Design and Testing of the API Real-time Metrology System for FAST

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API AUTOMATED PRECISION

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Automated Metrology Solutions

Product & Service offerings

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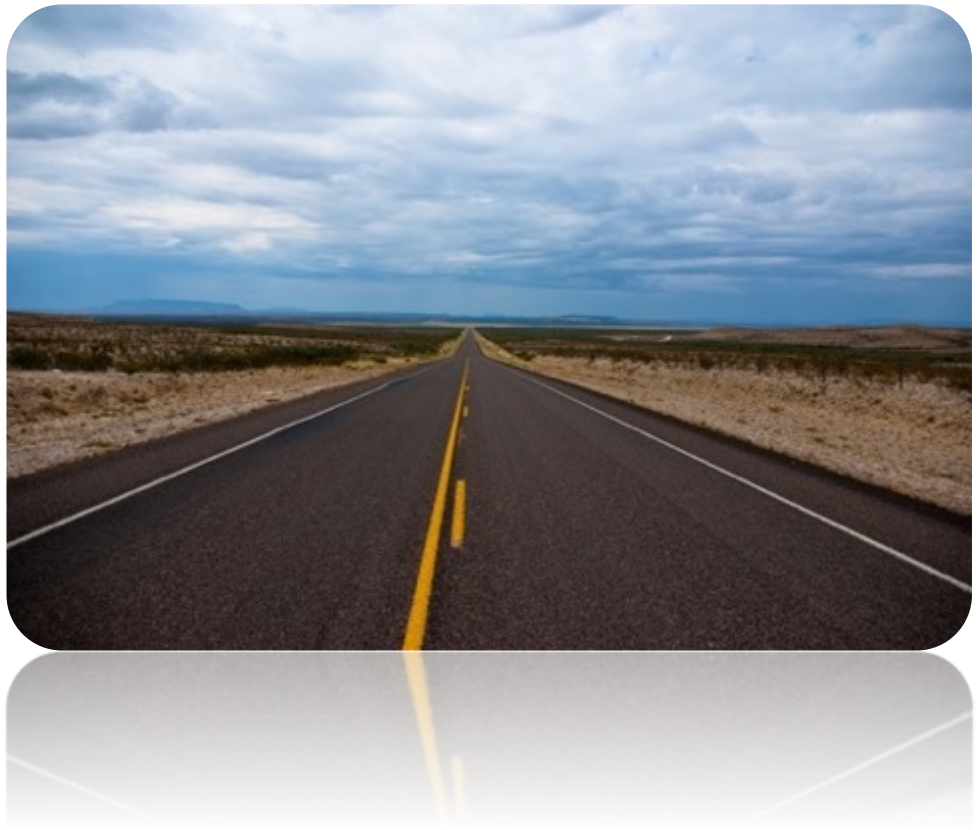
Vision

To achieve 100% customer satisfaction in providing advanced digital information solutions for industry.



Mission

Create a corporate environment that continuously seeks and invests in state-of-the-art sensor technologies and artificial intelligent solutions meeting current and future industry needs.

Continuous Innovation

Laser tracker was invented by Dr. Kam Lau at NIST in 1983 and Automated Precision Inc (API) was formed in 1987. Over the past 29 years, API continues to be a leader in dimensional metrology with enhanced sensor technologies and a growing portfolio of innovative precision measurement products and services.

Dr. Kam Lau at NIST Museum of Recent History with one of the first laser trackers invented.

1987 — Invention of 1st Generation Laser Tracker

1989 — API formed; API Technology Licensed to Leica

1991 — Spindle Analyzer, Compliance, Level, Ballbar, 6D Laser

1996 — CMM Controller Machine Error SwivelCheck

1999 — 2nd Phase: API Building; Tracker II™ (2nd Generation)

2002 — Tracker 2+, SmartTrack Sensor

2005 — Tracker3™, XD™ Laser

2007 — i360, IntelliProbe360, IntelliScan 360

2009 — 3rd Phase: Acquired API-ZC; Active Target™, VEC™

2010 — IntelliProbe 360 Wireless

2011 — Radian™ Laser Tracker

2014 — 4th Phase: Established AP Photonics; Omnitrac 2

2015 — 5th Phase: AP Group formed; vProbe

2016 — RapidScan / Automated Inspection

Growth in Technology

Global Growth Plan

- A global leader in the precision measurement industry founded by Dr. Kam Lau, the inventor of the laser tracking technology

- Headquartered in Rockville, Maryland, USA

- Offices in in Germany, China, Hong Kong, India, Brazil, Japan. Represented in over 60 countries, including Australia, South Korea, Taiwan, Thailand, Russia, Canada, etc., providing sales, services, calibration, repair and technical supports

- 300+ Personnel throughout the world

API Global Foot Print

Heidelberg, Germany

Beijing, Shanghai, China

São José dos Campos, Brazil

HQ, Rockville, MD

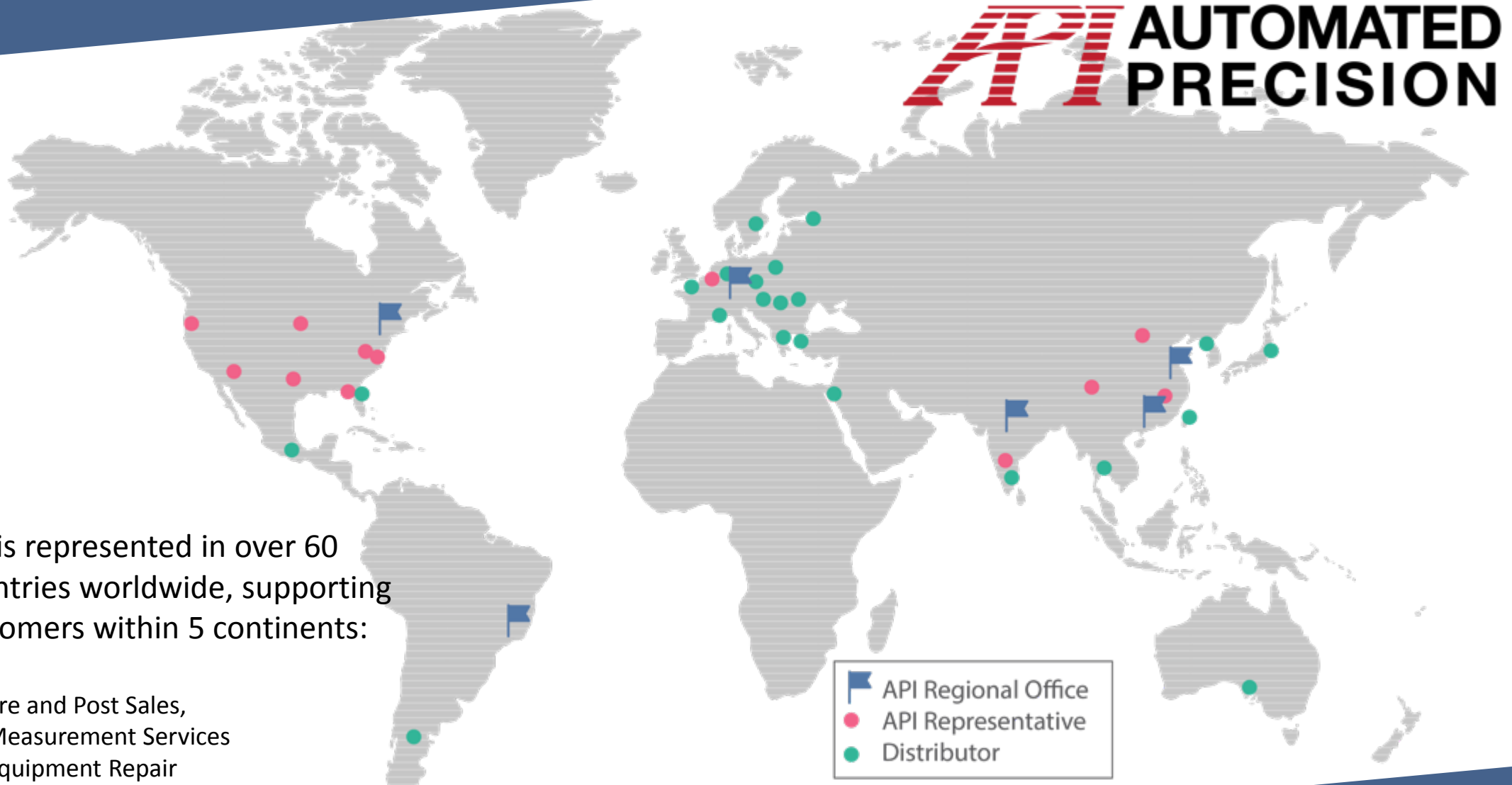
Noida, India

Chengdu, China

Hong Kong, China

Worldwide Coverage

API Global Expanded Foot Print



API is represented in over 60 countries worldwide, supporting customers within 5 continents:

- Pre and Post Sales,
- Measurement Services
- Equipment Repair
- Equipment Calibration & Technical Support

Worldwide responsiveness

Diverse Offerings

Equipment & Services

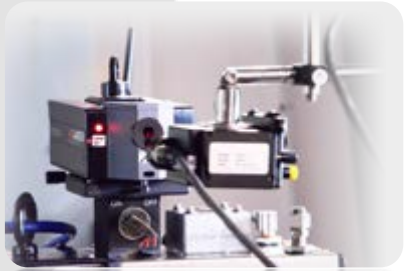
3-/6-D Tracker Systems

Automation

3D Non-Contact Systems

Equipment & Services

Engineering Services



Machine Tool Health

CMM / Robotic Machine

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Laser Tracker SYSTEMS

Premier Precision Portability

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RADIAN

Radian™ is the smallest, most accurate, most versatile, IFM+ADM laser tracker on the market. Take the instrument to the part, not the other way around.

KEY FEATURES

- IFM (Interferometer) technology
- High-speed ADM laser for rapid beam reacquisition with no minimum measurement distance.
- Accessories for enhanced measurements (i360, vProbe, AT)
- iVision video streaming and capture for remote monitoring
- Portable, weighing under 20lbs
- Adapts to existing tooling orientation

Most portable IFM laser tracker

OMNITRAC2 (OT2)

A milestone in portable measurement: OT) wireless ADM laser tracker advances the portability and convenience of modern laser trackers.

KEY FEATURES

- Portable and Flexible, easy to use
- Integrated cable free controller
- WiFi connectivity
- Battery operated
- Precise and stable Absolute Distance Measurement (ADM) technology
- No minimum measuring distance
- Autolock targets laser beam to the SMR automatically
- High-speed Dynamic Measurement

Most portable tracker on the market.

OMNITRAC2

Wireless Laser Tracker

Maneuver faster and safer within your work space with a cable free set-up.

Measure more volume in one session with long range measuring distance - less time at the computer and more time measuring your part!

Mounting versatility means more measurement flexibility. Mount sidewise, upside down, or directly on the part.

