Multilateration Technology Overview

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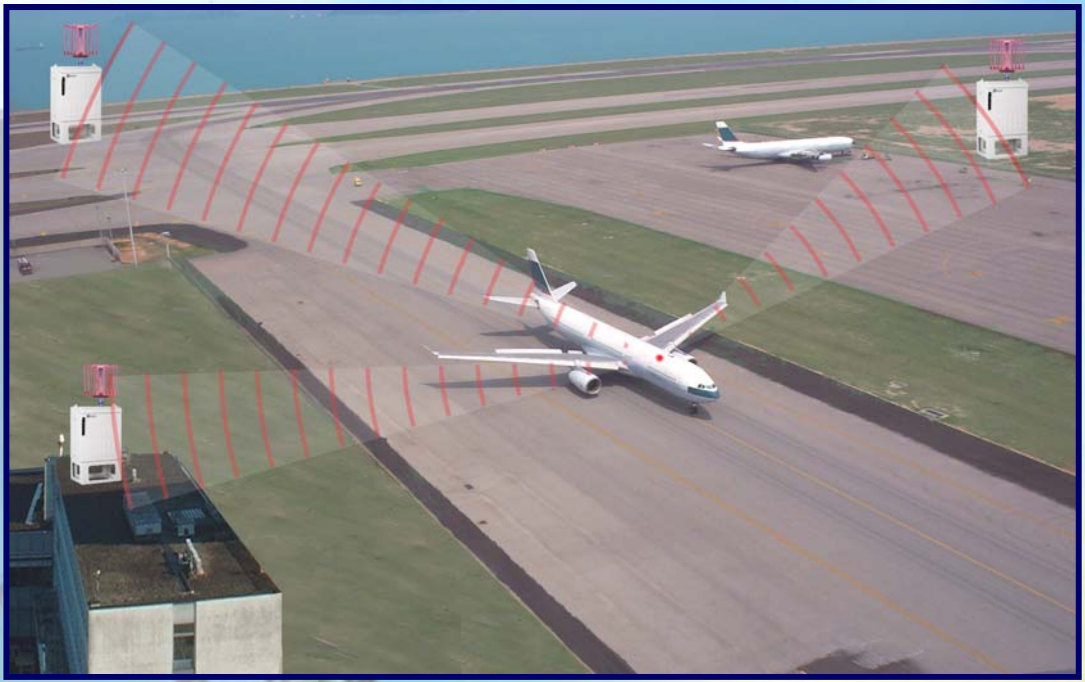
Presentation Agenda

- Multilateration Overview
- Transponder Types
- Multilateration Architecture
- Multilateration Algorithms
- Performance Characteristics
- Ongoing Issues

Multilateration Overview

Multilateration Surveillance

- **Tracks All Transponder Equipped Targets**
  - **Mode S**
  - **Mode A/C**
  - **Extended Squitter ADS-B**
- **Time Difference Of Arrival (TDOA) of Received Signals at Distributed Remote Units**



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Multilateration Constraints

- All Multilateration systems are affected equally by ...
  - Line Of Site
  - RF Signal Strength, Atmospheric Propagation

- All Multilateration systems are affected by ...
  - RF signal Multi-path
  - Signal Time stamping jitter and quantization
  - Multiple Signal Interference
  - Aircraft Transponder Performance
  - Communication Link Availability/Performance

Multilateration System Performance

Attribute	System Performance Specification
Update Rate	1 Hz (nominal)
Coverage	Typically provides Terminal Area up to Gates with one system. (dependent on RU siting)
Accuracy	• Better than 7.5m for all runways and taxiways; • Better than 20m for stands and apron
Target Capacity	Up to 500 targets/sec
Identification	Develops unique tracks for all Mode S and Mode A/C equipped aircraft using the 24-bit Mode S identification address and/or the 12-bit Mode A/C identity code. Determines the Mode A/C identity code for all aircraft, including Mode S equipped, inside the coverage area. The system provides the correct target ID with probabilities that exceed 99.9%
Probability of False ID	False Targets are less than 10^{-6}
Track Initiation	Track initiated within 5 seconds of initial transponder turn on or entrance into coverage area
Start-up Time	< 5 Minutes of initial start-up or restart in the event of main power loss
Switchover Time	< 1 second from primary to backup once fault has been identified.

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Why Multilateration?

- One Second Update Rate (Configurable)
- Highly Accurate Position
- Highly Reliable ID Information
- Distributed Sensors
  - Solves Line-Of-Site Problems
  - Improves System Reliability
- Usually Less Expensive Than SSR

Transponder Types

Transponder Types

- Mode A/C (also known as ATCRBS)
  - Four Digit Octal Code (12 bits)
  - Assigned by ATC
  - Only Respond To Interrogation
- Mode S
  - Six Digital Hexadecimal Code (24 bits)
  - Assigned Uniquely by Aircraft Transponder
  - Assigned Non-uniquely for Vehicles
  - Transmit Mode S Code Periodically
  - Respond To Interrogation for Mode A, Mode C, Flight ID
- Automatic Dependent Surveillance – Broadcast
  - Periodically Transmit ID, Position, etc.
  - No Interrogation Required

Multilateration Architecture

Architecture Decisions

- Processing Done By Remote Units
  - Processes All Detected Signals
  - Listen For Limited Time Periods
- Communication Between RU and Central Processing
  - Transmit Digitized Signal Data
  - Transmit All Detected Codes
  - Transmit Filtered Detected Codes
- Interrogation
  - Centralized vs. Distributed Interrogation
  - Active Interrogation vs. Passive Listening
  - All Call vs. Addressed
- Multipath Correction Scheme
  - Less Receiver Units, More Sophisticated Processing
  - More Receiver Units, Simpler Processing

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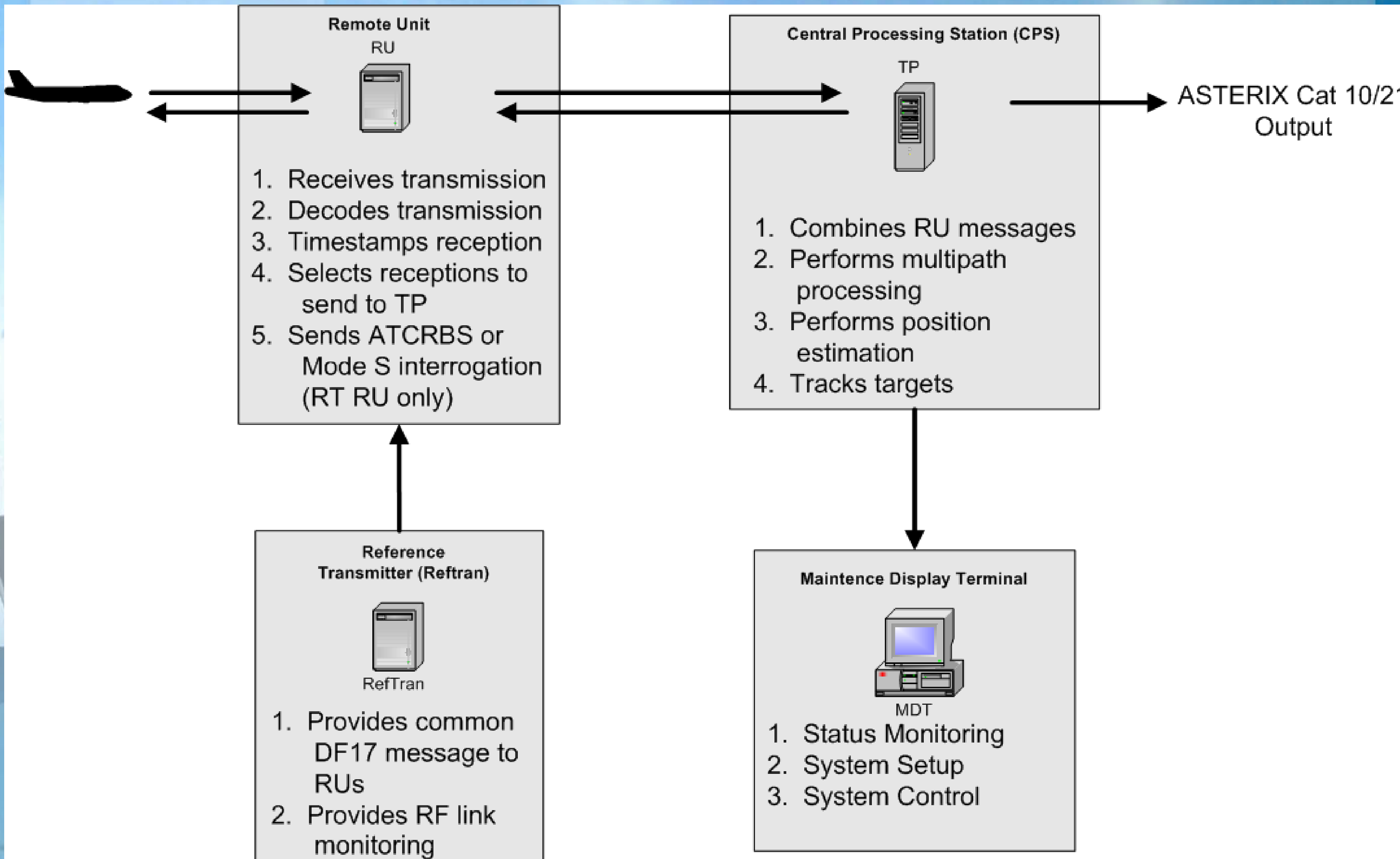
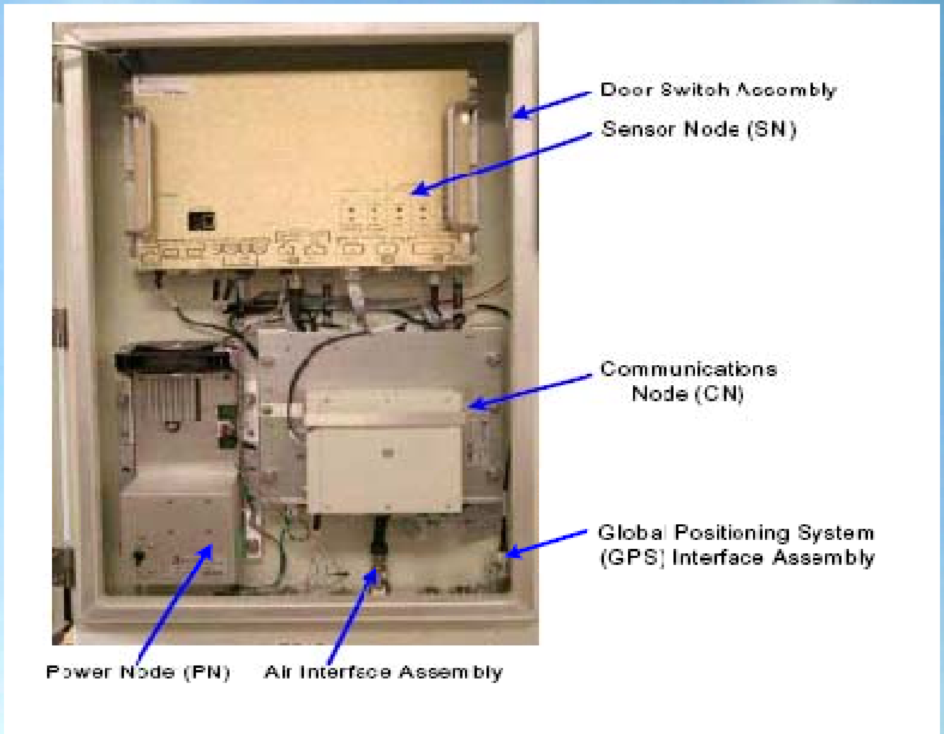
Multilateration System



