# GPS Accuracy in Urban Environments Using Post-Processed CORS Data

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# *Presentation Topics*

- Post Processing Overview
- Test Results in Obstructed Environments
- Next steps – Looking Ahead to 2020
- Summary

# National Positioning, Navigation, and Timing (PNT) Architecture Study

- In 2006 the Assistant Secretary of Defense for Networks and Information Integration (ASD/NII) and the Under Secretary of Transportation for Policy (UST/P) sponsored a National Positioning, Navigation, and Timing (PNT) Architecture Study to "provide more effective and efficient PNT capabilities focused on the 2025 time frame…"
- Several NOAA organizations, including the National Geodetic Survey (NGS), participated on the Architecture Development Team (ADT) and are, additionally, members of the Architecture Transition Team (ATT).
- The PNT Joint Capabilities Document (JCD) identified a number of validated gaps in capability which are projected to exist in the 2025 timeframe.

# *National Positioning, Navigation, and Timing (PNT) Architecture Study [1]*

- The team identified 7 gaps and the key gap related to this presentation was:
- ***Assured and real-time PNT in physically impeded environments.***
- The large data set gathered (approximately 106 Million data points) during the Census Address Canvassing can provide a very good assessment of what are the PNT capabilities of GPS in a partially impeded physical environment today.

1 National Positioning, Navigation, and Timing Architecture Study, Final Report, September 2008---This Document Is Cleared For Public Release

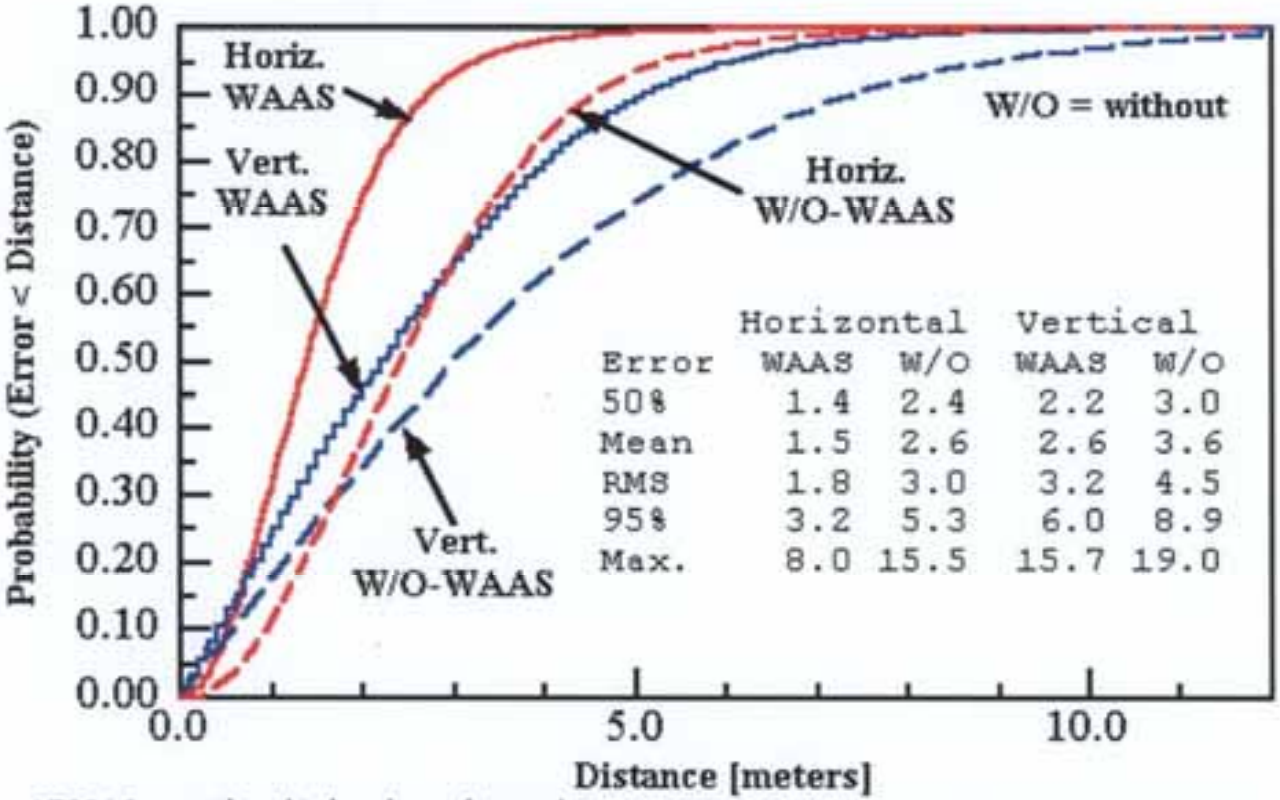
# Address Canvassing

- The Census Bureau used Hand Held Computers (HHCs) to capture GPS structure points for every housing unit during its Address Canvassing field operation.
  - The Address Canvassing operation supported the 2010 Census.
  - Address Canvassing is the first nationwide collection of housing unit structure points using GPS technology to be conducted by the Census Bureau.
  - Field collection occurred in spring 2009.
  - The Hand Held Computer has Wide Area Augmentation System (WAAS) capability to increase point position accuracy to 3 meters or less in an unobstructed environment.

# *NGS Post Processing of Census Data*

- The Hand Held Computer was modified to store all visible satellite pseudoranges when a GPS mapspot was recorded by an Address Canvasser.
- This data was post processed using the nearest CORS station to provide a more accurate coordinate for the structure address.
- Accuracy is three meters or less using a CORS station at a maximum distance of 200 Kms.
- Post Processing extends the increased accuracy to all data points when the WAAS satellite is blocked.

## WAAS VS. NON-WAAS COMPARISON
### Garmin GPSMAP 76 with GA29 antenna




| | Horizontal | | Vertical | |
|---|---|---|---|---|
| Error | WAAS | W/O | WAAS | W/O |
| 50% | 1.4 | 2.4 | 2.2 | 3.0 |
| Mean | 1.5 | 2.6 | 2.6 | 3.6 |
| RMS | 1.8 | 3.0 | 3.2 | 4.5 |
| 95% | 3.2 | 5.3 | 6.0 | 8.9 |
| Max. | 8.0 | 15.5 | 15.7 | 19.0 |