ADM in Radian and OT2

- ADM– Absolute Distance Measurement
- Over 14 years of development and refinement
- Range to 100 meters (can be extended)
- Accuracy 0.5ppm (recent certification report yields 9 micron error within 80 meters)
- Compact size 20mm x 75mm X 120mm
- Can be used as a standalone absolute distance meter with configurable output format
- 1550nm, 0.5mwatt, eye-safe

STS – New and Improved

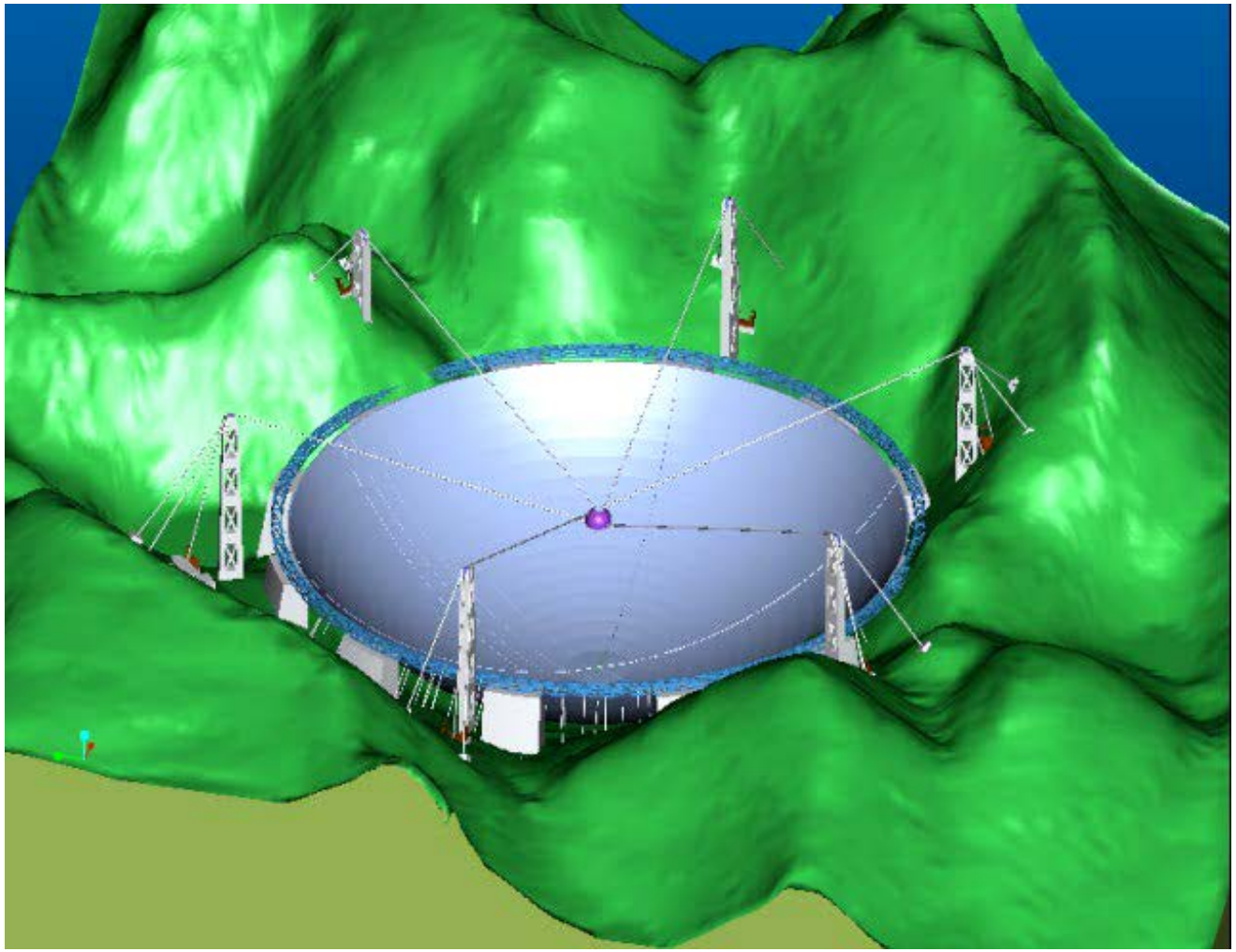
Smart Tracker Sensor

KEY FEATURES

- Angular Range
- Improve Dynamic Performance
- Improved Accuracy
- Improved Tracking Speed

Timing – December 2016

API FAST Metrology System Design



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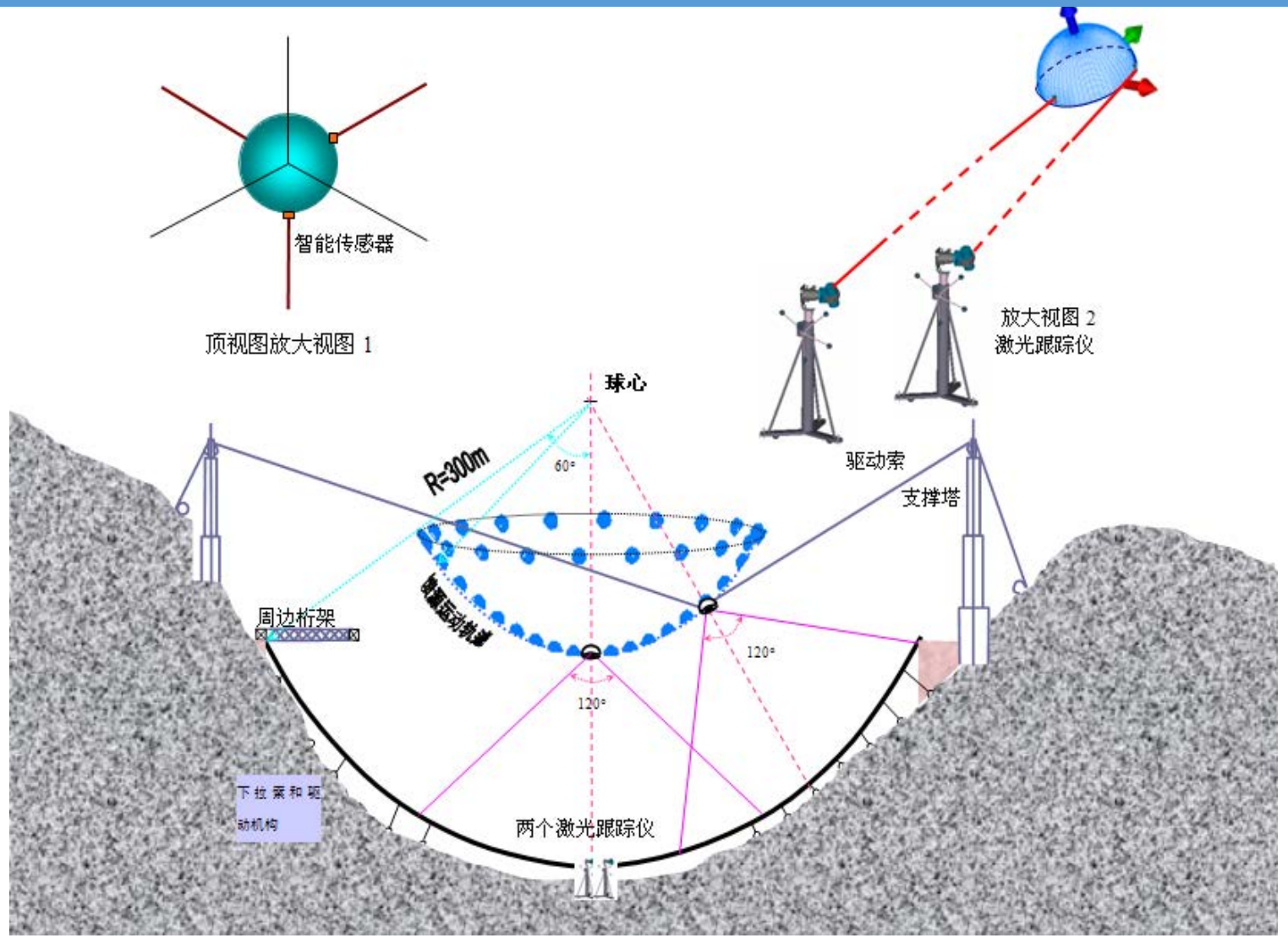
Metrology Considerations for Receiver Vs Reflective Surfaces



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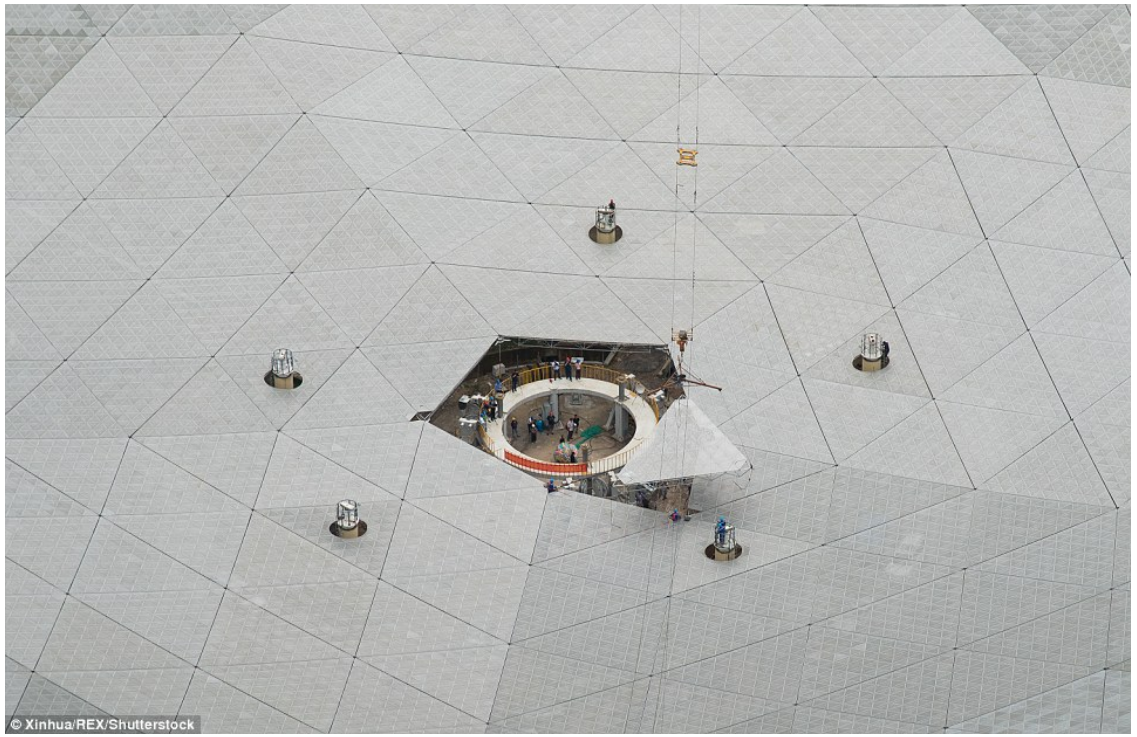

