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UWB Tracking System Design with TDOA Algorithm

Abstract

This presentation discusses an ultra-wideband (UWB) tracking system design effort using a tracking algorithm TDOA (Time Difference of Arrival). UWB technology is exploited to implement the tracking system due to its properties, such as high data rate, fine time resolution, and low power spectral density. A system design using commercially available UWB products is proposed. A two-stage weighted least square method is chosen to solve the TDOA non-linear equations. Matlab simulations in both two-dimensional space and three-dimensional space show that the tracking algorithm can achieve fine tracking resolution with low noise TDOA data. The error analysis reveals various ways to improve the tracking resolution. Lab experiments demonstrate the UWB-TDOA tracking capability with fine resolution. This research effort is motivated by a prototype development project Mini-AERCam (Autonomous Extra-vehicular Robotic Camera), a free-flying video camera system under development at NASA Johnson Space Center for aid in surveillance around the International Space Station (ISS).

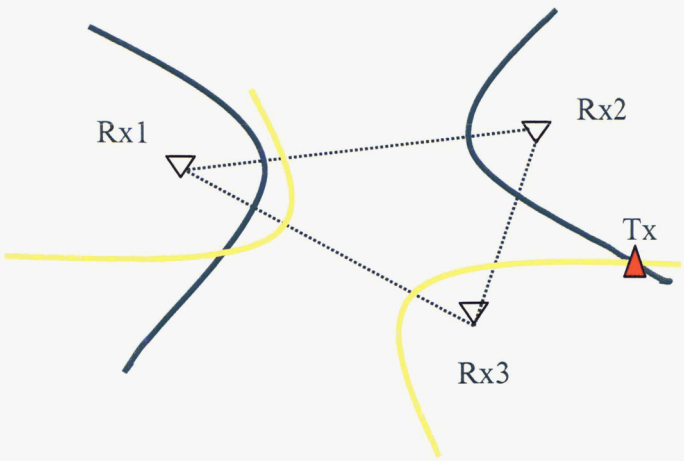

Figure 1. TDOA Tracking Algorithm

Figure 2. Mini-AERCam

UWB Tracking System Design with TDOA Algorithm

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NASA Johnson Space Center

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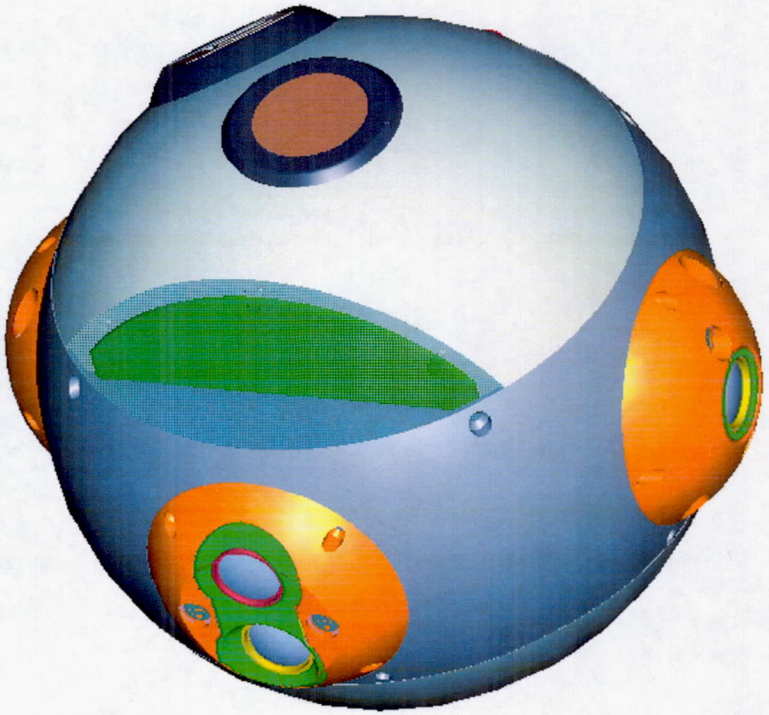
Outline

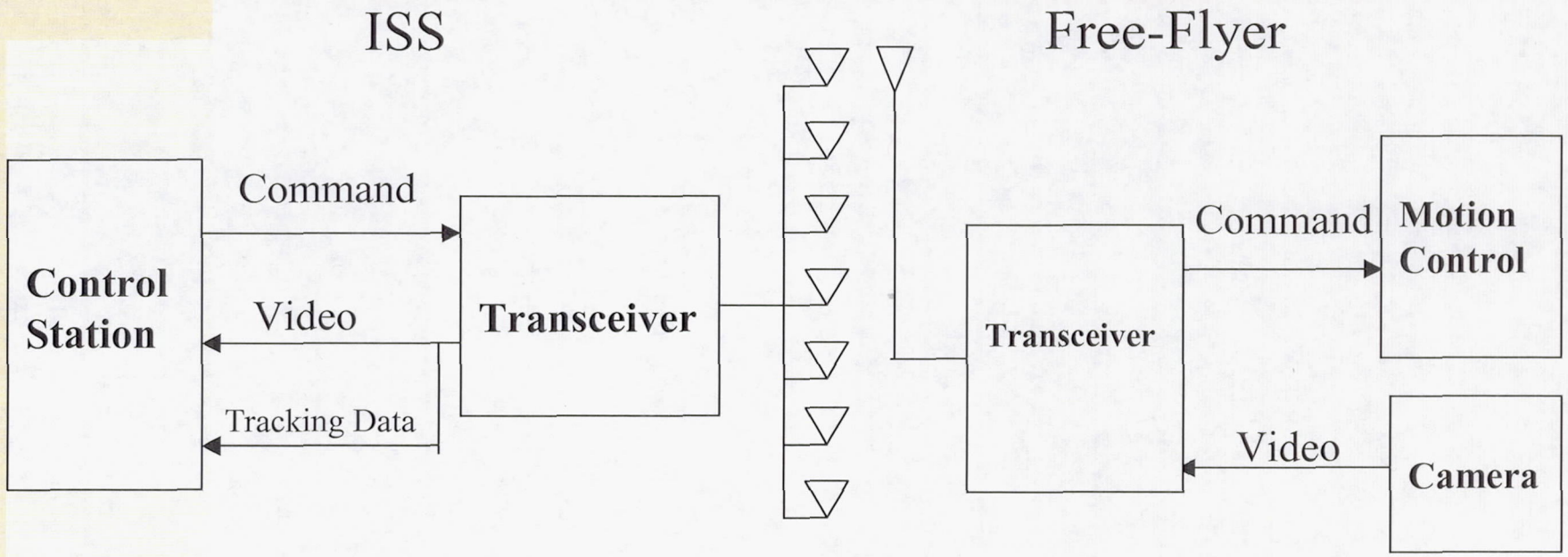
- Introduction to Mini-AERCam
- UWB Fine Time Resolution
- Tracking Principle
- TDOA Tracking Algorithm
- Tracking Simulation Demo
- Laboratory Experiment
- Conclusion and Future Work

AERCam Sprint (STS-87, 1997)

Mini-AERCam (RF tracking)



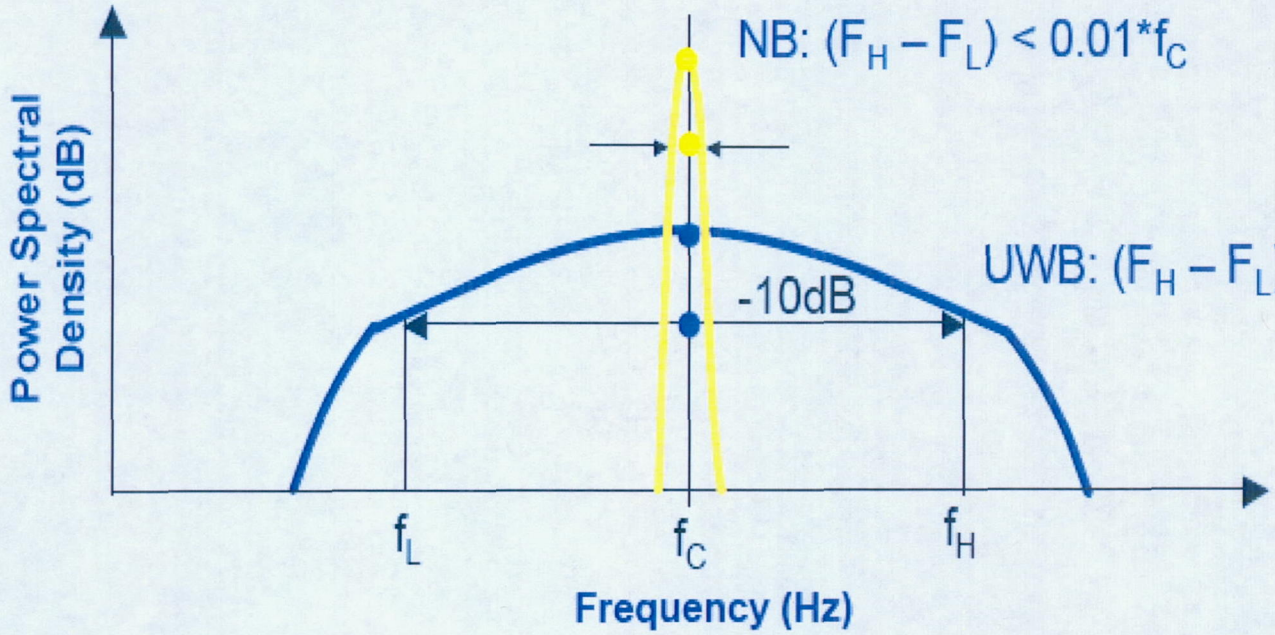
System Design (Block Diagram)



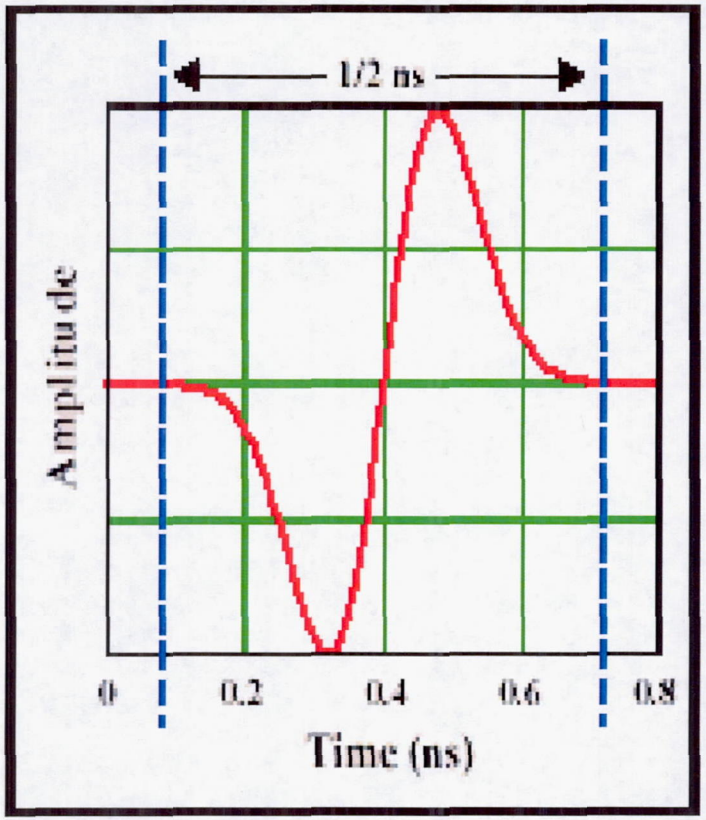
- To transmit commands from ISS to free-flyer for navigation (downlink).
- To transmit real-time data (video, telemetry) from free-flyer to ISS (uplink).
- To passively track the free-flyer using telemetry data

