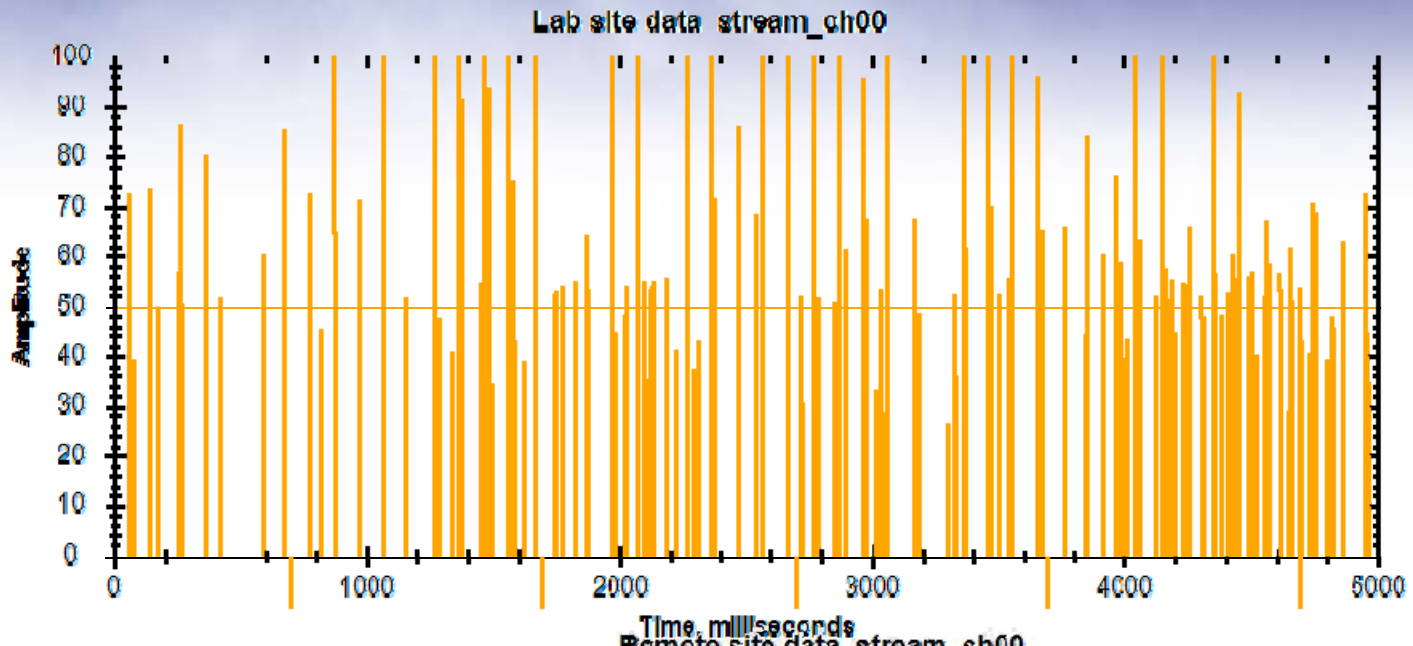