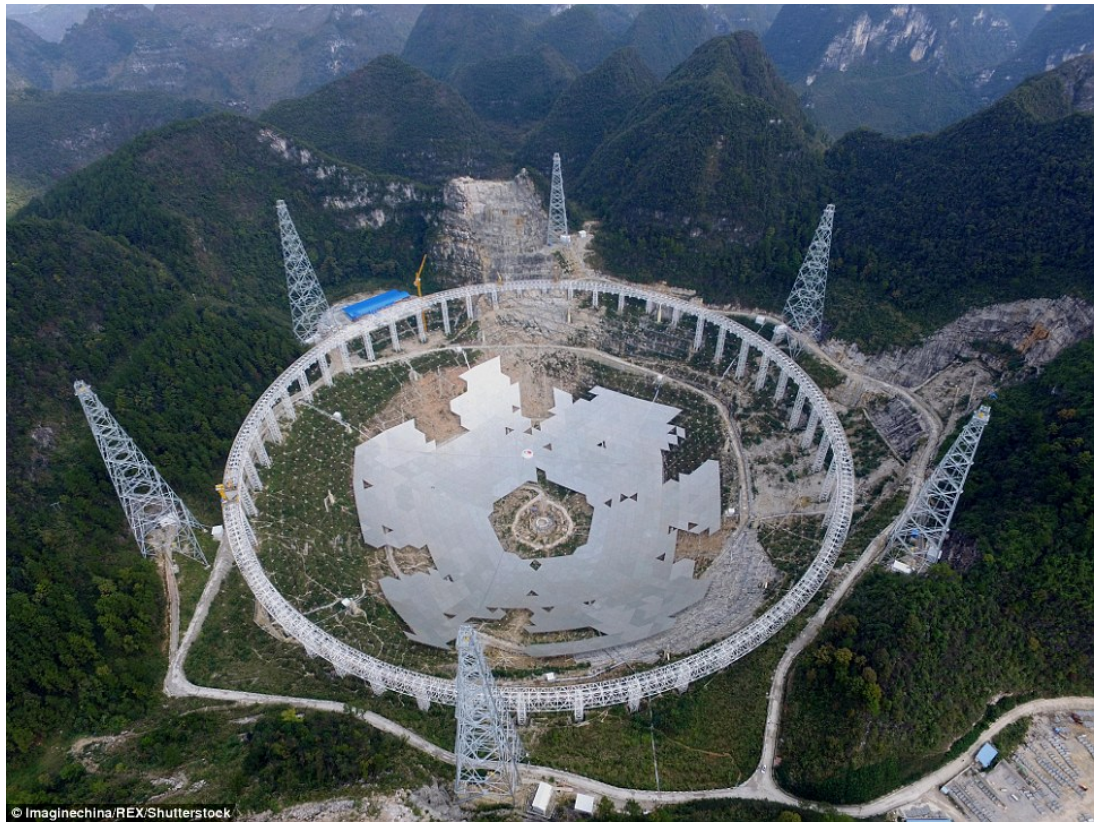

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FAST Real-Time Metrology System Requirements

FAST -- Five-Hundred-Meter Aperture Spherical Telescopic

Physically Parameters and Metrology Requirements:

- 500 meter diameter parabolic reflective surface antenna
- 4,450 triangular, flat panel reflectors with 11 meter on the side connected by 2,400 tension-controlled node joints
- At each time, a total of 1,000 node joint positions defines the effective parabolic surface and the pointing axis of the telescope, angle of sweep +/- 30 degrees
- Control accuracy of each node position -- 2mm (3D)
- Total acquisition time -- less than 1 minutes

Challenges FAST Metrology Requirements Presented

- Extremely large surface (500 meter diameter) with surface measurement accuracy to 2mm in 3D (equivalent to 4ppm accuracy)
- Environmental effect, in particular, uncertainty introduced by air turbulence
- 1,000 active points to be measured and fed back within 1 minute
- Absolute accuracy relative to the FAST metrology frame (absolute measurements sync with the 6D receiver measurements)
- System to be self-calibrated w.r.t. the metrology frame.

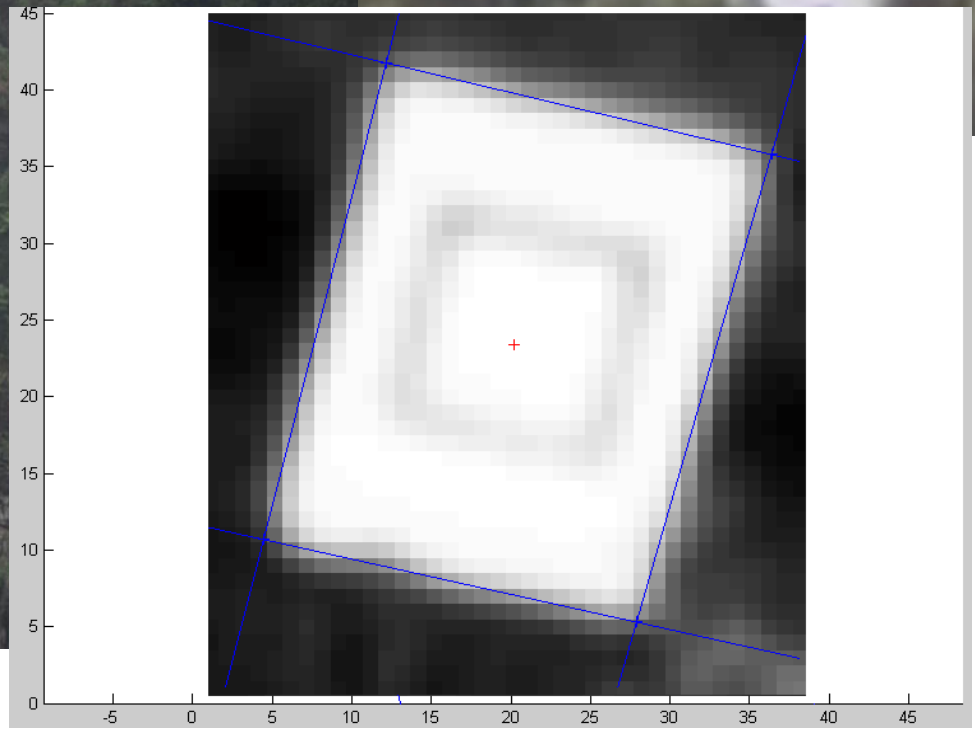
In 2008, API was awarded a contract by FAST Team to device and demonstrate a metrology method to meet the real-time metrology requirements

During the next 2 years, multiple studies were carried out in the API laboratory and in-field in Guizhou where the FAST site is located.

Studies and simulations included:

- Multiple-station triangulation vs trilateration vs single-station laser tracker measurement (very accurate but slow)
- Photogrammetry's ability to cover very large area makes sense
  - image fuzziness (due to air turbulence) over long-distance severely degrades the measuring accuracy
  - impossible to cover the entire telescope

FAST Site 16Meg Digital Camera (basis of photogrammetry) Test at 600 Meter Distance Away



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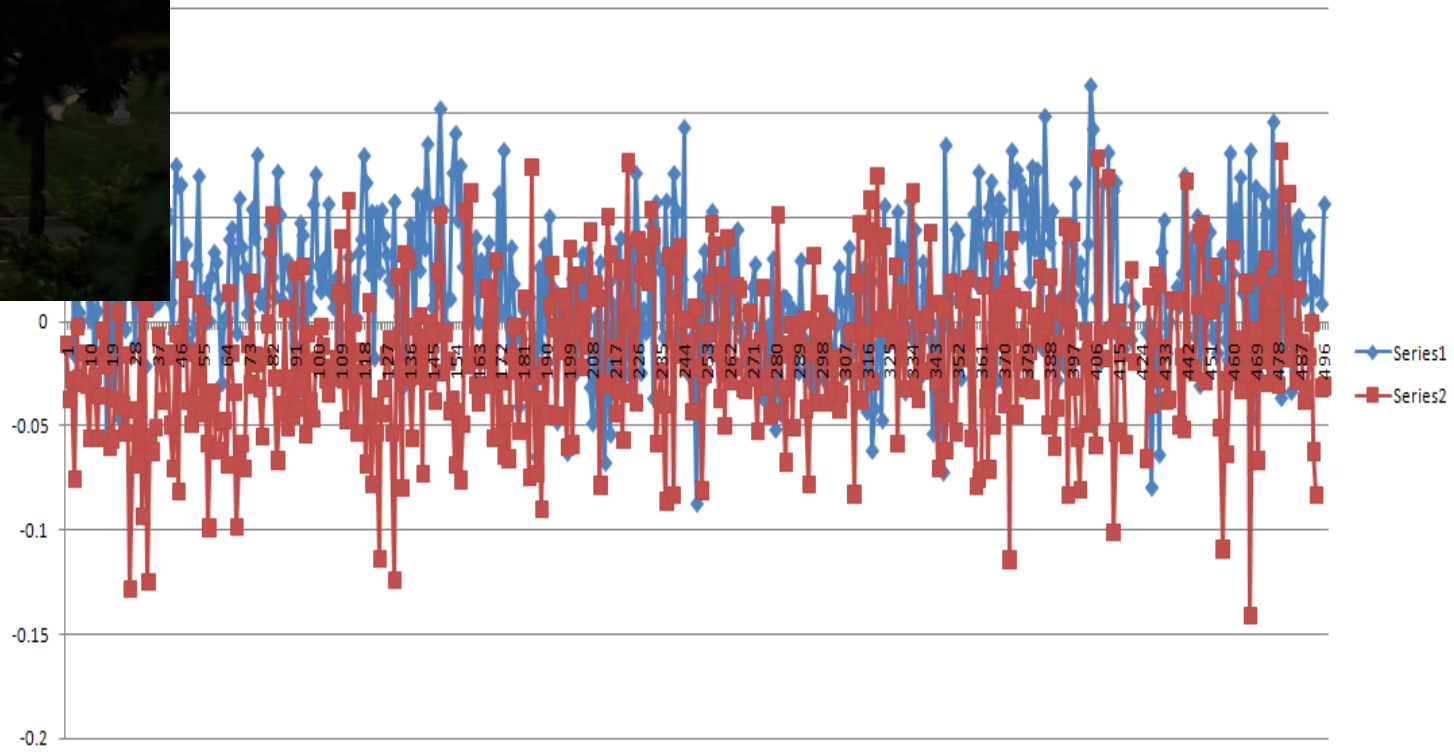
Field Test of Digital Differential Imaging Technique at 400 Meters



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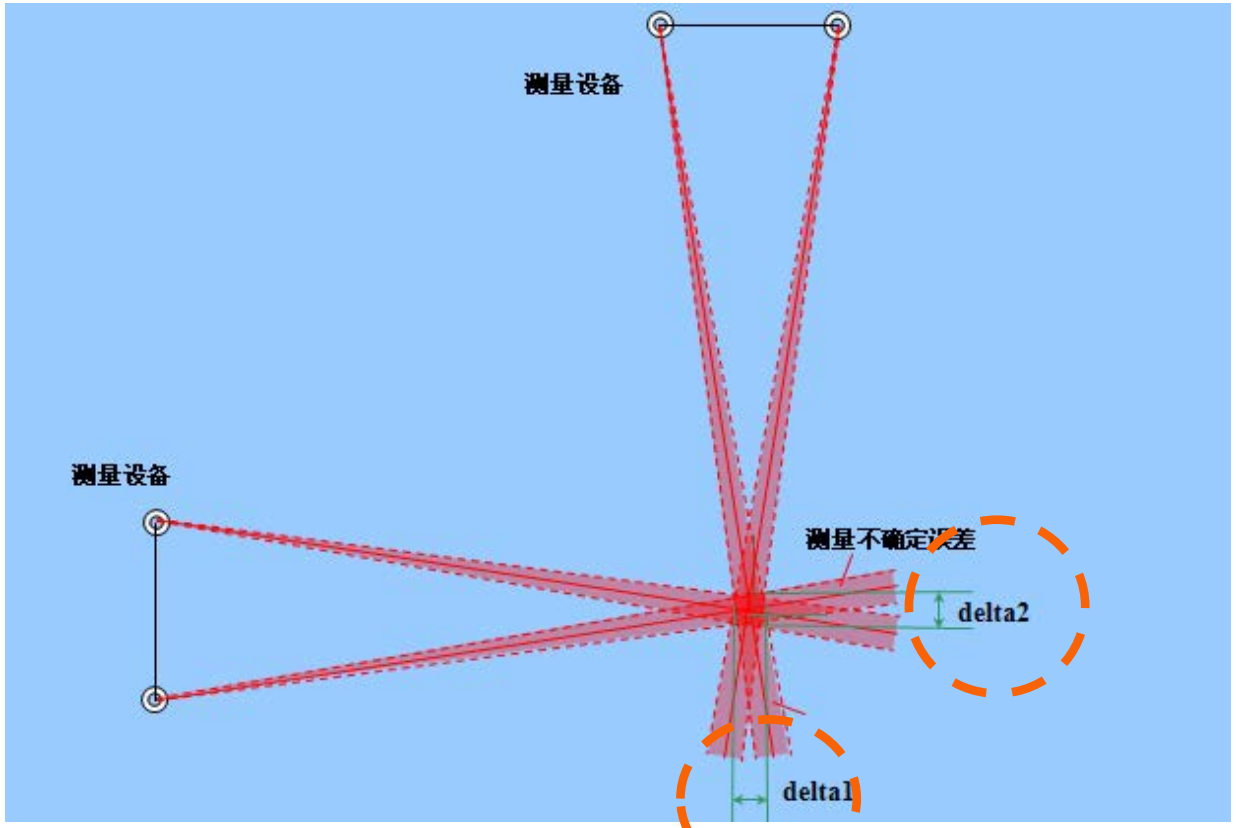
3D Error in Image Triangulation Improved by Over-redundancy