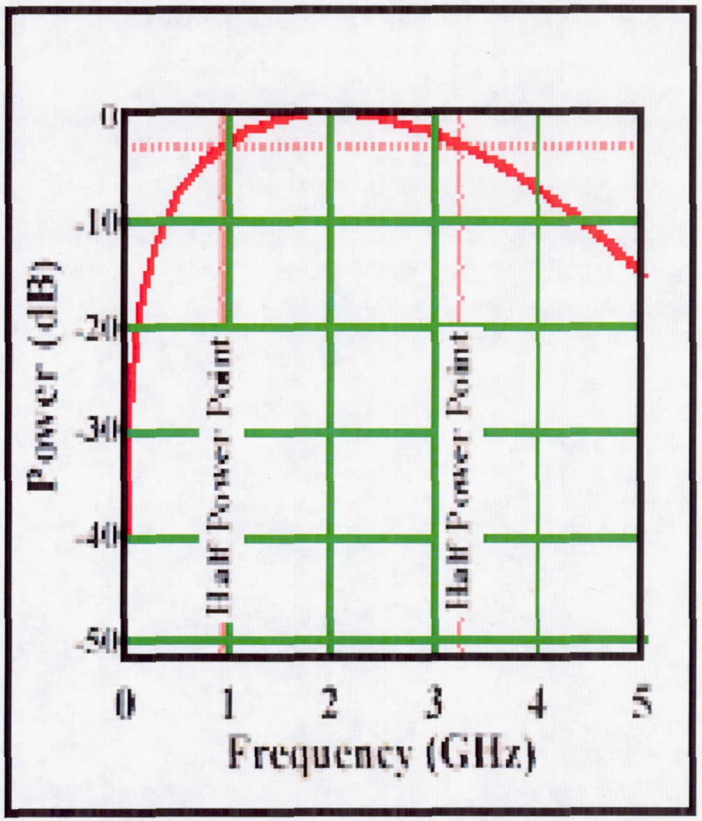
What is UWB ? (FCC Definition)

A ultra wideband device is defined as any device where the fractional bandwidth is greater than 0.20 or occupies 500 MHz or more of spectrum.



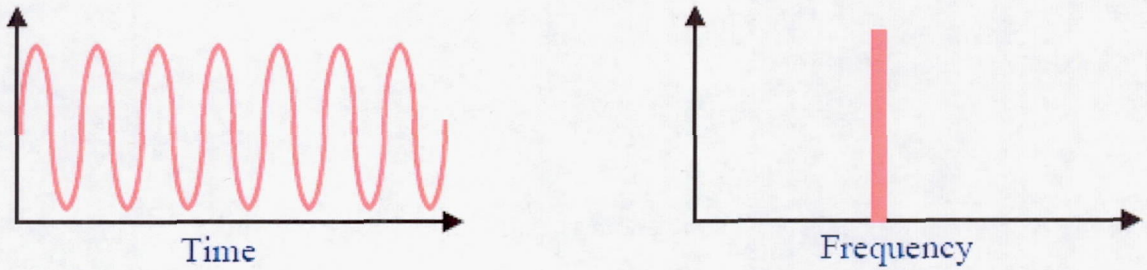
UWB Pulse in Time and Frequency Domain



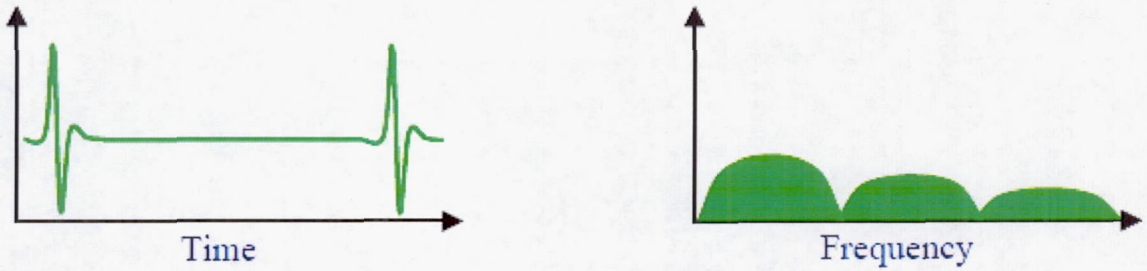


UWB Fine Time Resolution

Sinusoidal, Narrowband



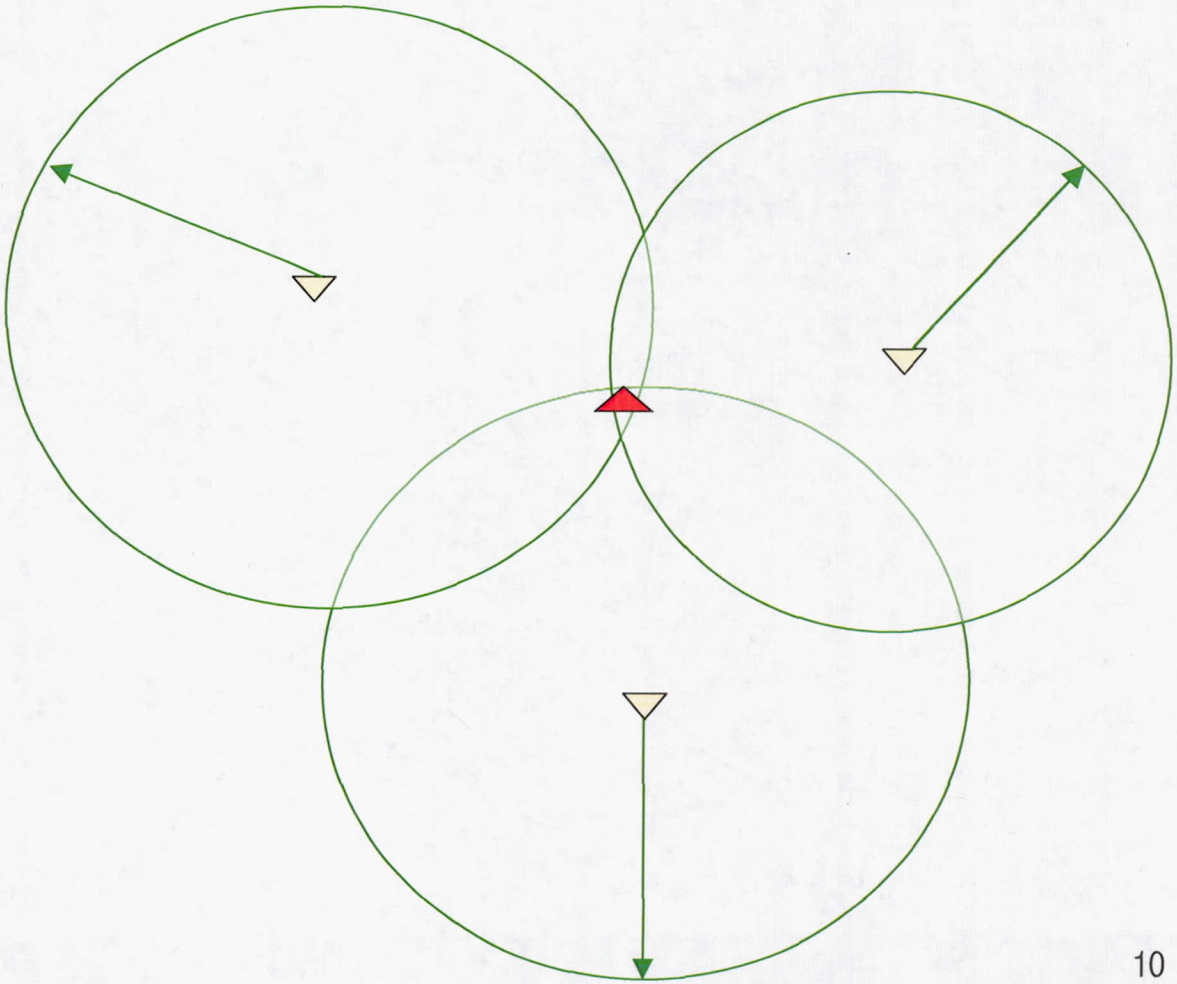
Impulse, Ultra-Wideband



Time Resolution vs. Range Resolution

- Time vs. Distance Resolution
  - 1ns ⇔ 0.3m (1 foot)
  - 1ps ⇔ 0.3 mm
  - 30ps ⇔ 1cm (Leading Edge Detection)

Time of Arrival (TOA)

