The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2025-50

Satellite Navigation Science and Technology for Africa

23 March - 9 April, 2009

Mapping and Surveying

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Satellite Navigation Science and Technology for Africa:

Mapping and Surveying

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Abdus Salam International Centre for Theoretical Physics, March 31, 2009

Acknowledgement

Contributions from Mr. Bob Mergel of the Columbus State Community College

and Mr. Steve Kenyon

of the National Geospatial-Intelligence Agency (NGA)

are gratefully acknowledged

Newest GPS satellite launch

- The L1/L2 transmitters of SVN49/PRN01, launched on 24 March, were activated on 28 March.
- Several stations in the International GNSS Service are now tracking the satellite.
- However, the satellite has not yet been declared healthy and is not yet included in almanacs.
- The L5 transmitter appears not to have been activated yet. This is expected in early April.
- Current *GPS constellation* consists of 32 Block II/IIA/IIR/IIR-M satellites

Presentation overview

- What is surveying?
- Primary objectives of surveying
- GPS techniques used in surveying
- Example applications
  - Static surveying
  - Kinematic surveying
  - Network-based GPS
  - Precise Point Positioning (PPP)
  - Example performance analysis
- Newest trends in GPS techniques
- Trimble Geomatics Office (Lab)
  - Mission planning
  - Example data processing demo

Definitions

- SURVEYING: The art, technology and science of locating points on, under or near the earth's surface.
- SURVEYOR: Expert in the art and science of performing measurements.

Definitions

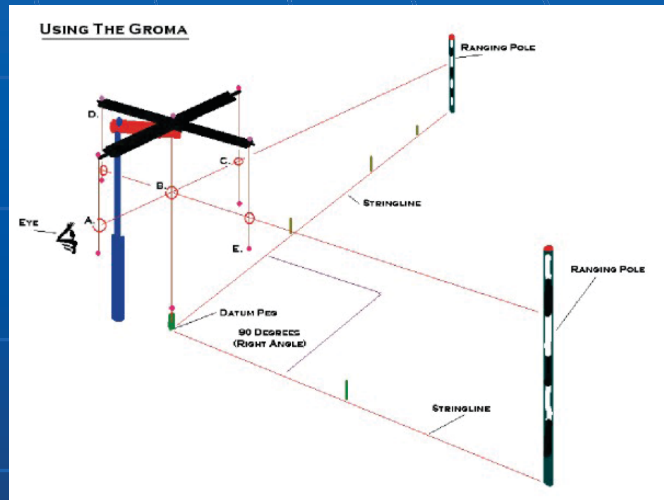
- **GEOMATICS**: Geomatics and Surveying are used interchangeably. However, both include all methods for gathering & processing information about the physical earth & environment – process information – disseminate products
  - Conventional ground systems surveys
  - Aerial surveying methods
  - Satellite surveying methods

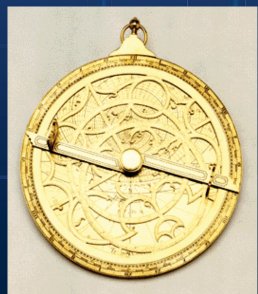
History of Surveying

- Oldest & most important of the arts/sciences.
- Egypt ~ 1400 B.C.
  - Rope Stretchers – Measure and Map the Land – Tax the Occupants
- Greece: Science of Geometry and Early Surveying Instruments (Diopter)

History of Surveying

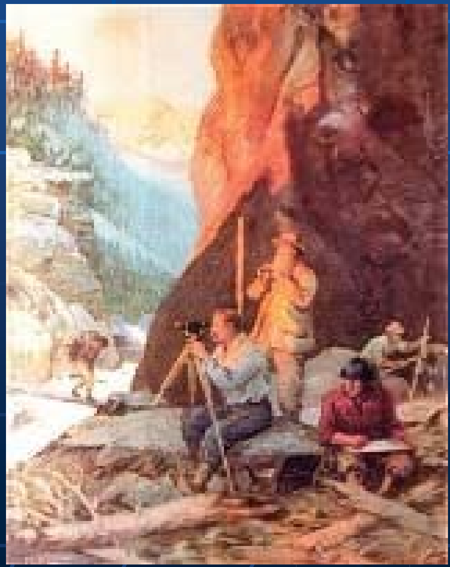
- Romans: Groma for sighting and the libella for leveling. Extensive Architectural and Engineering Works
- Middle Ages: Greek & Roman Techniques kept alive by Arabs.





History of Surveying

- 18th & 19th Century – England & France – Need to Establish National Boundaries and for Exploration
- U.S. – Public Land Survey System - Land Act of 1796:
  - The Office of Surveyor General was created and provisions made for deputy surveyors to serve him
  - Edward Tiffin was the fourth and last Surveyor General. In 1815 he prepared a manual on surveying public lands

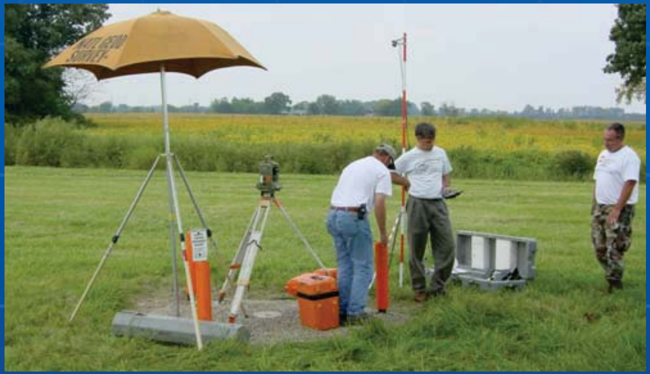


Purpose

- Surveys involve measurement of horizontal and vertical distances and horizontal and vertical angles for two (2) major purposes:
- Data Gathering
- Construction Layout

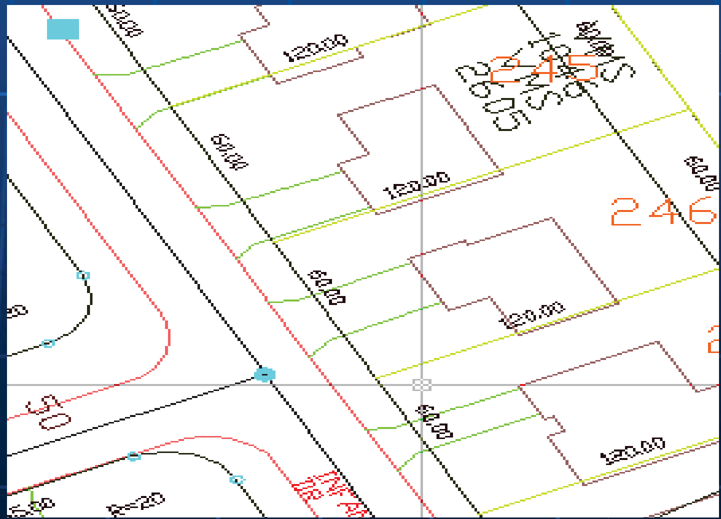
Purpose

- **DATA GATHERING**
  - **Determine the horizontal location of points on the earth's surface.**
  - **Determine the elevations of points above or below a reference surface, usually mean sea level (MSL).**
  - **Determine the lengths and directions of lines.**