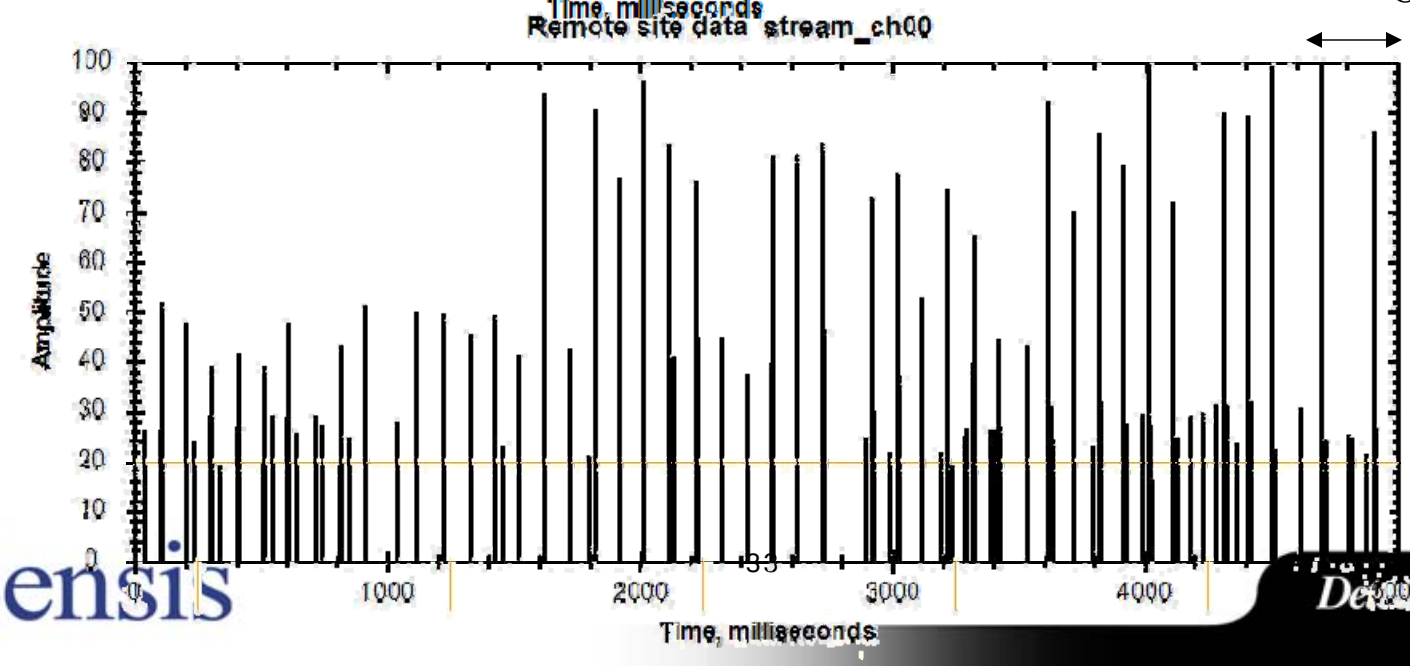
Two targets



