Ultra-Wideband Tracking System Design for Relative Navigation

Jianjun (David) Ni, Dickey Arndt, Phong Ngo, Kent Dekome, John Dusl

Abstract

This presentation briefly discusses a design effort for a prototype ultra-wideband (UWB) time-difference-of-arrival (TDOA) tracking system that is currently under development at NASA Johnson Space Center (JSC). The system is being designed for use in localization and navigation of a rover in a GPS deprived environment for surface missions. In one application enabled by the UWB tracking, a robotic vehicle carrying equipments can autonomously follow a crewed rover from work site to work site such that resources can be carried from one landing mission to the next thereby saving up-mass. The UWB Systems Group at JSC has developed a UWB TDOA High Resolution Proximity Tracking System which can achieve sub-inch tracking accuracy of a target within the radius of the tracking baseline [1]. By extending the tracking capability beyond the radius of the tracking baseline, a tracking system is being designed to enable relative navigation between two vehicles for surface missions. A prototype UWB TDOA tracking system has been designed, implemented, tested, and proven feasible for relative navigation of robotic vehicles. Future work includes testing the system with the application code to increase the tracking update rate and evaluating the linear tracking baseline to improve the flexibility of antenna mounting on the following vehicle.

References

[1]. Jianjun (David) Ni, et al; "UWB TDOA Proximity High Resolution Tracking System", IEEE Symposium for Space Applications of Wireless & RFID (SWIRF), Houston, TX, May 2007.

UWB TDOA Tracking for Relative Navigation

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UWB Systems Group / EV4
Avionic Systems Division (EV)
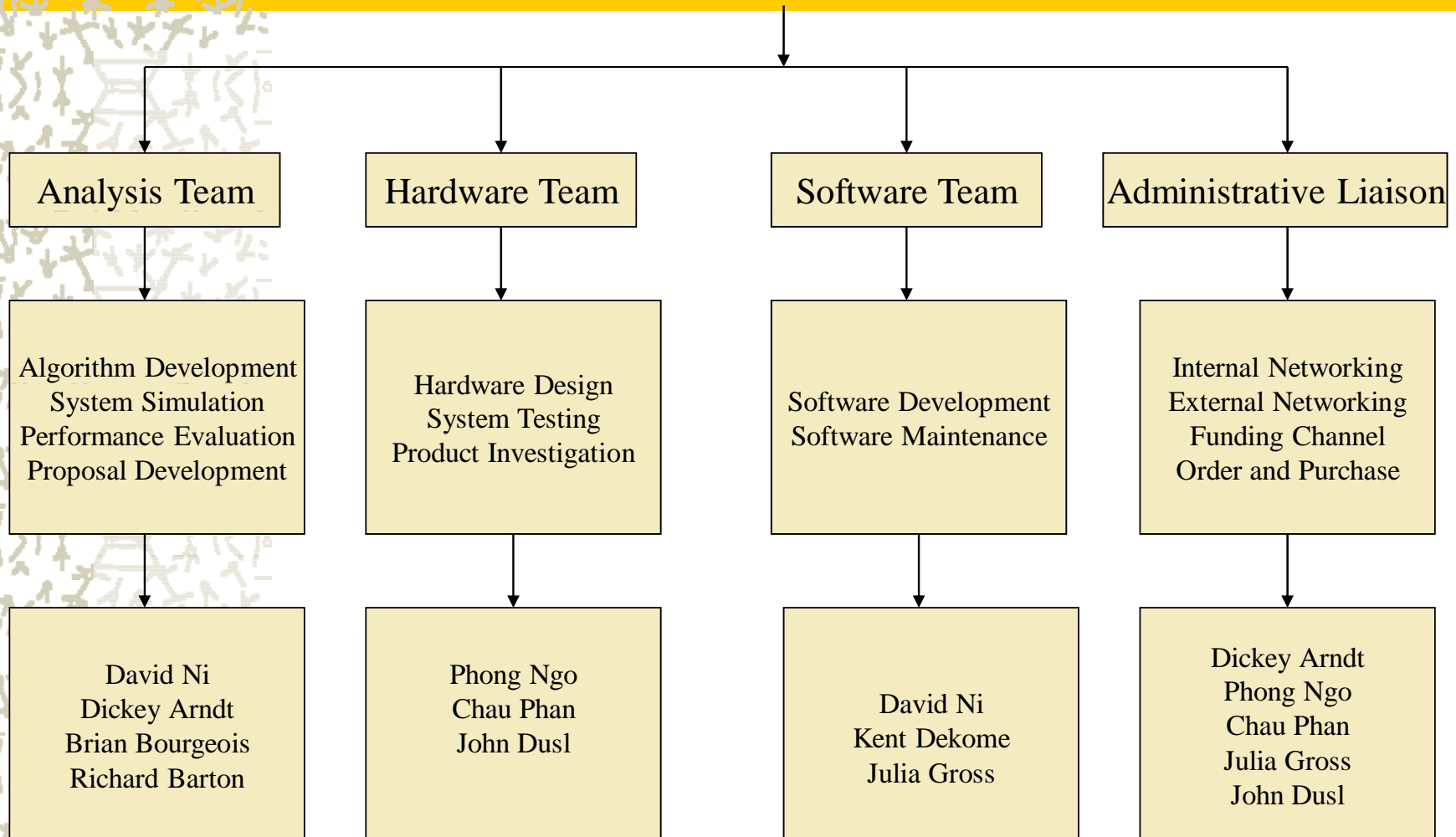
NASA Johnson Space Center

JSC Today - Quote of the Day

- " No one can whistle a symphony. It takes a whole orchestra to play it."