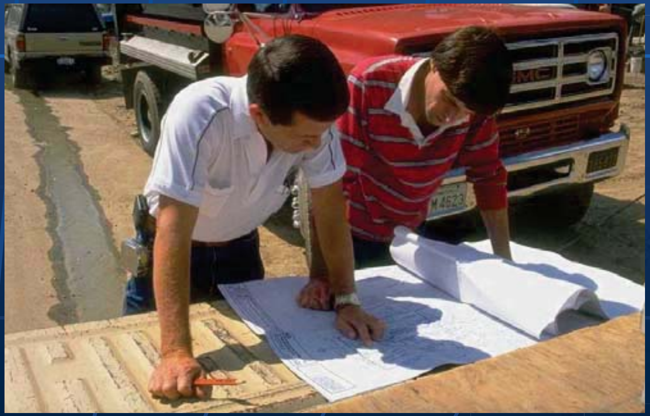
Purpose

- **DATA GATHERING continued**
  - **Determine the configuration of the ground.**
  - **Determine evidence of boundary lines.**
  - **Determine the areas of tracts of land bounded by given lines.**



Purpose

- CONSTRUCTION LAYOUT Lay off (measure) distances, angles and grade lines for the purpose of locating construction lines for buildings, landscapes, transportation systems, bridges, tunnels, utilities, or other architectural/engineering works.



Field Surveying Reference Systems

Use of Global Positioning Systems (GPS) to Establish Primary Control

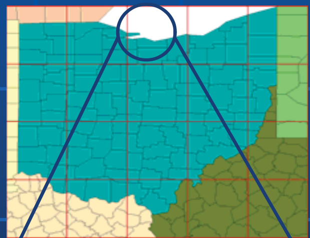

Now, where in
the world am I?

Reference Systems

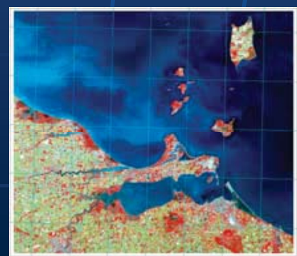
Earth

Geography

Geodesy

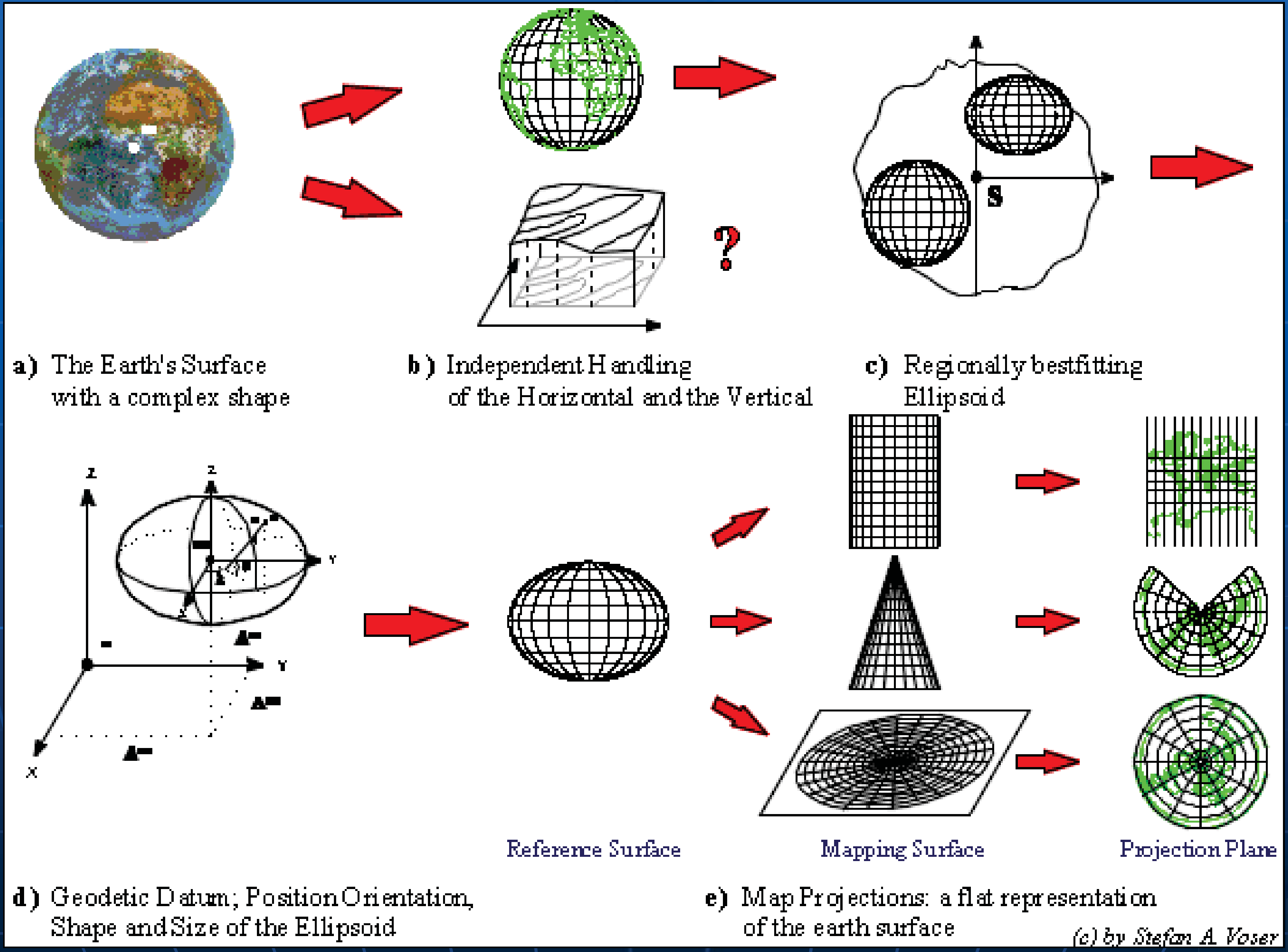


Geographic Datum
Ground Control Points



Geographic Coordinate System
Spherical Model –
Latitude, Longitude

Geodetic System – Ellipsoidal Model
ECEF - GRS 80, WGS84, ITRF
State Plane Coordinates


a) The Earth's Surface with a complex shape
b) Independent Handling of the Horizontal and the Vertical
c) Regionally bestfitting Ellipsoid
S
d) Geodetic Datum; Position Orientation, Shape and Size of the Ellipsoid
Reference Surface
Mapping Surface
Projection Plane
e) Map Projections: a flat representation of the earth surface
(c) by Stefan A. Voser