冗余测量提高测量精度

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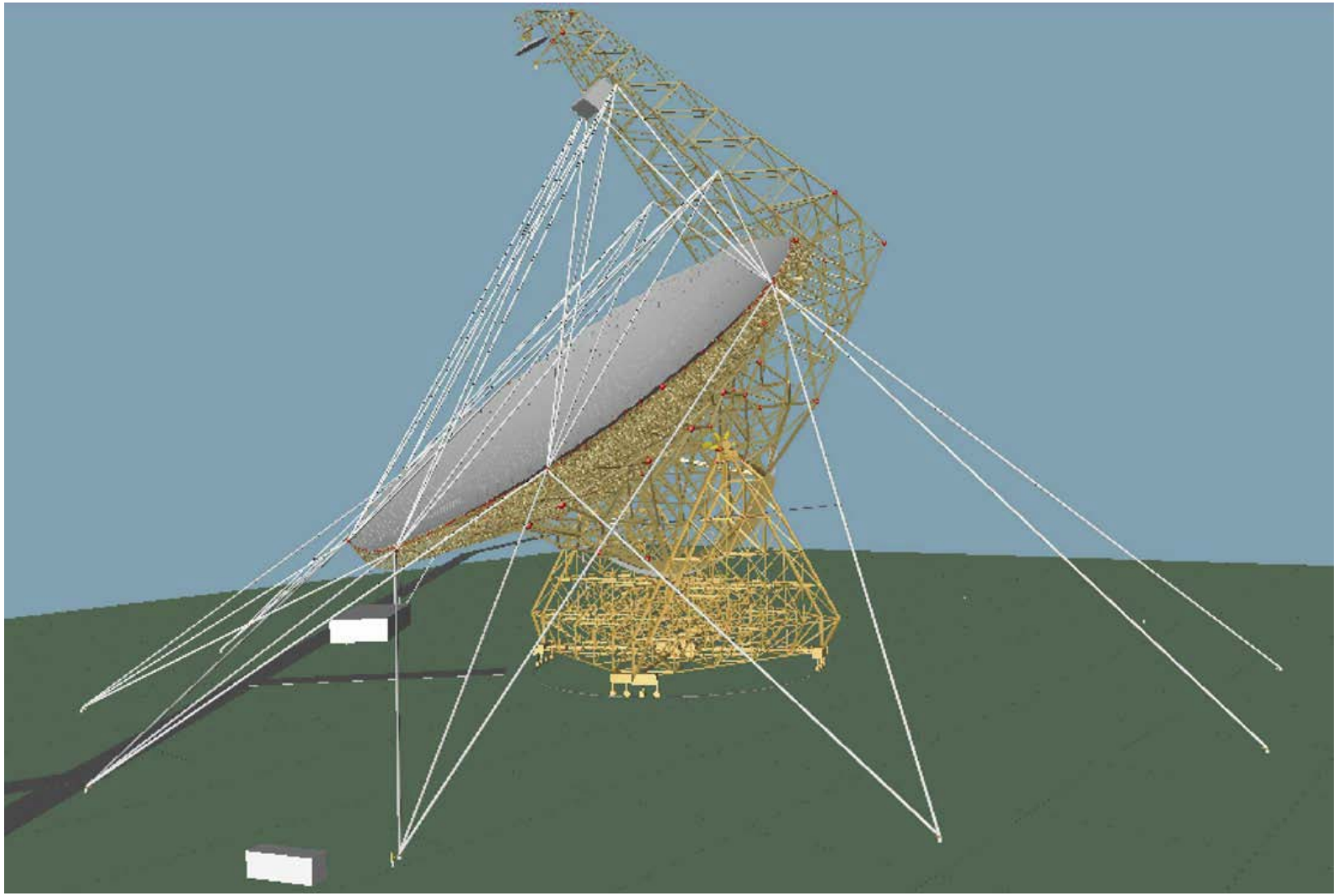
Green Bank Telescope (Trilateration）



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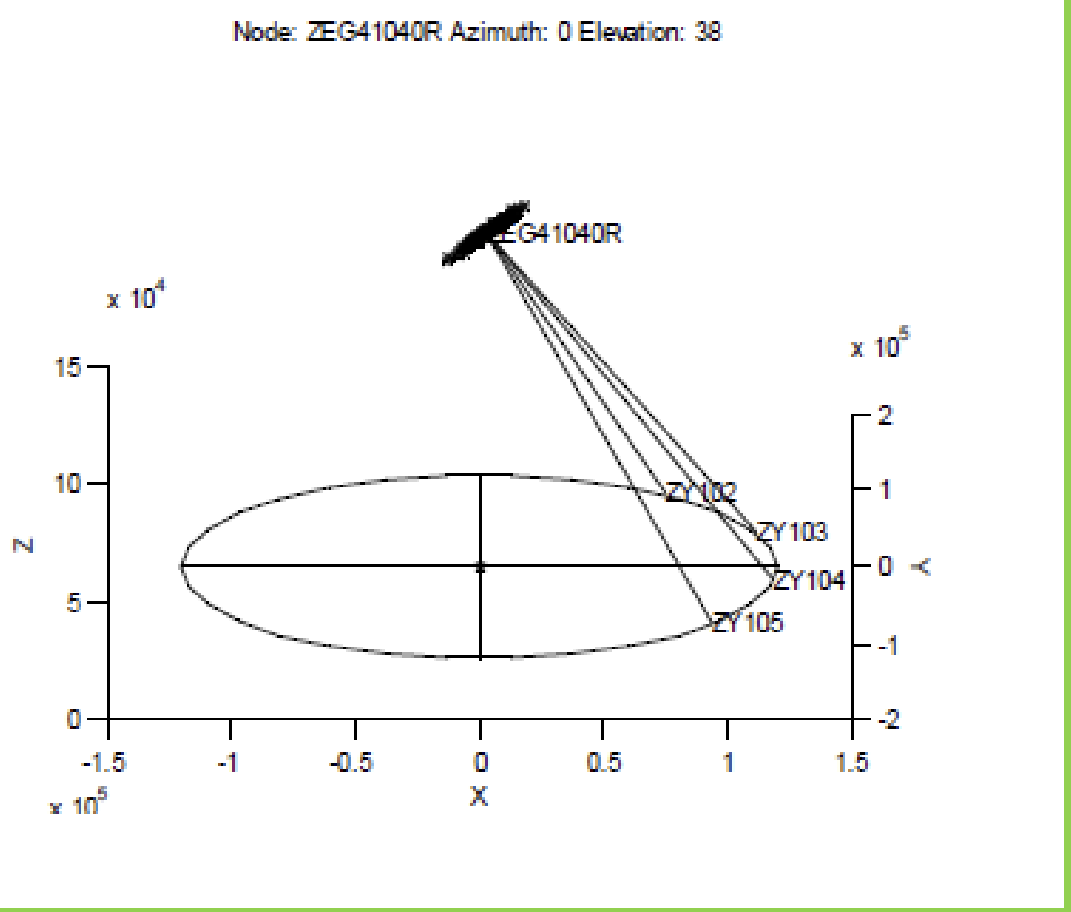
Lateral Error from Trilateration

Accuracy Improvement can be achieved:

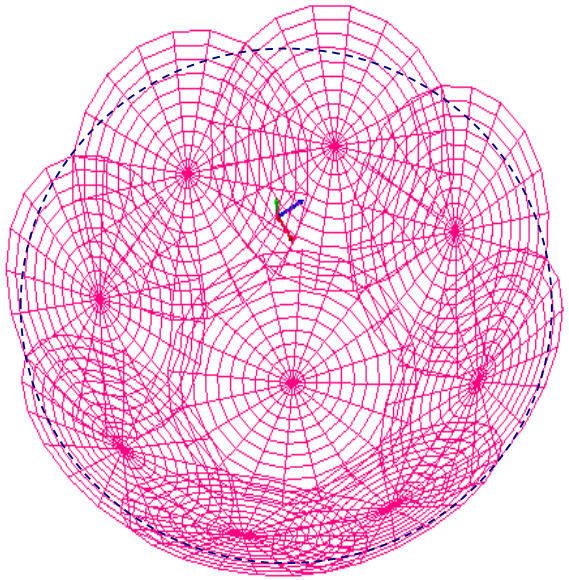
(1) Trilateration redundancy

(2) Single-station laser tracker



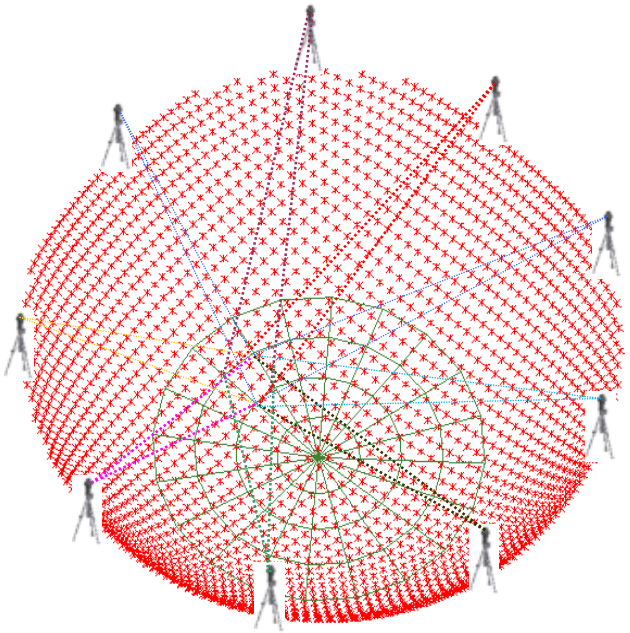
Evolutions of the FAST Metrology Concept