    -- H.E. Luccock

# UWB Systems Group
(A Functional Team Architecture)

Analysis Team	Hardware Team	Software Team	Administrative Liaison
Algorithm Development System Simulation Performance Evaluation Proposal Development	Hardware Design System Testing Product Investigation	Software Development Software Maintenance	Internal Networking External Networking Funding Channel Order and Purchase
David Ni Dickey Arndt Brian Bourgeois Richard Barton	Phong Ngo Chau Phan John Dusl	David Ni Kent Dekome Julia Gross	Dickey Arndt Phong Ngo Chau Phan Julia Gross John Dusl

Outline

- UWB Technology Development at JSC
- UWB Fine Time Resolution
- TDOA Tracking Methodology
- TDOA Resolution Analysis
- Tracking System Design and Software
- Summary

UWB AOA Long Range Tracking

- UWB AOA long range tracking with the SCOUT vehicle at the Meteor Crater, Arizona in 2005 and 2006
- Excellent tracking performance with less than 1% error at ranges up to 4000 ft
- No RF interference with on-board GPS, video, audio, and telemetry systems

UWB Antenna

UWB Radio
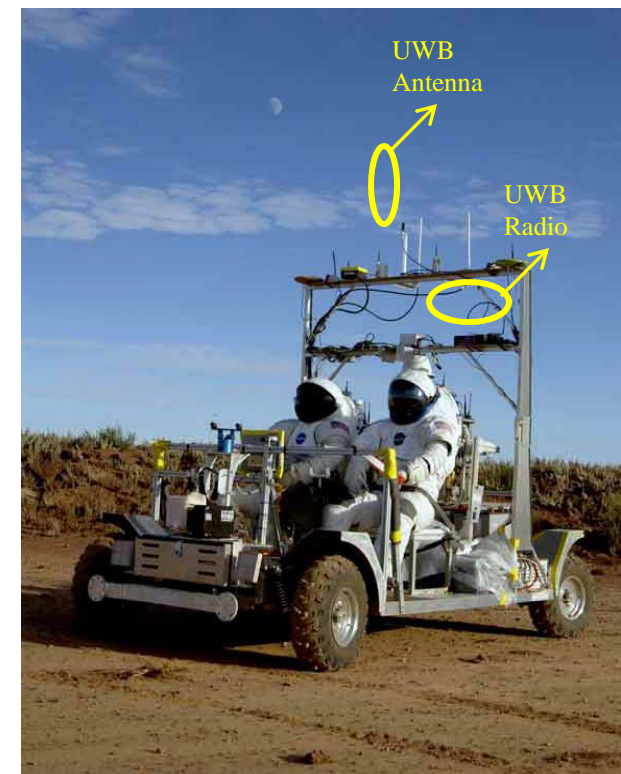
UWB TDOA High Resolution Tracking
for 2D Docking Mechanism

- Use Time Difference of Arrival (TDOA) technique to provide sub-inch tracking resolution
- Two tracking points on target to accurately guide the target into its docking station

UWB TDOA 3D High Resolution Tracking
for Robotic Control

- UWB TDOA 3D tracking at Honeywell's Moonyard Facility
- Real-time trajectory can be displayed and recorded
- Tracking accuracy within1 inch in the xy plane and within 2 inches in the z direction
- Tracking data are passed to the robotic control system

Why UWB?

- Immunity to interference from narrow band RF systems due to ultra-wide bandwidth
- Low impact on other RF systems due to extremely low power spectral densities
- **Capable of precise tracking due to sub-nanosecond time resolution**
- Robust performance in multipath environments
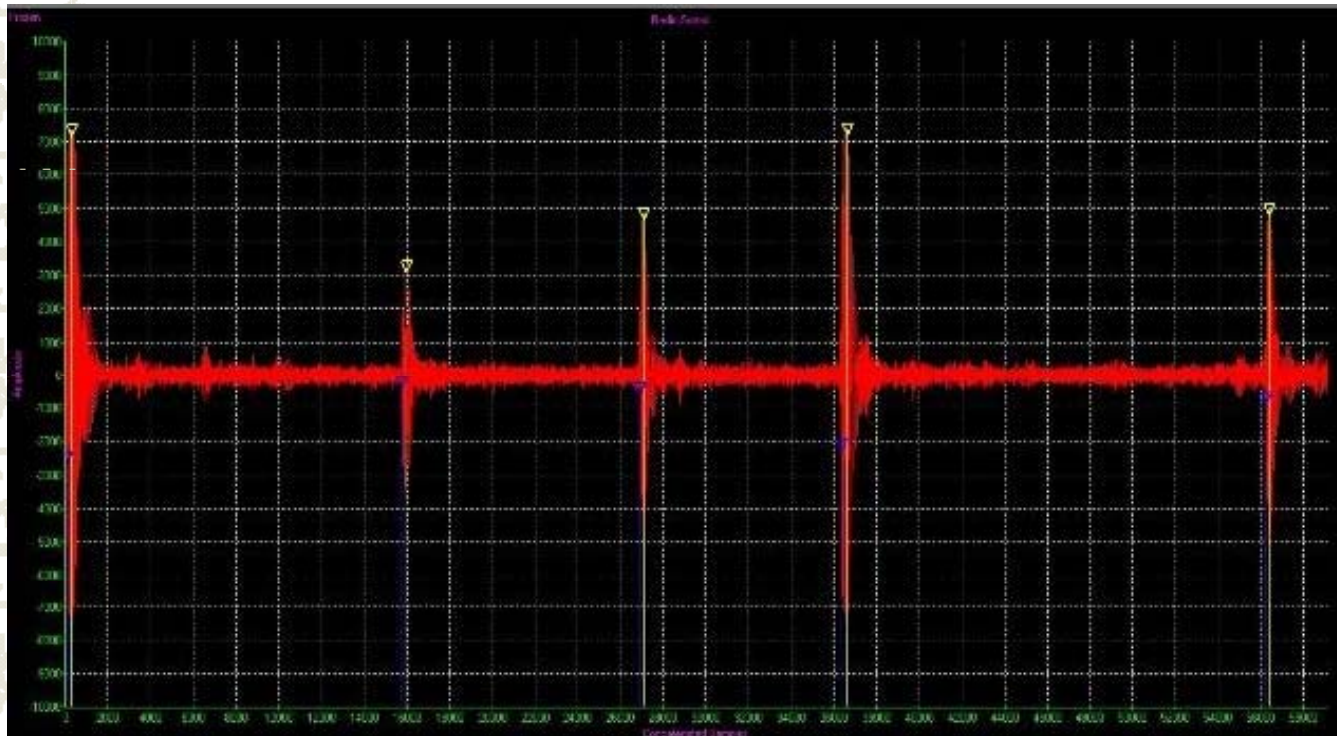
Hyperbola: $b^2 x^2 - a^2 y^2 = a^2 b^2$