Branches of Surveying

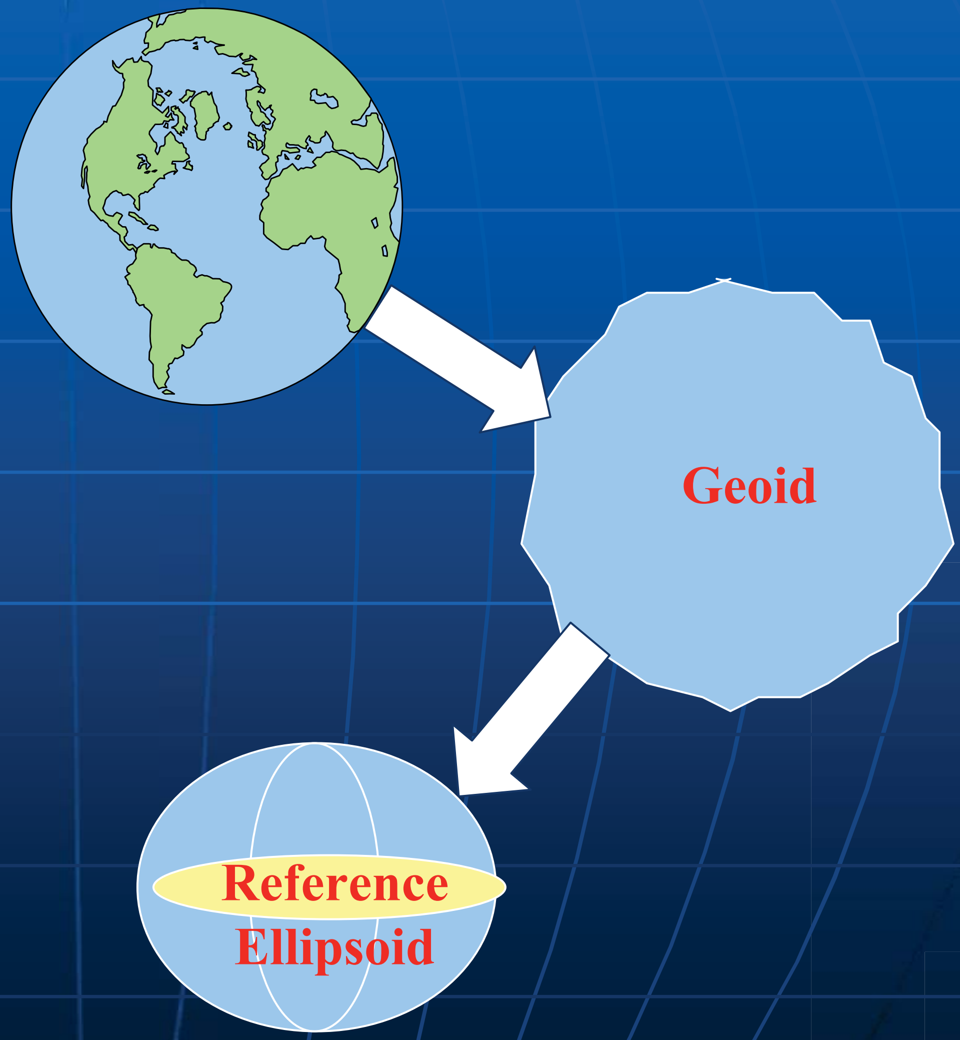
- **Plane surveying** techniques assumes that all plumb lines are parallel and all horizontal distances and angles are projected onto one horizontal plane. The distances involved are short enough that error resulting from the earth's curvature is negligible.

Branches of Surveying

- **Plane Surveying**
  - Flat horizontal surface of earth.
  - Perform computations on a plane.
  - Simplifies computations & techniques.

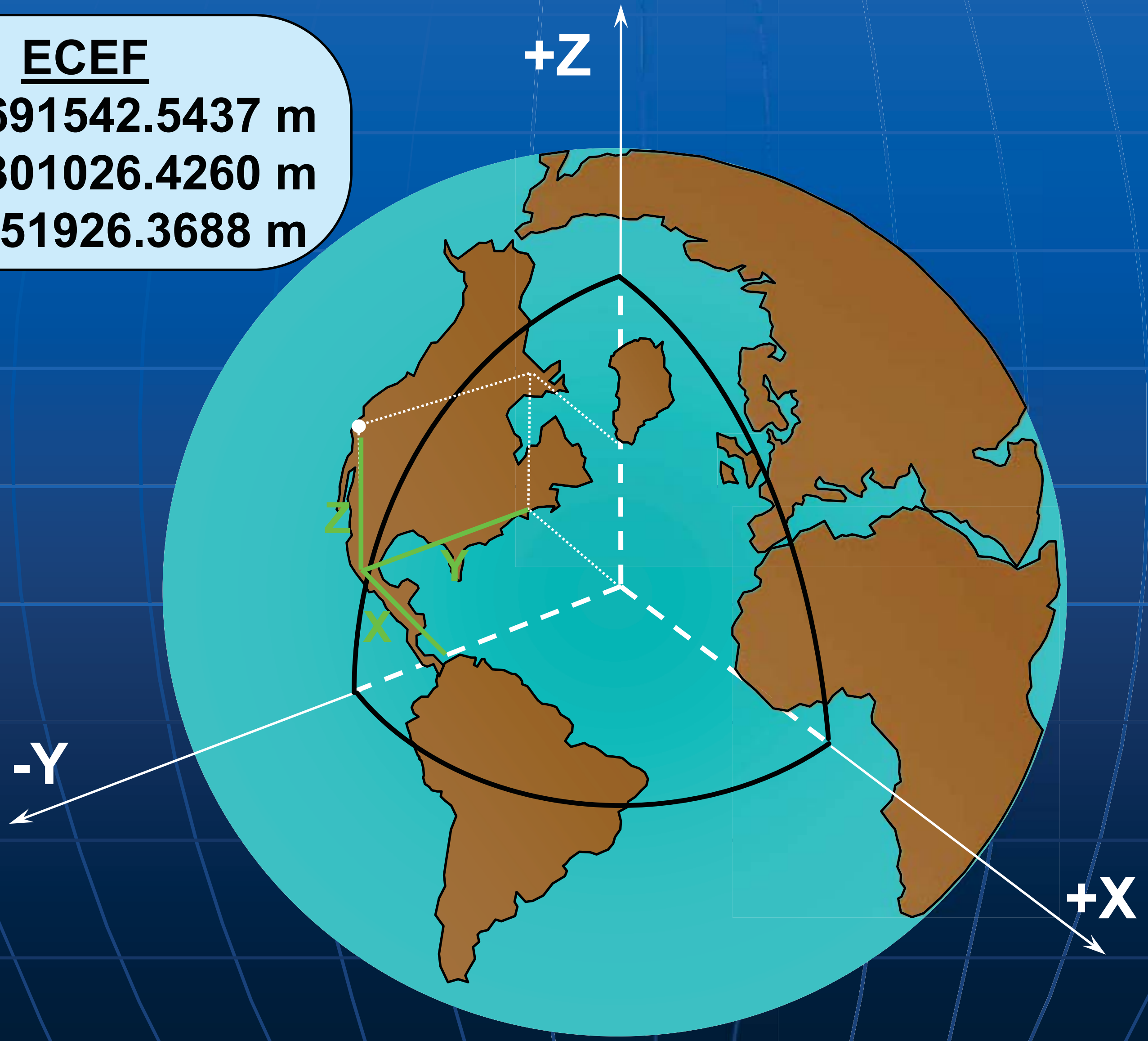
Branches of Surveying

- Geodetic surveying techniques take into account the curvature of the earth wherein all distances and horizontal angles are projected onto the surface of the reference ellipsoid that closely approximates the earth.
- The geoid is that equipotential surface which would coincide with the mean ocean surface of the Earth, if the oceans were in equilibrium