Remote Unit Component



Characteristic	Value
Receiver	1090 MHz +/- 3 MHz Receiving Frequency Mode A, C, S, 1090ES ADS-B Input Impedance 50 Ω Voltage Standing Wave Radio (VSWR) maximum 1.5 Sensitivity: minimum -90 dBm Dynamic Range: nominal 90 dB
Transmitter	1030 MHz Transmit Frequency Mode A, C, S ICAO Annex 10 compliant

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Antennas Component

Sector Antenna

Omni Antenna

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Time Synchronization Component

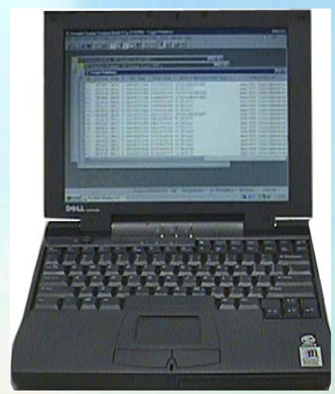
Reference Transmitter

GPS Time Source

Processing Components

Central Maintenance Terminal

Central Processing Station



Local Maintenance Terminal

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Remote Unit - Central Processor Communication

- Aerodromes Support a Variety Of Communication
  - Fiber Optic
    - Single Mode, Multi-mode
    - Point-to-point
    - Ring
  - Cat-5 Ethernet
    - Point-to-point
    - Ring
    - Power-Over-Ethernet
  - Telco Copper
    - DDM Modem
  - Dedicated Copper
    - DSL Modems
  - Wireless Networking
    - Variety of Frequencies

RU to CPS Communication is the most common problem with both installation and operation of multilateration systems!

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Multilateration Algorithms

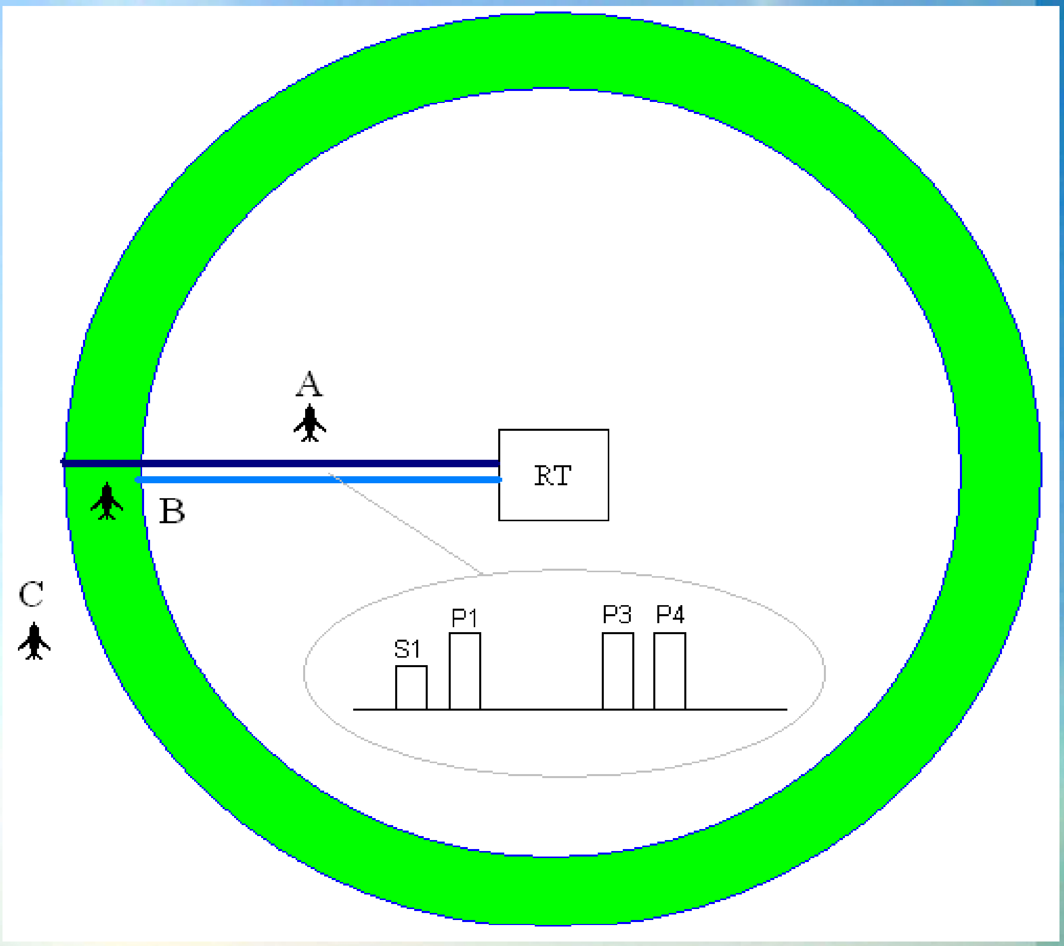
Interrogation

- Interrogation Schemes
  - Mode A/C All Call
  - Mode A/C Whisper Shout
  - Mode S All Call
  - Mode S Addressed
- Related Issues
  - Passive Processing vs. Data Comm. Capacity
  - Update Rate vs. Transponder Occupancy
  - Prioritization of Interrogation
  - Scheduling Among Multiple Transmit Units

Mode A/C (ATCRBS) Interrogation

Whisper / Shout Technique

- Interrogation Pulse is detected by targets out to certain range (dark blue)
- Suppression Pulse is detected by targets out to a smaller range (light blue)
- Only targets that detect the Interrogation Pulse, but do not detect the Suppression Pulse will respond
- Target B responds
- Targets A & C do not



Mode S Interrogation

- Must Interrogate Each Mode S Transponder Aircraft for Mode A Code and Mode C Height
- May also Interrogate Mode S Aircraft For Other Data Such as Flight ID
- Use of Addressed Mode S Interrogations Minimizes Transponder Occupancy and FRUIT
- Interrogation Algorithms May Consider:
  - Time Since Last Update
  - Validity of Other Data
  - Region of the Aerodrome
  - State Of Aircraft Track

Time Synchronization

- Time Synchronization within a multilateration system is key to achieving accuracy and low false track rates
- There are two primary methods of time synchronization:
  - Common Time Source (i.e. GPS, Central Clock)
    - Supports accuracy of approximately 10 meters
    - Simple processing
  - Alignment of Free Running Clocks
    - Supports accuracy of approximately 3-5 meters
    - Requires somewhat elaborate processing

Time Synchronization

- RU “Clocks” used for time stamping aircraft transponder signals are not synchronized.
- System requires a method of correcting the time used for TDOA calculations, known as <u>Time Tracking</u>.
  - Individual RU clocks must be corrected to a known reference for accurate time tracking
  - Multilateration is not possible unless the RU clocks are corrected to a known reference.
  - Reference Transmitters (RX) provides the <u>Reference Signal</u> used by the MLAT system to correct the individual RU times used for accurate time tracking.
- As part of system optimization, surveyed RU and RX antenna locations are manually entered into the System Adaptation

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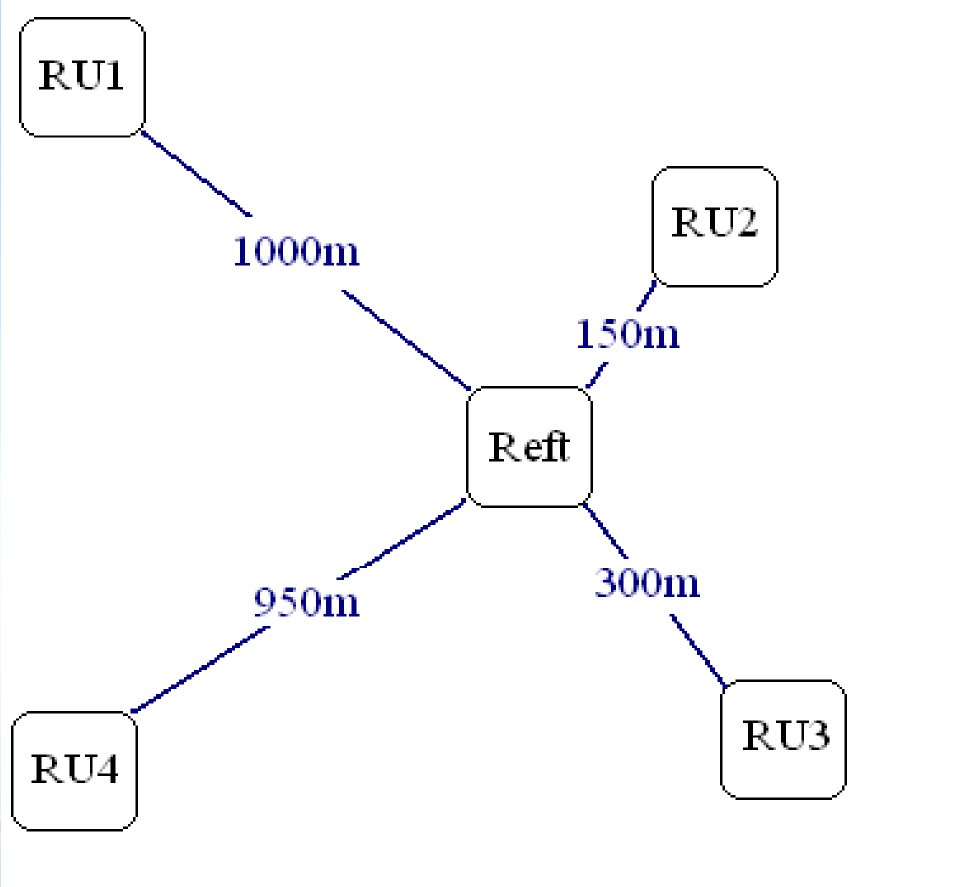
Time Synchronization

To make sense of reported RU detections of Reftran signals, software must use the precise locations of the antennas.