Time Difference of Arrival (TDOA)

Rx1
(x1, y1)

Rx2
(x2, y2)

Rx3
(x3, y3)

Tx
(x, y)
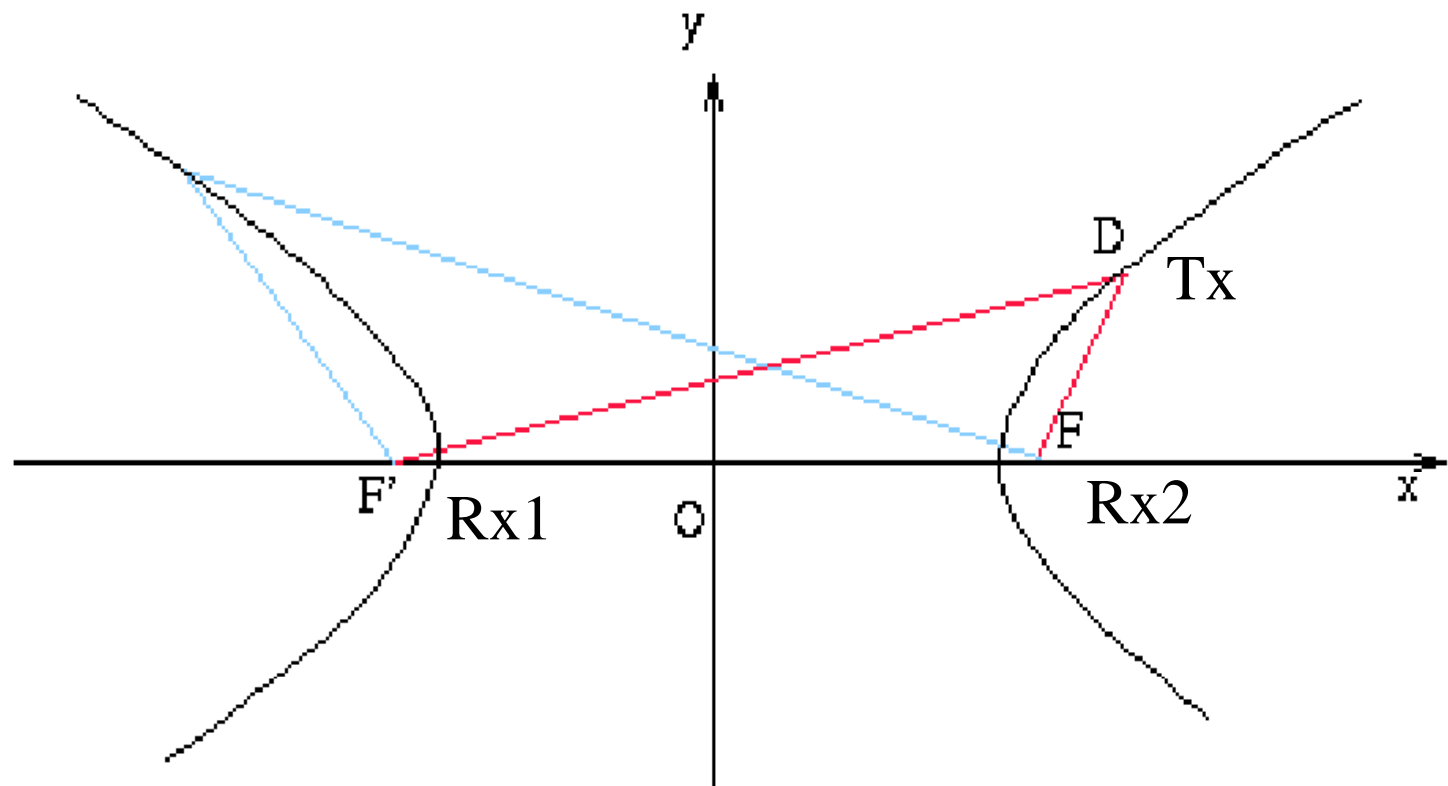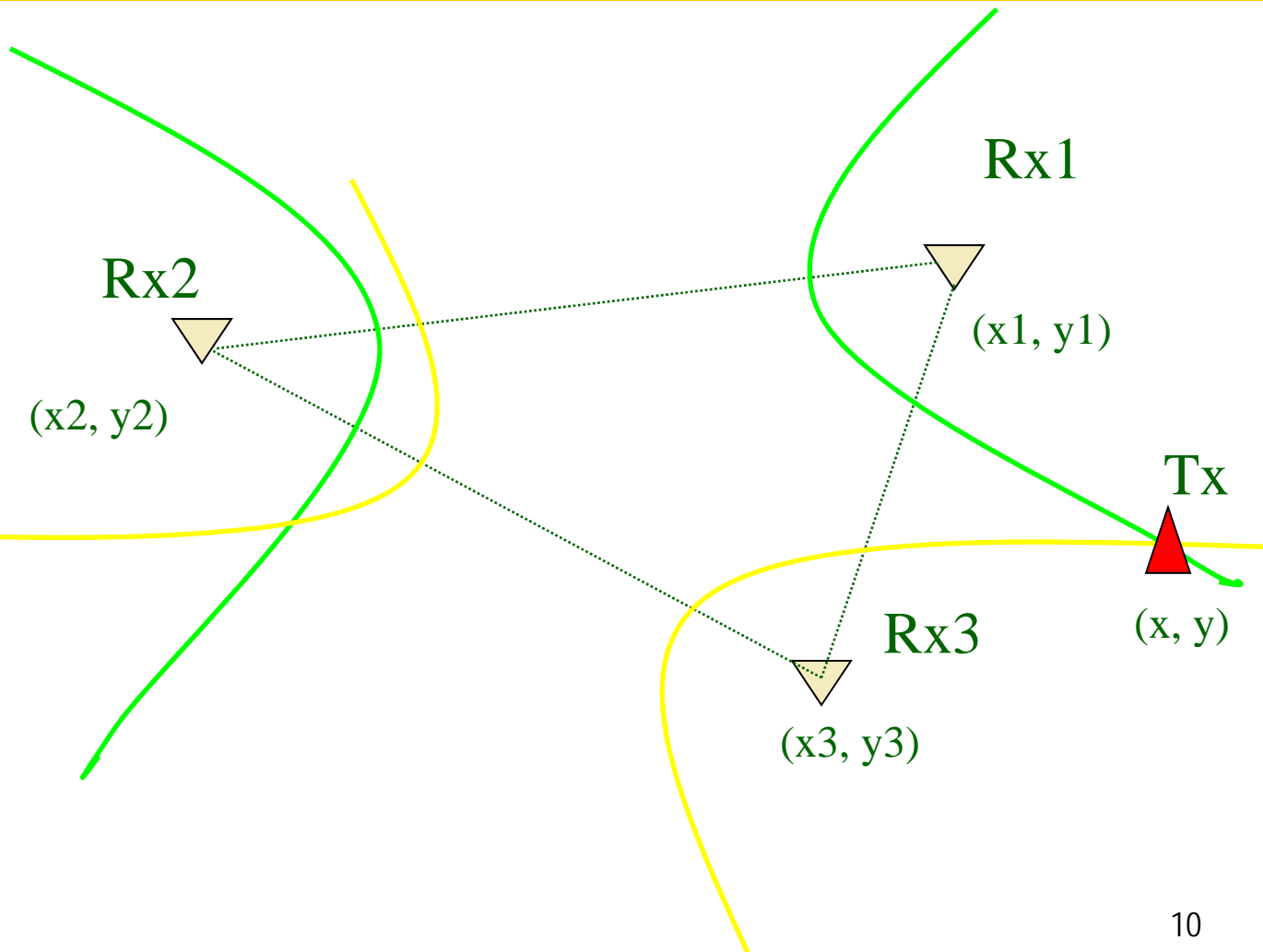
Advantages of TDOA