ECEF Coordinate System

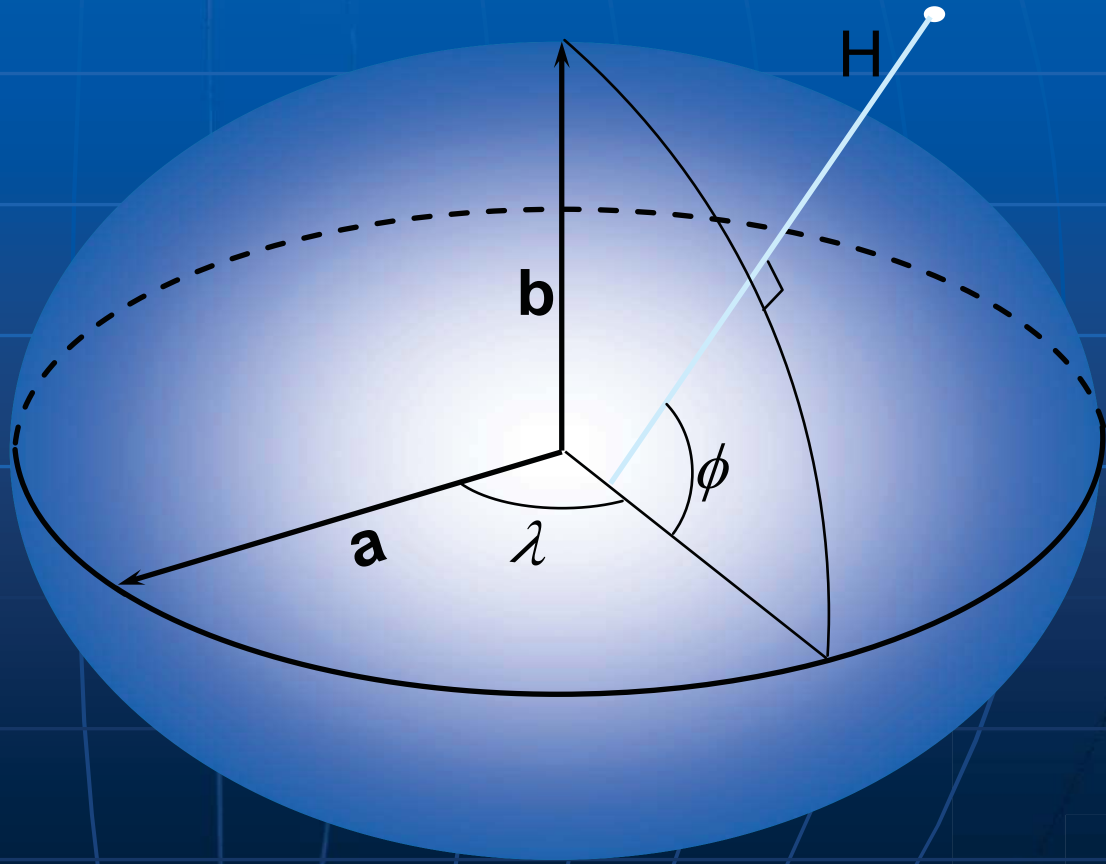
ECEF
X = -2691542.5437 m
Y = -4301026.4260 m
Z = 3851926.3688 m