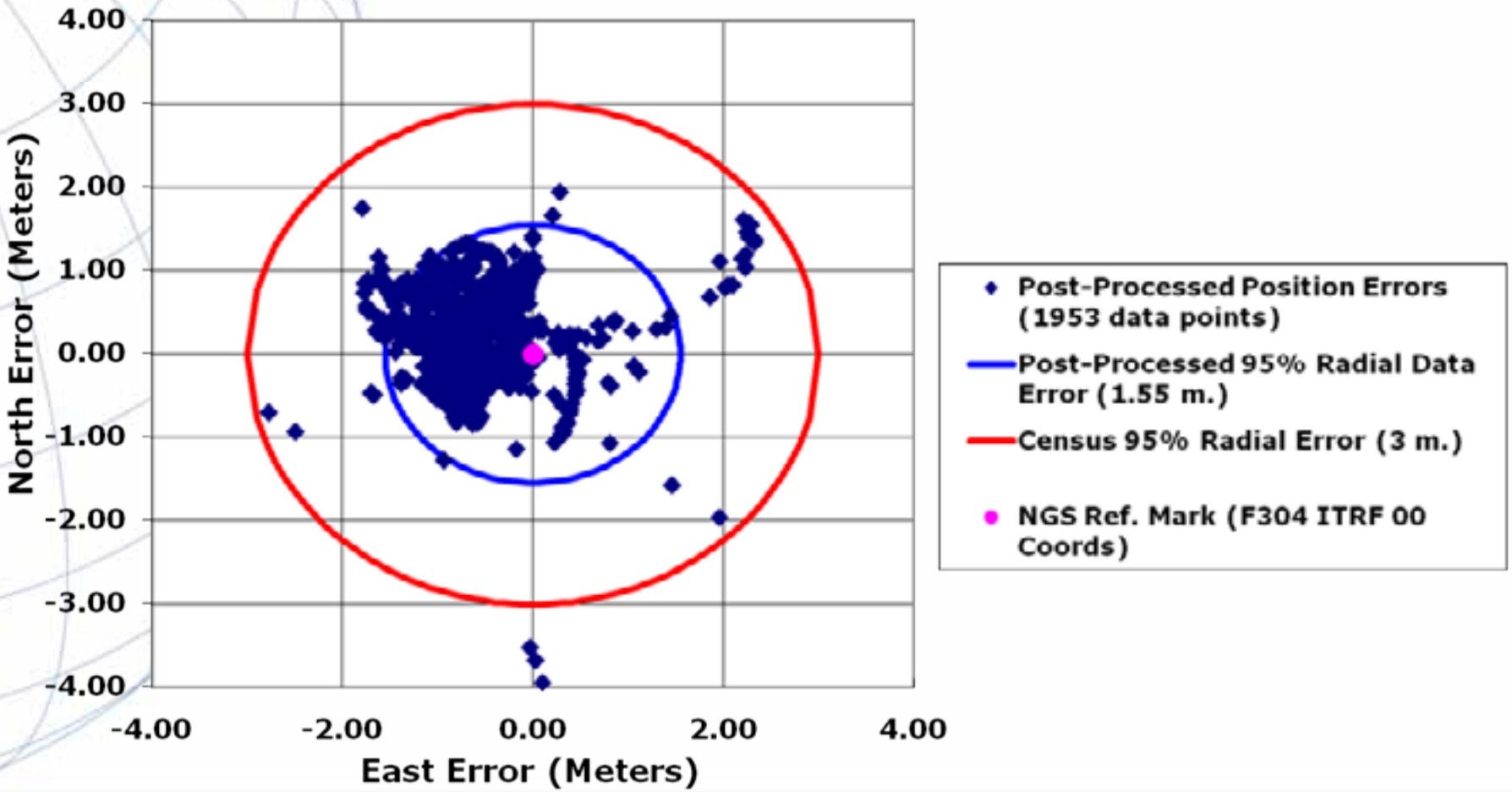
172815 samples (4 days) each session
WAAS & Non-WAAS non-simultaneous
Samples every 2 seconds

Note: Max. error depends greatly on the length of the observation period and is generally not a robust statistic.

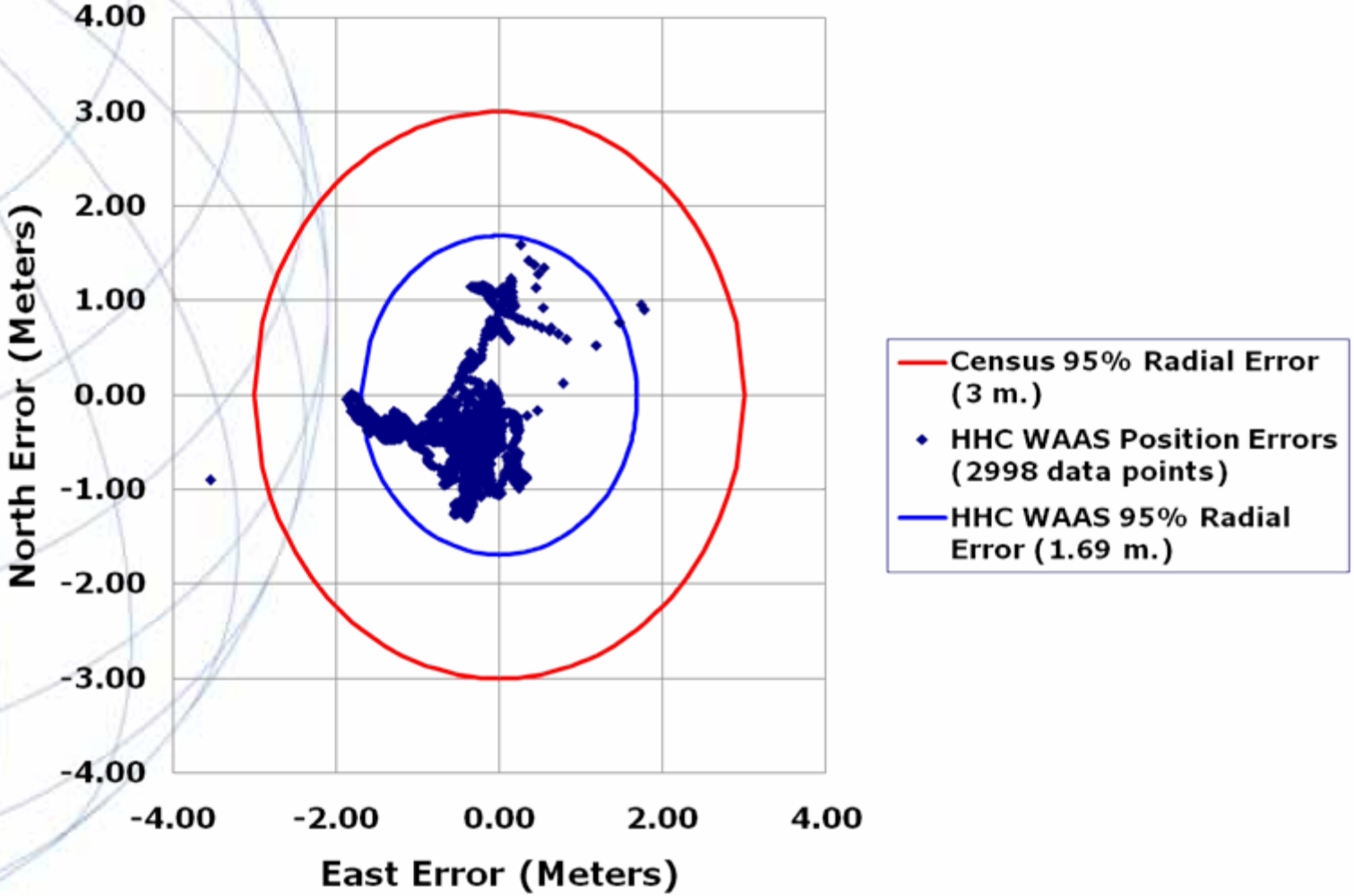
[1] Wilson, David L. *GPS WAAS Accuracy.* http://users.erols.com/dlwilson/gpswaas.htm