- **Example MLAT system shown has 4 RUs.**
- **The distance between each RU antenna and the Reftran antenna is precisely known.**

Figure not to scale

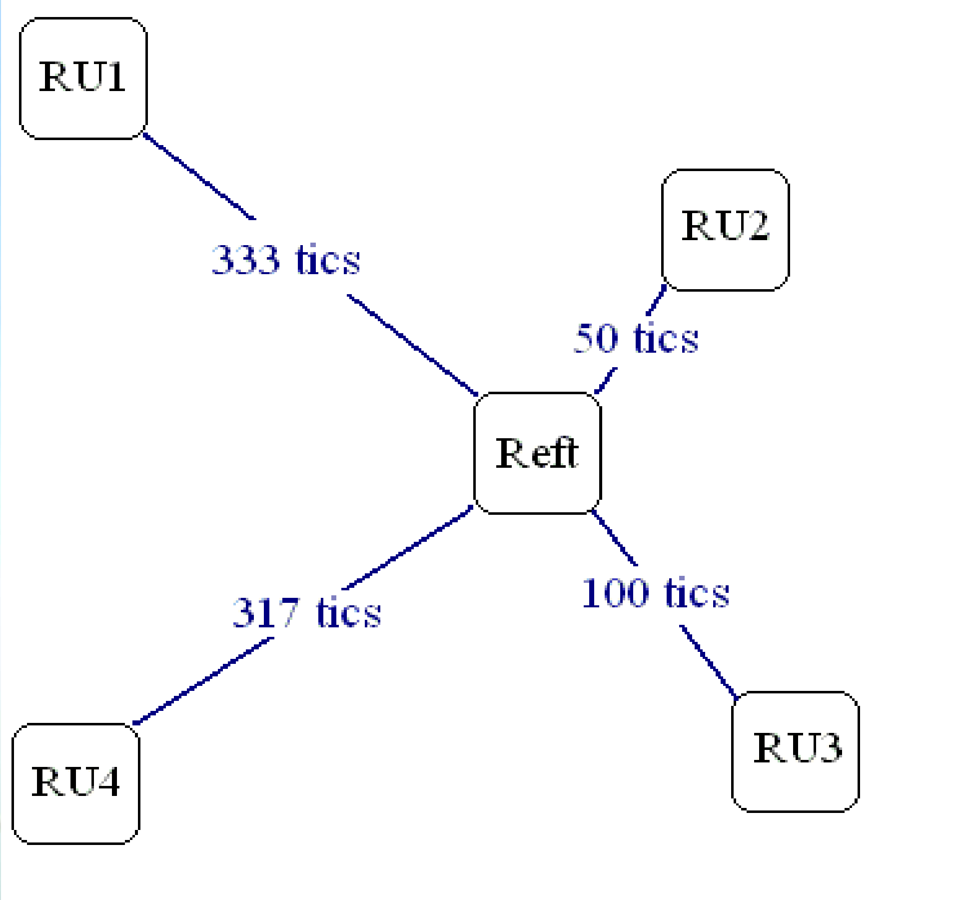


Time Synchronization

RU-Reftran distances are used to calculate expected travel times for the signals transmitted by the Reftran.

- Speed of light: 3e8 meters per second
- Equals 3 meters per tic
- Used to calculate expected TDOAs

Figure not to scale



Assume that RU1 is the Reference RU. This means that the travel time for RU1 is the basis for the relative travel times associated with the other RUs. It also means that the other RU clock values will be converted so they are in terms of RU1's clock value.

The table below lists the initial information available:

RU	Travel Time for Reftran Signal	Relative Travel time for Reftran Signal	Actual RU timestamp for Reftran detection
1	333 tics	0 tics	1,105,000,000
2	50 tics	-283 tics	0,703,000,000
3	100 tics	-233 tics	2,008,000,000
4	317 tics	-16 tics	0,901,000,000

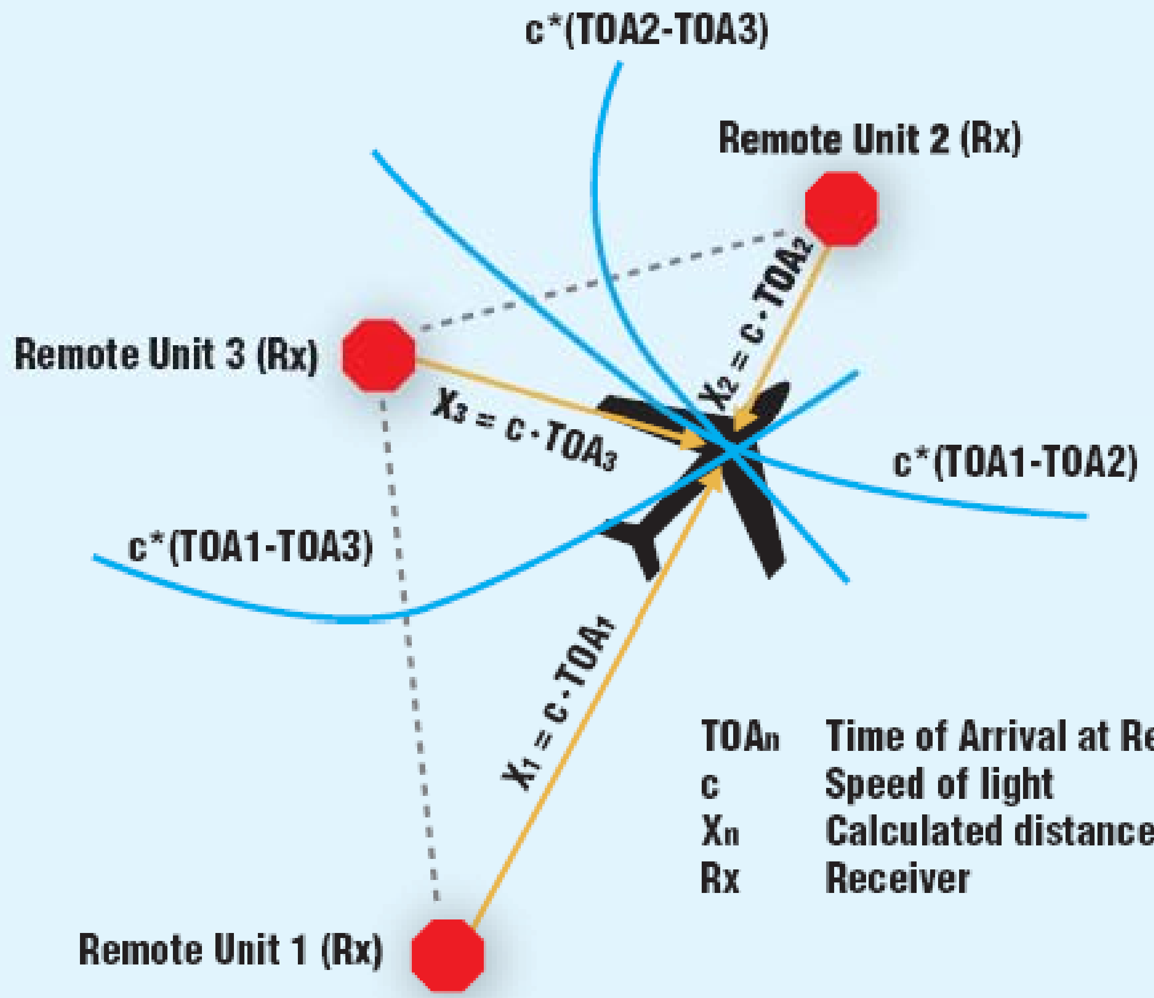
Time Synchronization

Refsync uses differences between an RU clock and the Reference RU clock, corrected for different travel times, to correlate the RU clocks

- **RU2 timestamp of 0,703,000,000 ~= RU1 timestamp of 1,105,000,000**
- **Signal expected to arrive at RU2 283 tics before arriving at RU1**
- **Delta of 0,402,000,000 adjusted by 283 tics to obtain corrected time**

RU	Actual RU timestamp for Reftran detection (tics)	Offset from Reference RU clock (tics)	Adjustment to offset based on relative travel times (tics)	RU Offset (tics)
1	1,105,000,000	0	0	0
2	0,703,000,000	+0,402,000,000	-283	+ 0,401,999,717
3	2,008,000,000	- 0,903,000,000	-233	- 0,903,000,233
4	0,901,000,000	+0,204,000,000	-16	+ 0,203,999,984

Time Difference Of Arrival



TOA_n	Time of Arrival at Remote Unit n
c	Speed of light
X_n	Calculated distance from TDOA algorithm
Rx	Receiver

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Error Detection and Elimination

- Time Difference Of Arrival and Error Detection and Elimination are Performed in Parallel, and also Iteratively
- The goal is to remove inaccurate timestamps from the data to support calculation of accurate position estimates

TDOA Example

Position Estimation processing

- Offsets in Refsync's time tracking tables used to correct RU time stamps

RU	Raw RU Time stamp	Corrected RU Time Stamp
1	2,100,007,888	1,000,000,007
2	1,000,000,000	1,000,000,000
3	0,123,456,789	0,999,999,987
4	2,098,765,432	0,999,999,980
5	0,767.676,767	1,000,000,015
6	0,456,321,998	1,000,000,120