Reference Ellipsoid

a = semi-major axis
b = semi-minor axis
Flattening $f = \frac{(a-b)}{a}$

$\phi \equiv$ latitude
$\lambda \equiv$ longitude
H $\equiv$ ellipsoidal height



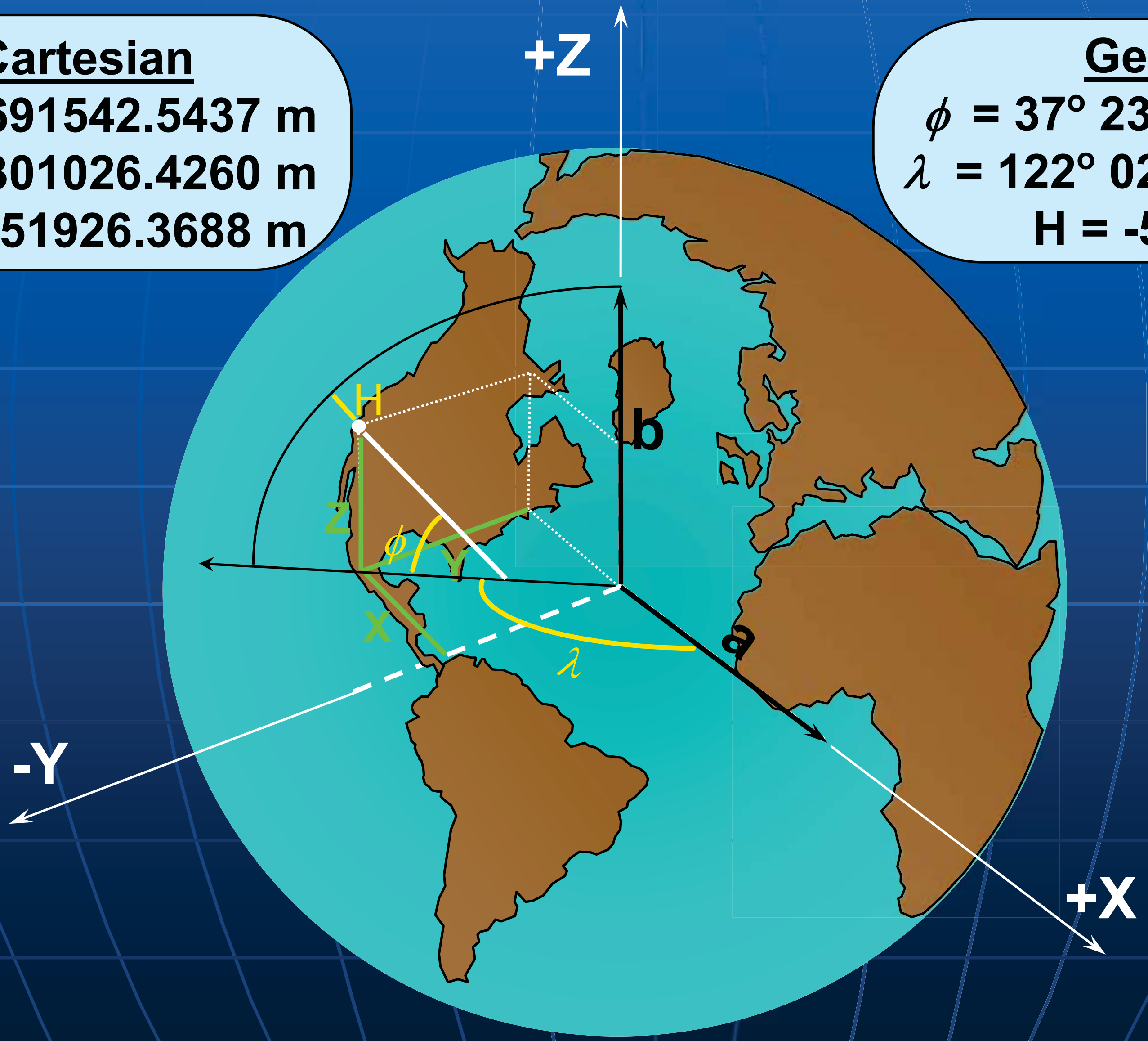
WGS-84 Ellipsoid

a = 6378137.000000 m
b = 6356752.314245 m
1/f = 298.2572235630

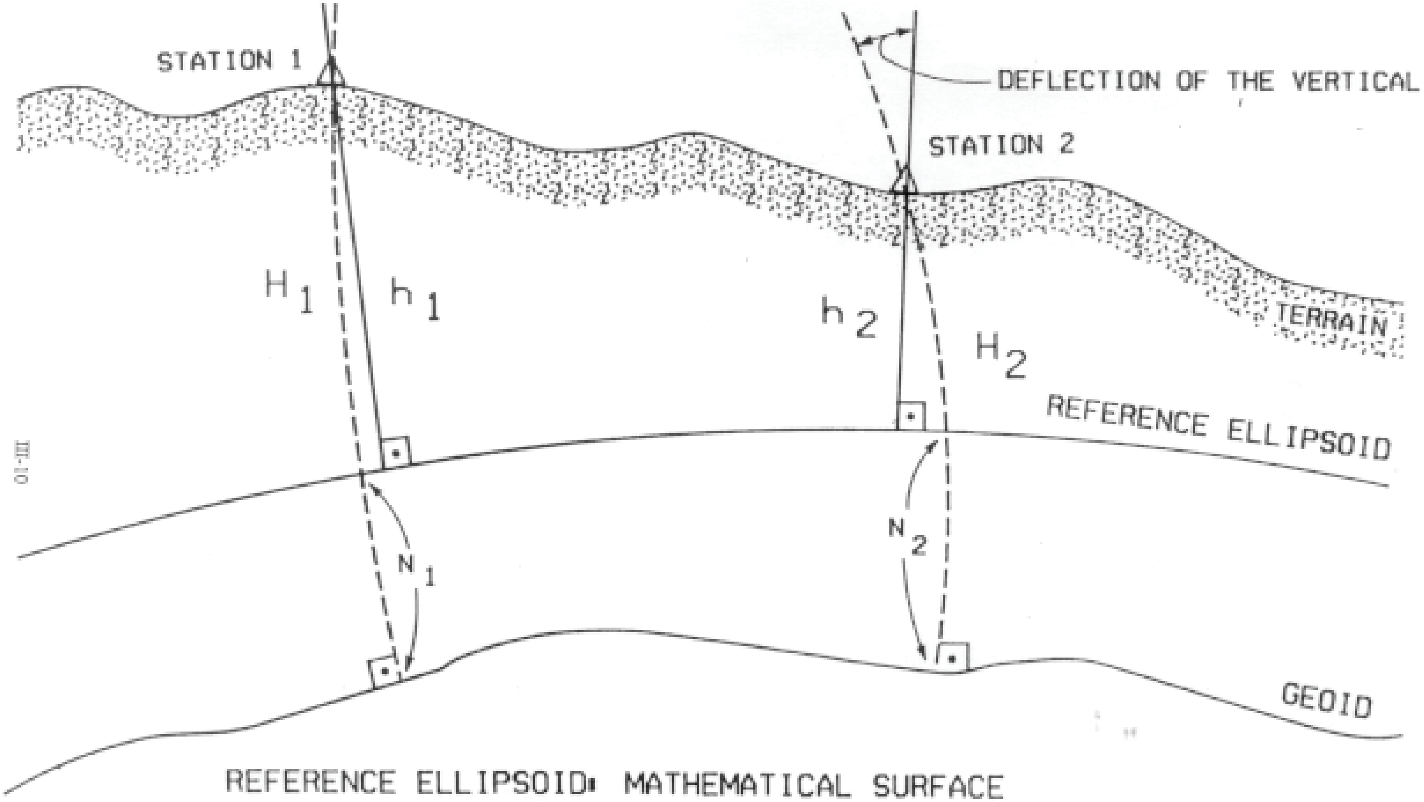
Cartesian and Geodetic Coordinates

Cartesian
X = -2691542.5437 m
Y = -4301026.4260 m
Z = 3851926.3688 m

Geodetic
ϕ = 37° 23' 26.38035" N
λ = 122° 02' 16.62574" W
H = -5.4083 m