# Present CORS Network

# *Post-Processed Position Errors at NGS MARK F304 (Melbourne, FL) re CORS BRTW Ref. Station @ 120 Km.*



# HHC WAAS Position Errors at NGS F304 (Melbourne, FL) Ref. Mark



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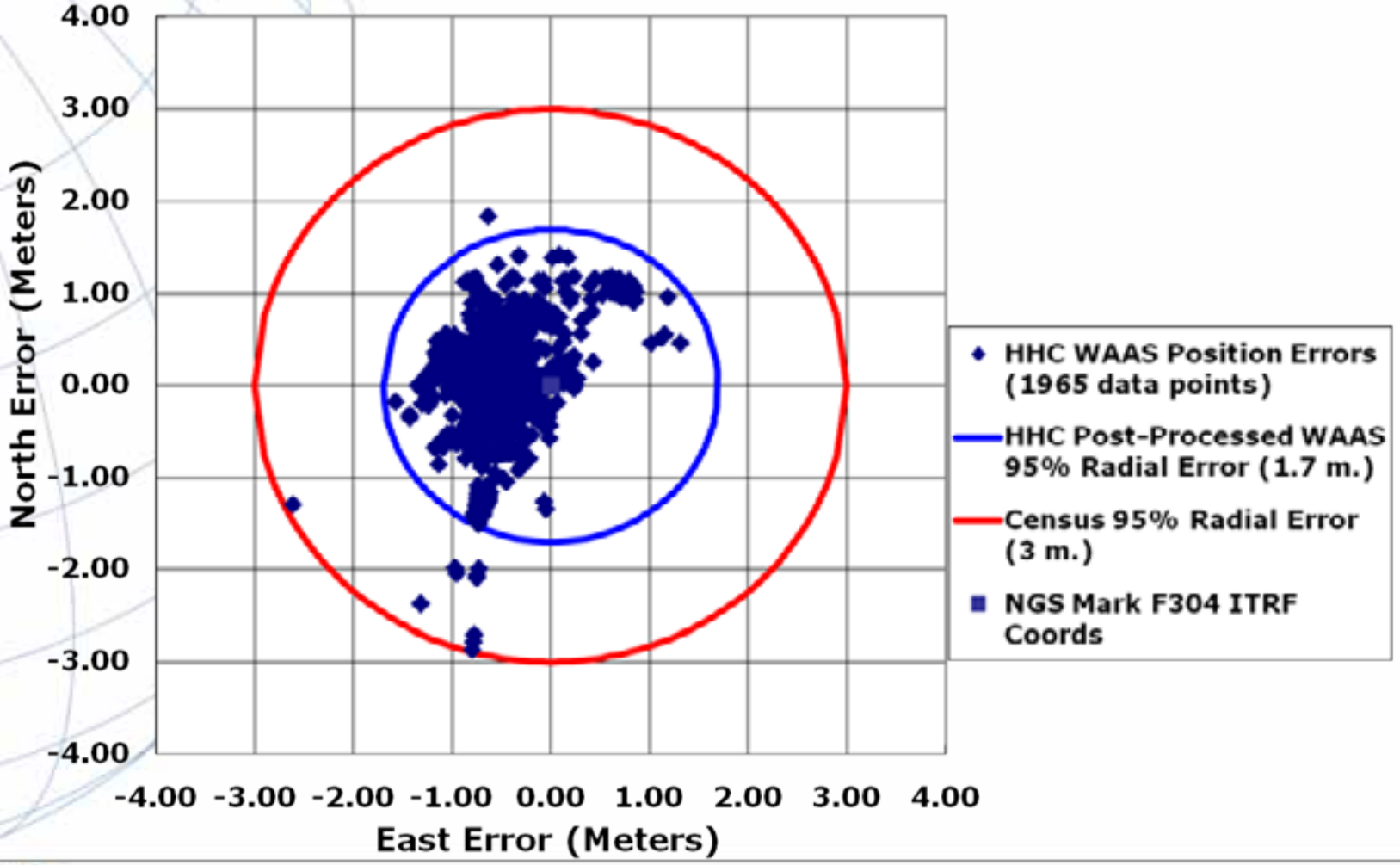
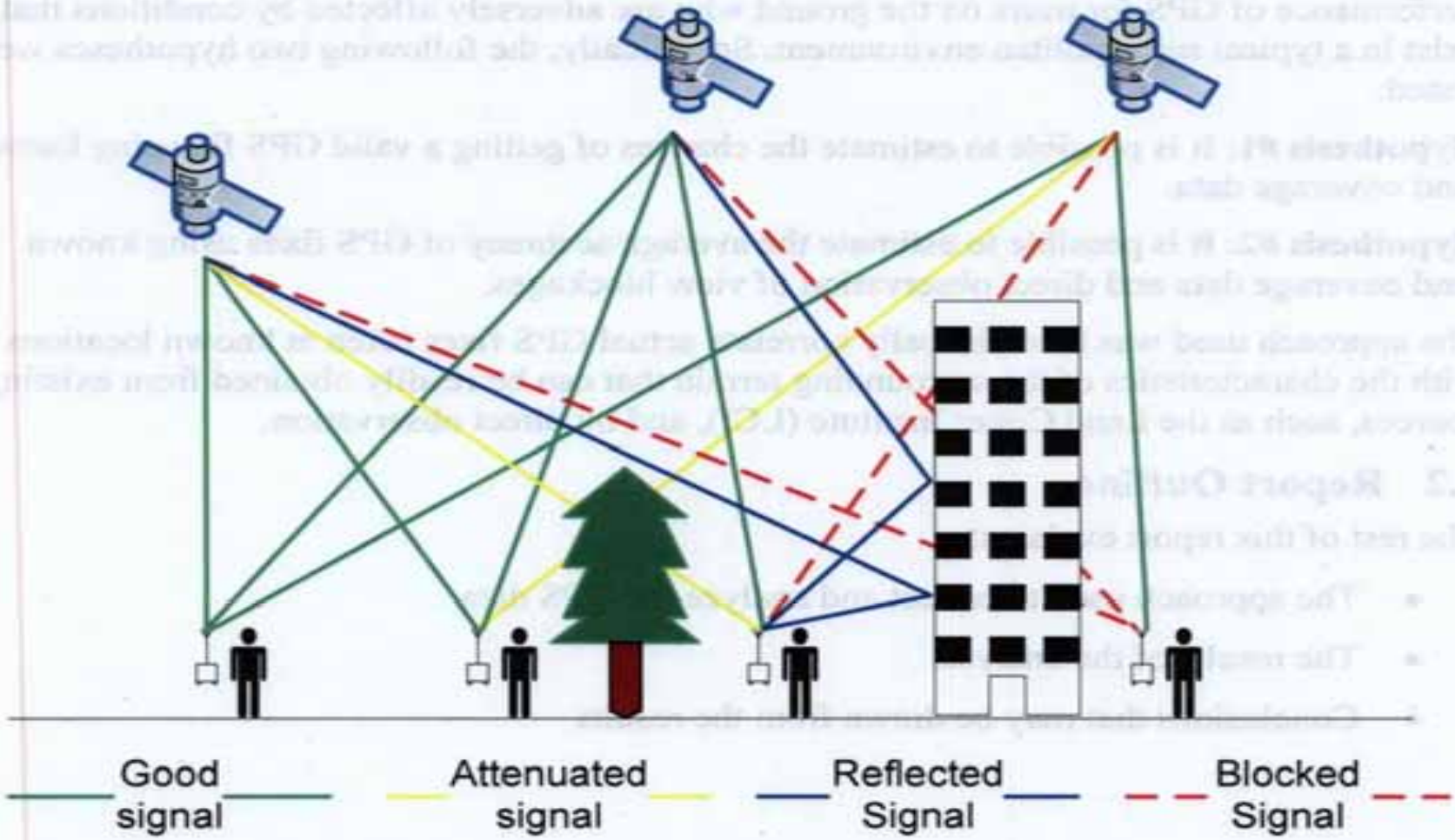