- No synchronization between Tx and Rx
- Simplex (one-way) data estimation
- Cross-correlation plus Peak Detection (CCPD) works well to obtain TDOA

TDOA Equations (2D)

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

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

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

TDOA Algorithm

🐞 Taylor Series Expansion Least Squares
Iterative Algorithm
(Initialization problem and convergence problem)

🐞 Two-Stage Weighted Least Squares Algorithm
(one more receiver)

Resolution Analysis (setting)

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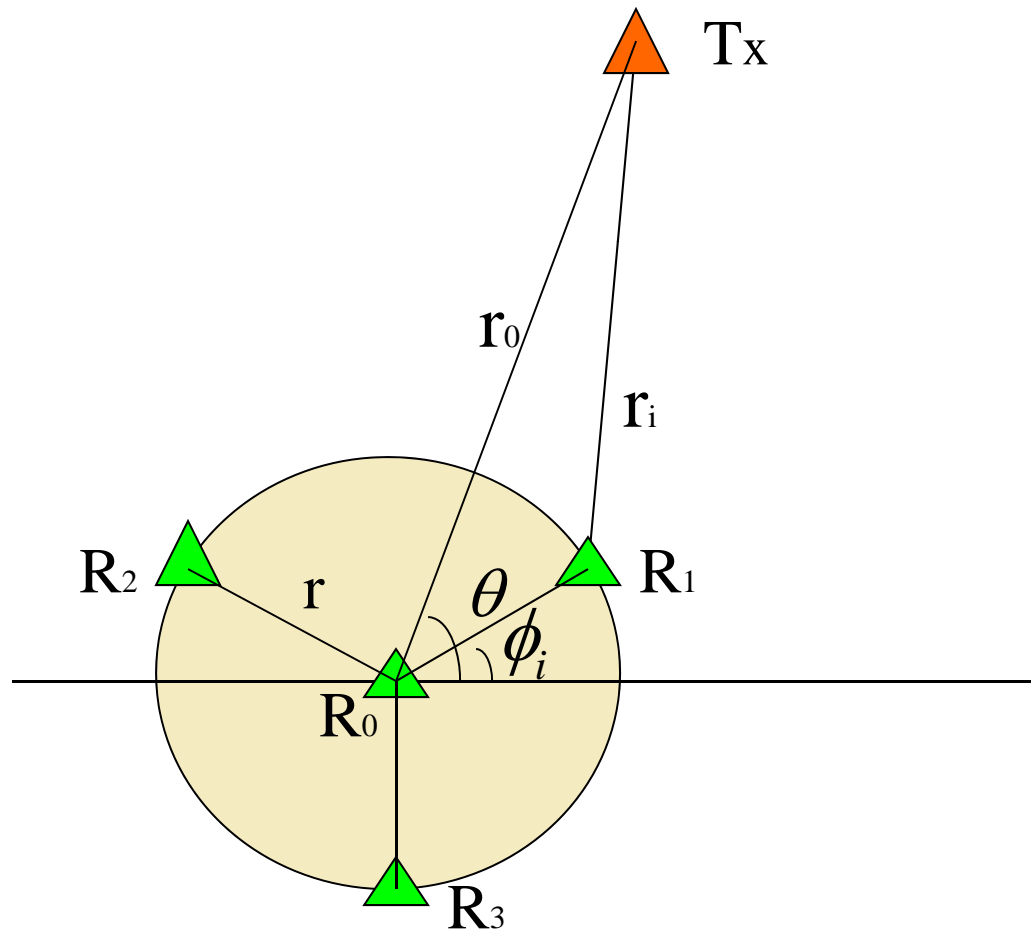
$$\text{MSE} \approx \frac{4c^2\sigma^2 r_0^4}{Mr^4 \overline{v}^4}$$

$$\text{CRLB} \approx \frac{2c^2\sigma^2 r_0^2}{Mr^2}$$

where

$$\overline{v}^4 = \frac{1}{M}\sum_{i=1}^{M} v_i^4 = \begin{cases} \frac{3}{8}, M \neq 4 \\ \frac{3}{8} + \frac{1}{8}\cos(4\theta), M = 4 \end{cases}$$