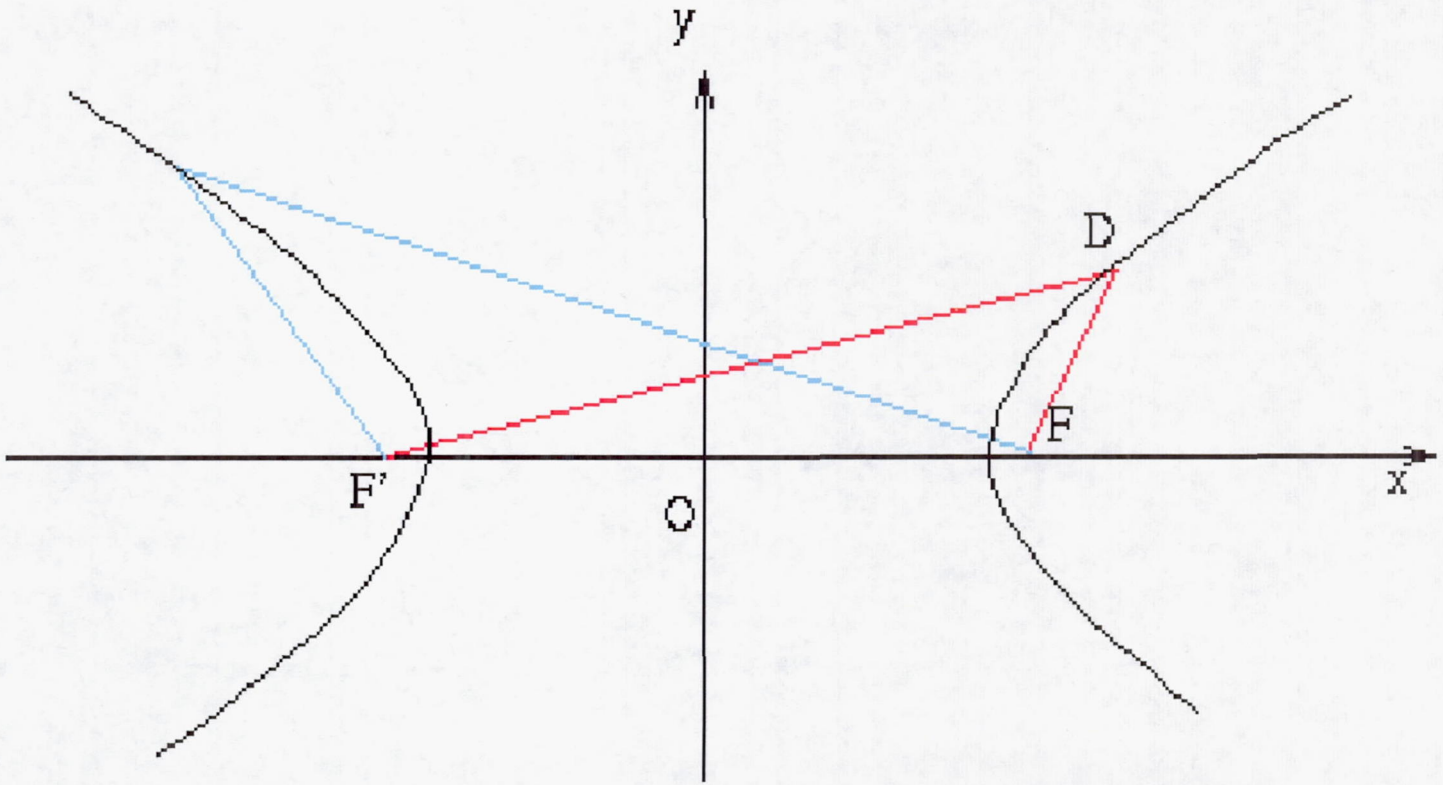


Drawbacks of TOA

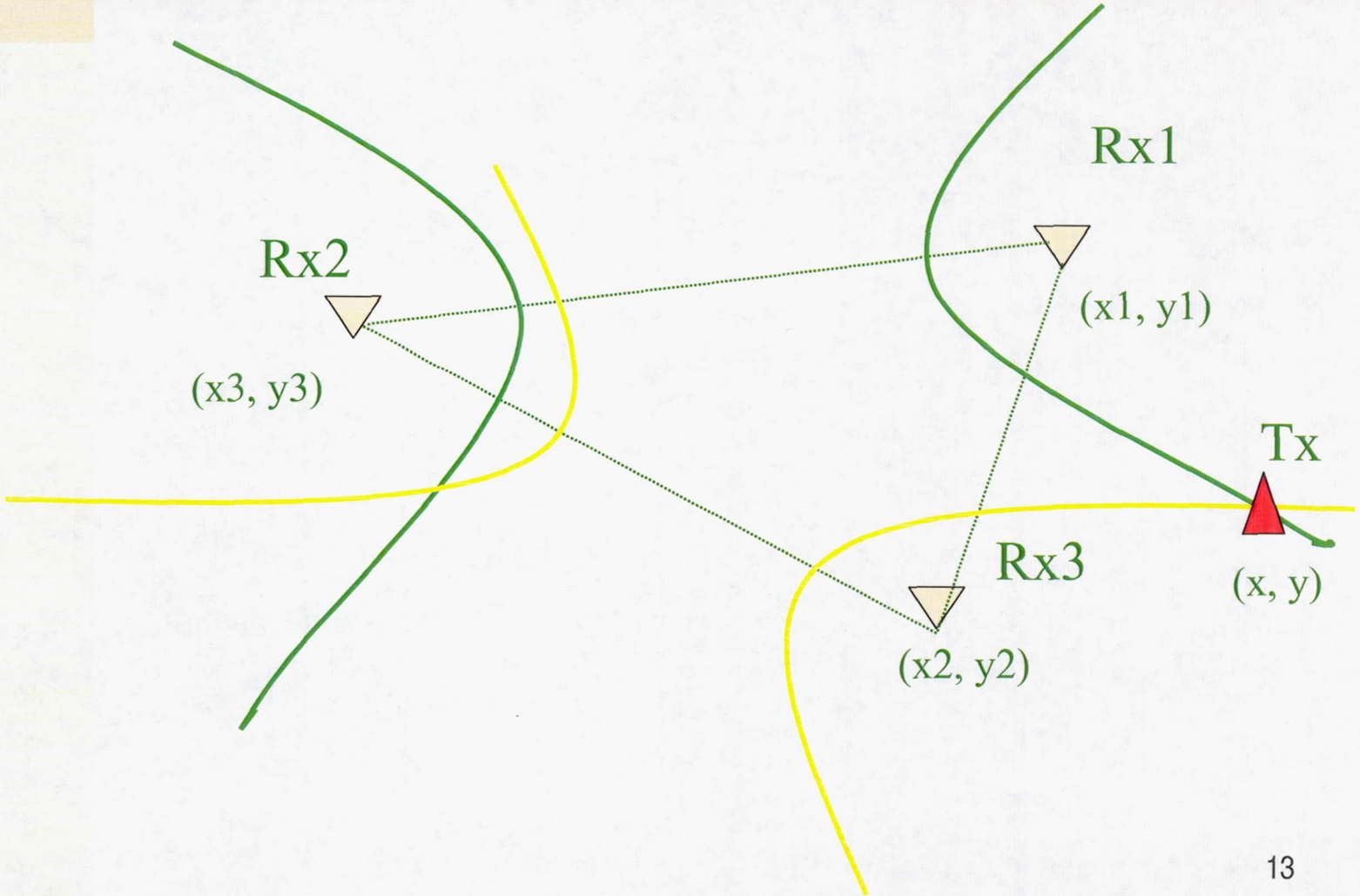
- Ranging: requires duplex transmission and incurs overhead (Asynchronization)
- Synchronization: hard to achieve the synchronization precision between the transmitter and receiver ; 1microsecond synchronization error can easily translate into 300 meters of range error

Time Difference of Arrival (TDOA)

Hyperbola: $b^2 x^2 - a^2 y^2 = a^2 b^2$



Time Difference of Arrival (TDOA)



Advantages of TDOA

- No synchronization between Tx and Rx
- Simplex (one-way) data estimation

TDOA Equations

$$D_{12} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_2 - x)^2 + (y_2 - y)^2} = \tau_{12} c$$

$$D_{13} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2} = \tau_{13} c$$

$$D_{23} = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2} = \tau_{23} c$$

Taylor Series Expansion Non-linear Least Squares (NLLS) Iterative Algorithm

$$f_k(x,y) = f_k(x_0,y_0) + \frac{\partial f_k}{\partial x}(x - x_0) + \frac{\partial f_k}{\partial y}(y - y_0)$$

$$\mathbf{A}\,\mathbf{p}_T = \mathbf{b}$$

$$\mathbf{A} = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} \\ \vdots & \vdots \\ \frac{\partial f_K}{\partial x} & \frac{\partial f_K}{\partial y} \end{bmatrix} \quad \mathbf{p}_T = \begin{bmatrix} (x - x_0) \\ (y - y_0) \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} r_1 - f_1(x_0,y_0) \\ \vdots \\ r_K - f_K(x_0,y_0) \end{bmatrix}$$

$$\hat{\mathbf{p}}_T = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b}$$

Two-Stage Weighted LS Algorithm

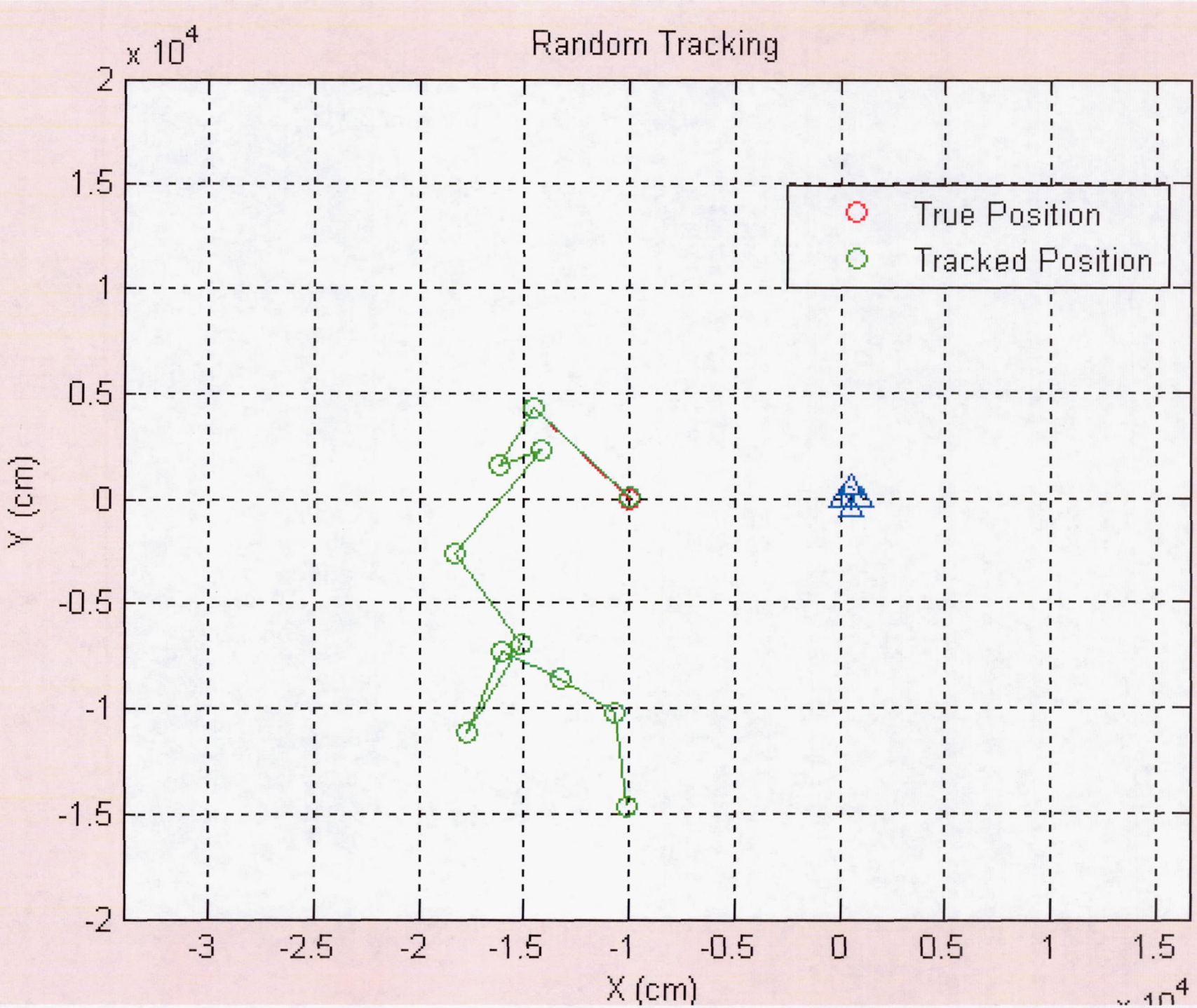
- No Initialization Problem (no first guess)
- No Convergence Problem (always converges)
- No Iteration Problem (low computation cost)
- Achieved Cramer-Rao Lower Bound (optimal estimator)
- No Free Lunch (need one more receiver)