# GPS Post-Processed & WAAS Accuracy at Melbourne, FL NGS Reference Marks

| | |
|---|---|
| Post-Processed with 120 Km Ref. Station | 1.55 m. (95%) @ F304 |
| WAAS @ F304 | 1.69 m. (95%) |
| WAAS @ 5062 (THRON) | 1.50 m. (95%) |
| WAAS Post-Processed with 120 Km Ref. Station | 1.70 m. (95%) @ F304 |




**GPS Signal Reception Problem Illustration**

Bohne, Paul F. & Nobile, Marc P. MITRE Technical Report MTR070200, “Average GPS signal Availability Estimation”, pp. 1-1, September 2007.

# Table 1 Post-Processed Results Church Parking Lot

| RMS (m.) | WAAS? Yes=2 No=1 | East Error (m.) | North Error (m.) | Time HH/MM/SS | Data Point Desig. |
|---|---|---|---|---|---|
| 19.6 | 2 | -10.29 | 8.66 | 140851 | T2 |
| 2.6 | 2 | -0.61 | -1.14 | 141027 | T4 |
| 9.9 | 1 | -2.04 | 1.04 | 141107 | T5 |
| 5.6 | 1 | -1.91 | -0.52 | 141149 | T6 |
| 3.2 | 1 | -1.57 | -0.85 | 141237 | T7 |
| 2.7 | 2 | -0.47 | -0.66 | 141812 | T14 |
| 2 | 2 | -1.38 | 1.42 | 141856 | T15 |
| 2.4 | 2 | 0.01 | -3.63 | 141938 | T16 |
| 10.2 | 2 | 7.94 | -10.5 | 142101 | T18 |
| 8.8 | 2 | -7.21 | 7.47 | 142146 | T19 |
| 24 | 2 | 0.61 | -4.08 | 142235 | T20 |
| 1.2 | 2 | 0.72 | 0.27 | 142317 | T21 |

**About 60% of post-processed data within 3 m. of a parking lot reference stripe in a good GPS signal environment**

**Data taken 04/13/2009 using CORS station "gode" located at the NASA Goddard Space Flight Center**

# Table 2 Post-Processed "Church II" Results

| RMS (m.) | WAAS? Yes=2 No=1 | East Error (m.) | North Error (m.) | Time HH/MM/SS | Data Point Desig. |
|---|---|---|---|---|---|
| 25.5 | 1 | 2.09 | -1.74 | 143343 | H1 |
| 32.5 | 1 | 2.58 | -0.46 | 143514 | H2 |
| 35.7 | 1 | 5.82 | -5.5 | 143914 | H5 |
| 18.2 | 1 | 1.85 | -0.78 | 144015 | H6 |
| 12.8 | 1 | 4.54 | 1.66 | 144111 | H7 |
| 2.1 | 1 | -3.5 | 5.3 | 144214 | H8 |
| 3.5 | 1 | 2.19 | -3.4 | 144325 | H9 |
| 13.1 | 1 | -8.23 | 3.56 | 144431 | H10 |
| 13.6 | 1 | -3.9 | 1.33 | 144600 | H11 |
| 16.2 | 1 | -0.1 | 0.47 | 144709 | H12 |
| 6.6 | 1 | -9.91 | 7.3 | 144809 | H13 |
| 47.9 | 1 | -4.59 | 1.82 | 144908 | H14 |
| 20 | 1 | -22.17 | 6.93 | 145108 | H15 |
| 20.7 | 1 | -15.84 | 6.51 | 145206 | H16 |

**About 30% of Post Processed Data Within 3 m. of Map Spot**

**About 60% of Data Within 5 m. of Map Spot in a partially obstructed environment.**

# *Maryland Test Results November 2008*

- First Data Set from Harris with SiRF Chip Set Message ID-28 Enabled
- 5 Test Address Canvassing Residential Areas, a Parking Lot and a Baseball Park
- 400 Data Points Post Processed; Post Processed Points used as Data Quality Indicator for Map Spot Data
- Parking Lot - 2 of 3 Post Processed Points within 3 Meters. All Map Spots Were WAAS Corrected

# Maryland Residential Area Test Results 11/20 & 11/21/2008

- 11/20 – 16% of Map Spot Data Within 3 m. of Post Processed Data; 36% Within 5 m.
- 11/20 - WAAS Corrections on 25% of Data (200 Data Points)
- 11/21 – 14% of Map Spot Data Within 3 m. of Post Processed Data; 31% Within 5 m.
- 11/21 - WAAS Corrections on 18% of Data (196 Data Points)

# *Address Canvassing Results from NGS Post-Processing Software*

| TOTAL OUTPUT | 75,715,492 | % of TOTAL |
|---|---|---|
| Acceptable Solutions / Data Meets Census Requirements | 60,454,515 | 79.84% |
| Unacceptable Solutions / Data Requirements Not Met | 12,449,324 | 16.44% |
| No Solution for Raw GPS or Post Processed Data | 2,811,653 | 3.71% |