DPU Digital Photogrammetry Unit



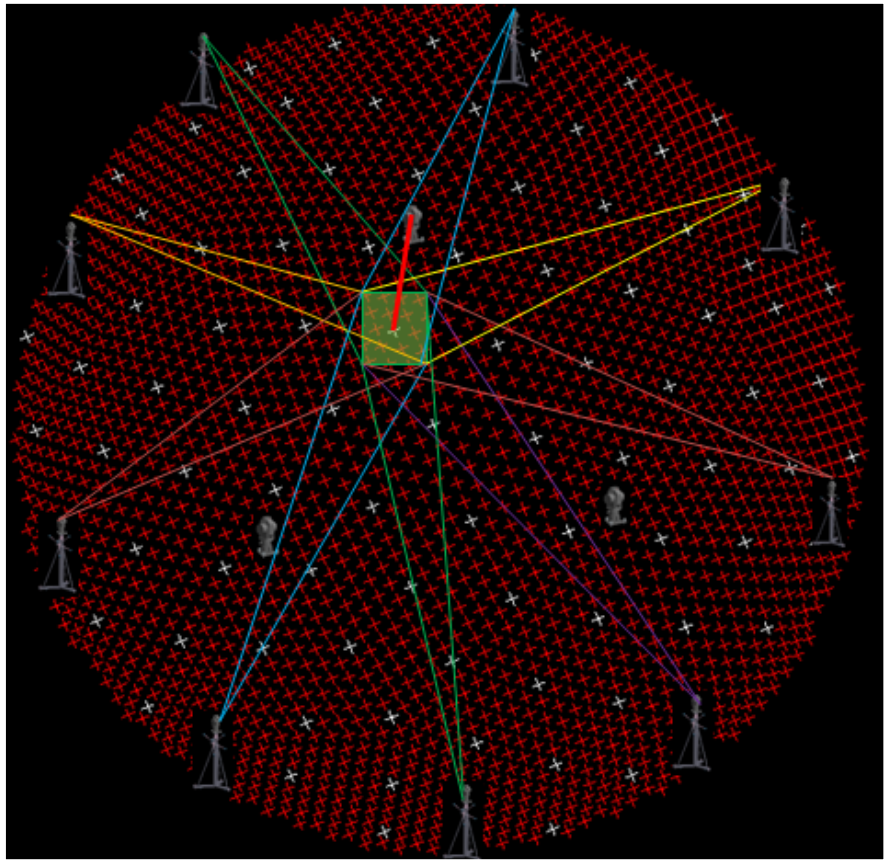
9- 1-axis DPUs

(difficult to effectively construct redundancy)



9 2-axis DPUs

(Absence of absolute coordinate)



6 DPUs +3 Trackers

(absolute w/ redundancy)

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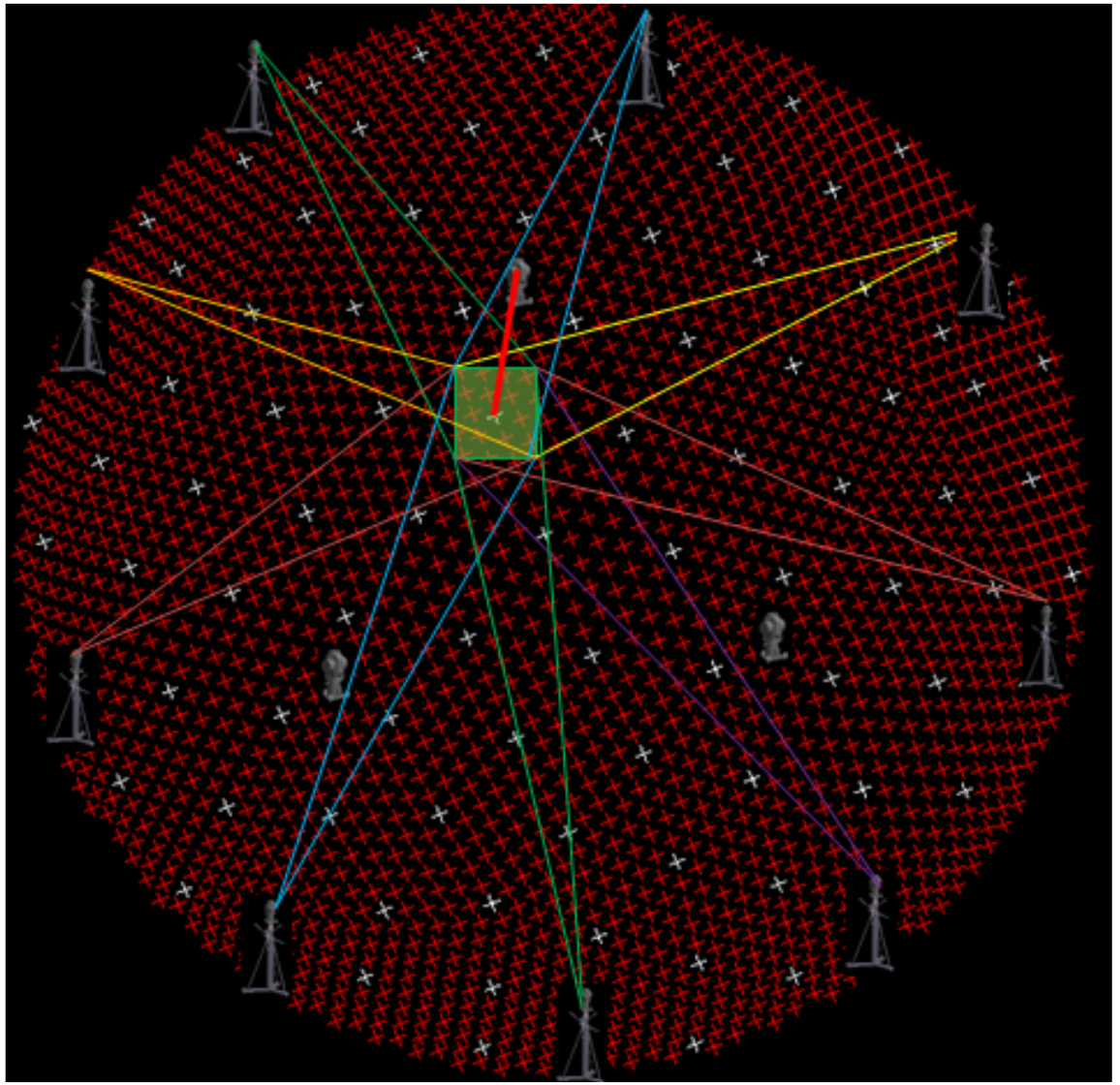
6+3

6 DPUs + 3 Laser Trackers

- 6 Digital Photogrammetry Units (DPUs)
- 3 Long-Range Laser Trackers (LT)
- 2,400 node joints(red) divided into 25 zones
- Each zone (green) covers 40+ nodes and at least one node (blue) is measured by a LT
- LT measurement produces the absolute and precise 3D positions of the node
- All 40+ nodes are triangulated simultaneously with 6 DPUs giving multiple redundancy
- Accuracies further improved with relative measurements of each node w.r.t. the absolute node measurement
- Each zone takes 2.5 seconds to measure



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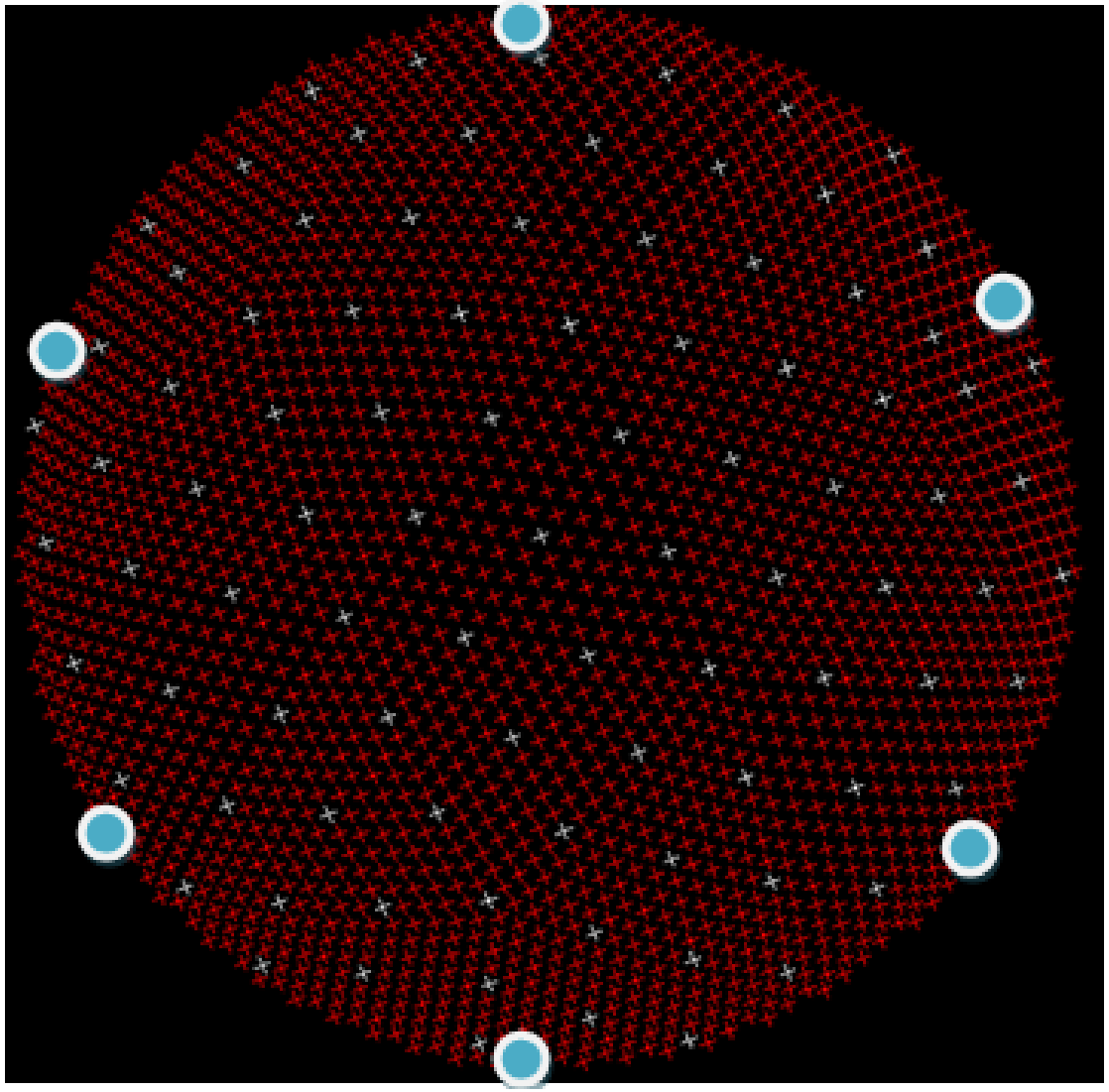
6+3 Methodology

- Large blue dots represent the locations of the 6 DPUs
- Small blue dots represent the Absolute Position Nodes measured by LTs
- Red dots represent the 2,400 active nodes of the 1,000 flat panels