Identical data to previous slide, plotted as circles

Simultaneous data from two sites (5 sec.)





Offset to align GPS 1PPS

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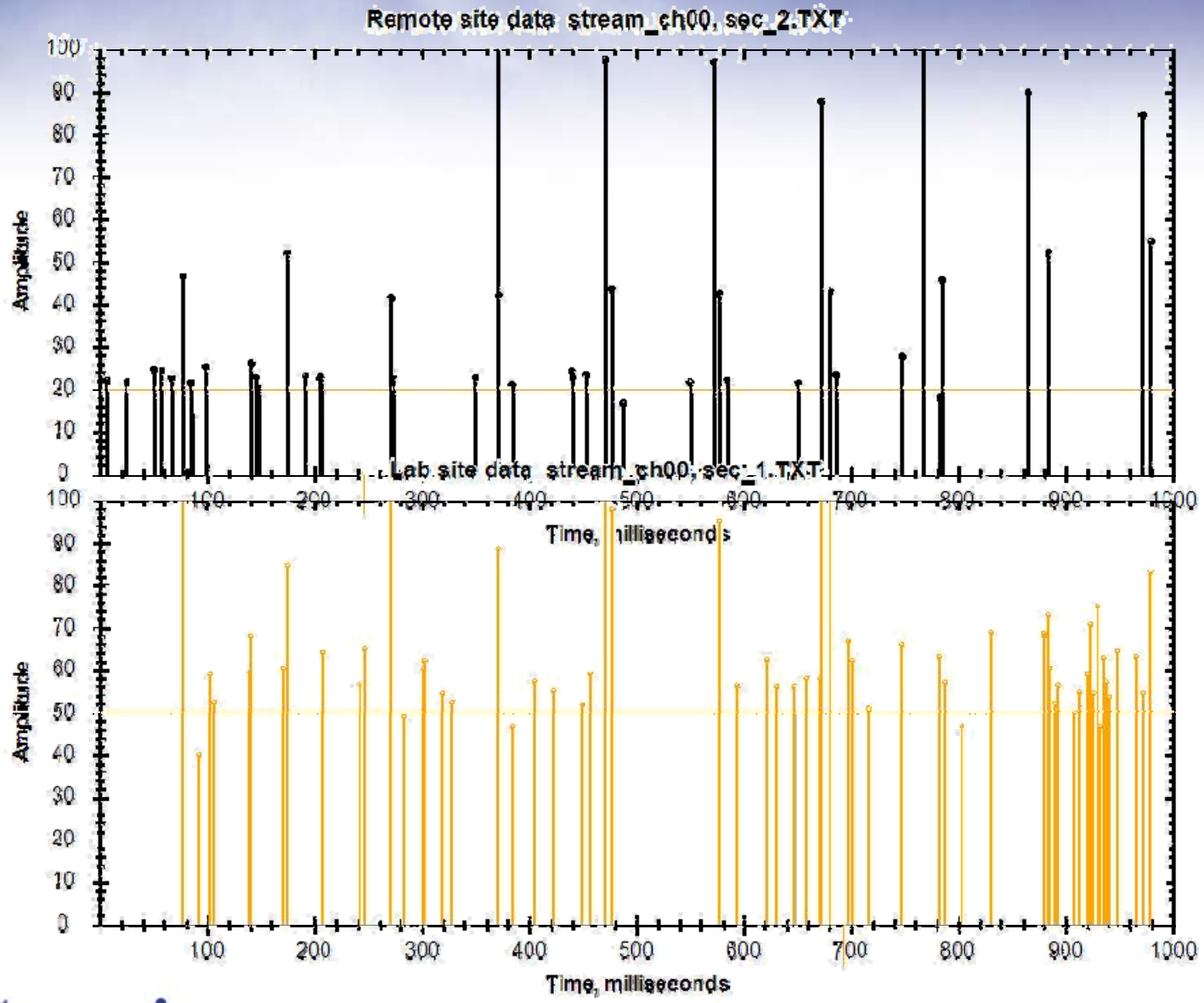
Simultaneous data, two sites (1 sec.)