# POTENTIAL SOLUTIONS

| DISTANCE (m) RAW to PP | Number of MSPs | % of MSPs | AVG DISTANCE RAW to PP | AVG RMS RAW to PP |
|---|---|---|---|---|
| 0 - 5.0 | 32,661,843 | 54.03% | 2.70 | 1.70 |
| 5.0 - 10.0 | 16,269,070 | 26.91% | 7.06 | 2.02 |
| 10.0 - 15.0 | 6,036,542 | 9.99% | 12.13 | 2.18 |
| 15.0 - 20.0 | 2,620,523 | 4.33% | 17.18 | 2.25 |
| Greater than 20.0 | 2,866,537 | 4.74% | | |

# *Analysis of the Effects of Surface Features on the Accuracy of Post-Processed Structure Points in the 2010 Address Canvassing*

- Objective : To assess the effects of selected surface features on the accuracy of the GPS Post-Processed data.
- General surface conditions were selected based on two criteria:
  - Tree canopy cover
  - Development intensity

# *Research methodology*

- MAF Structure Points (MSPs) and related data elements will be identified and extracted from the MAF/TIGER database (MTDB).
- From the data extract, partial county-level test sites will be selected and output to shapefile format.
- Analysts will visually inspect and categorize surface conditions for selected variables.
- The output from these processes will be provided to the NGS for analysis.

# *Pre-Processing Tasks*

- Selection of test site locations
- Creation of shapefiles
- Creation of ArcGIS projects
  - data extract will be plotted in ArcGIS and reviewed for selection of test areas
  - areas chosen for review will include urban core, suburban residential and rural development in a variety of geographic locations
- Imagery assessment

# *Canopy Attribute*

- I_CANOPY attribute
  - **L** – Low - less than 30% of the surrounding 50 m –urban center, new suburban
  - **M** – Med – greater than 30% and less than 60% of the surrounding 50 m – older suburbs, some rural
  - **H** – High – greater than 60% of the surrounding 50 m – rural, some suburban (rarely)

# *Man-made Development Attribute*

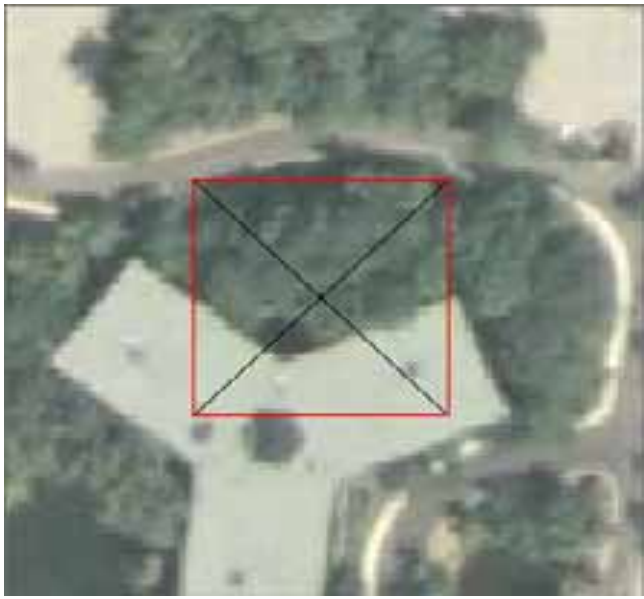
- I_DV_INT attribute
  - **L** – Low Density, low density suburban, single family detached (large lots), rural
  - **M** – Med Density, higher density suburban (small lots), townhouses, some multi-unit structures
  - **H** – High Density, large towers, large apartment buildings, urban core

    - In some instances it may be useful to extend the review to the 125m square (Figure 1), in order to assess development intensity.

# *Low Canopy Cover*

| Low Development Density | Med Development Density | High Development Density |
|---|---|---|
|  |  |  |

# *Medium Canopy Cover*

| Low Development Density | Med Development Density | High Development Density |
|---|---|---|
|  |  |  |

# *Test Data Subsets*

- 11 test areas
  - around 3000 MSPs (MAF Structure Points) per test area

  - 7 test areas, with about 21,000 MSPs
  - part of the core review

  - 33,110 MSP's reviewed

# WAAS Percentages re Canopy Cover and Level of Development / All Data Sets

| I_CANOPY | I_DV_INT | WAAS | Number | % of All | Category Total | % of Category |
|---|---|---|---|---|---|---|
| H | L | GPS Only | 372 | 1.12% | 518 | 71.81% |
| H | L | WAAS | 146 | 0.44% | | 28.19% |
| H | M | GPS Only | 144 | 0.43% | 196 | 73.47% |
| H | M | WAAS | 52 | 0.16% | | 26.53% |
| L | H | GPS Only | 2337 | 7.06% | 4553 | 51.33% |
| L | H | WAAS | 2216 | 6.69% | | 48.67% |
| L | L | GPS Only | 1883 | 5.69% | 3328 | 56.58% |
| L | L | WAAS | 1445 | 4.36% | | 43.42% |
| L | M | GPS Only | 8894 | 26.86% | 20334 | 43.74% |
| L | M | WAAS | 11440 | 34.55% | | 56.26% |
| M | H | GPS Only | 101 | 0.31% | 208 | 48.56% |
| M | H | WAAS | 107 | 0.32% | | 51.44% |
| M | L | GPS Only | 1082 | 3.27% | 1567 | 69.05% |
| M | L | WAAS | 485 | 1.46% | | 30.95% |
| M | M | GPS Only | 1397 | 4.22% | 2406 | 58.06% |
| M | M | WAAS | 1009 | 3.05% | | 41.94% |

# WAAS Percentages and Accuracy re Canopy Cover and Level of Development for Larger Data Sets

| Canopy Cover | Development Density | Relative Accuracy (95 %) | Category Total | WAAS % of Category |
|---|---|---|---|---|
| Low | Low | 23.9 m. | 3328 | 43.4% |
| Low | Medium | 22.5 m. | 20334 | 56.2% |
| Low | High | 26.3 m. | 4553 | 48.7% |
| All | All | 24.4 m. | 33110 | 51.0% |

# Summary Test Conclusions

- NGS Post-Processing accuracy using CORS Reference stations was less than three meters (95%) in unobstructed environments.
- The 95% relative accuracy estimate for the 60 million data points processed during the Address Canvassing was 15 – 20 m.
- Post-processed coordinates minus map spot coordinates in partially obstructed environments range from 22.5 m. to 26.3 m. @ 95% accuracy in subsets analyzed. Fifty four percent (54% - 32.6 million points) of all data sets processed were between 0-5 m.

# *Next Steps*

- What future methodologies can be used to improve the accuracy in partially obstructed environments for the 2020 Census or other future applications in the urban environment?

- Multiple GNSS Constellations
- Miniature Geodetic Type Antennas in Hand Held GPS Receivers
- Automated Spatial Analysis

# Study Conditions [1]

- Population data obtained from the Center for International Earth Science Information Network at Columbia University.
- Cities exceeding a half million people were selected.
- Total of 5173 sites used to produce separate statistics in open sky and urban sites.
- Mask angles of 15 and 30 degrees used in addition to multipath models in urban sites.
- GPS and GALILEO (Walker 27/3/1) constellations of 24 and 27 satellites respectively were considered.
- Future GPS-III, Galileo and combined GPS-III/Galileo signals considered.