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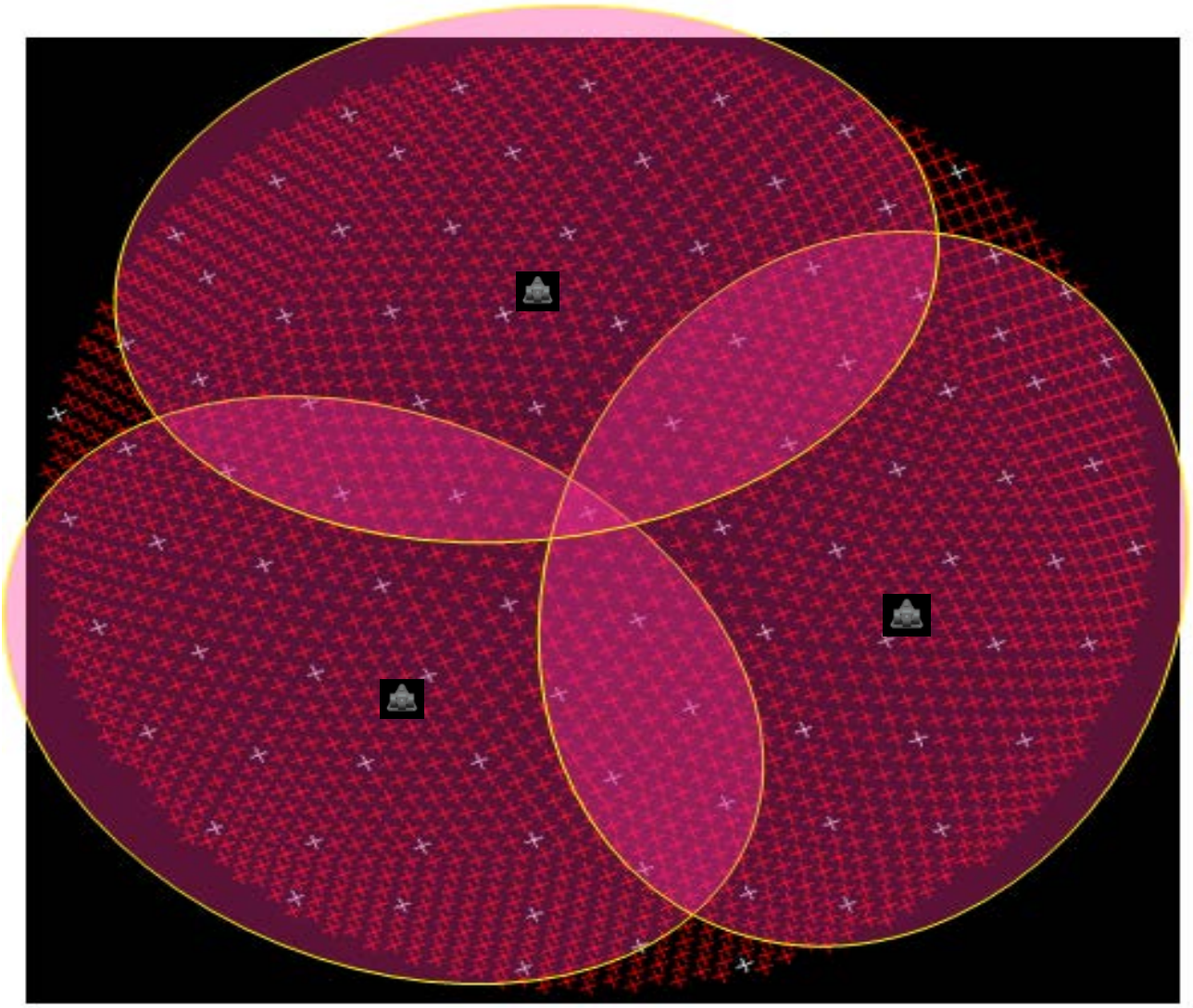
6+3 Methodolgy

Absolute Node Positions are Measured by 1 of 3 Long-range Laser Trackers



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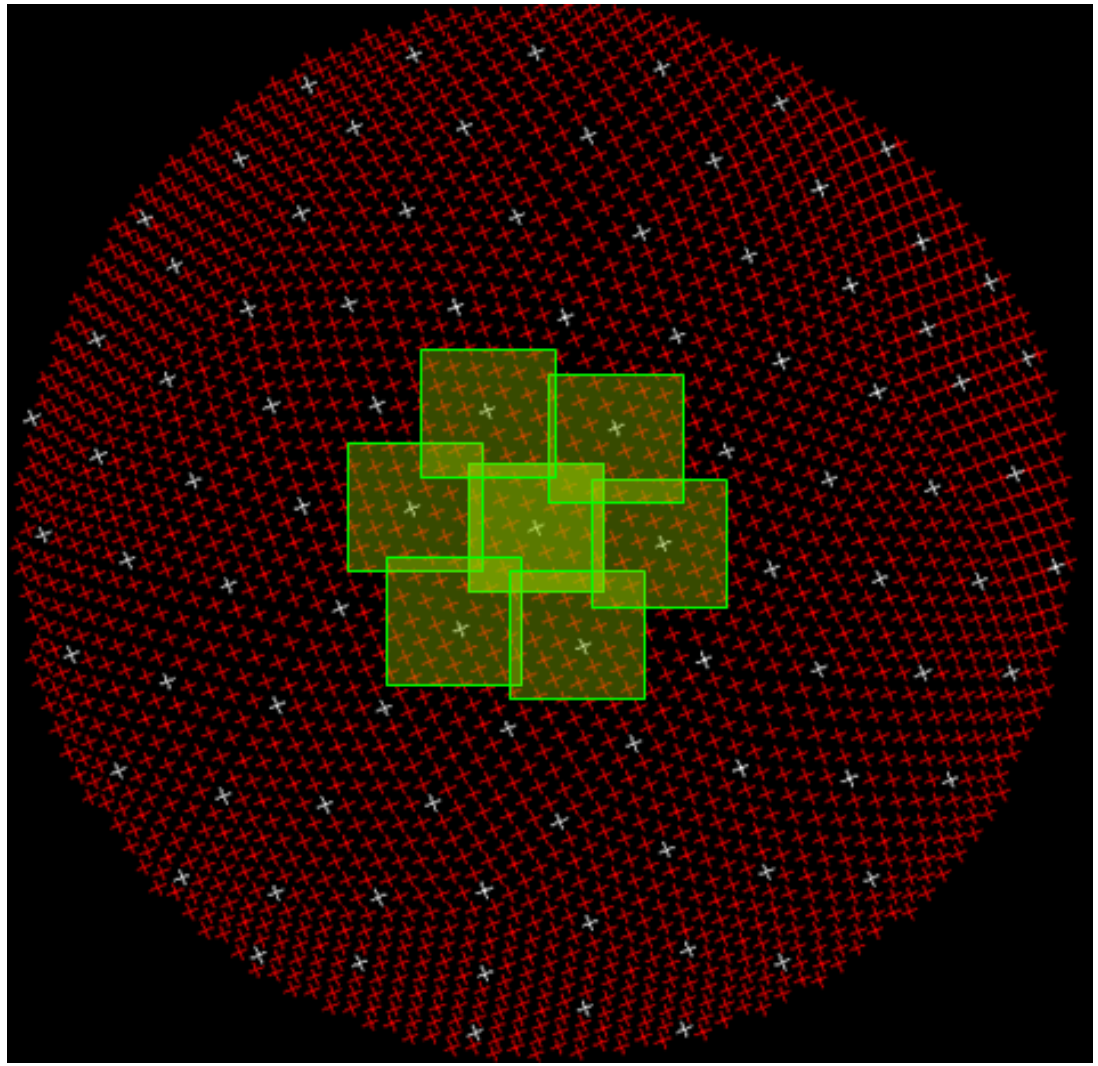
6+3 Methodology

Measuring Zones
(40m x 40m)

Each Zone covers 40+ nodes and at least one absolute position node in the center



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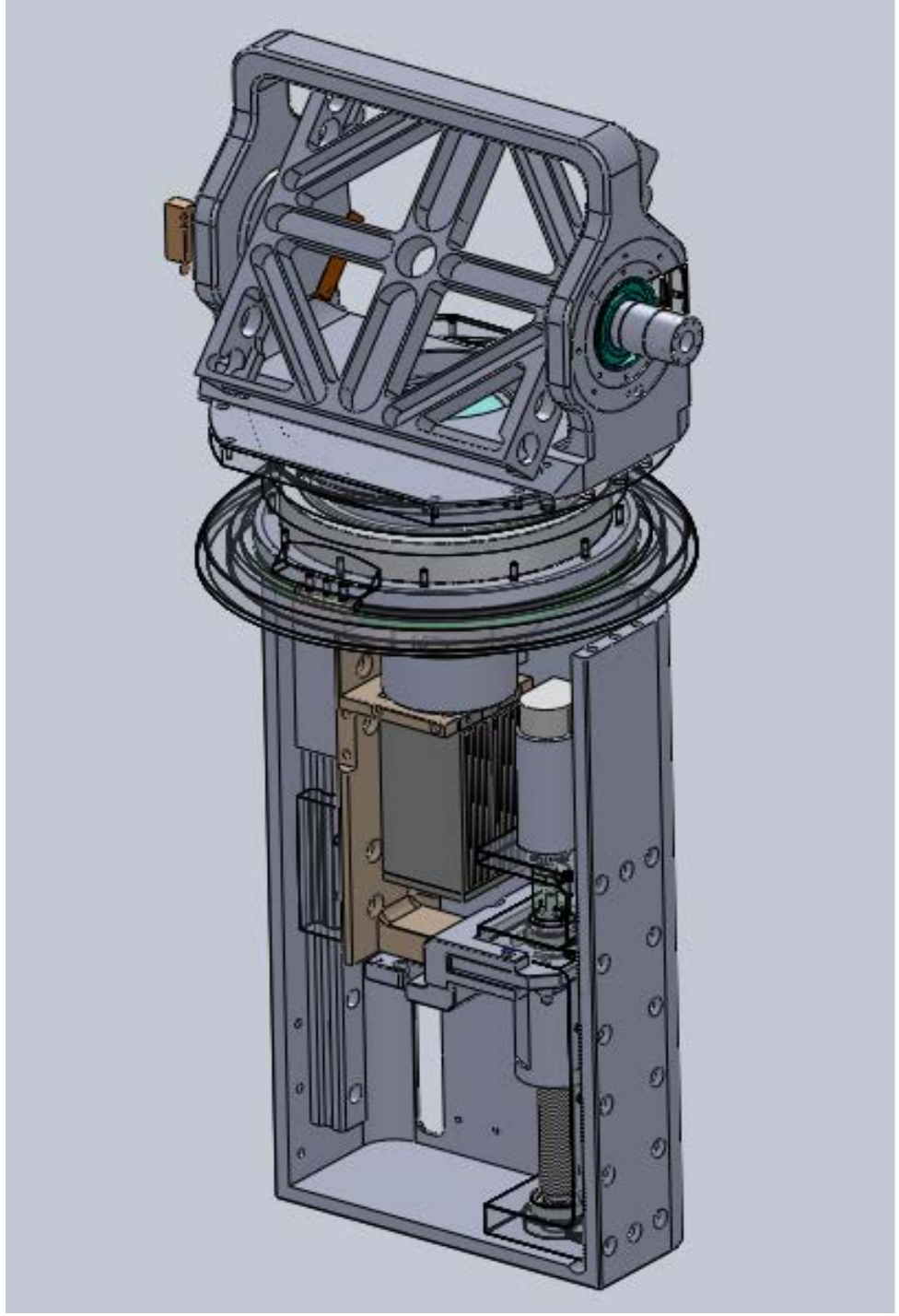
DPU Design and Functional Specifications

- **Consists of a 2-axis precision servo-gimbal, high-resolution digital camera with programmable zoom, control and communication systems**
- **Control and Measuring software with GUI interface**
- **DPU systematic error compensation and optimization**
- **Multiple station synchronization and central controlled**
- **Absolution coordinate self-calibration of within the FAST metrology system**



Internal Design of a DPU

- **Dual-servo precision gimbal**
- **Auto-zoom control**
- **Angle resolution: 0.01”**

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Digital Photogrammetry Unit (DPU)