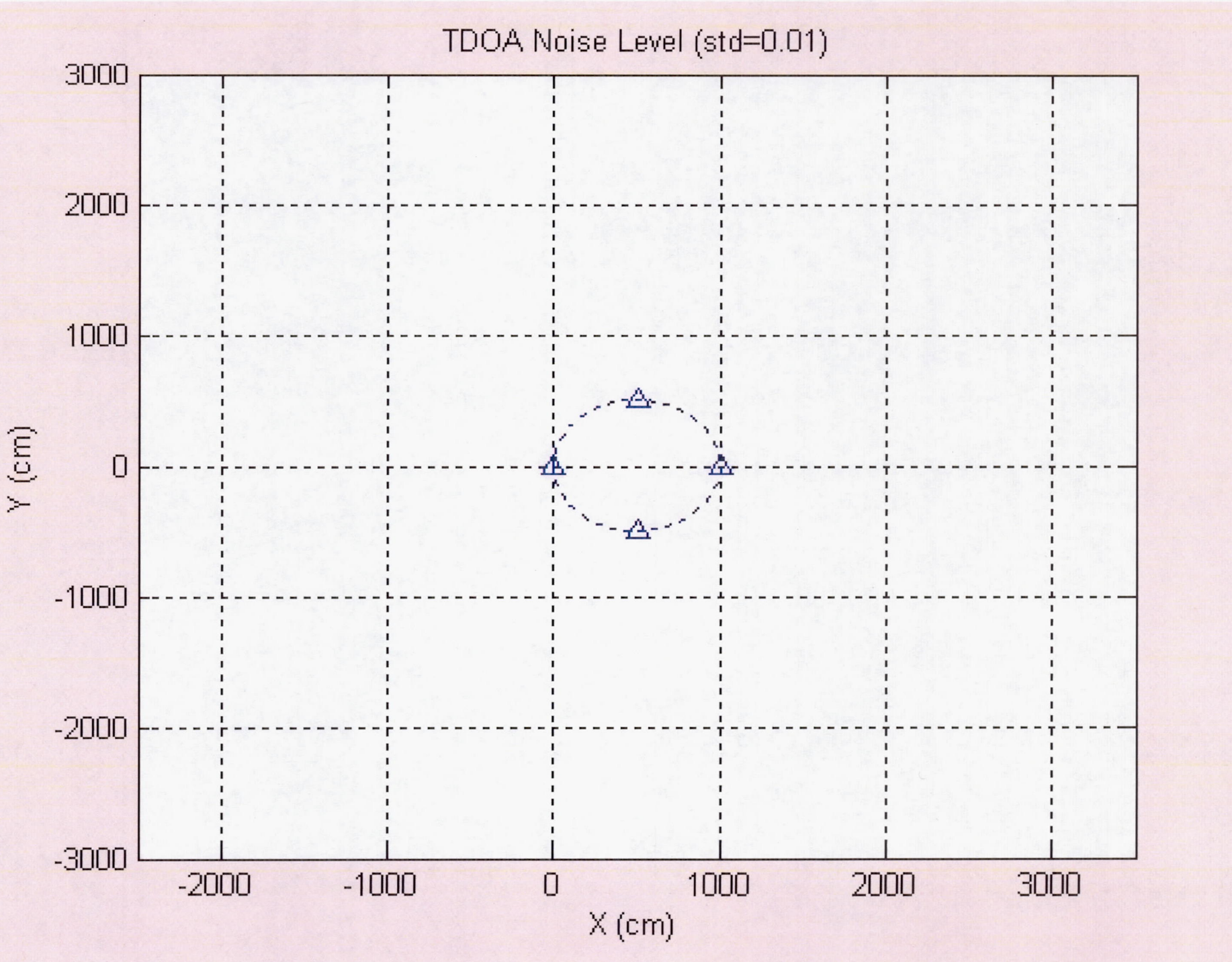
Tracking Simulation Demo

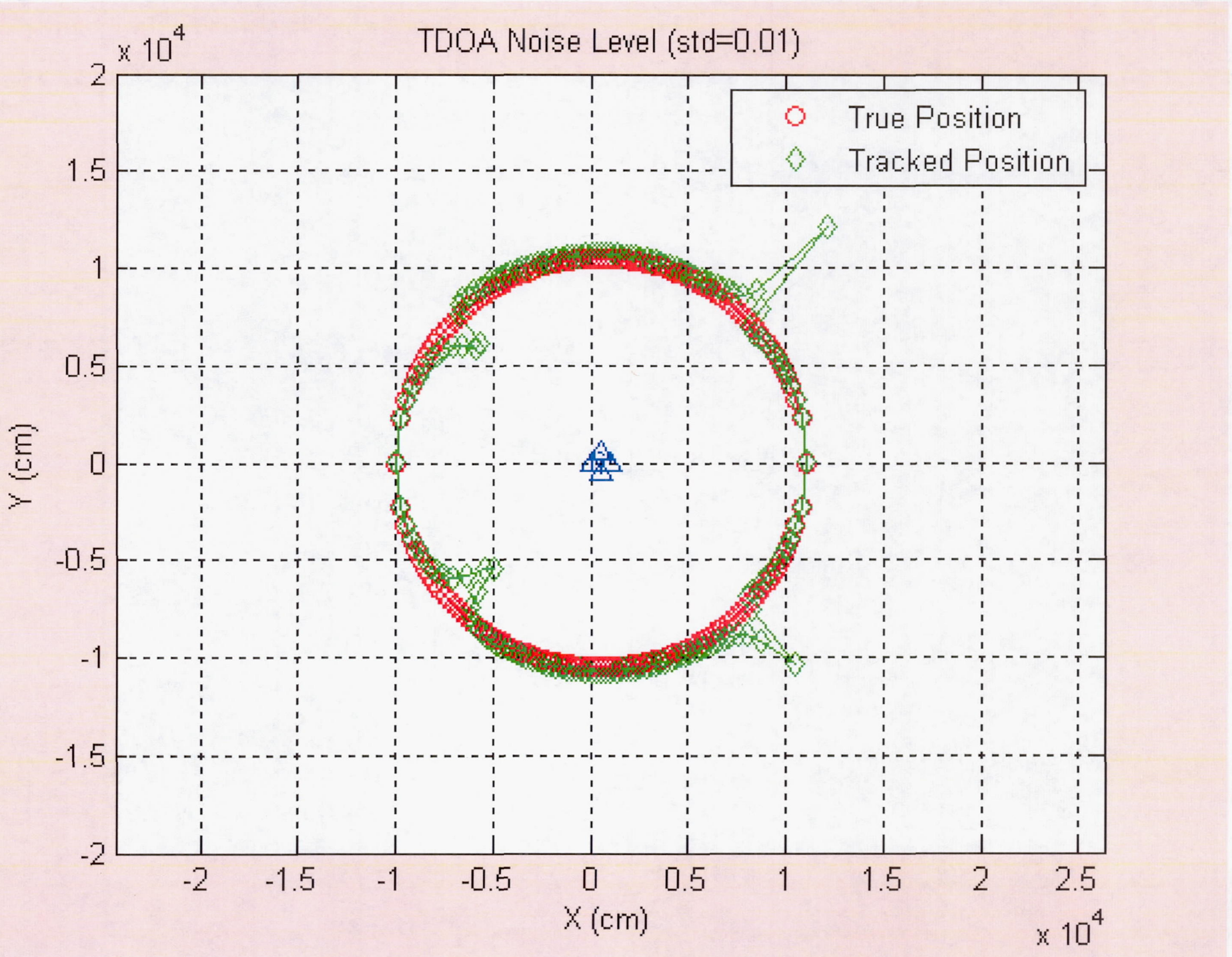
- Random Tracking
- Orbit Tracking

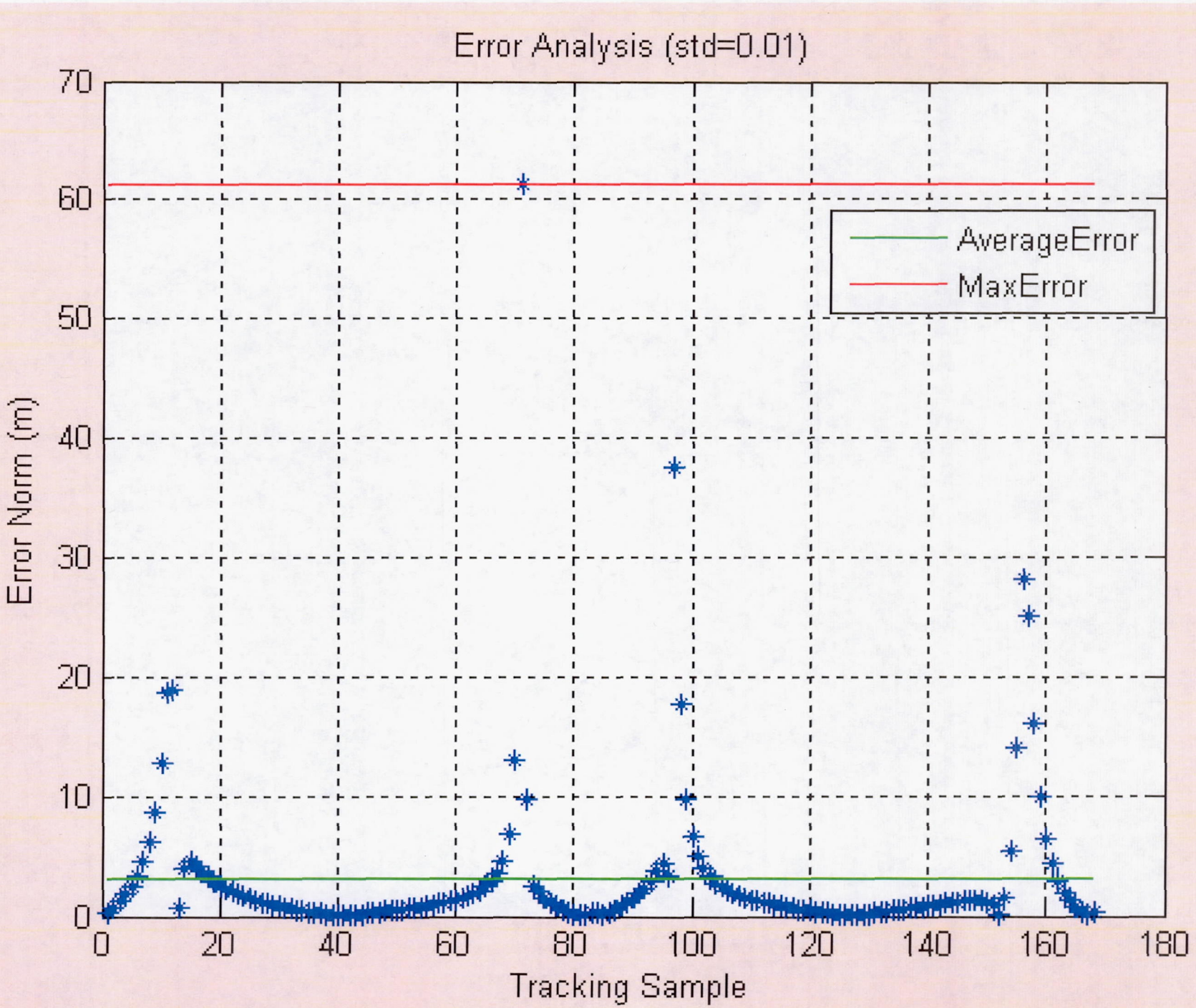
1. TDOA Estimation Noise Level (std=0.01)
2. TDOA Estimation Noise Level (std=0.001)
3. TDOA Estimation Noise Level (std=0.0001)

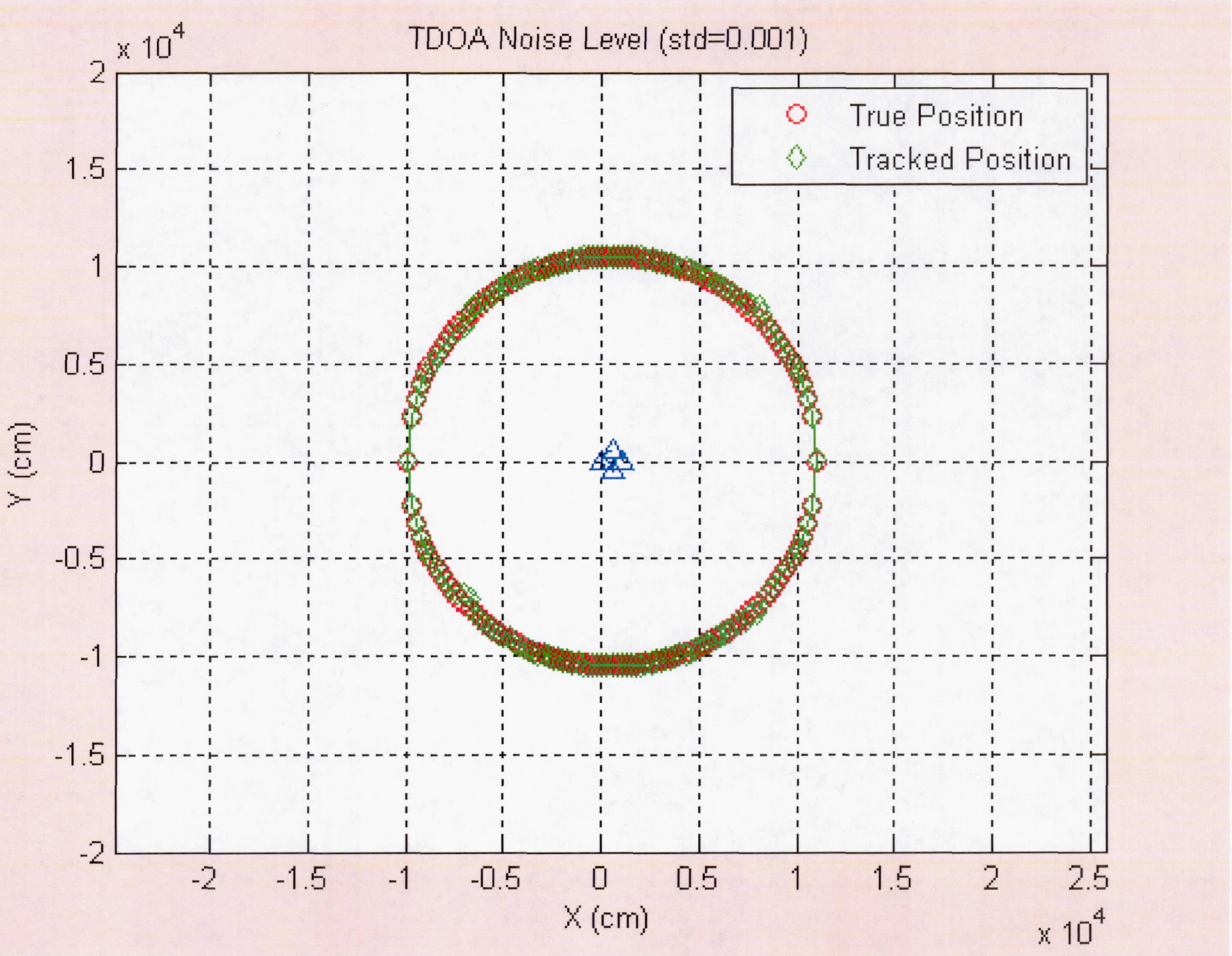
- Receiving Antenna Configuration
- 3D Orbit Tracking