Orthometric vs Ellipsoidal Height



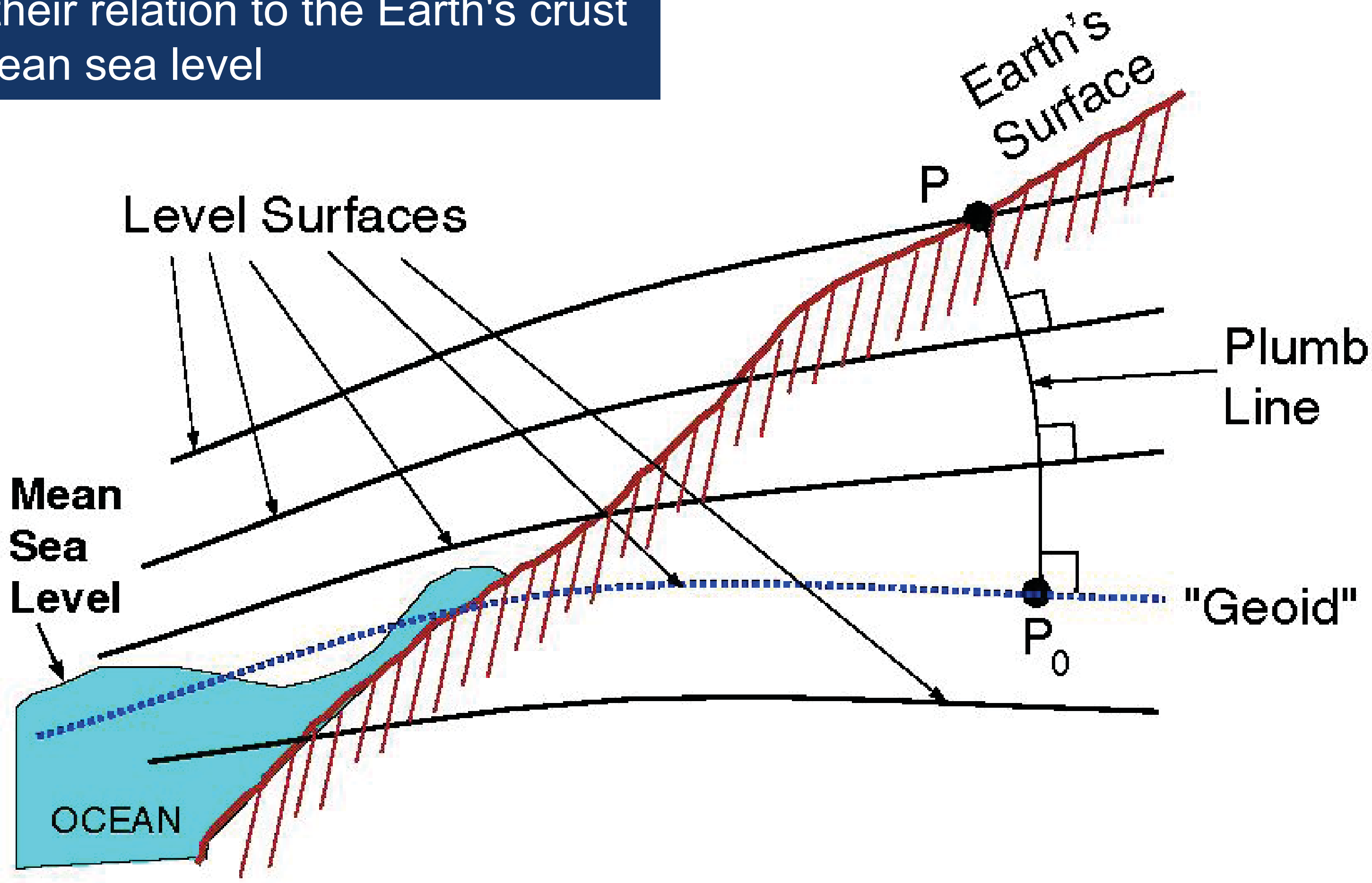
REFERENCE ELLIPSOID: MATHEMATICAL SURFACE
GEOID: NOMINALLY EQUATED TO DISTORTED SEA-LEVEL

TO DETERMINE ELEVATIONS USING GPS:

h = H + N

H = ELEVATIONS (MEASURED FROM GEOID)
h = ELLIPSOIDAL HEIGHT (FROM GPS)
N = GEOID SEPARATION FROM ELLIPSOID (computed from a geoid model)

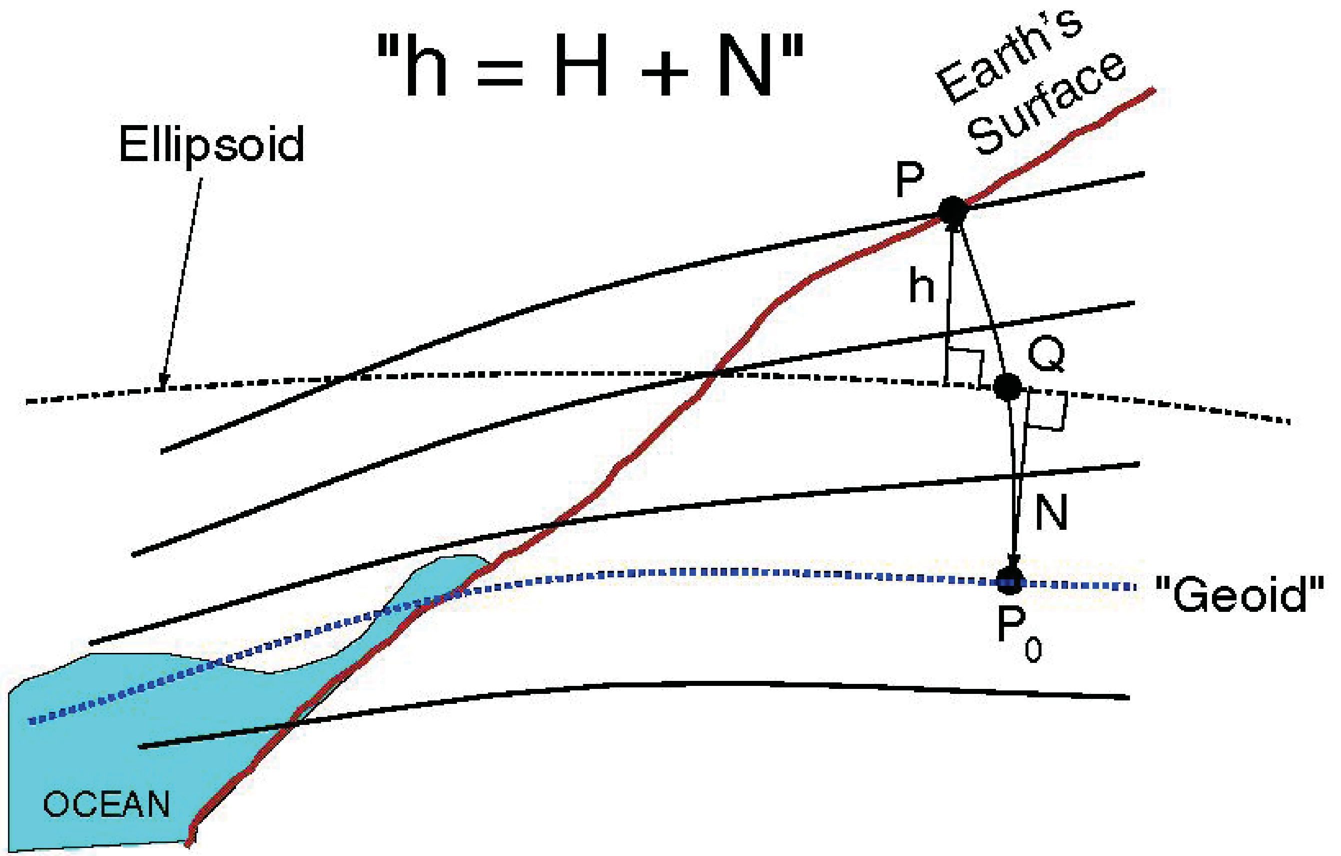
Schematic diagram showing some of the "level surfaces" of the Earth, including the geoid, and their relation to the Earth's crust and local mean sea level