Proximity Case

- M=4

$$\text{MSE} \approx \frac{8c^2\sigma^2 r_0^4}{(3+\cos(4\theta))r^4}$$

- Proximity case: rang is close to baseline size

$$\text{MSE} \approx 4c^2\sigma^2$$

Proximity High Resolution

$$\text{MSE} \approx 4c^2\sigma^2$$

$$\overline{\varepsilon} = 2c\sigma$$

$$c = 3 \times 10^8 \text{ m/s}$$

$$\sigma = 10^{-9} \text{ s}, \ \overline{\varepsilon} = 0.6 \ m$$

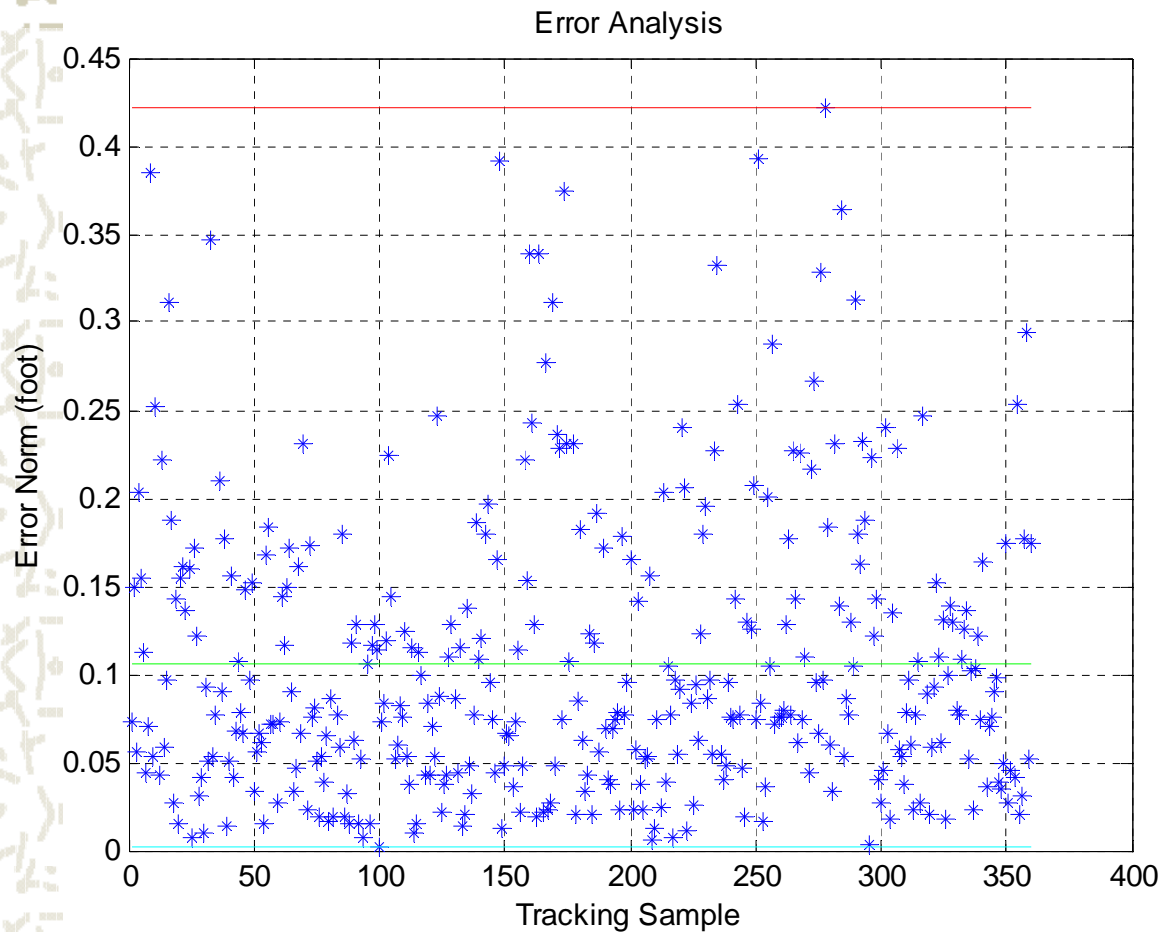$$\sigma = 10^{-11} \text{ s}, \ \overline{\varepsilon} = 0.006 \ m$$
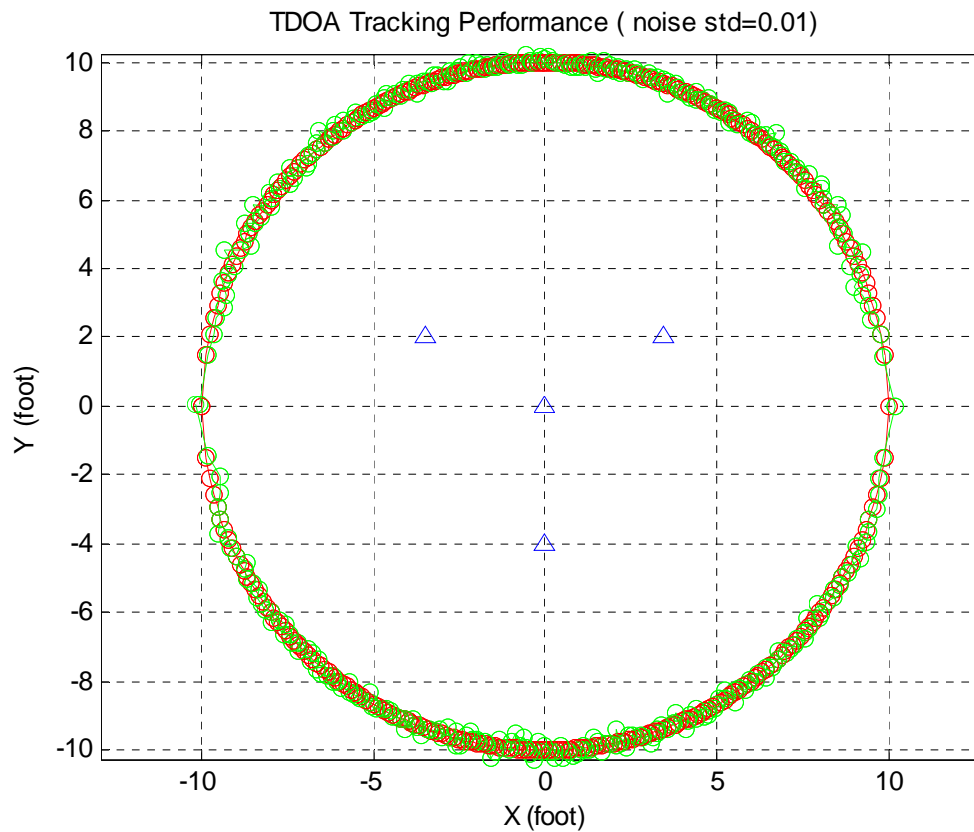
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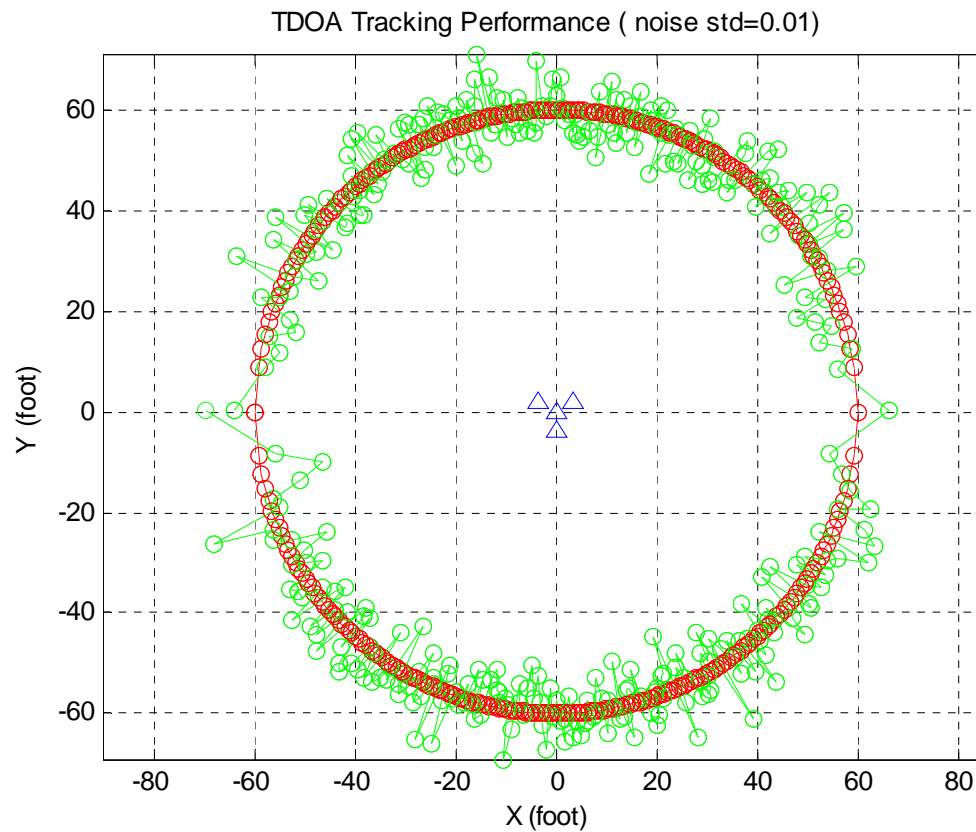# Tracking Performance (radius = 4 feet, range=10 feet)