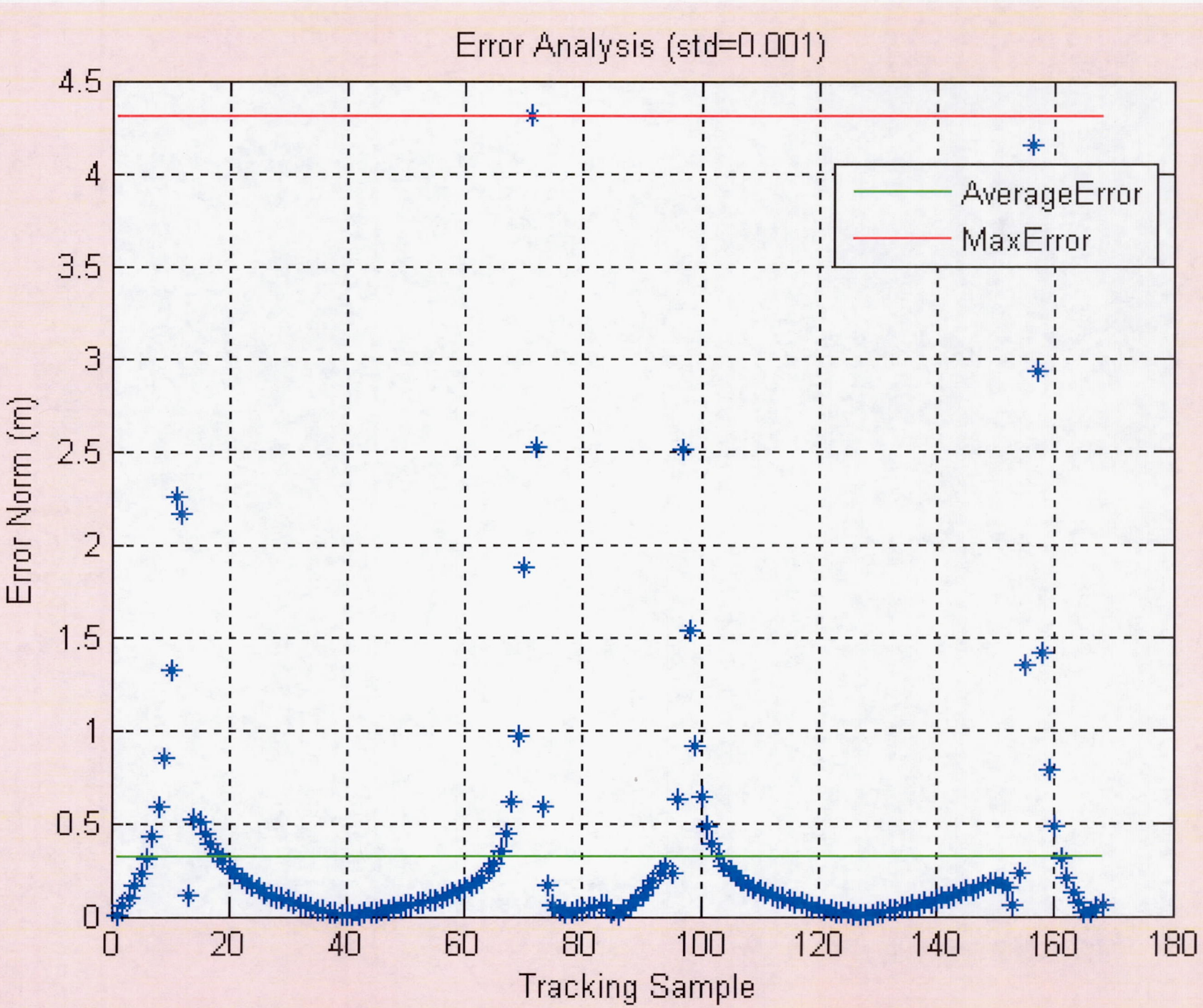

Random Tracking
x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Y (cm)
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
X (cm)
True Position
Tracked Position

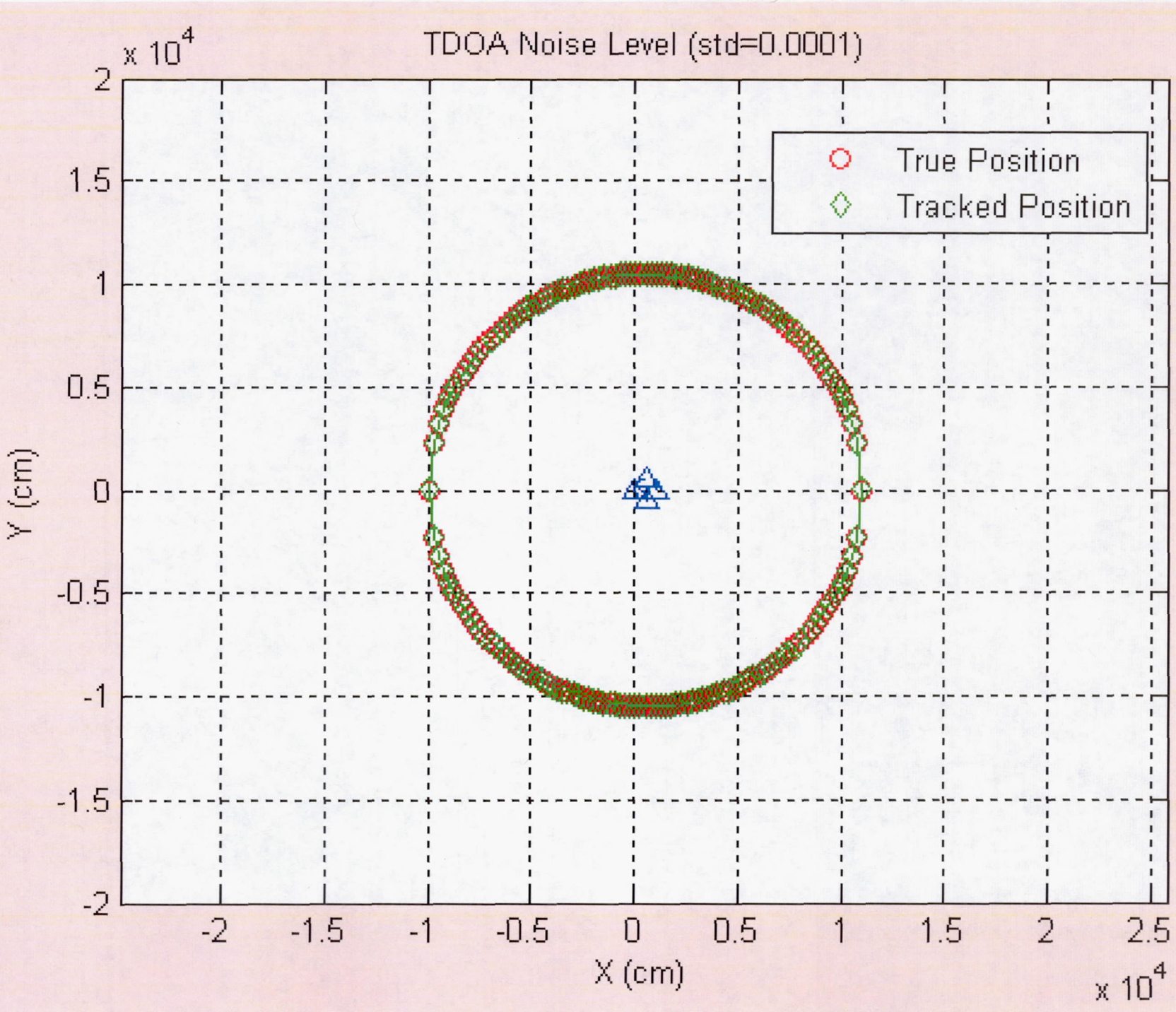

TDOA Noise Level (std=0.01)
3000
2000
1000
0
-1000
-2000
-3000
Y (cm)
-2000
-1000
0
1000
2000
3000
X (cm)

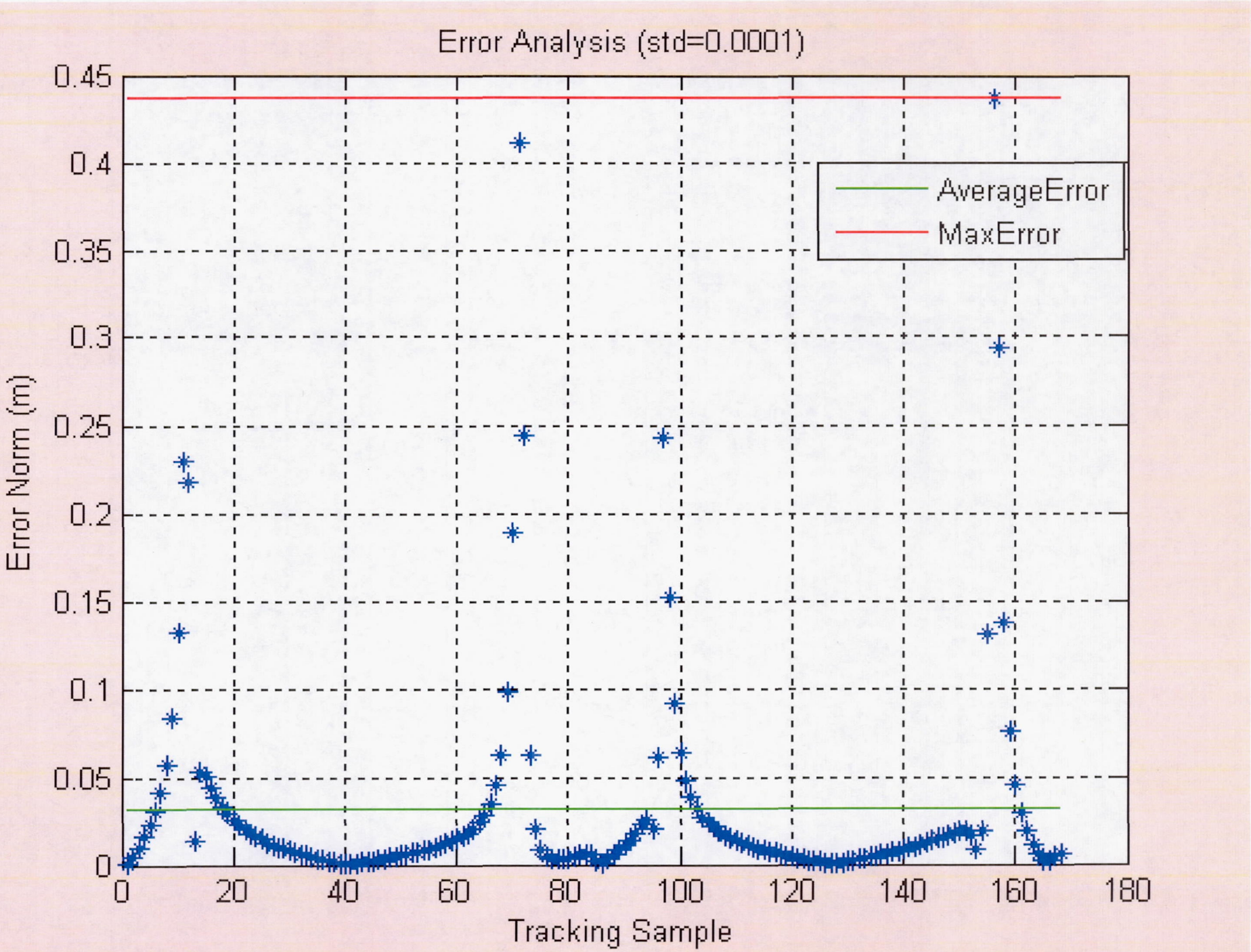

TDOA Noise Level (std=0.01)
x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Y (cm)
True Position
Tracked Position
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
X (cm)
x 10^4