Level Surface = Equipotential Surface

H (Orthometric Height) = Distance along Plumb line (P_0 to P)

http://www.ngs.noaa.gov/GEOID/geoid_def.html



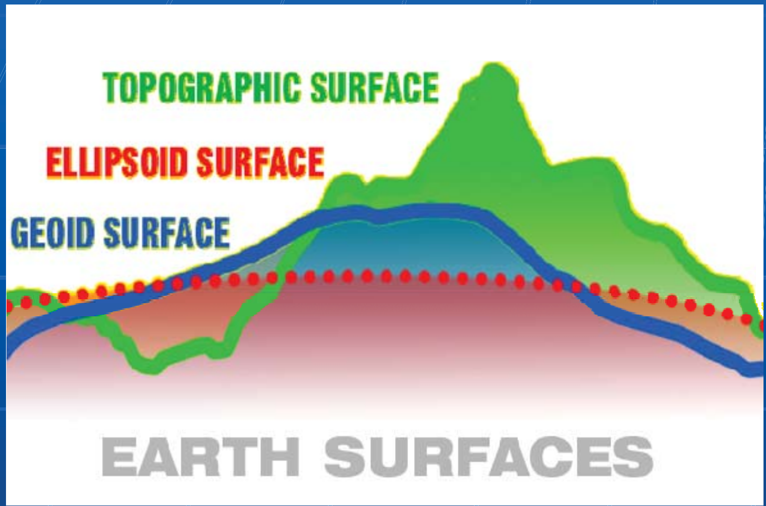
h (Ellipsoid Height) = Distance along ellipsoid normal (Q to P)

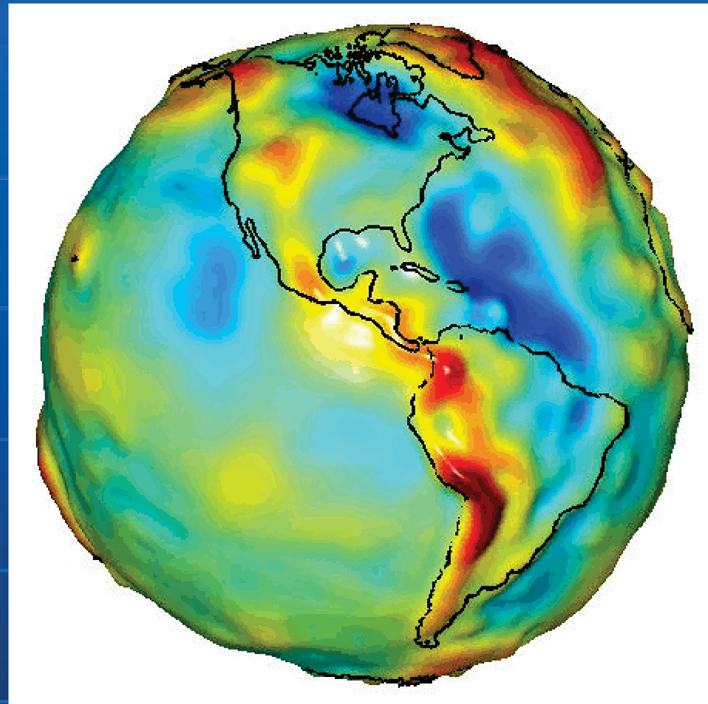
N (Geoid Height) = Distance along ellipsoid normal (Q to P_0)

H (Orthometric Height) = Distance along Plumb line (P_0 to P)

Schematic diagram showing the relationship between the geoid, orthometric heights and ellipsoid. Note that the ellipsoid is drawn *above* the geoid. This is the actual case for all points in the conterminous United States. Also note that the ellipsoid does not coincide with any level surface, but rather cuts across them. This is because the ellipsoid is a geometric invention, and not defined by the actual gravity field of the Earth itself.

WGS 84 Earth Gravity Models





Geoid Accuracy (vertical)

Initial WGS 84 Earth Gravity Model (1987)
180 model (4 – 6 m) - 1 degree resolution

⬇

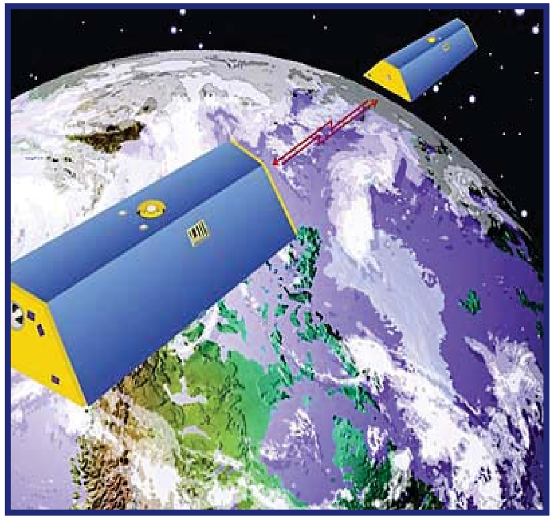
Earth Gravity Model 1996 (EGM96)
360 model (.5 - 1 m) - 30' resolution

➡ **NEXT**

NGA EGM Developments

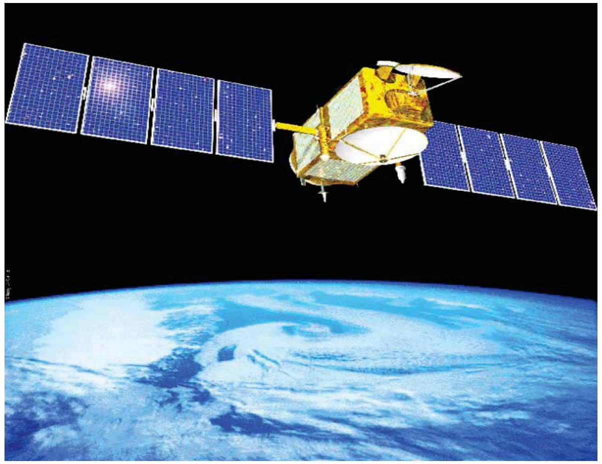
EGM96

- 30'x30' resolution
- Global 50 cm RMS accuracy
- 40+ satellites used for long λ's
- GEOSAT
- 130 K coefficients