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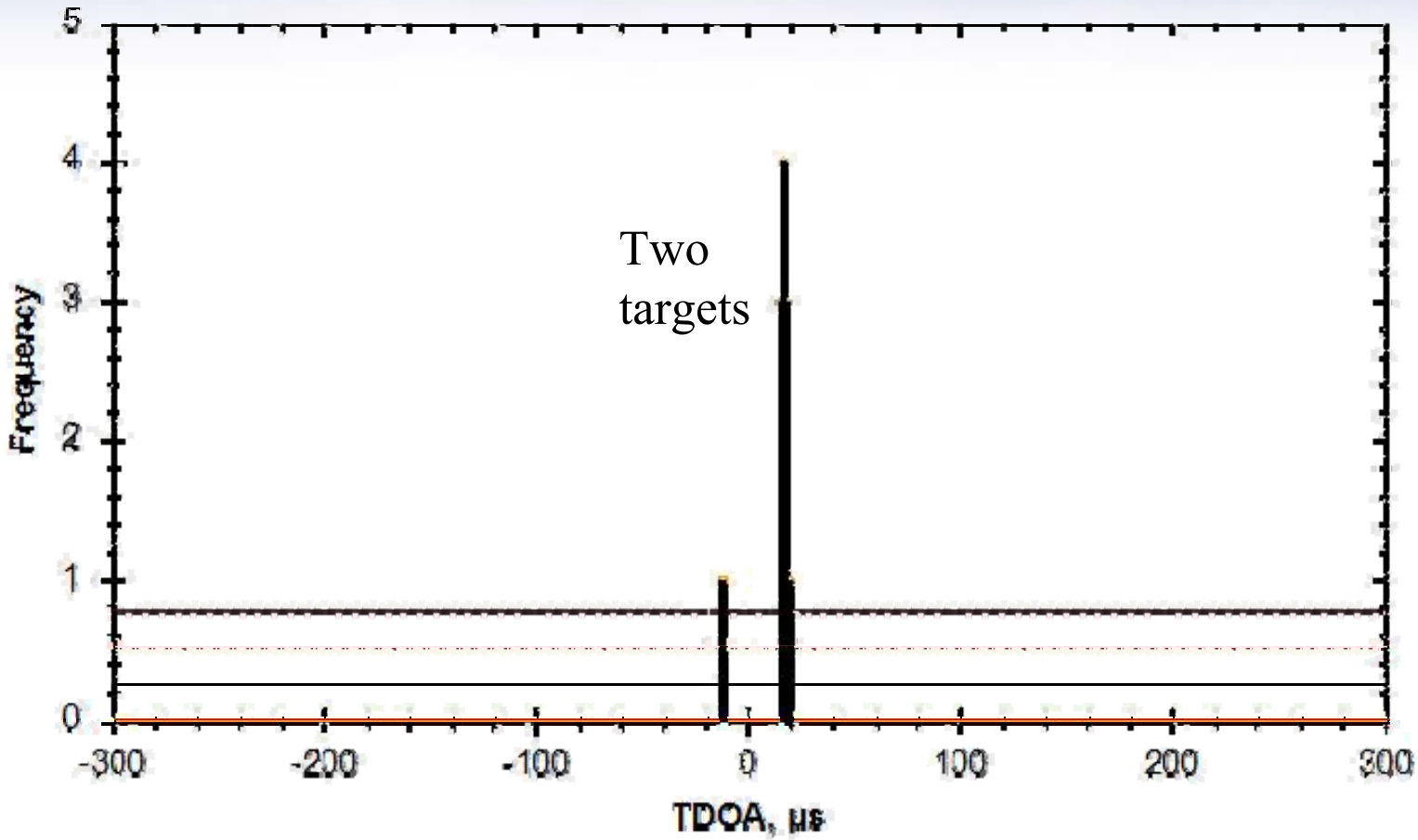
TDOA frequency plot