Error Analysis (std=0.01)
Error Norm (m)
Tracking Sample
AverageError
MaxError
0
10
20
30
40
50
60
70
0
20
40
60
80
100
120
140
160
180


TDOA Noise Level (std=0.001)
x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Y (cm)
True Position
Tracked Position
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
X (cm)
x 10^4


Error Analysis (std=0.001)
Error Norm (m)
Tracking Sample
AverageError
MaxError
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
20
40
60
80
100
120
140
160
180

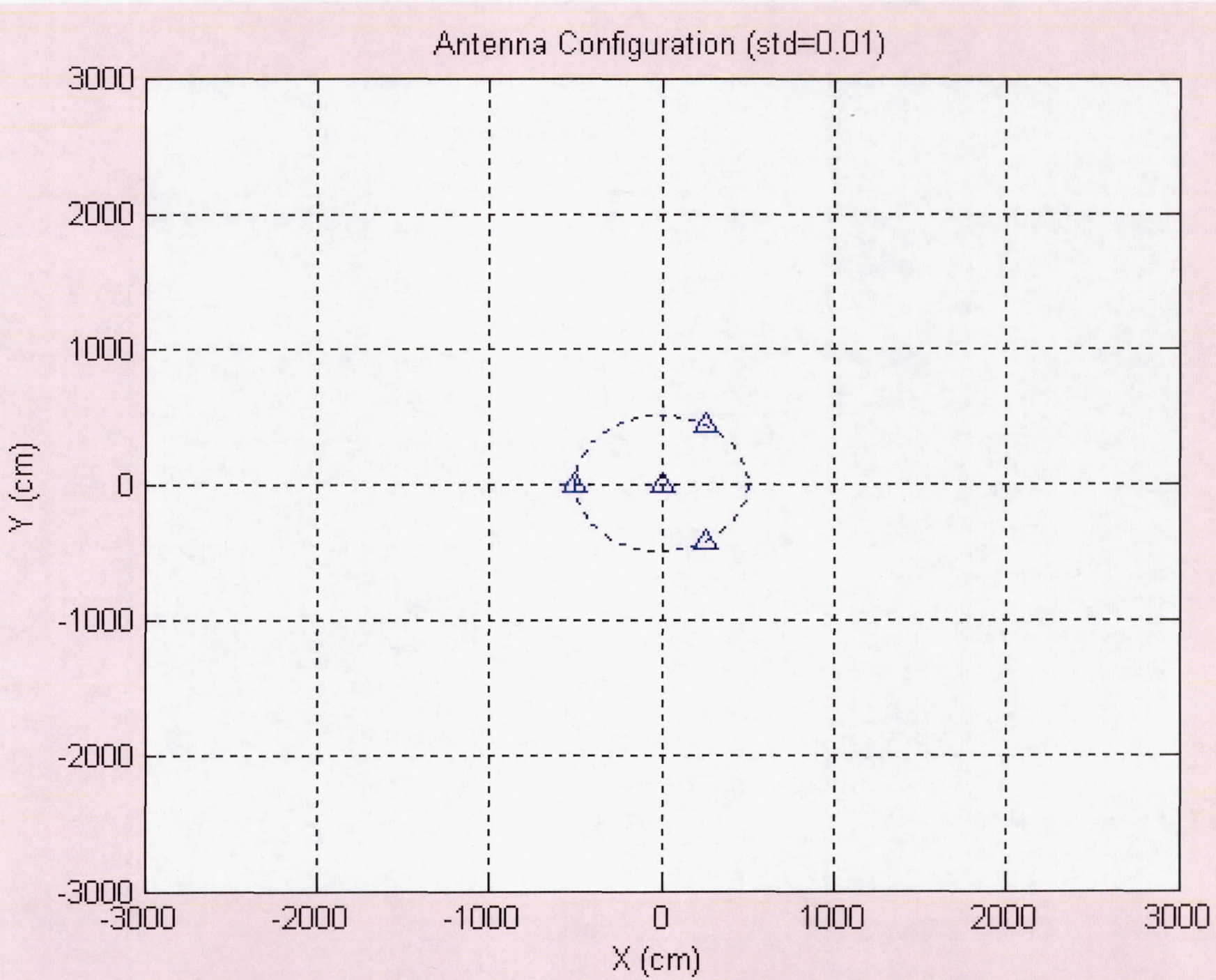

TDOA Noise Level (std=0.0001)
x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Y (cm)
True Position
Tracked Position
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
X (cm)
x 10^4

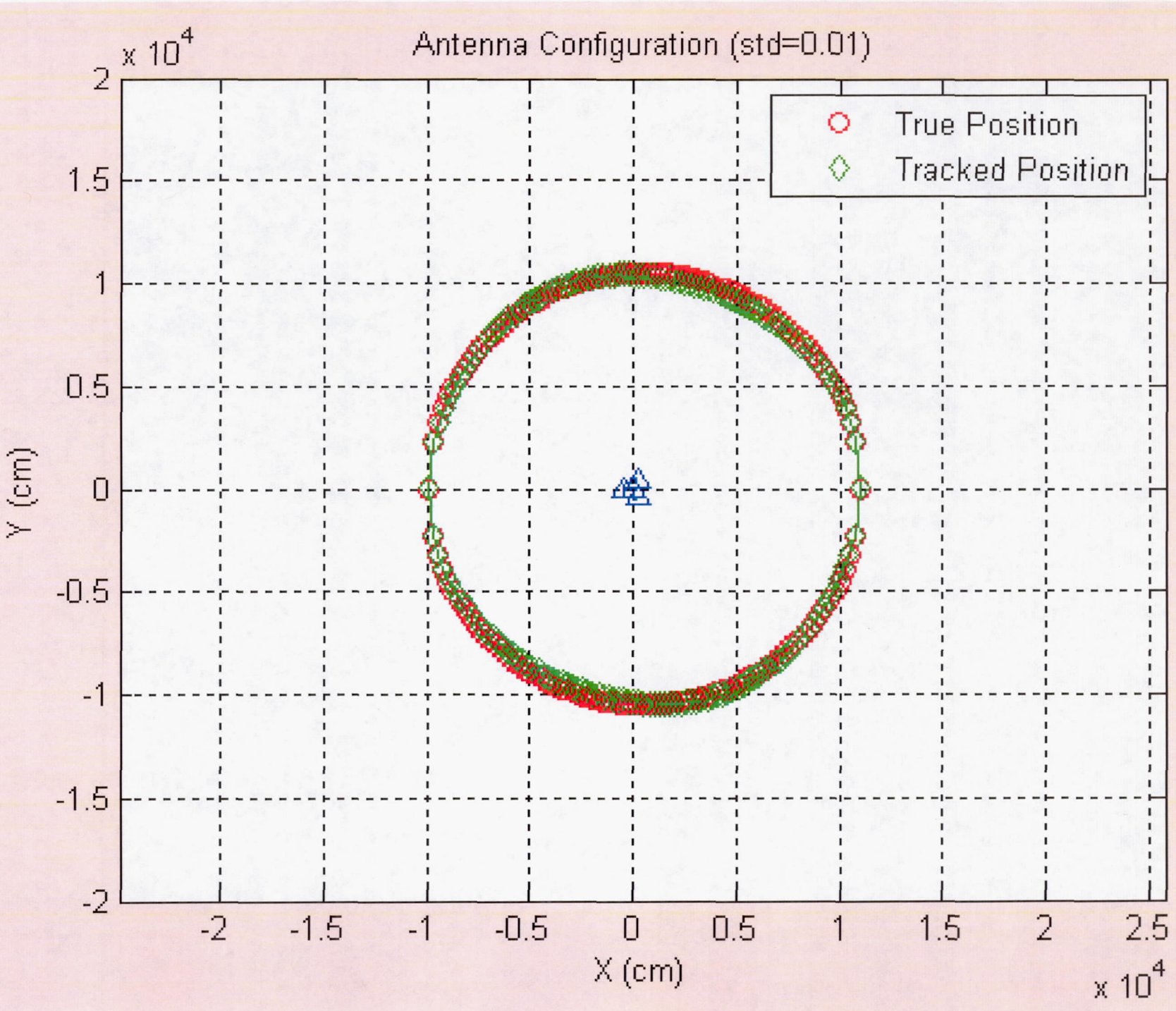

Error Analysis (std=0.0001)
Error Norm (m)
Tracking Sample
AverageError
MaxError
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
120
140
160
180