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TDOA Example

Position Estimation processing

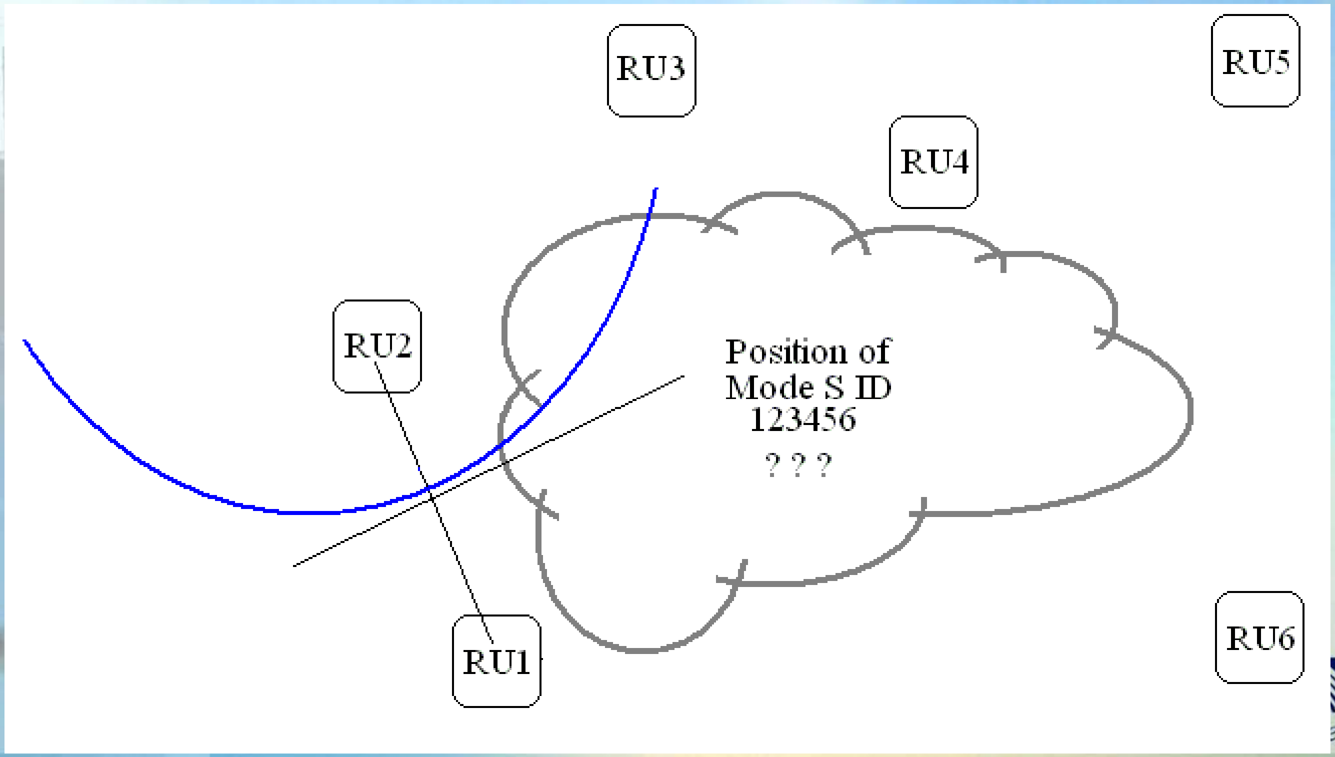
- Corrected time stamps = Time of Arrival
- TAPER uses Time Difference of Arrival to calculate positions
- RU-RU TDOAs are listed in the table below (notice the -/+ symmetry)

RU *n*	RU1 - *n*	RU2 - *n*	RU3 - *n*	RU4 - *n*	RU5 - *n*	RU6 – *n*
1	NA	- 7	- 20	- 27	8	113
2	7	NA	- 13	- 20	15	120
3	20	13	NA	- 7	28	133
4	27	20	7	NA	35	140
5	- 8	- 15	- 28	- 35	NA	105
6	- 113	- 120	-133	- 140	- 105	NA

TDOA Example

Position Estimation processing

- Each TDOA value represents an arc
- To comply with single TDOA value, target position must be on the arc
- Intersection of all arcs indicates target position



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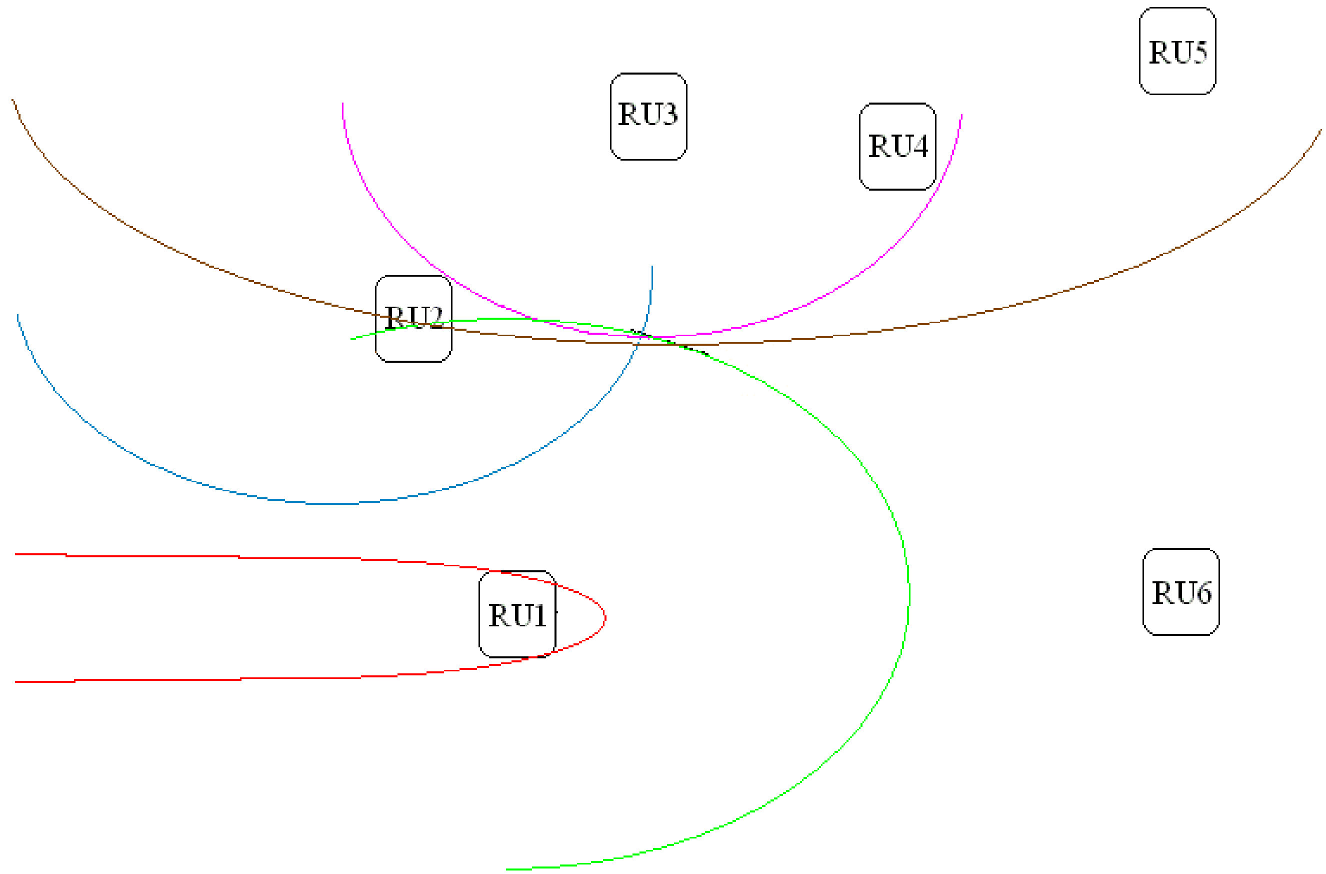
TDOA Example

Position Estimation Processing

- TDOA arcs for RU1 – RU*n* pairs
- Intersection of all arcs represents target location



TDOA Pair	Color	Measured TDOA
RU1 – RU2	Light Blue	7
RU1 – RU3	Purple	20
RU1 – RU4	Brown	27
RU1 – RU5	Green	- 8
RU1 – RU6	Red	- 113

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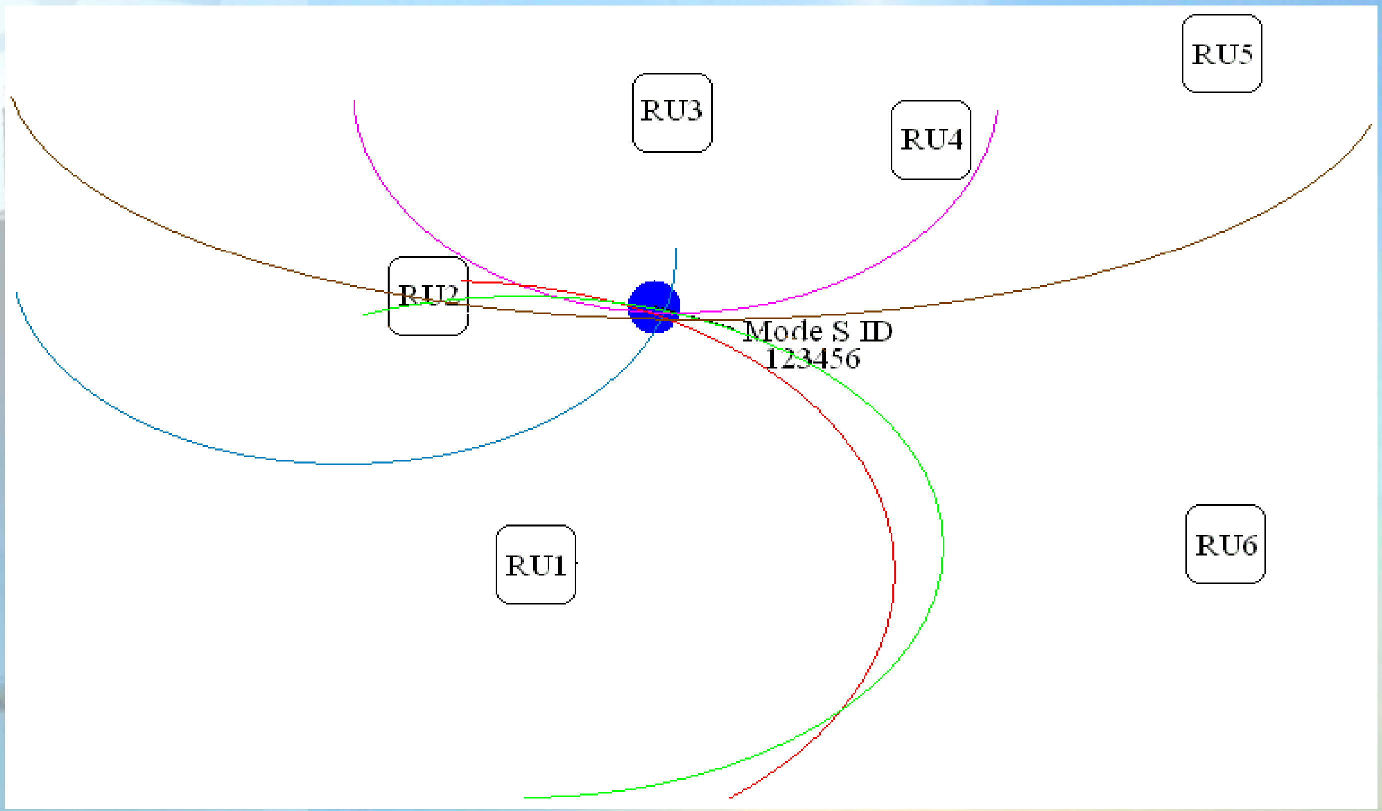
TDOA Example