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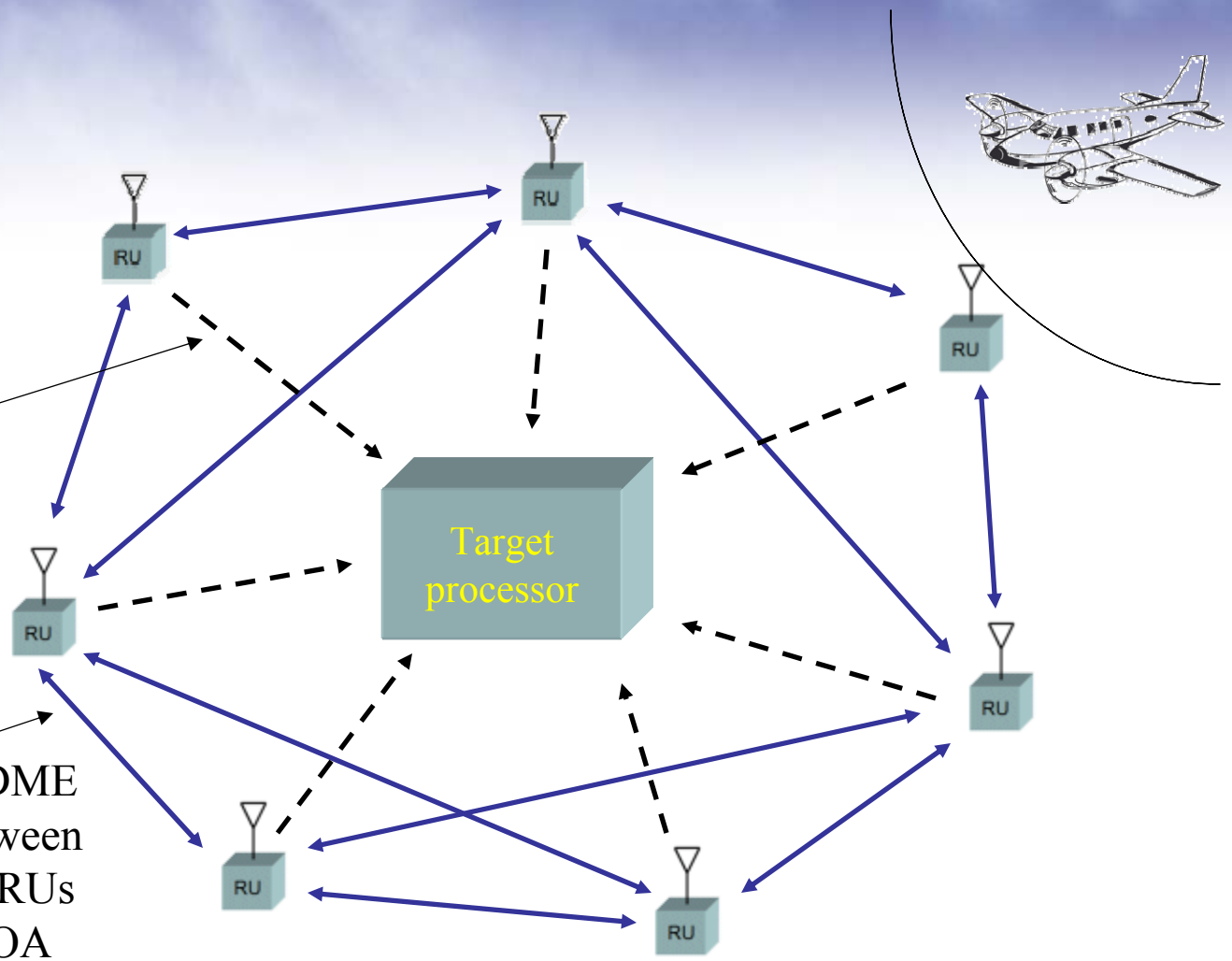
DME-based MLAT