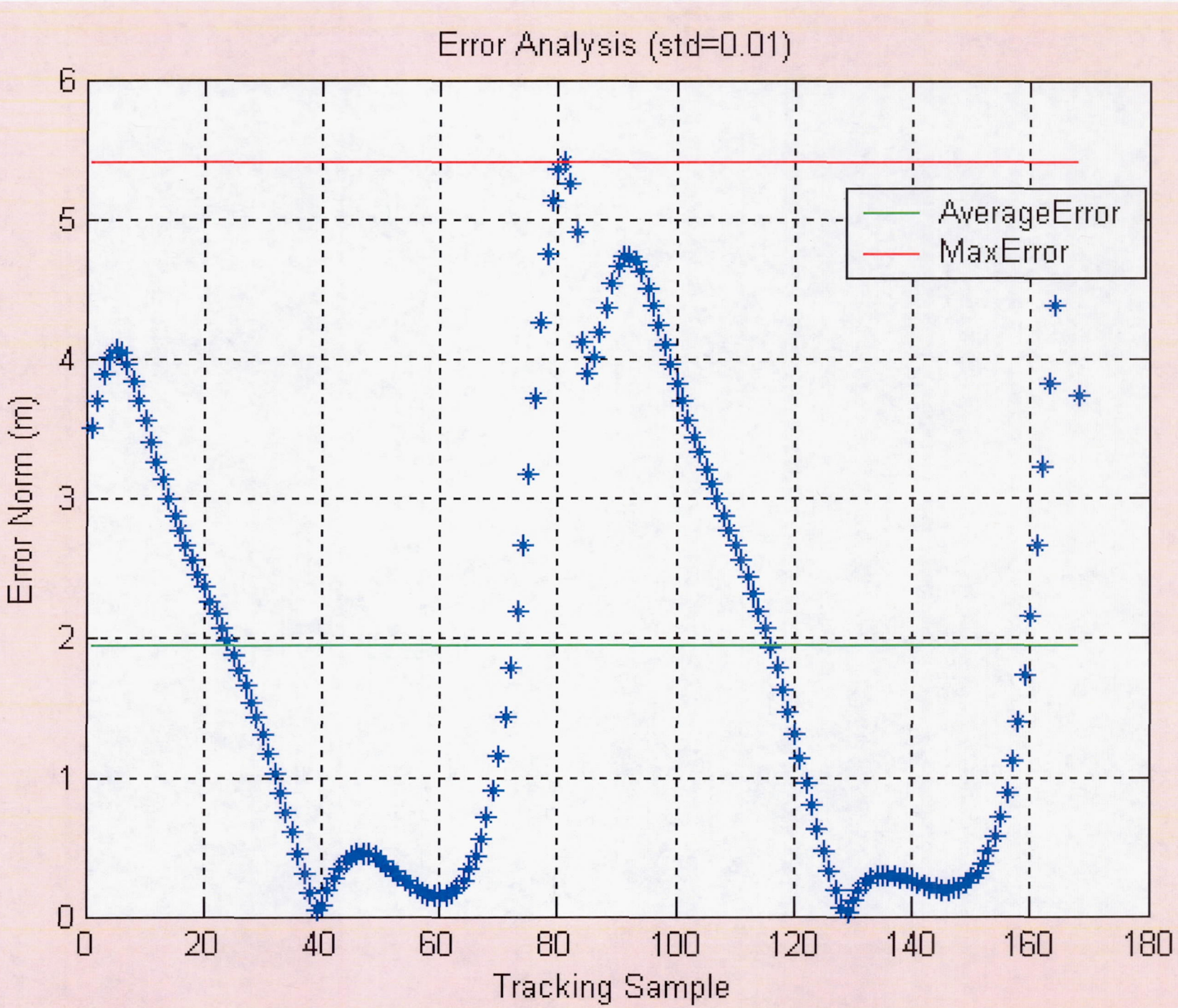
Error Analysis

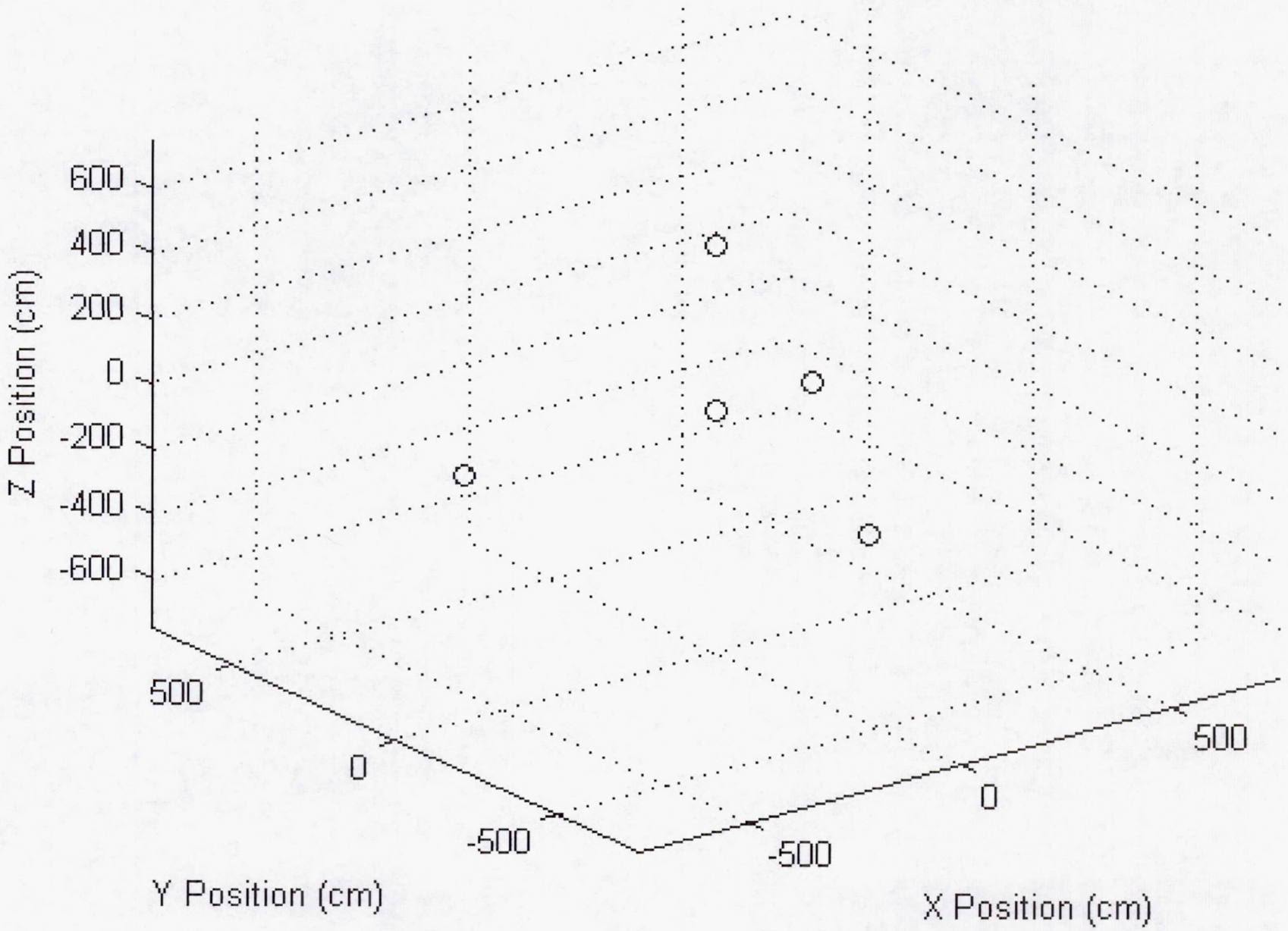
Standard Deviation of TDOA (ns)	Maximum Error (m)	Average Error (m)
0.01	61.3271	3.1372
0.001	4.3110	0.3172
0.0001	0.4366	0.0317

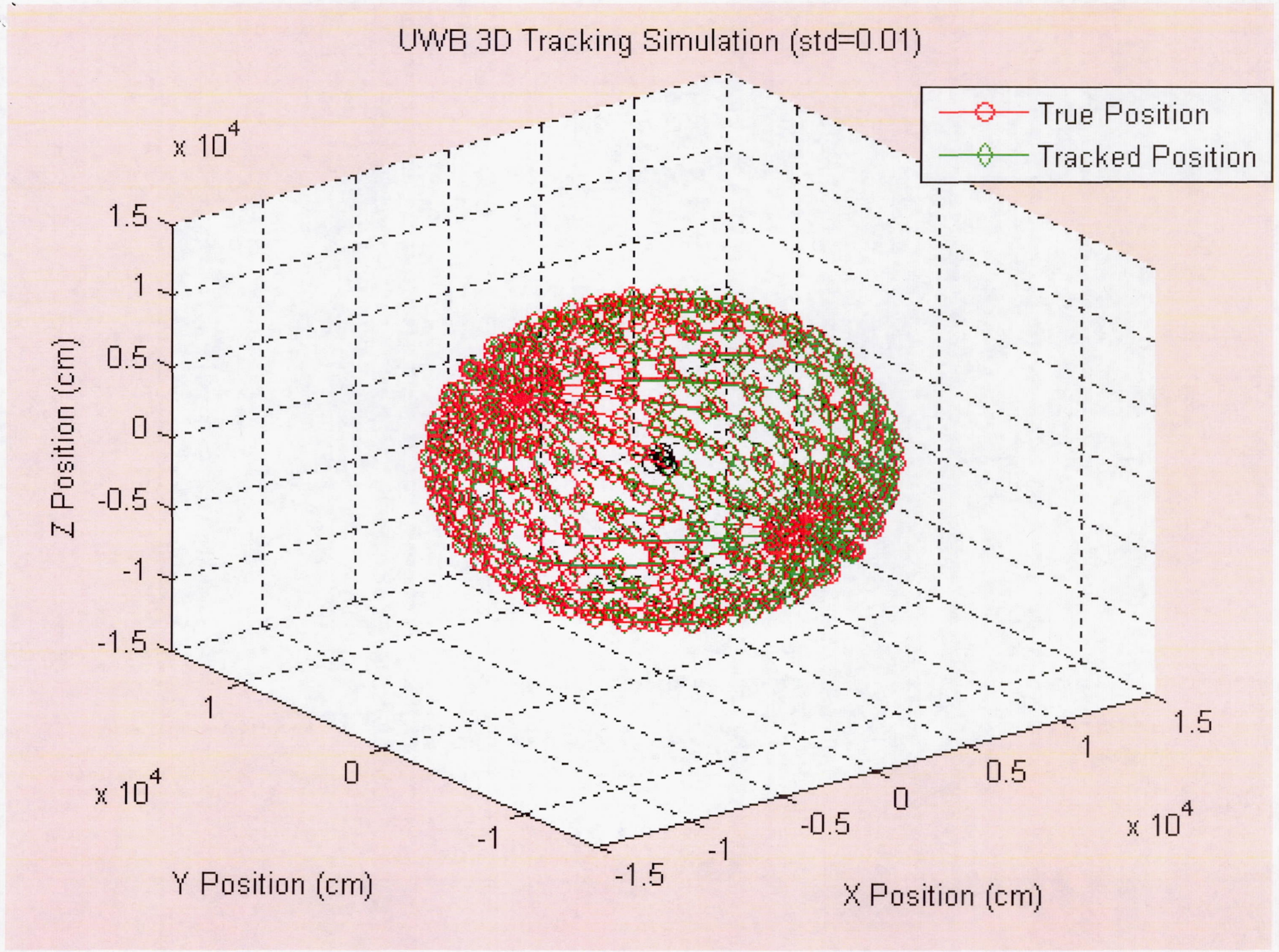
- The tracking error is linear to the standard deviation of TDOA data

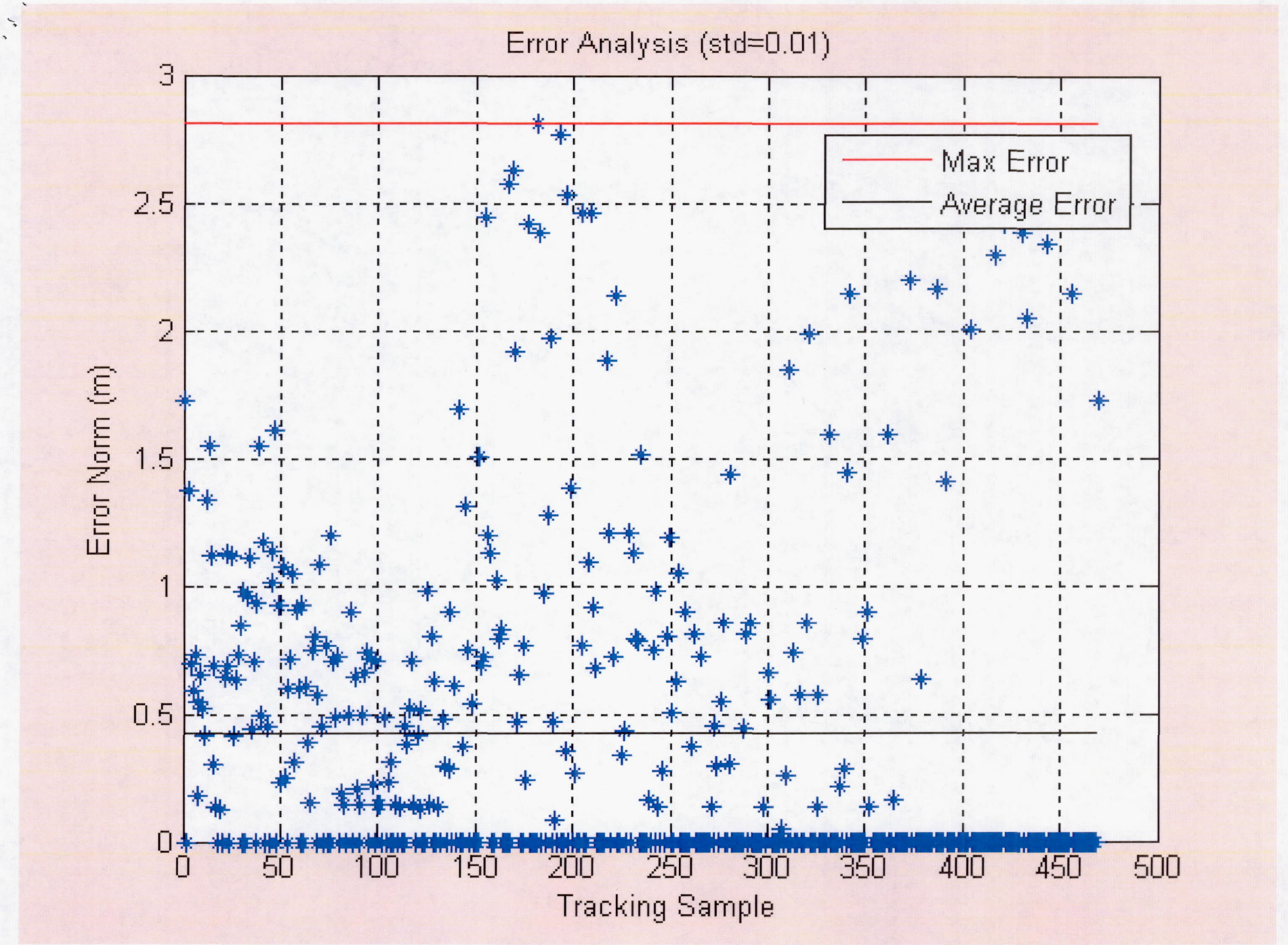

Antenna Configuration (std=0.01)
3000
2000
1000
0
-1000
-2000
-3000
Y (cm)
-3000
-2000
-1000
0
1000
2000
3000
X (cm)