Position Estimation processing

- For target already in track, propagated position is used as first guess
- Propagated position is used to work backwards
- Position used to calculate Expected TDOA values for RU-RU pairs



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TDOA Example

Position Estimation processing

- If target is actually on the blue dot, then the expected TDOA for RU1 & RU2 can be calculated
- Continue for all RU-RU pairs
- Table shows RU1 – RU*n* entries
- Complete table has 15 entries
- Delta column shows difference between actual and expected TDOAs
- Deltas compared with Max TDOA Delta for Prop. Track Position parameter
- Resulting curves shown on next slide

TDOA Pair	Color	Predicted TDOA	Measured TDOA	| Delta |
RU1 – RU2	Light Blue	6	7	1
RU1 – RU3	Purple	16	20	4
RU1 – RU4	Brown	12	27	15
RU1 – RU5	Green	- 11	- 8	3
RU1 – RU6	Red	- 8	- 113	105
RU2 – RU3	Not shown	9	13	4

TDOA Example

Position Estimation processing, course multipath check

- Some Delta values exceed the Max TDOA for Propagated Track Position parameter threshold (typical value = 20 tics)
- Information is used to eliminate RU detections that may be corrupted by multipath (reflected signals take much longer to reach an RU than expected)
- Notice that every pair that includes RU6 fails the check…
- RU6 is eliminated from the cluster & is not considered for further processing

TDOA Pair	Color	Predicted TDOA	Measured TDOA	| Delta |
RU1 – RU6	Red	- 8	- 113	105
RU2 – RU6	Not shown	- 19	- 120	101
RU3 – RU6	Not shown	- 28	- 133	105
RU4 – RU6	Not shown	- 20	- 140	120
RU5 – RU6	Not shown	0	- 105	105

TDOA Example

Position Estimation processing, fine multipath check

- Increased the resolution of multipath detection using Max TDOA Closed-form Solutions parameter (typical value = 5 tics)
- Instead of propagated track position, now use the calculated answer using any 3 RUs in the cluster to evaluate the remaining RUs
- RU6 has been eliminated, RUs 1, 2, 3, 4, and 5 remain
- Many, many iterations as size of cluster grows
- N choose K = N! / [(N-K)! K!]

RUs in the Closed-form Solution calculation	RUs to be evaluated using position
1, 2, 3	4, 5
1, 2, 4	3, 5
1, 2, 5	3, 4
1, 3, 4	2, 5
1, 3, 5	2, 4
1, 4, 5	2, 3
2, 3, 4	1, 5
2, 3, 5	1, 4
2, 4, 5	1, 3
3, 4, 5	1, 2

TDOA Example

- Position Estimation, fine Multipath check
- Common failures can be detected
- Max TDOA Closed-form Solution parameter used to evaluate
- RU4 always fails a comparison
- Closed-form solutions that use RU4 always result in both compared RUs failing
- RU4 is eliminated using fine Multipath check

Iteration	Closed-form RUs	Failed RUs	Passed RUs
1	1, 2, 3	4	5
2	1, 2, 4	3, 5	
3	1, 2, 5	4	3
4	1, 3, 4	2	5
5	1, 3, 5	4	2
6	1, 4, 5	2, 3	
7	2, 3, 4	1, 5	
8	2, 3, 5	4	1
9	2, 4, 5	3	1
10	3, 4, 5	1, 2	

The Multilateration Tracker performs the following main functions:

- Qualifies Position Estimates
- Models Target Track behavior
- Maintains database of Target Track information
- Sends interrogation requests

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Multilateration Tracking

- Three Simultaneous models:
  - Stationary Model
  - Constant Velocity Model
  - Accelerating Model
- Only one is actively applied to the target track
- Parameters allow for control of:
  - How each model works
  - How ASTP transitions from one model to another

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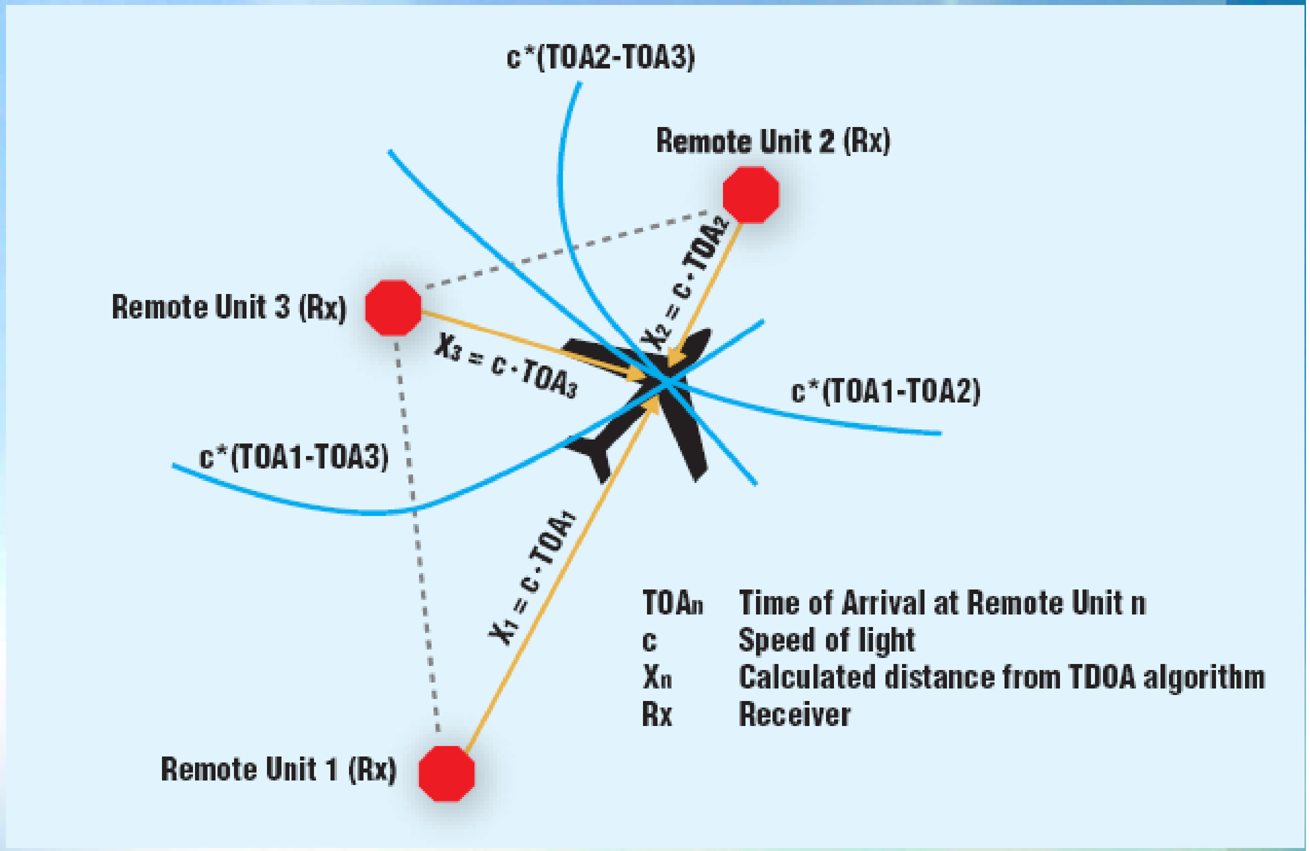
Processing Regions

- *The following regions are examples of processing regions defined for the multilateration system to minimize the number of bad positions received.*
  - *AIRPORT COVERAGE Region*
  - *MULTIPATH Region*
  - *NUMBER REPLIES Region*
  - *MLAT TRACKER Region*
  - *CRITICAL RU Region*

Range Aided

- Uses Two-Way Interrogation-Reply time to Calculate Range From Interrogating Unit
- For Targets Outside of the Multilateration System Unit Cluster, Can Improve Accuracy
- Unpredictability of Target Transponder Response Time Reduces Accuracy
- Accuracies of Approximately 75 Meters Are Possible