1. Aircraft emits DME pulses

2. RUs collect pulse stream for 0.5 sec., then reports timestamps to Target Processor (TP)

3. TP correlates DME pulse streams between multiple pairs of RUs and derives TDOA values for each pair



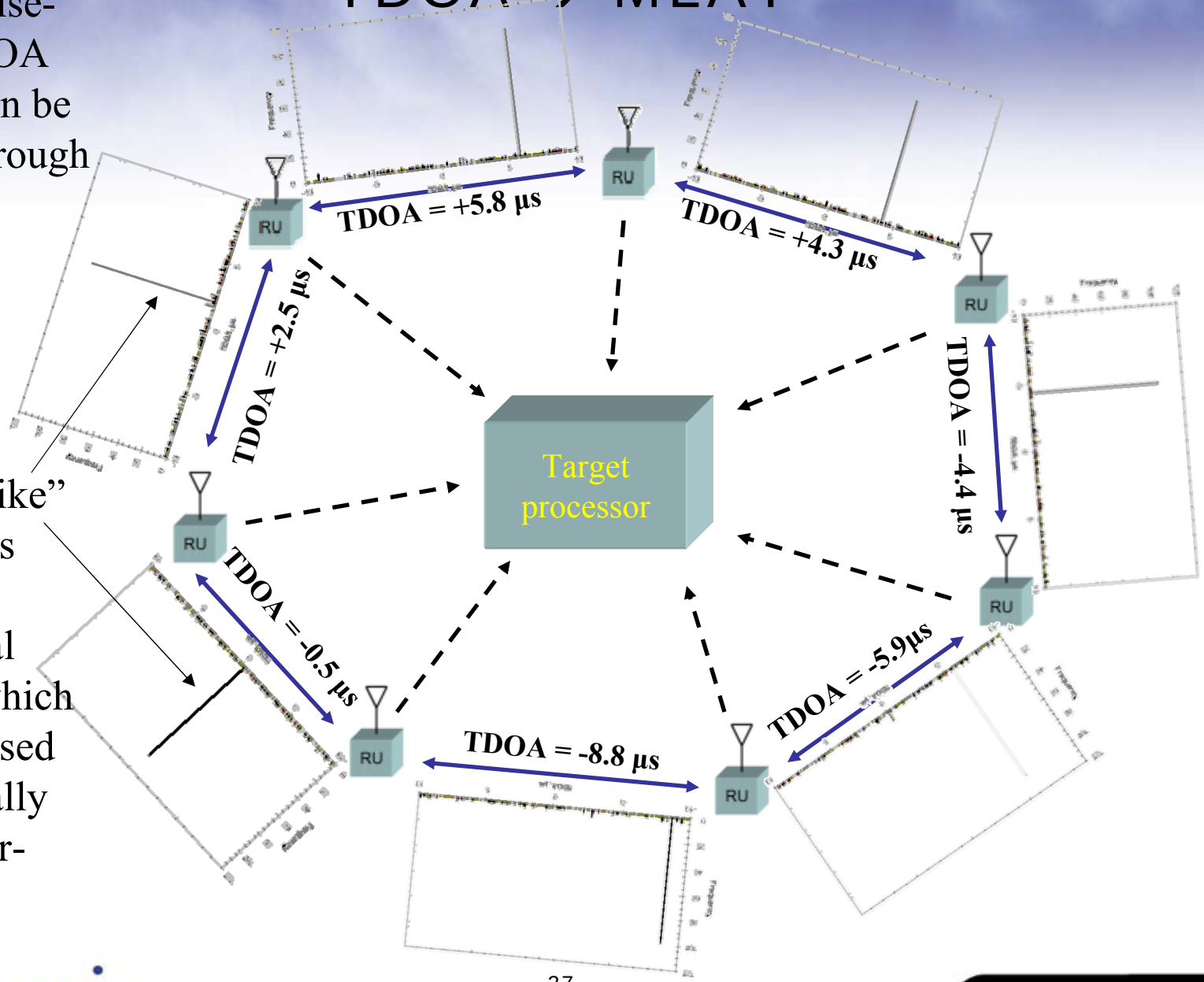
4. TDOAs *of individual pulses* form the basis for standard multilateration calculations

Sensis
Detect the Difference

TDOA → MLAT

Gross pulse-train TDOA values can be used for rough MLAT position estimates

Each "spike" represents many individual pulses, which may be used individually for higher-precision MLAT



Sensis

Detect the Difference

Discussion

- **Questions to be investigated**
  - How accurately can DME pulses be timestamped?
  - How brief can the reporting period be while still producing reliable position estimates?
  - How does ΔTDOA during a reporting period affect pulse stream correlation?
  - Multipath susceptibility
  - Interrogator waveform consistency
- **Implications**
  - Once correlated, DME pulses can be used for multilateration
  - This technique could also be used to multilaterate with other forms of pulsed emissions whose time interval is irregular
- **Acknowledgments**
  - This work was generously supported by Eurocontrol (http://www.eurocontrol.int) under contract E06/11020EB, with special thanks to Mr. Eric Potier and Mr. Andrew Desmond-Kennedy.