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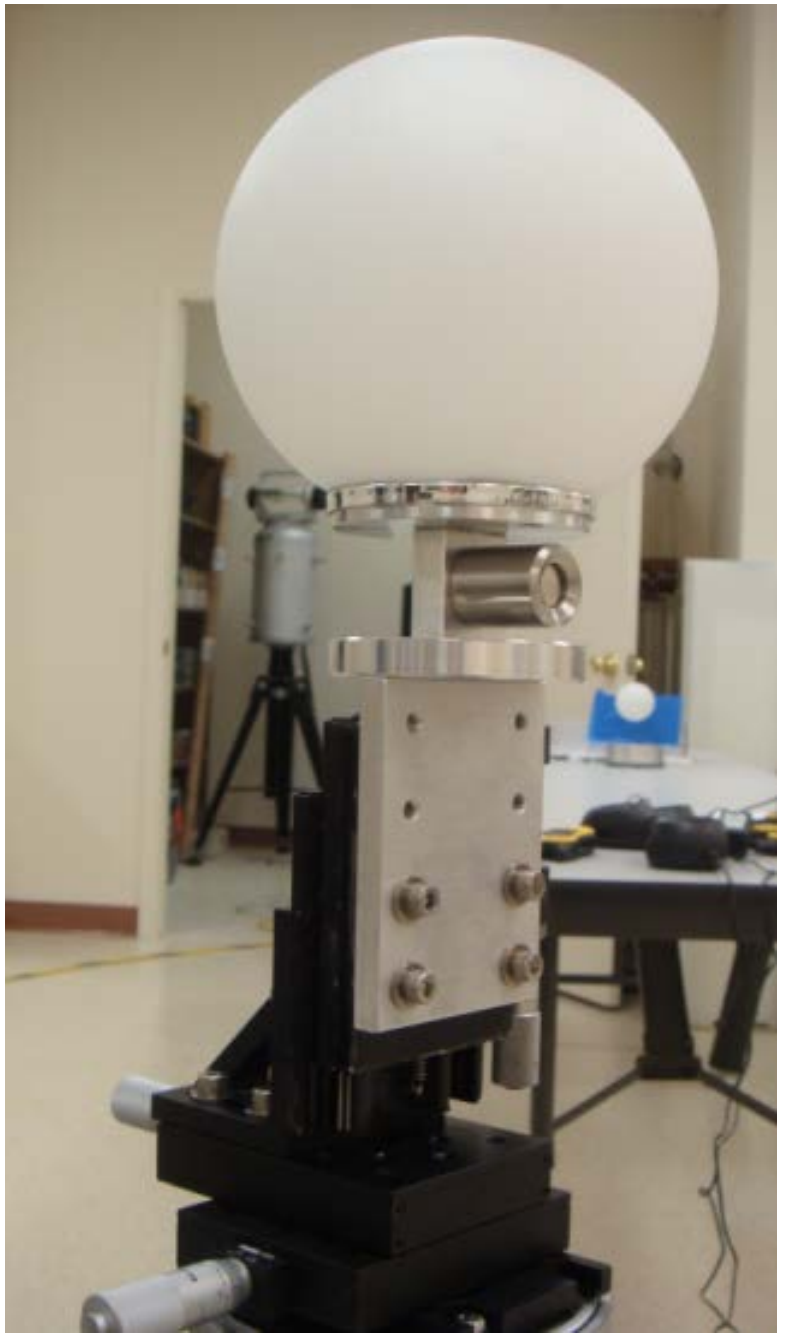
Combo Target

8” diameter defused glass ball
with high-power LED light source



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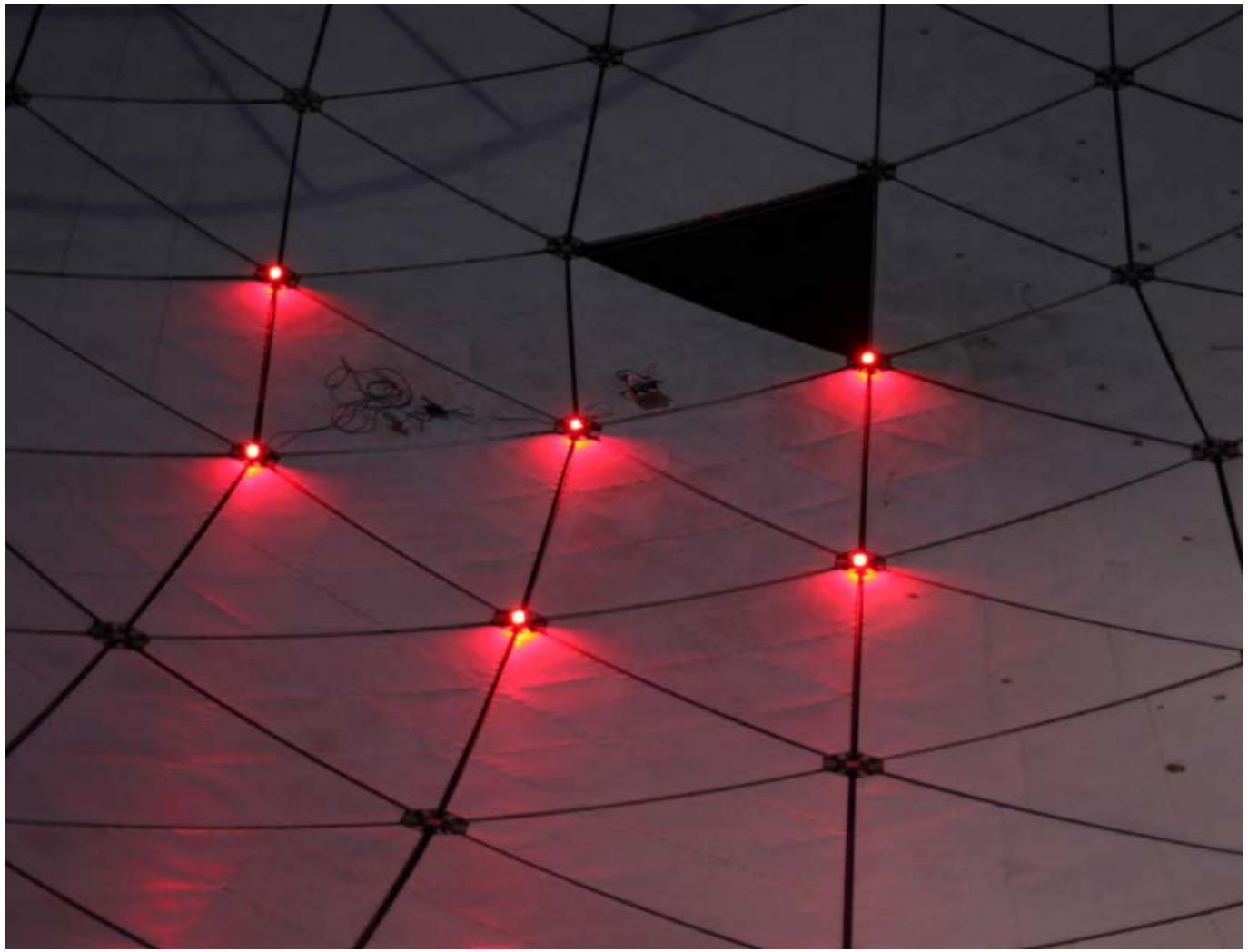
10:1 Scale Combo Target Tested at MiYun, Beijing



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2 mm Accuracy Field Test in Maryland

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1 of 3 DPUs in the Maryland Field Test

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1 of 3 DPUs in Maryland Field Test

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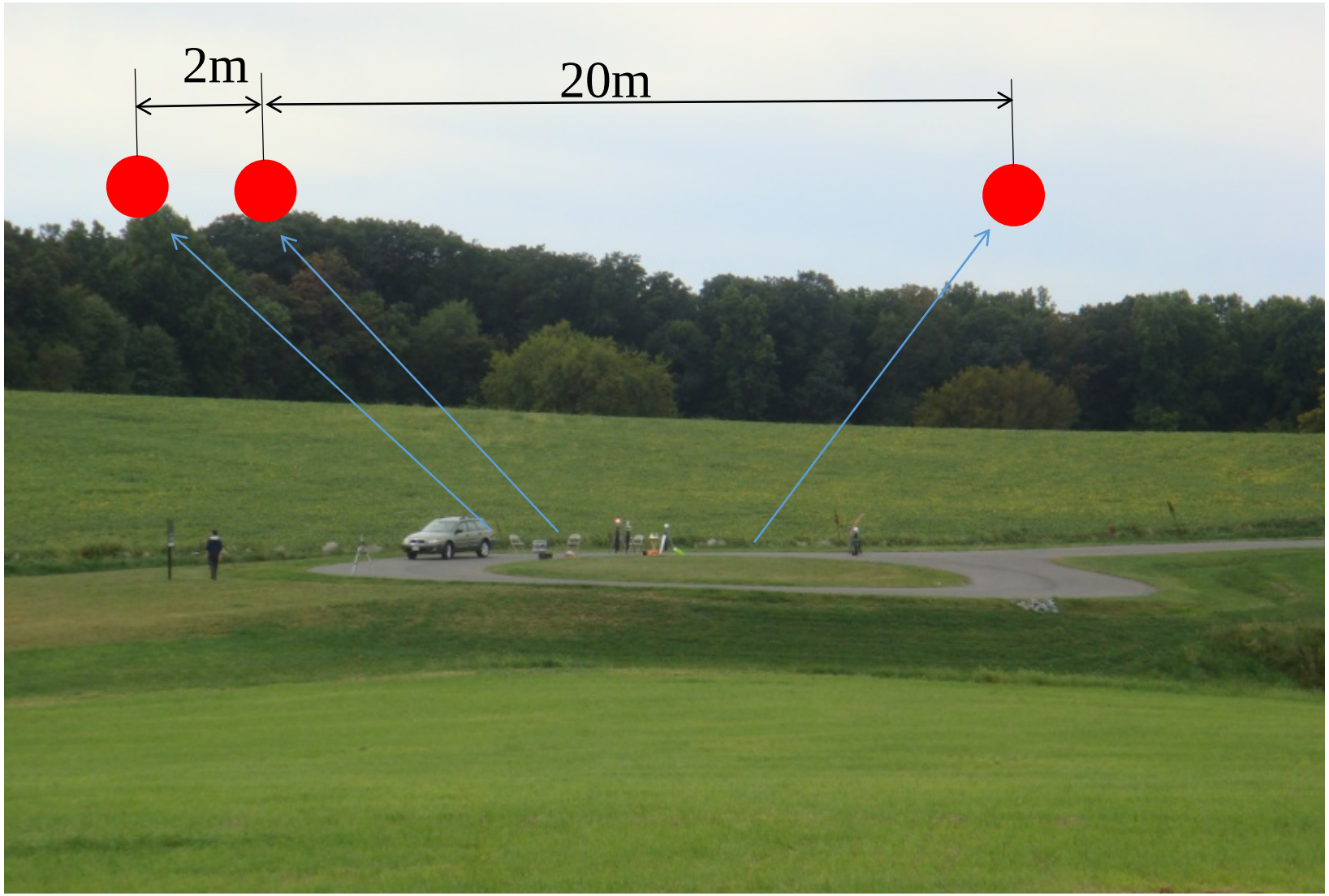
Right absolute node measured by LT and DPUs

Left two nodes measured by DPUs

Differential measurements determine the accuracy of the left two nodes w.r.t. the right node