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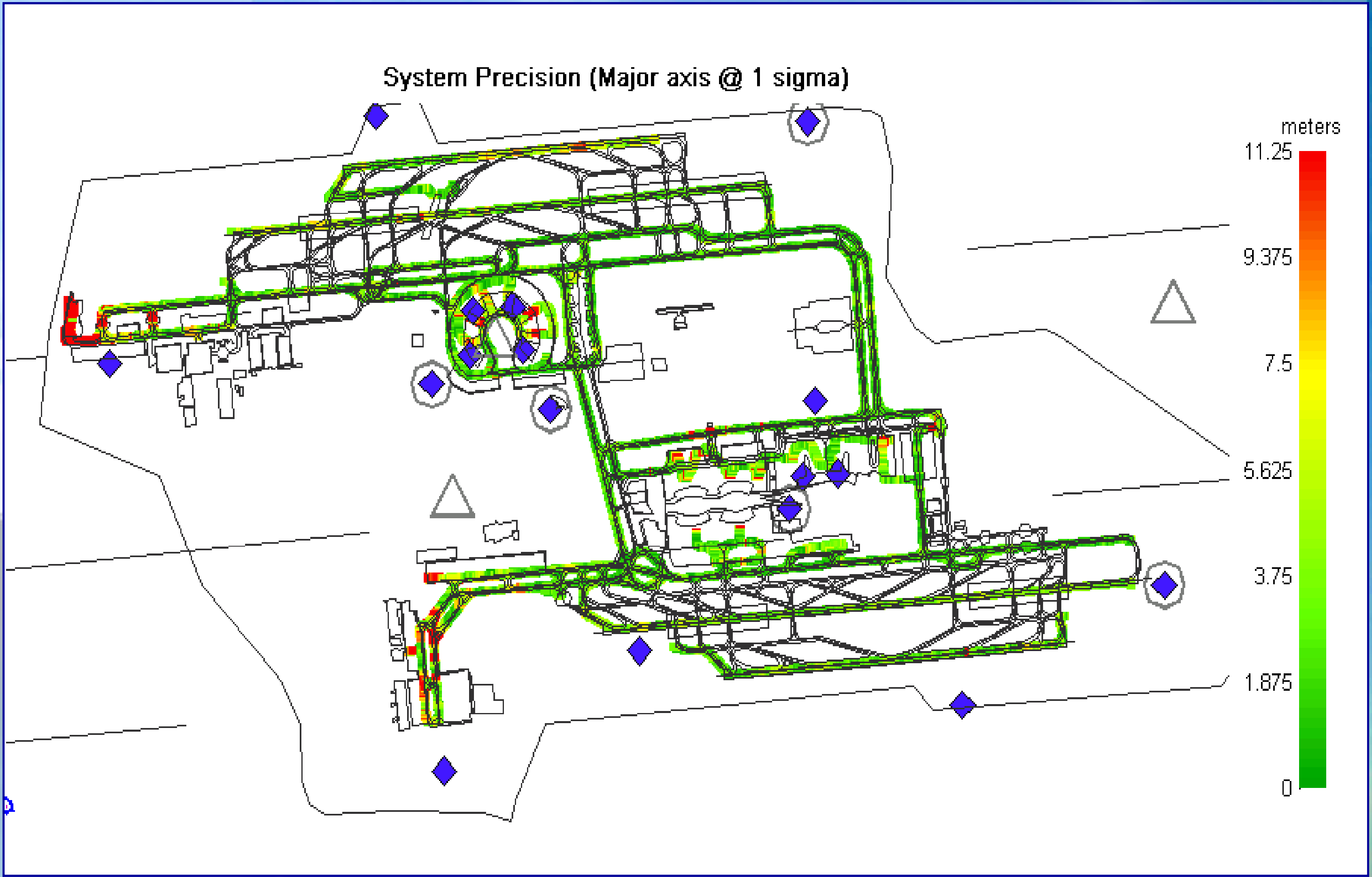
Performance Characteristics

Coverage

- Typical Coverage Requirements Include:
  - All Runway and Taxiway Surfaces
  - All or Most Apron Areas
    - Include all centerlines, not always to the gate
    - May exclude infrequently used
    - May exclude very difficult to cover areas
  - Approach and Departure Corridors
    - Out far enough to overlap with Terminal/Approach Radar
  - Above the Aerodrome surface up to 100-300 meters

Coverage Analysis



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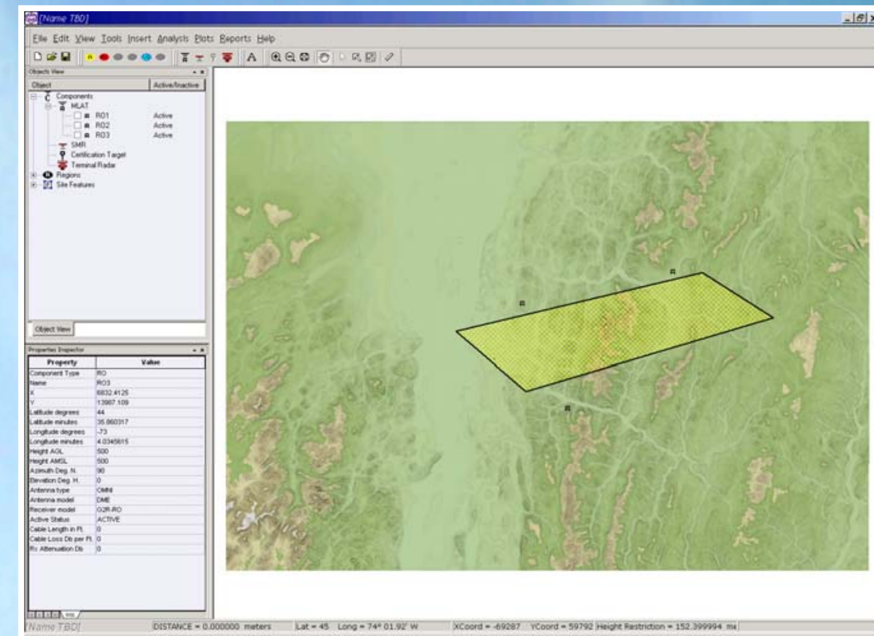
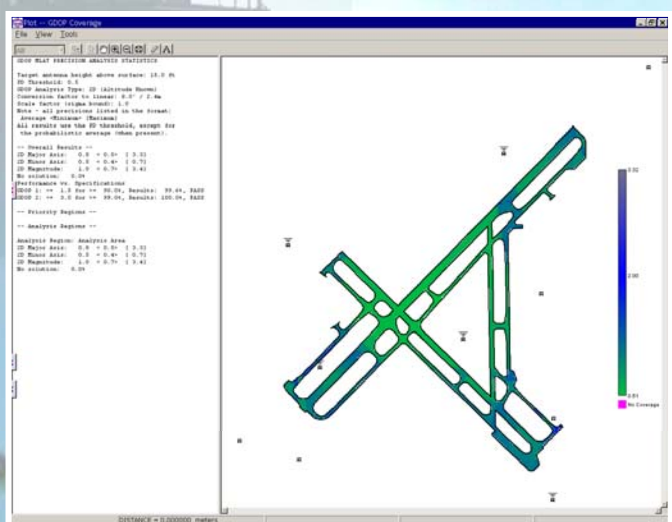
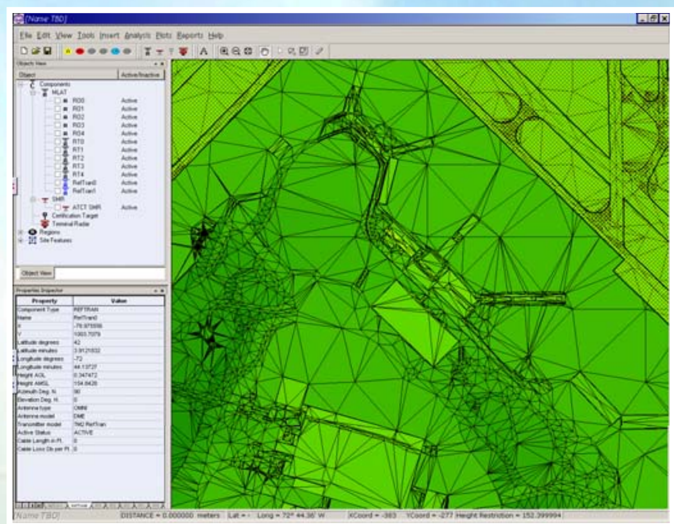
Coverage Prediction Tool

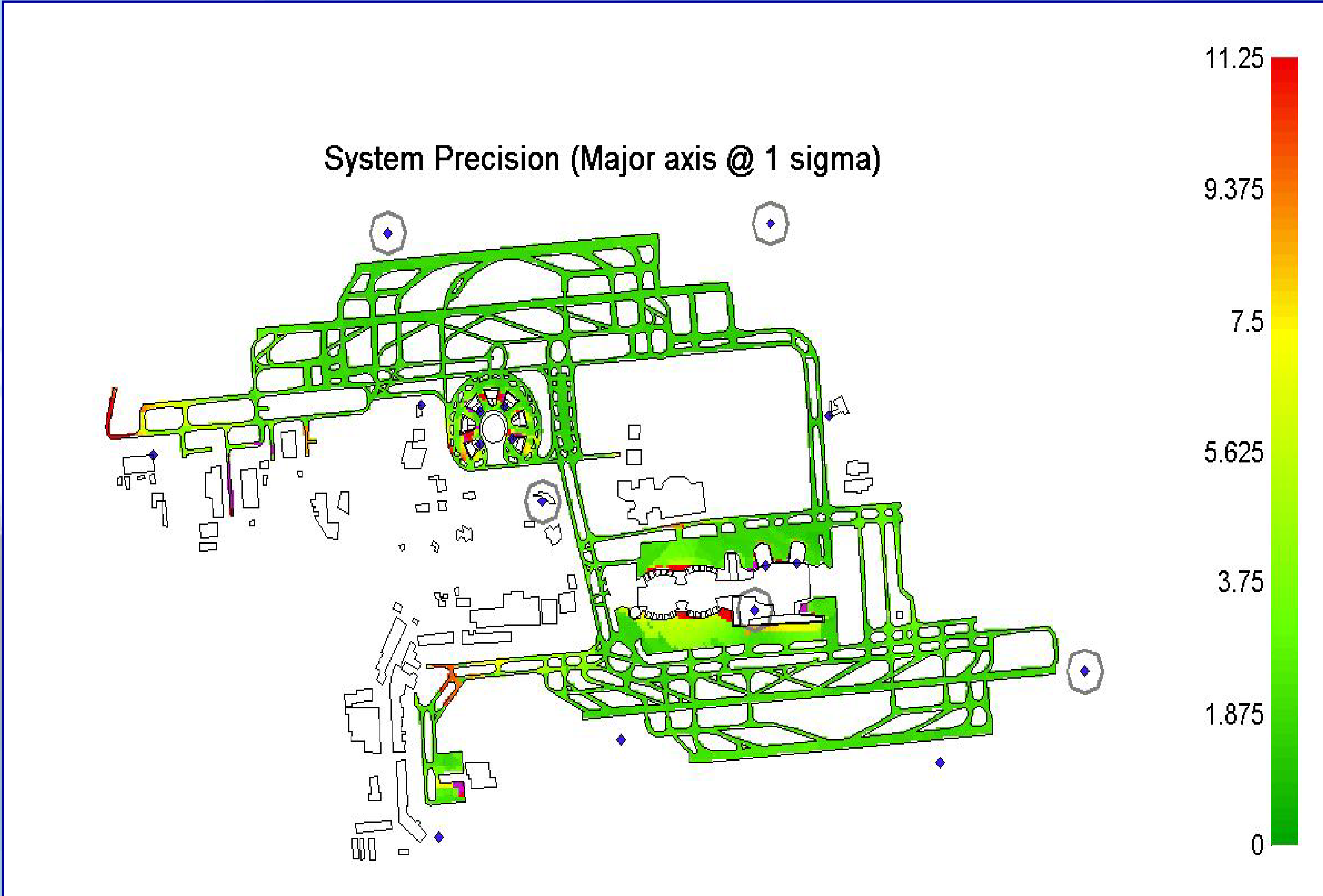


- **Airport or Geographic Topography imported via electronic map**
  - **2D or 3D**
- **Surveillance coverage and precision models**
  - **Line of Site**
  - **Antenna Models**
  - **Propagation Models**