TDOA Tracking Performance (noise std=0.01)

Error Analysis
(radius = 4 feet, range=10 feet)

Error Analysis

Tracking Performance (radius = 4 feet, range=60 feet)

TDOA Tracking Performance (noise std=0.01)

Error Analysis
(radius = 4 feet, range=60 feet)

Tracking Performance vs. Range
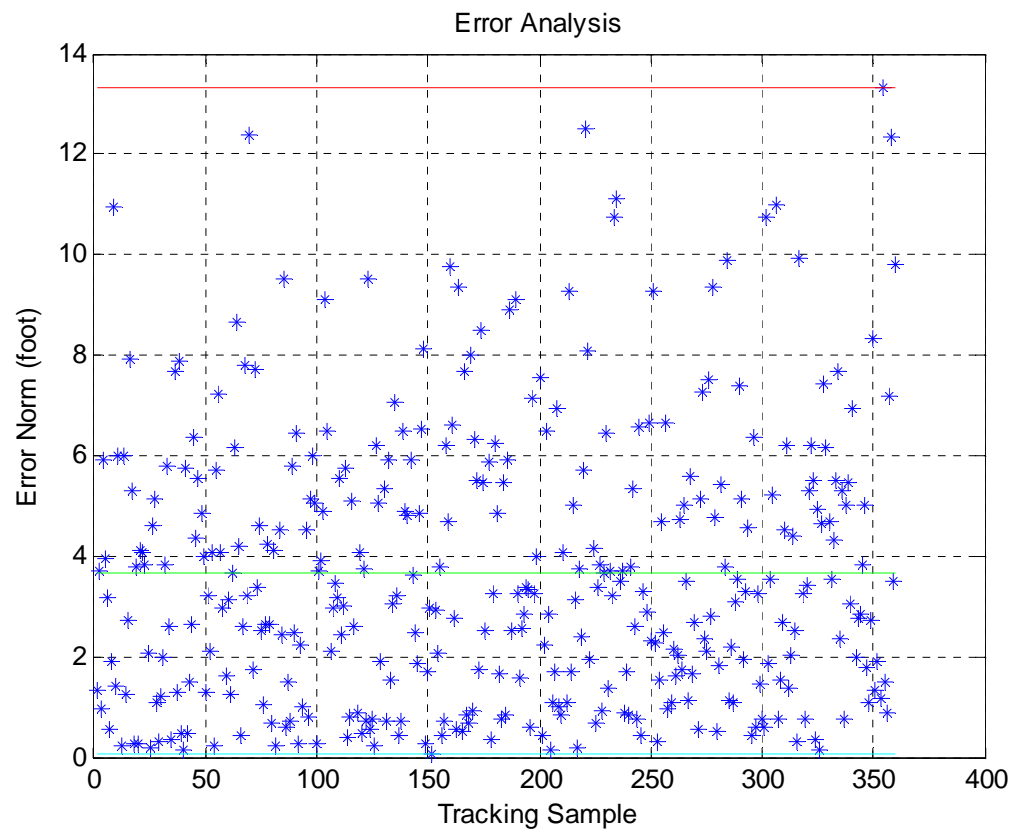
Error Analysis (vs. Range)
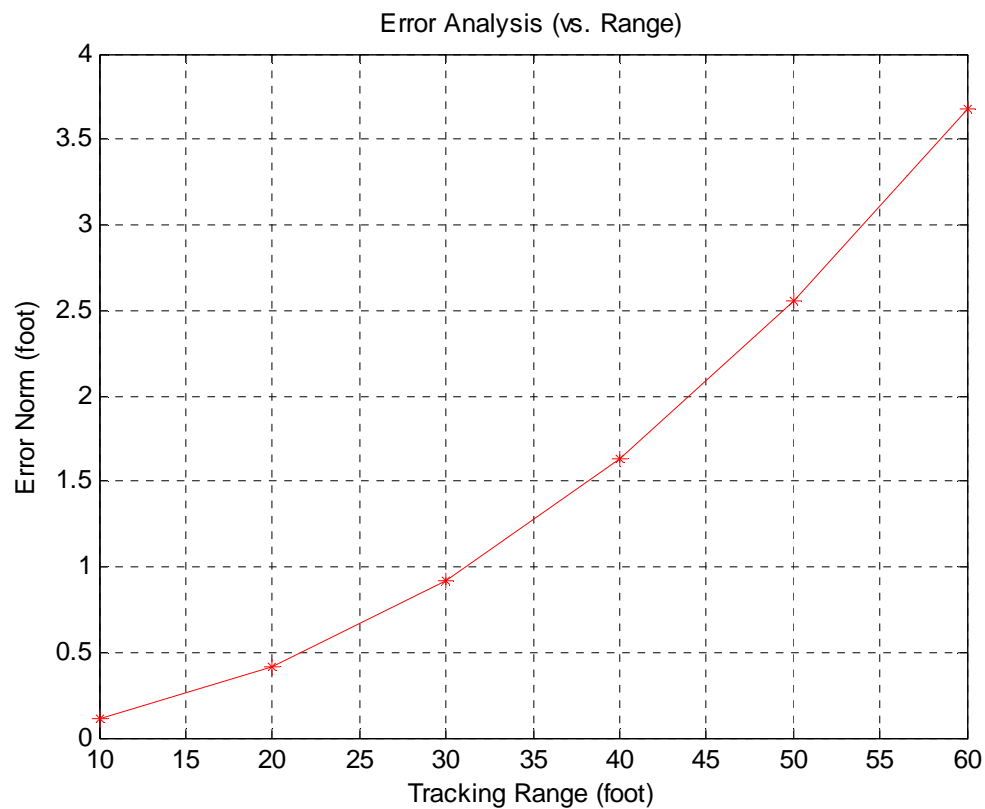
Tracking Performance vs. Range
(Comparison with Baseline Radius)

Tracking Error Analysis

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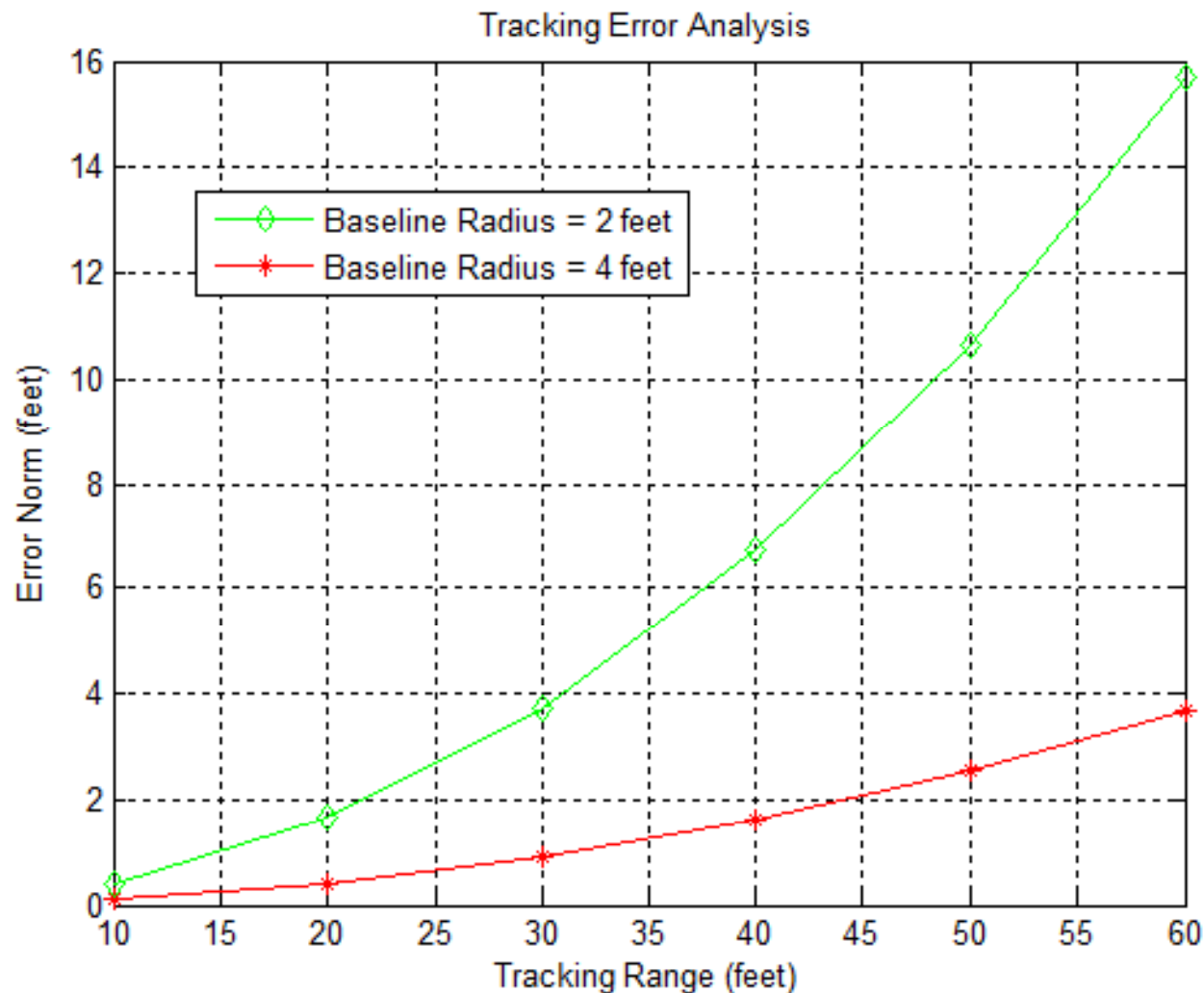
Tracking System Set-up