Antenna Configuration (std=0.01)
x 10^4
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Y (cm)
True Position
Tracked Position
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
X (cm)
x 10^4


Error Analysis (std=0.01)
Error Norm (m)
Tracking Sample
AverageError
MaxError
0
1
2
3
4
5
6
0
20
40
60
80
100
120
140
160
180


UWB 3D Tracking Simulation
Z Position (cm)
600
400
200
0
-200
-400
-600
500
0
-500
Y Position (cm)
-500
0
500
X Position (cm)

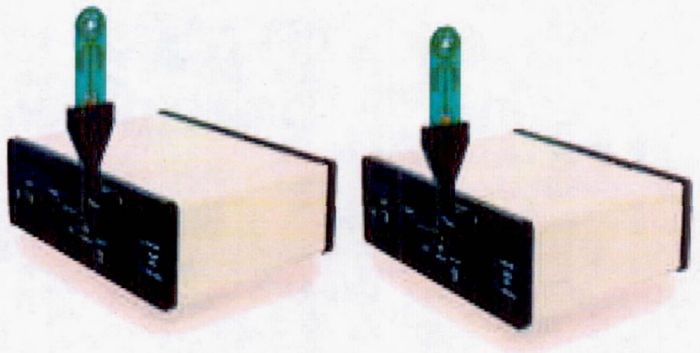

UWB 3D Tracking Simulation (std=0.01)
True Position
Tracked Position
x 10^4
1.5
1
0.5
0
-0.5
-1
-1.5
Z Position (cm)
x 10^4
1
0
-1
-1.5
Y Position (cm)
-1.5
-1
-0.5
0
0.5
1
1.5
x 10^4
X Position (cm)


Error Analysis (std=0.01)
Max Error
Average Error
Error Norm (m)
Tracking Sample
0
0.5
1
1.5
2
2.5
3
0
50
100
150
200
250
300
350
400
450
500

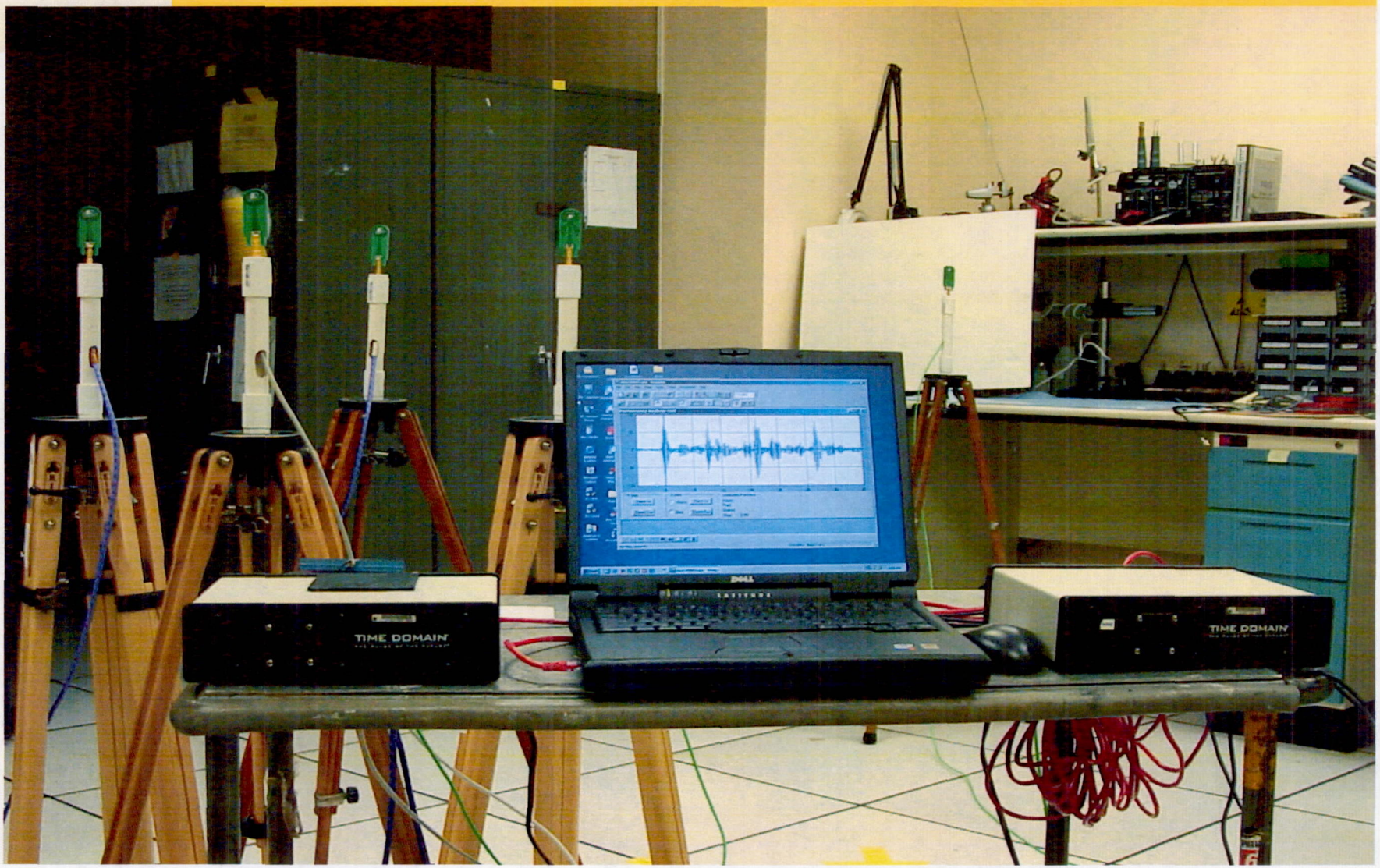
Lab Experiments (UWB PulsON 200 Radio)

- Signal Generator

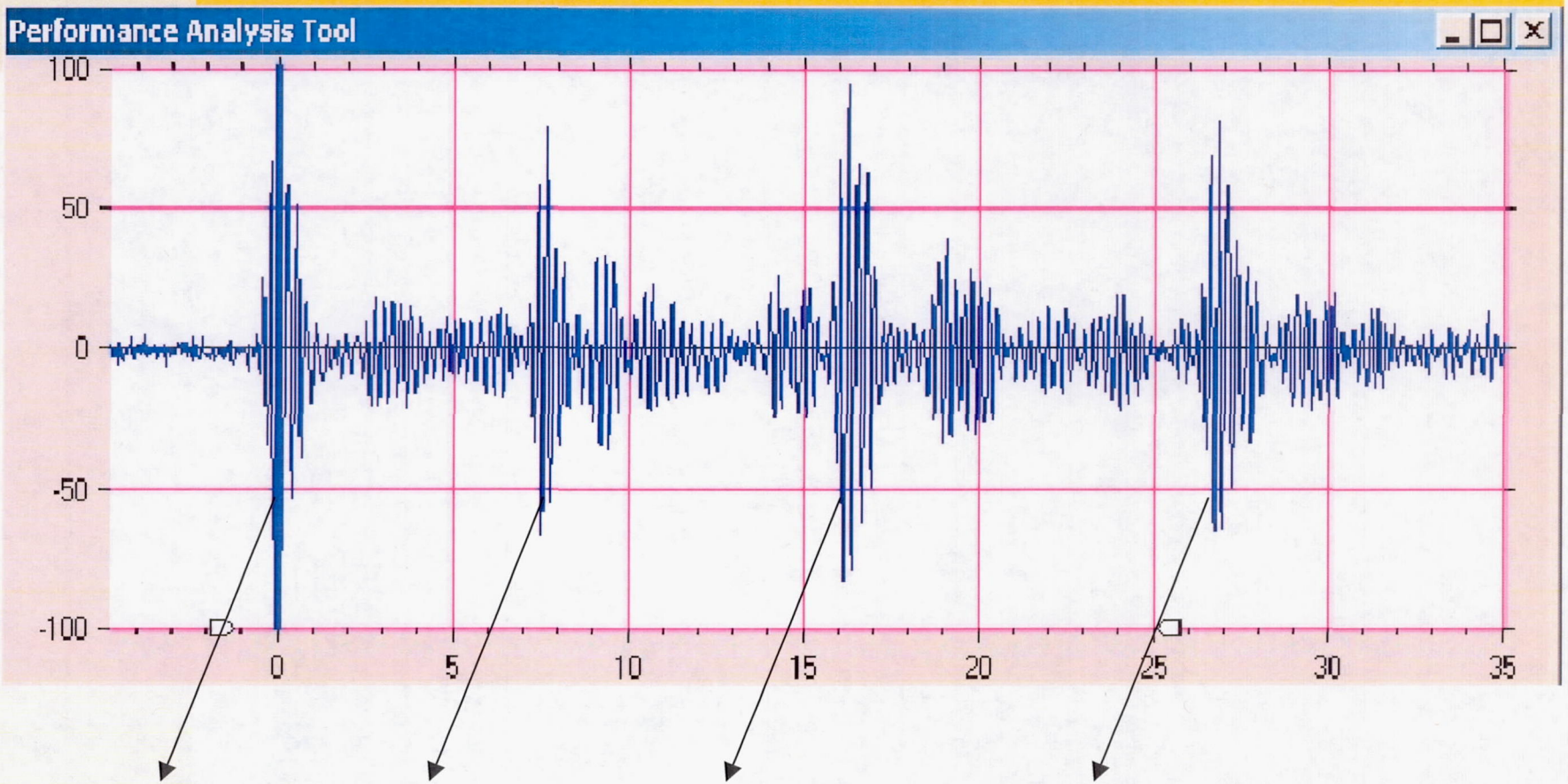
- Evaluation Kit



Lab Experiments (setup)



Lab Experiments (Four Antenna Scheme)



Lab Test

- 15 feet by 15 feet lab space
- 3 antennas mounted evenly on a circle of radius 62cm with the reference antenna at center
- TDOA data measured from EVK Radios and fed into the tracking algorithm
- Observed position error (less than 1 foot)

Error Analysis

$$(x, y) = f(x_i, y_i, \tau_{i1})$$

$$Cov(x, y) = g(m_\tau, \sigma_\tau^2)$$

σ_τ^2 TDOA measurement resolution

m_τ Receiving antennas configuration

Conclusion and Future Work

- A UWB tracking scheme has been established and simulations show TDOA algorithm achieves fine resolution in small error region
- The preliminary lab experiments demonstrate the tracking capability of the UWB technology
- Enhanced TDOA estimation method and optimal antenna configuration will be investigated to improve the resolution
- 2D tracking capability will be extended to 3D

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