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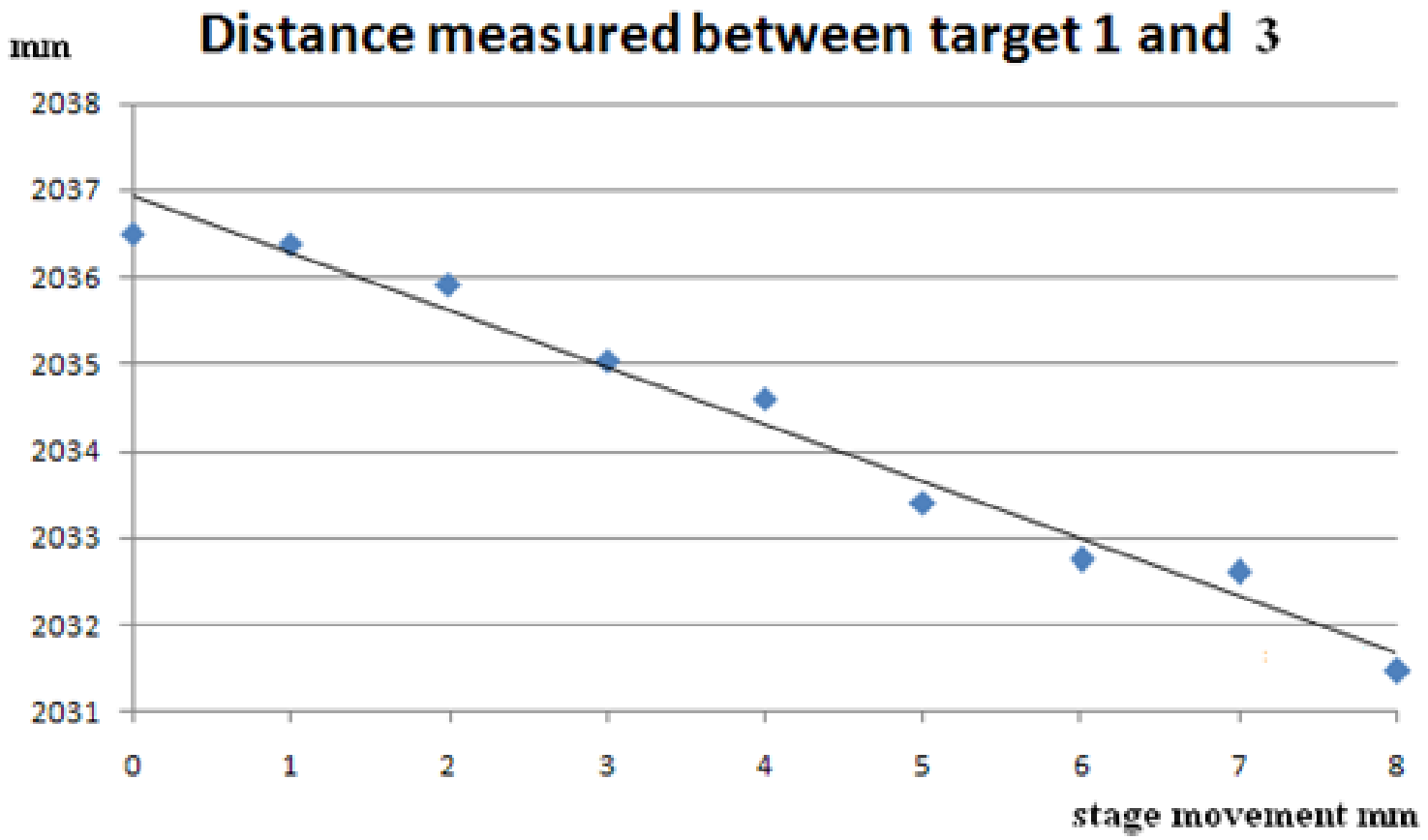


图 65 室外 DPU 与靶球距离 200m 距离，沿 x 方向微动 1mm，移动靶球 3 与参考靶球 1（相距 2m）之间相对距离 3D 测试结果，
标准方差为 0.2177mm

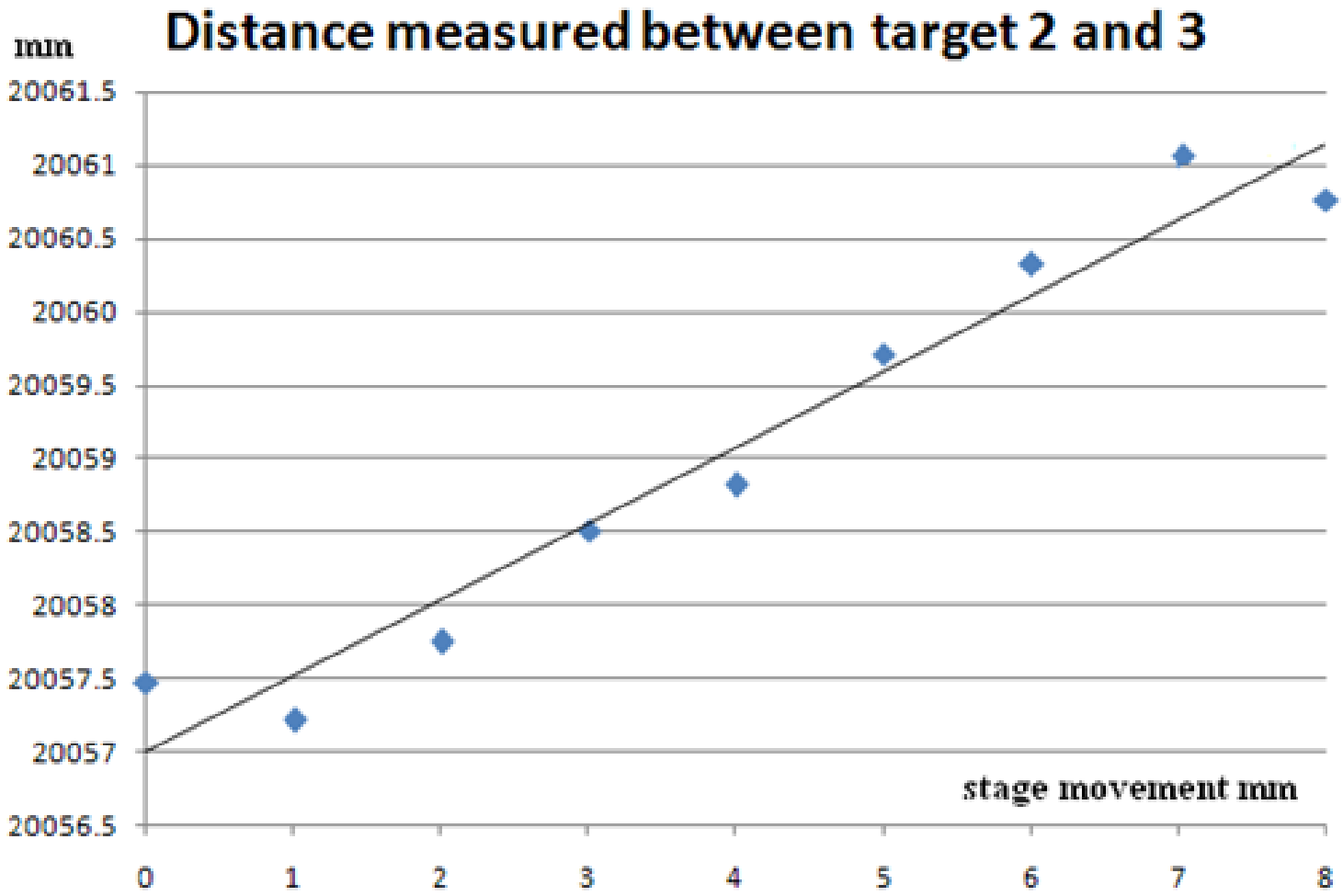
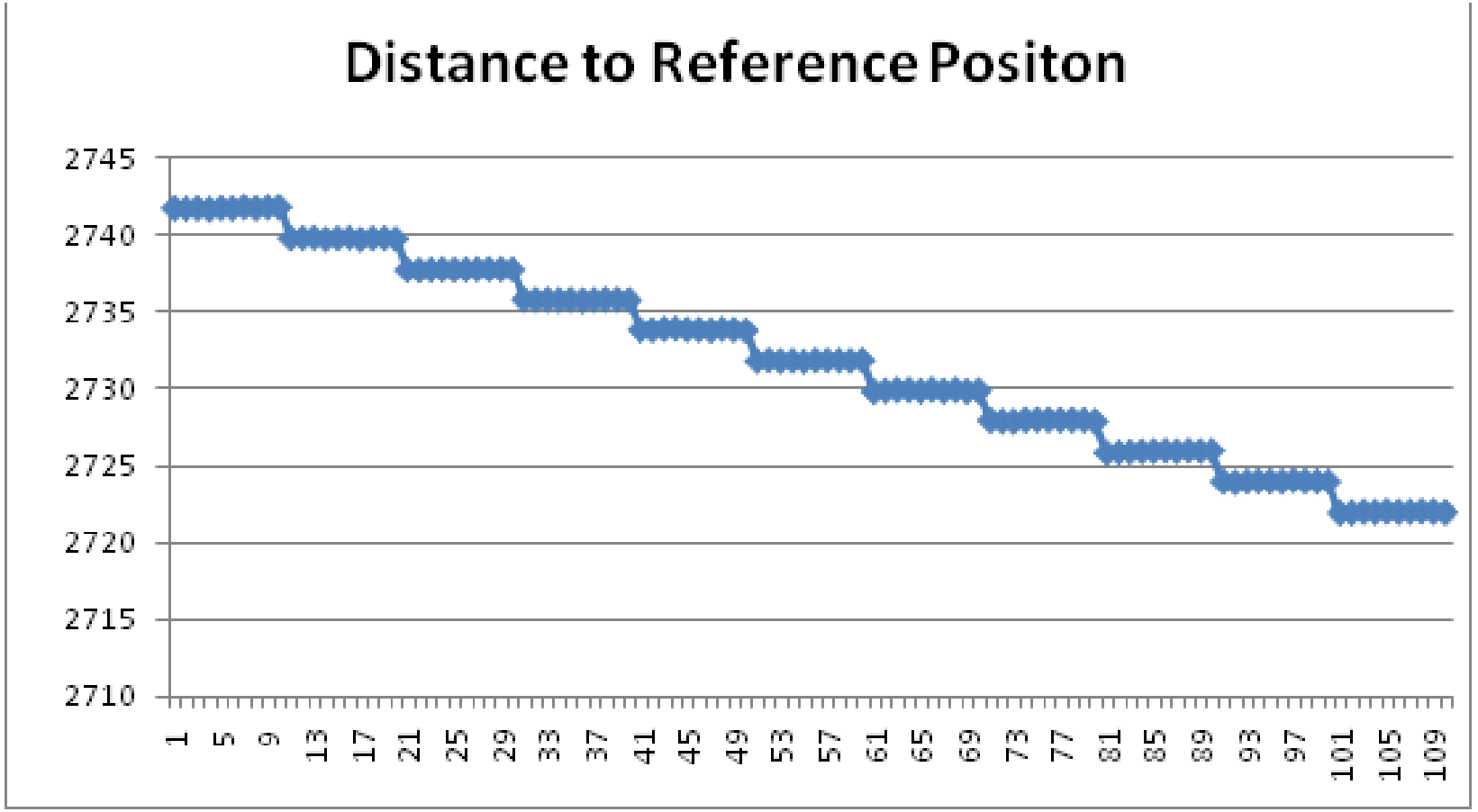


图 66 室外 DPU 与靶球距离 200m 距离，沿 x 方向微动 1mm，移动靶球 3 与参考靶球 2（相距 20m）之间相对距离 3D 测试结果，标准方差为 0.275mm。

Large 2mm Steps (x10) Test Across a DPU



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Conclusions

- An advanced 6 DPUs + 3 Long-Range LTs (6+3) real-time metrology concept was developed for the FAST project
- The concept was based on the redundant measurements from the use of multiple DPUs and laser tracker measurements as absolute references and for the elimination of the air turbulence effect in long distance photogrammetric measurement
- A 3-DPU prototype system was build and tested in an 400-meter diameter open field in Maryland and later in FAST's 10:1 experimental site in MiYun, Beijing
- Results showed the 6+3 system has the potential of meeting the FAST's requirements of measuring 1,000 reflective panel absolute positions to better than 2mm accuracy within 1 minute

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Providing advanced digital information for industry.

Thank you

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