Following Vehicle

Leading Vehicle

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Tracking Software

- ★ Experimental Code Version
  - Coded with Matlab
  - Pros: flexibility for change
  - Cons: slower speed
- ★ Application Code Version
  - Coded with C++
  - Pros: faster update rate
  - Cons: need compile

Summary and Future Work

- A prototype UWB TDOA tracking system has been designed, implemented, tested, and proven feasible for relative navigation of robotic vehicles.

- Future work includes testing the system with the application code to increase the tracking update rate and evaluating the linear tracking baseline to improve the flexibility of antenna mounting on the following vehicle.
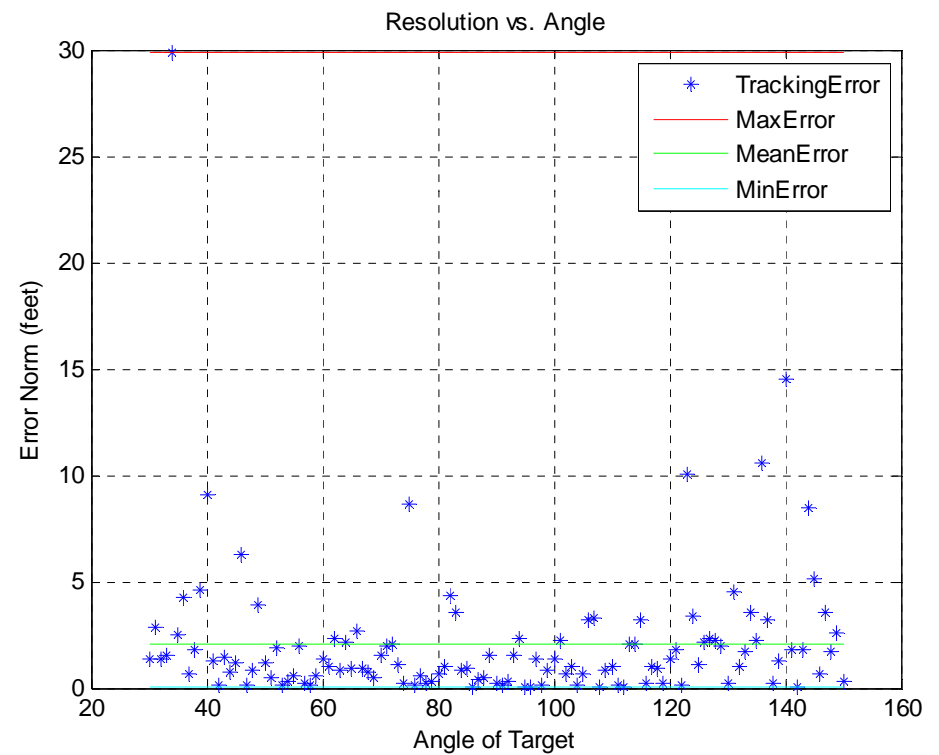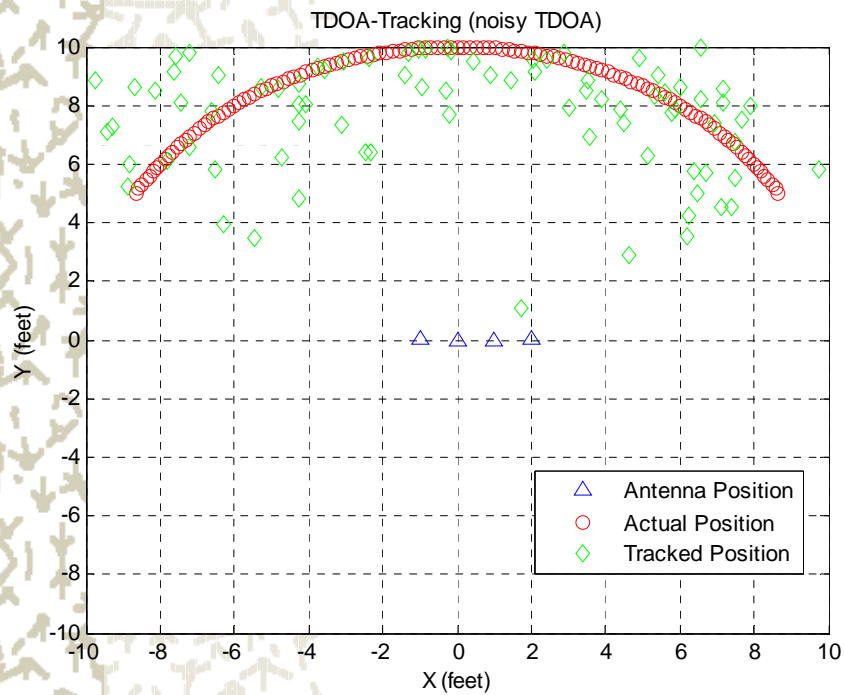
Backup Slides

Demo to ER personnel at Antenna Range
    Behind B14.

Collect comments and suggestions to improve
the system performance to meet ER's needs.

TDOA (3′ BL, 2′AE at 10′)

TDOA (6′ BL, 0.5′AE at 10′)