1 *Combined Performances for Open GPS/GALILEO Receivers*, EU-US Cooperation on Satellite Navigation, Working Group C, July 19, 2010

# *Half-Sky Study Global Statistic of Mean HPE for Average Solar Cycle*

HPE

| | | SF: BOC(1,1) | SF: MBOC | DF: MBOC-BPSK10 |
|---|---|---|---|---|
| | HPE | Open Sky | Open Sky | Open Sky |
| GPS | %ge pdop • 10 & nsat • 4 | 63.16% | 63.16% | 63.16% |
| | mean | 9.39 | 7.68 | 4.08 |
| | stdev | 1.94 | 2.08 | 0.60 |
| | RMS | 9.59 | 7.96 | 4.12 |
| | Median | 9.33 | 7.77 | 3.96 |
| | 95th | 12.59 | 11.03 | 5.11 |
| | | | | |
| Galileo | %ge pdop • 10 & nsat • 4 | 78.57% | 78.57% | 78.57% |
| | mean | 10.48 | 9.09 | 6.11 |
| | stdev | 2.18 | 2.17 | 1.02 |
| | RMS | 10.70 | 9.35 | 6.20 |
| | Median | 10.42 | 9.01 | 6.25 |
| | 95th | 14.17 | 12.81 | 7.47 |
| | | | | |
| GPS & Galileo | %ge pdop • 10 & nsat • 4 | 98.92% | 98.92% | 98.92% |
| | mean | 6.11 | 5.28 | 3.22 |
| | stdev | 1.30 | 1.36 | 0.57 |
| | RMS | 6.24 | 5.45 | 3.27 |
| | Median | 6.05 | 5.31 | 3.18 |
| | 95th | 8.34 | 7.58 | 4.10 |

# Urban Global Study (30 Deg.)
# Global Statistics of HPE

| HPE | | BOC(1,1) | MBOC | Dual Frequency |
|---|---|---|---|---|
| | | Urban | Urban | Urban |
| GPS | Availability [%] | 57,28 | 57,28 | 57,28 |
| | Mean [m] | 11,19 | 6,43 | 7,26 |
| | StDev [m] | 0,93 | 0,69 | 0,90 |
| | RMS [m] | 11,23 | 6,47 | 7,32 |
| | Median [m] | 11,14 | 6,40 | 7,24 |
| | 95th perc. [m] | 12,66 | 7,65 | 8,72 |
| Galileo | Availability [%] | 75,02 | 75,02 | 75,02 |
| | Mean [m] | 11,36 | 6,97 | 7,85 |
| | StDev [m] | 2,16 | 1,52 | 1,86 |
| | RMS [m] | 11,56 | 7,13 | 8,07 |
| | Median [m] | 11,31 | 6,68 | 7,52 |
| | 95th perc. [m] | 15,93 | 10,03 | 11,57 |
| GPS + Galileo | Availability [%] | 98,93 | 98,93 | 98,93 |
| | Mean [m] | 6,82 | 4,11 | 4,37 |
| | StDev [m] | 0,70 | 0,49 | 0,54 |
| | RMS [m] | 6,86 | 4,14 | 4,40 |
| | Median [m] | 6,71 | 4,03 | 4,30 |
| | 95th perc. [m] | 8,02 | 5,05 | 5,31 |

# Census Accuracy re EU-US Studies

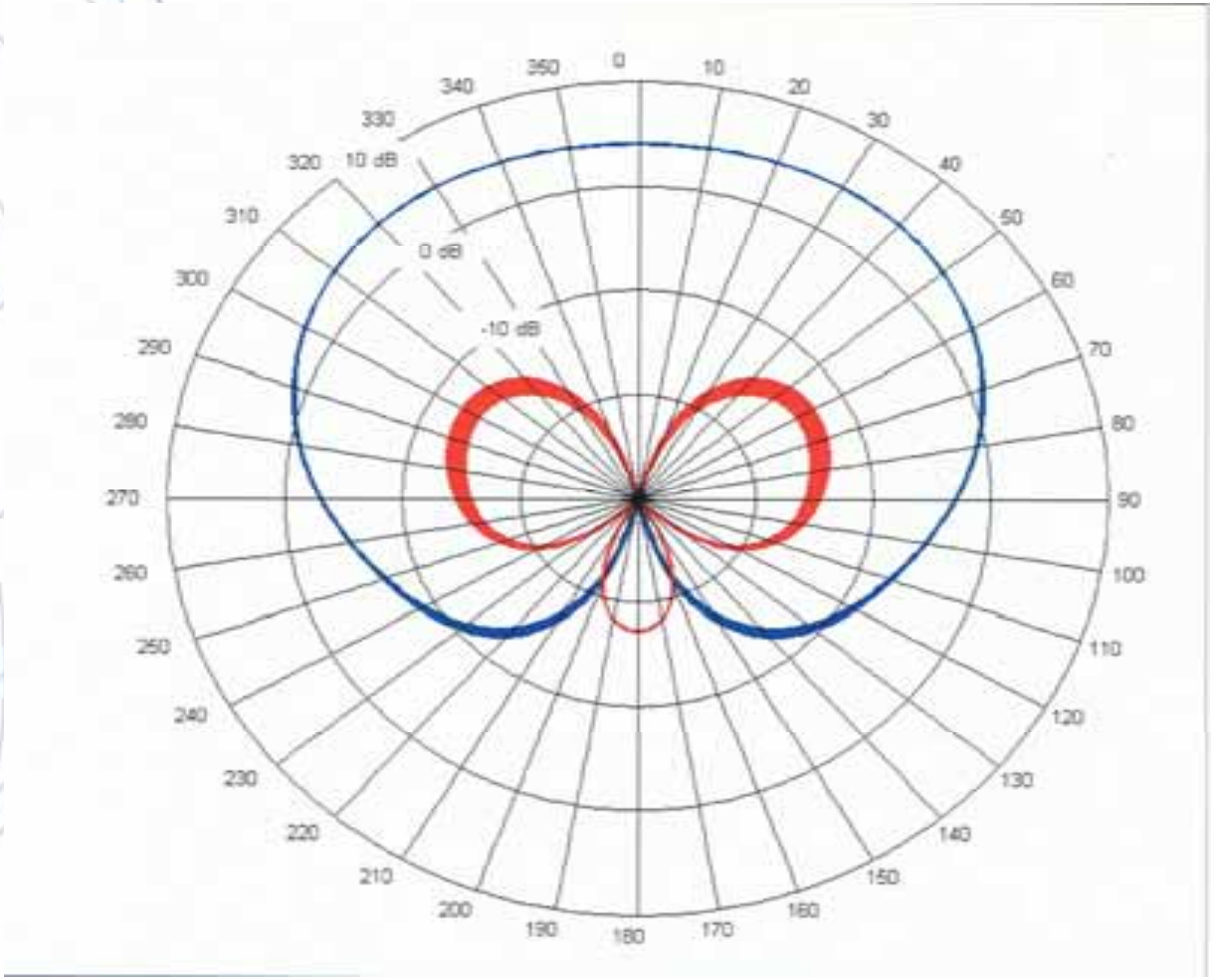
| | 2 sigma (95%) | GPS and Galileo 2 sigma (95%) |
|---|---|---|
| GPS L1 C/A – Post Processed | 15 - 20 m. | 10.5 m. |
| Half Sky / GPS-III or Galileo | 12.6 – 14.2 m. | 8.3 m. |
| Urban 30 deg. Mask / GPS III-F or Galileo | 12.7 – 15.9 m. | 8.0 m. |