Coverage Analysis

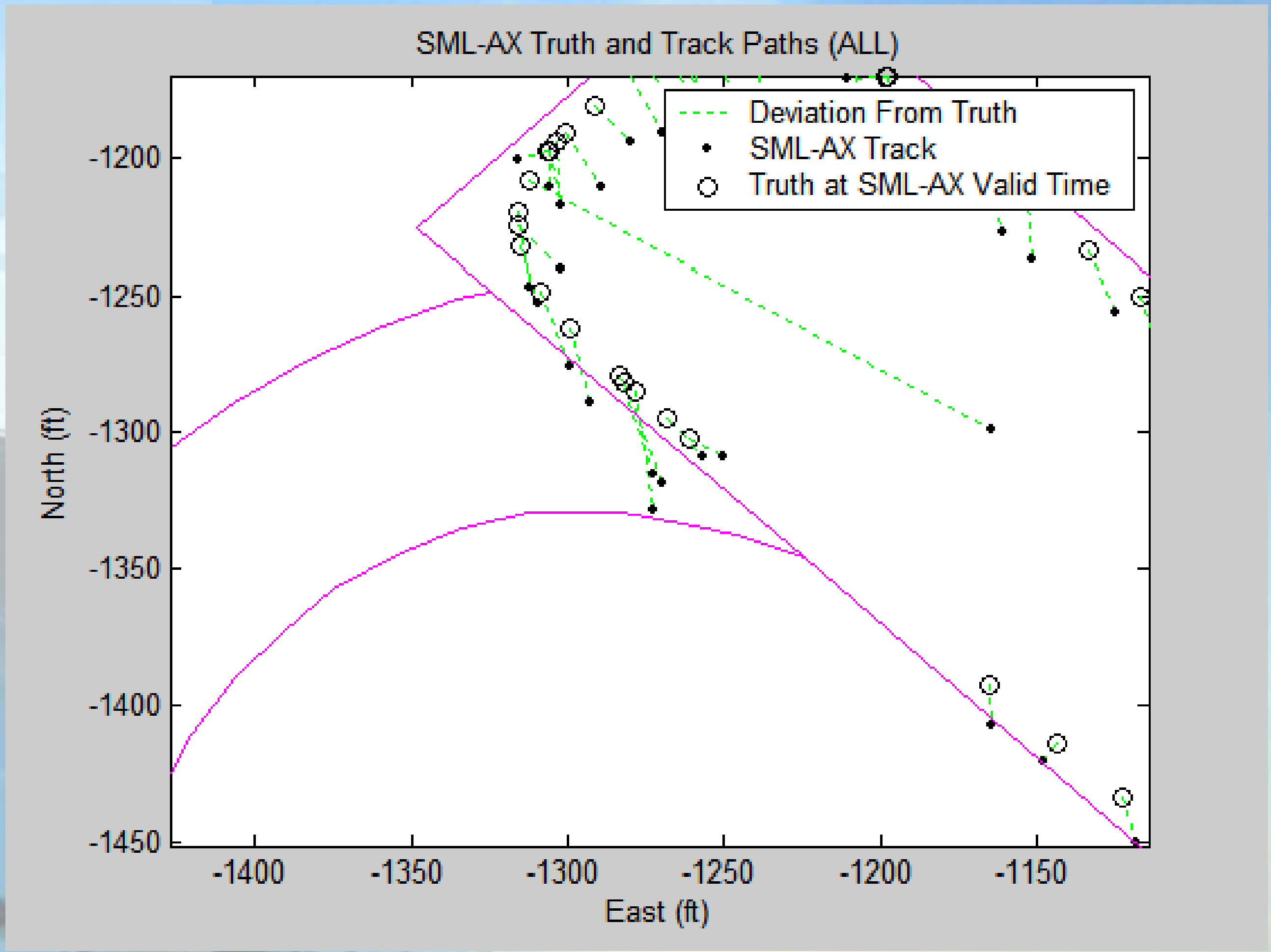


Accuracy

- Multilateration Accuracy is typically validated using an instrumented vehicle and sometimes an instrumented aircraft.
  - The instrumented vehicle typically drives over all airport surfaces of interest including centerlines and edges
  - The instrumented aircraft typically flies all approach and departure routes and sometimes at fixed height above the runways

Test Vehicle Analysis

Vehicle Truth and Track Plot identifies the truth position (black circle), the detected position (black dot) and the deviation from truth (green line).



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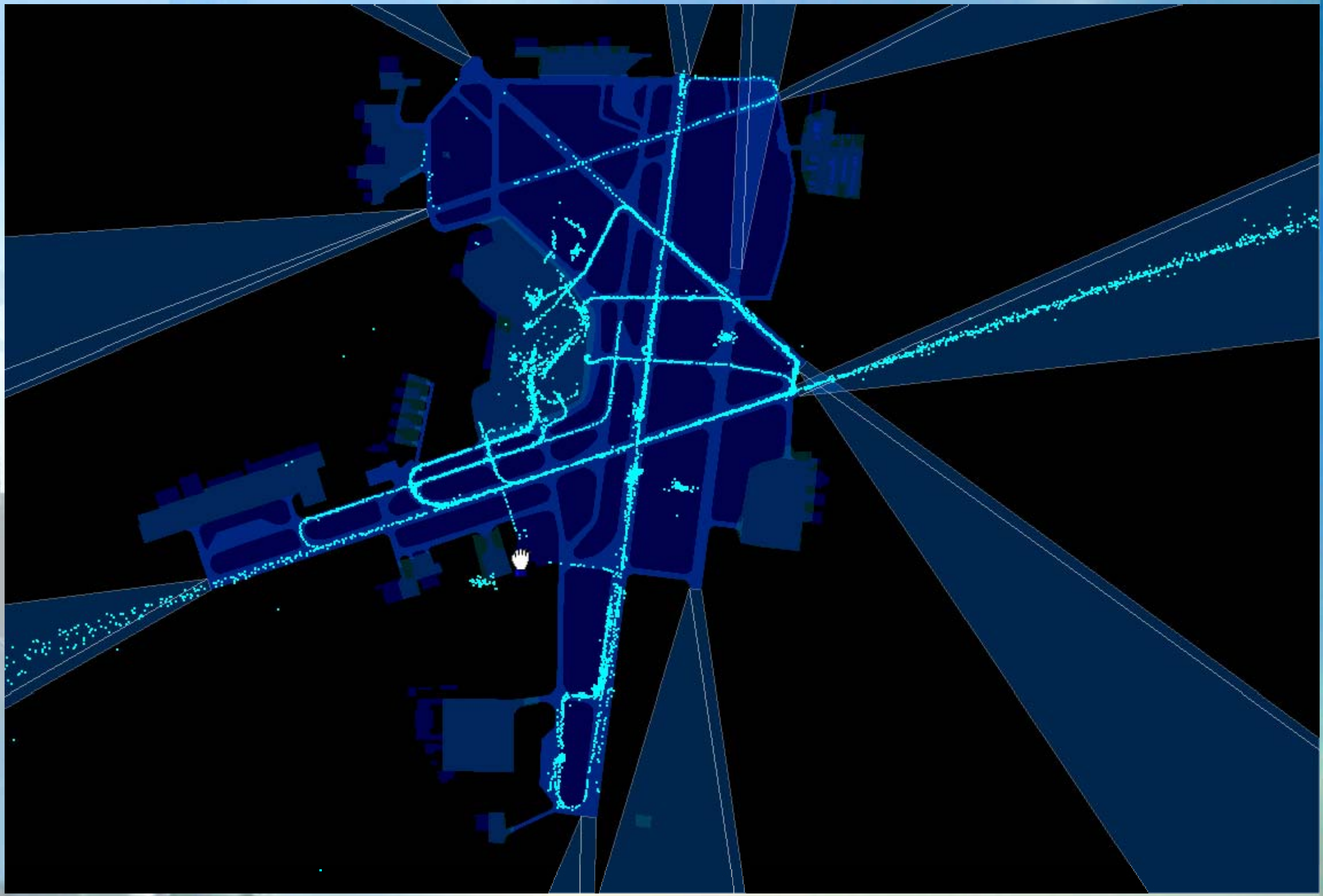
Update Rate