# *Multipath Mitigation Antenna Research*

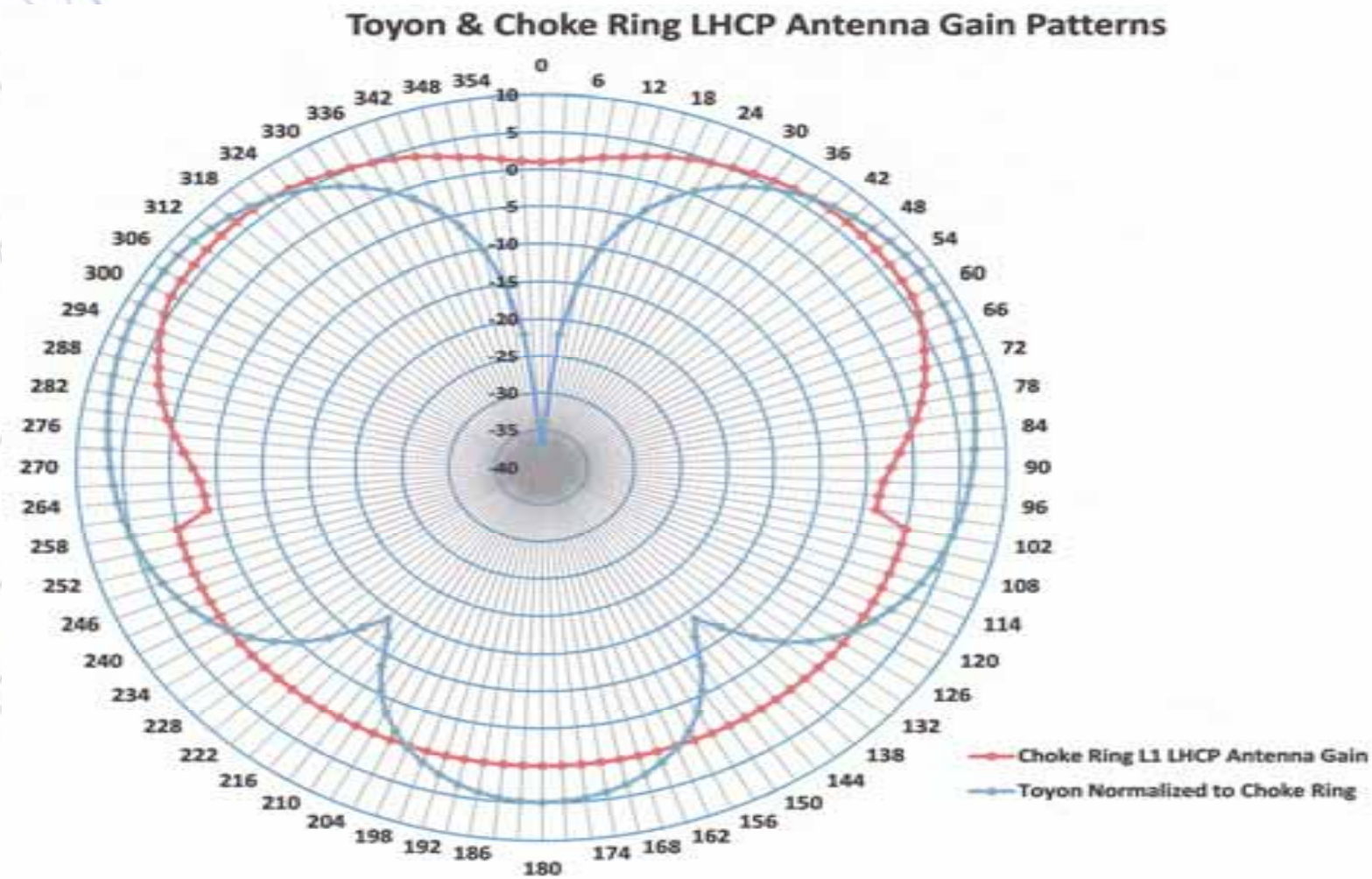
- Small Business Innovation Research (SBIR) Grants awarded to Toyon Research Corporation
  - Phase I and Phase II Grants

- Prototype Antenna delivered to NGS in August 2008
  - Tests conducted near a lighthouse in South Carolina
  - Objective is to evaluate multipath mitigation at high elevation angles
  - Compare results with choke ring antenna

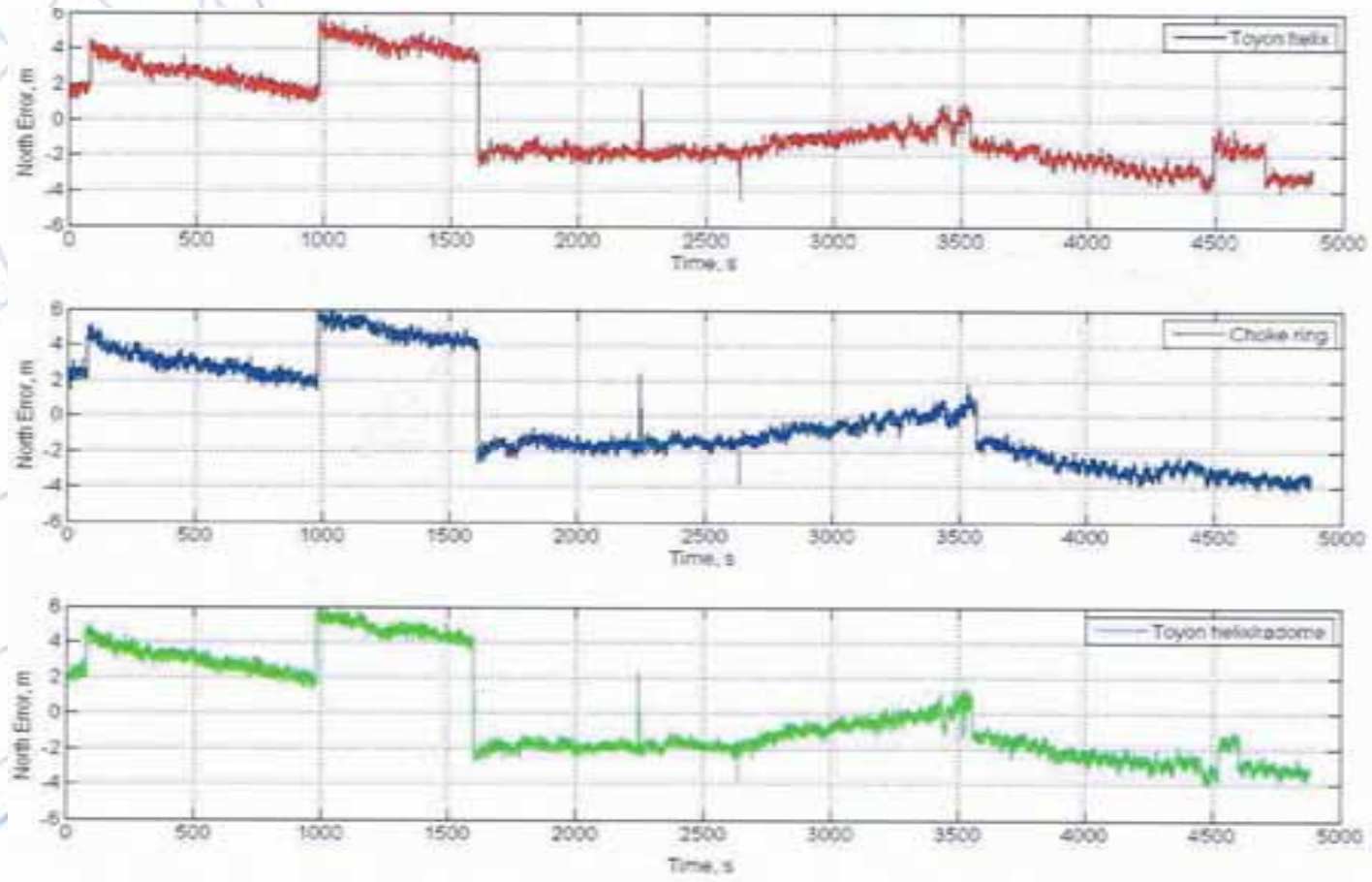
# Toyon Antenna Patterns (RHCP & LHCP)



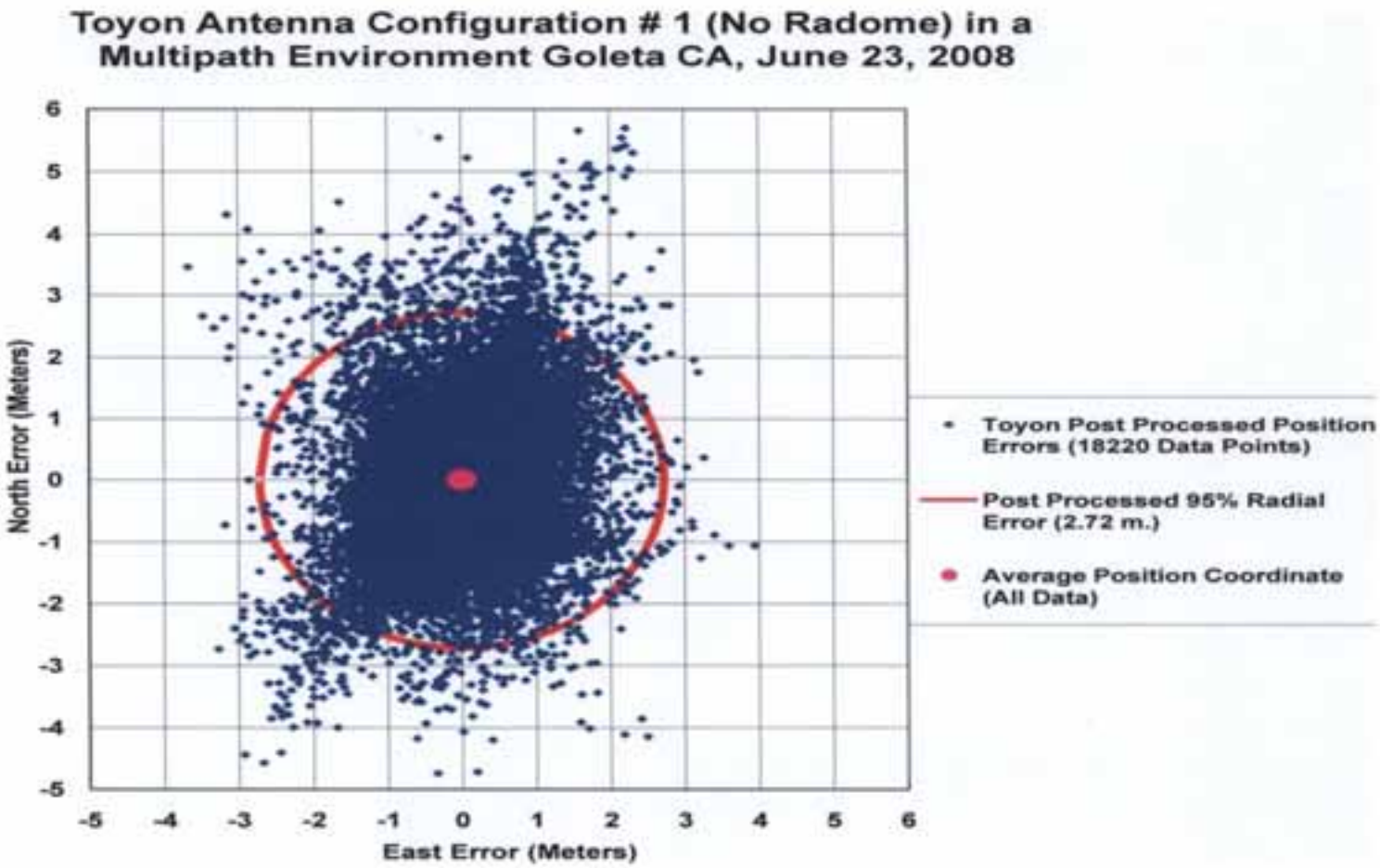
# LHCP Patterns



# North & East Errors / Stand Alone Point Positioning



# Post-Processed Accuracy Using a Multipath Mitigation Antenna about 3.5 m. from Residence



# *Airborne Lidar Data Used with a Filter to Remove Canopy Cover*

*Precise Geodetic Infrastructure: National Requirements for a Shared Resource*
Committee on the National Requirements for Precision Geodetic Infrastructure; Committee on Seismology and Geodynamics; National Research Council /ISBN 978-0-309-15811-4, p. 60.

# *Summary of Next Steps*

- Use of Multiple GNSS Constellations
  - Increases Accuracy by approximately 40%
- Use of Multipath Mitigation Antennas in Hand Held GPS receivers
  - antenna increases accuracy in an obstructed environment from 5 m. to less than 3 m. with post processing
- Automated Spatial Analysis provides “ground truth” data to evaluate GPS accuracy from imagery
  - Use of Lidar allows removal of canopy cover using filtering