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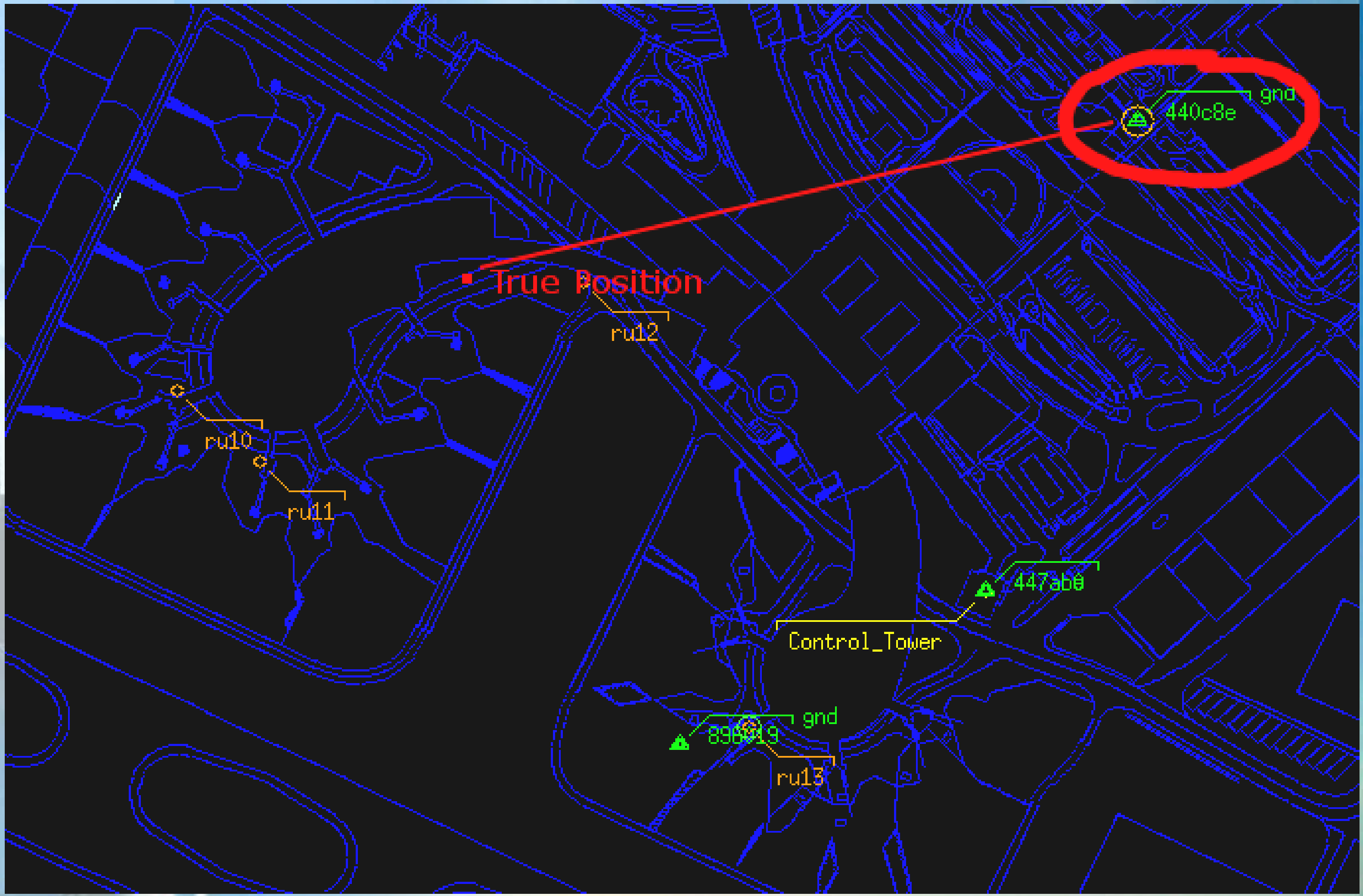
- False Tracks are also a major concern for Multilateration systems since they can cause false operator alerts
- False Tracks in Multilateration are mostly caused by:
  - Corrupted Timestamps
  - Poor GDOP

False Position Calculation



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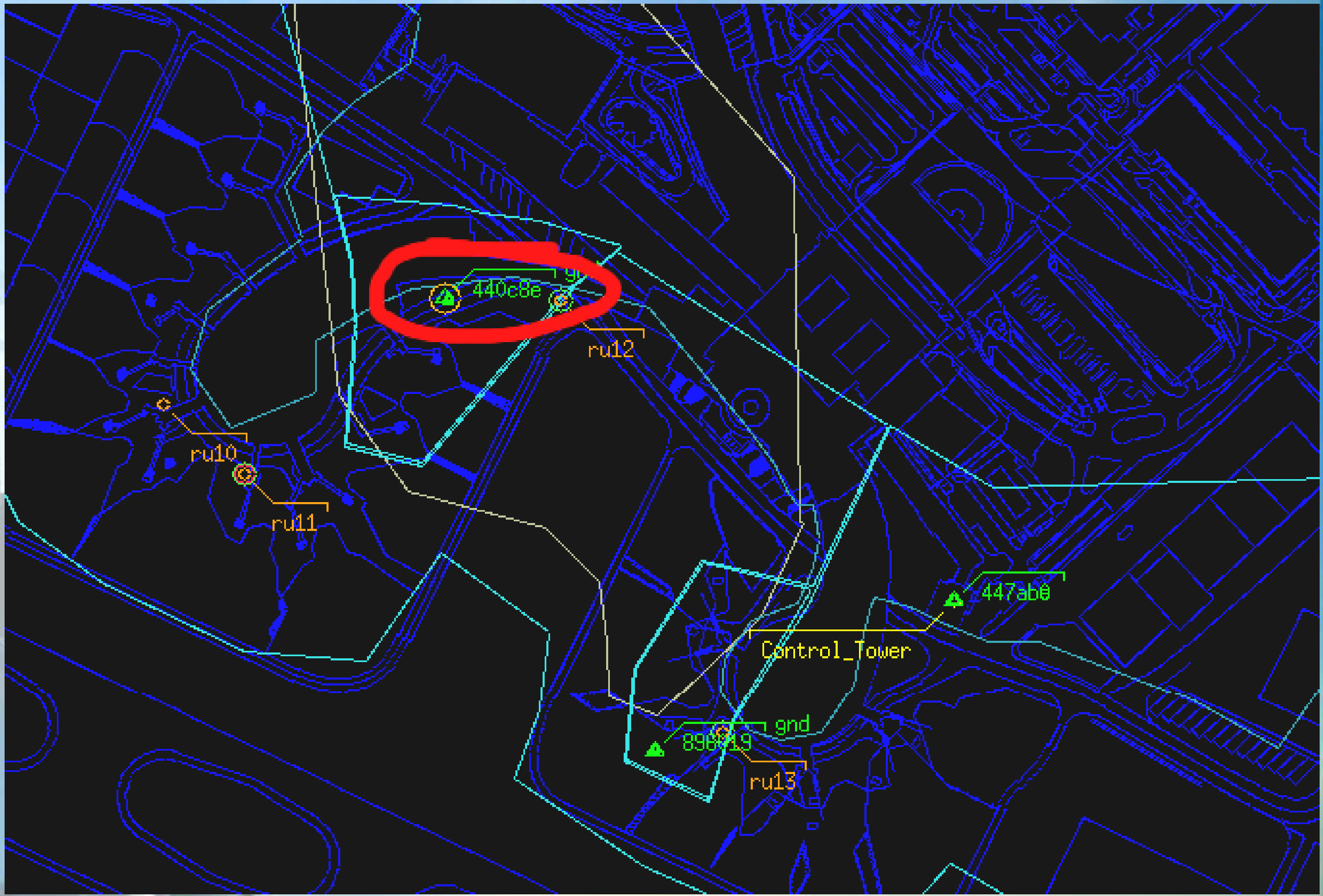
Region Processing Corrected Position Calculation



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Ongoing Issues

Aircraft Equipage

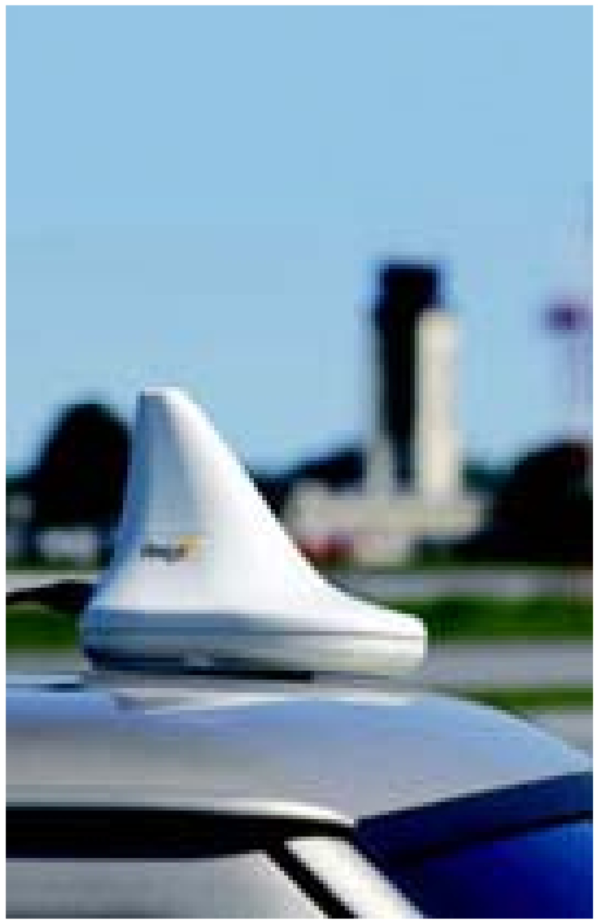
- Understanding the Distribution of Aircraft Equipage at an Aerodrome
- Identifying Aircraft with Poorly Performing Transponders

Aircraft Transponder Procedures

- Developing Procedures – Lots of Examples
- Communicating to Users (Airlines)
- Controller Monitoring
- Training Pilots (ATC Reminders)

Vehicle Equipage

- **Seamless aircraft and vehicle surveillance picture**
  - **ADS-B Squitter Unit**
  - **Squits Position and Identification Messages**
  - **Data Received by Sensis MDS**
  - **Portable or Permanent Mounts**
- **Too Many Vehicles May Overload or Clutter the System**



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Transponder Occupancy

- Many ANSP's have concerns about Transponder Occupancy
  - False TCAS
  - Degradation in SSR performance
- Disagreement about how to calculate or measure occupancy impact
- Multilateration Manufacturers Provide Flexibility
  - Passive Processing
  - Whisper/Shout
  - Addressed Interrogations
  - Transmit Power Controls

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Airport Construction

- Airport Design is not Often Driven by the Needs of Surveillance
- “Dead End” Apron Areas are Most Difficult
  - Typically Requires Addition of Multiple Units
- Airport Construction Affects Multilateration
  - Blocks RF Transmission
  - Adds Varying Reflections
  - Generally, system performance is tuned for an airport configuration, changes may degrade performance

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