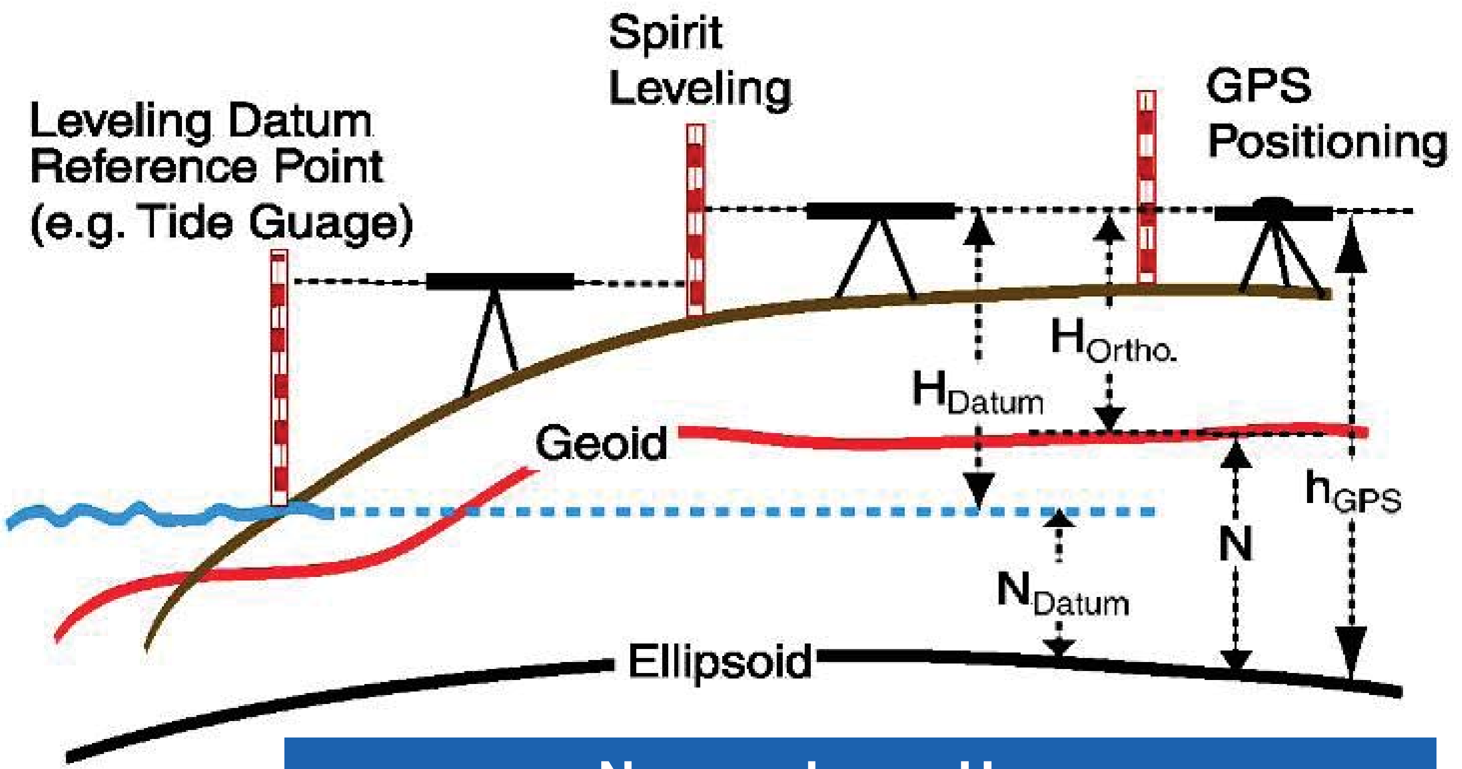


EGM08

- 5'x5' resolution
- Global 10 cm RMS accuracy
- GRACE used for long λ's
- ERS-1, ERS-2, GEOSAT, TOPEX, etc.
- SRTM, ICESAT
- 4.7 M coefficients



Geoid Height Estimation From GPS/Leveling Data



$$N_{Datum} = h_{GPS} - H_{Datum}$$

N – geoid undulation

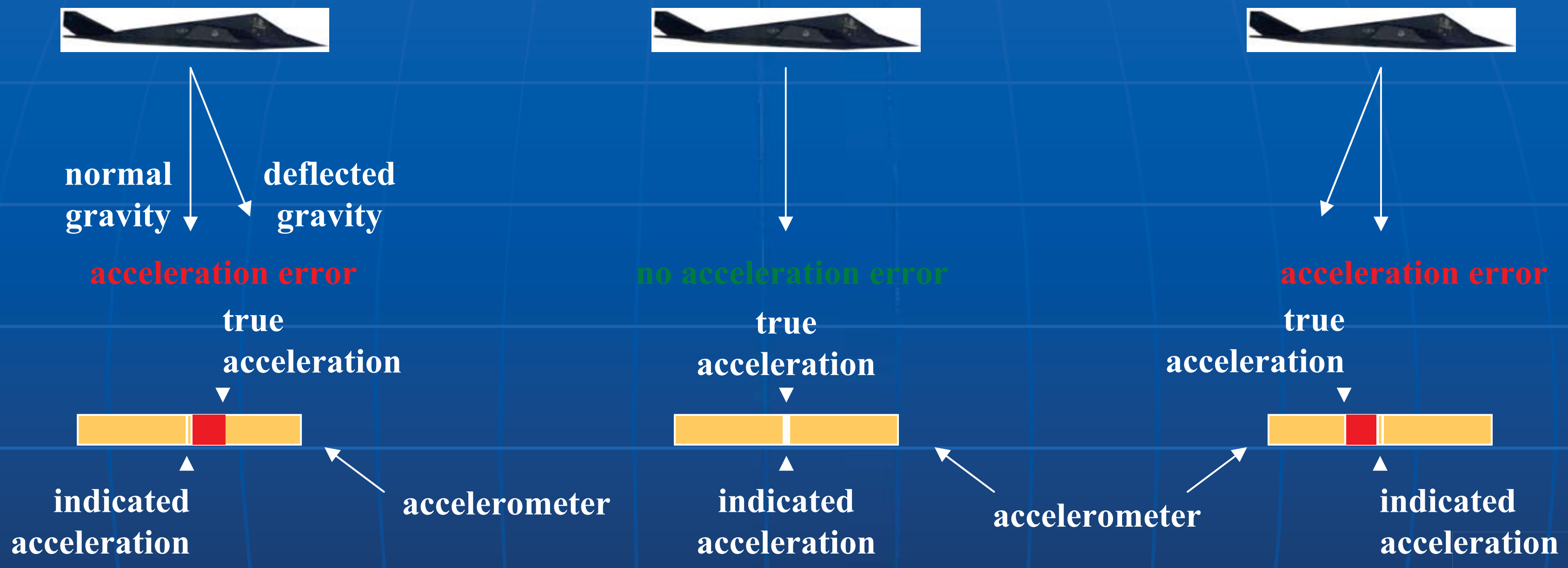
GPS/Leveling Comparisons Globally

Thinned set consisting of 12387 points. ±2 m edit applied.
Conversion of Height Anomalies to Geoid Undulations applied in EGMs using DTM2006.0 elevation coefficients to commensurate Nmax.

Model (Nmax)	Bias Removed		Linear Trend Removed	
	Number Passed Edit	Weighted Std. Dev. (cm)	Number Passed Edit	Weighted Std. Dev. (cm)
EGM96 (360)	12220	30.3	12173	27.0
GGM02C_EGM96 (360)	12305	25.6	12258	23.2
EIGEN-GL04C (360)	12299	26.2	12252	23.5
EGM2008 (360)	12329	**23.0**	12283	**20.9**
EGM2008 (2190)	12352	**13.0**	12305	**10.3**

Gravity Affects Inertial Navigation

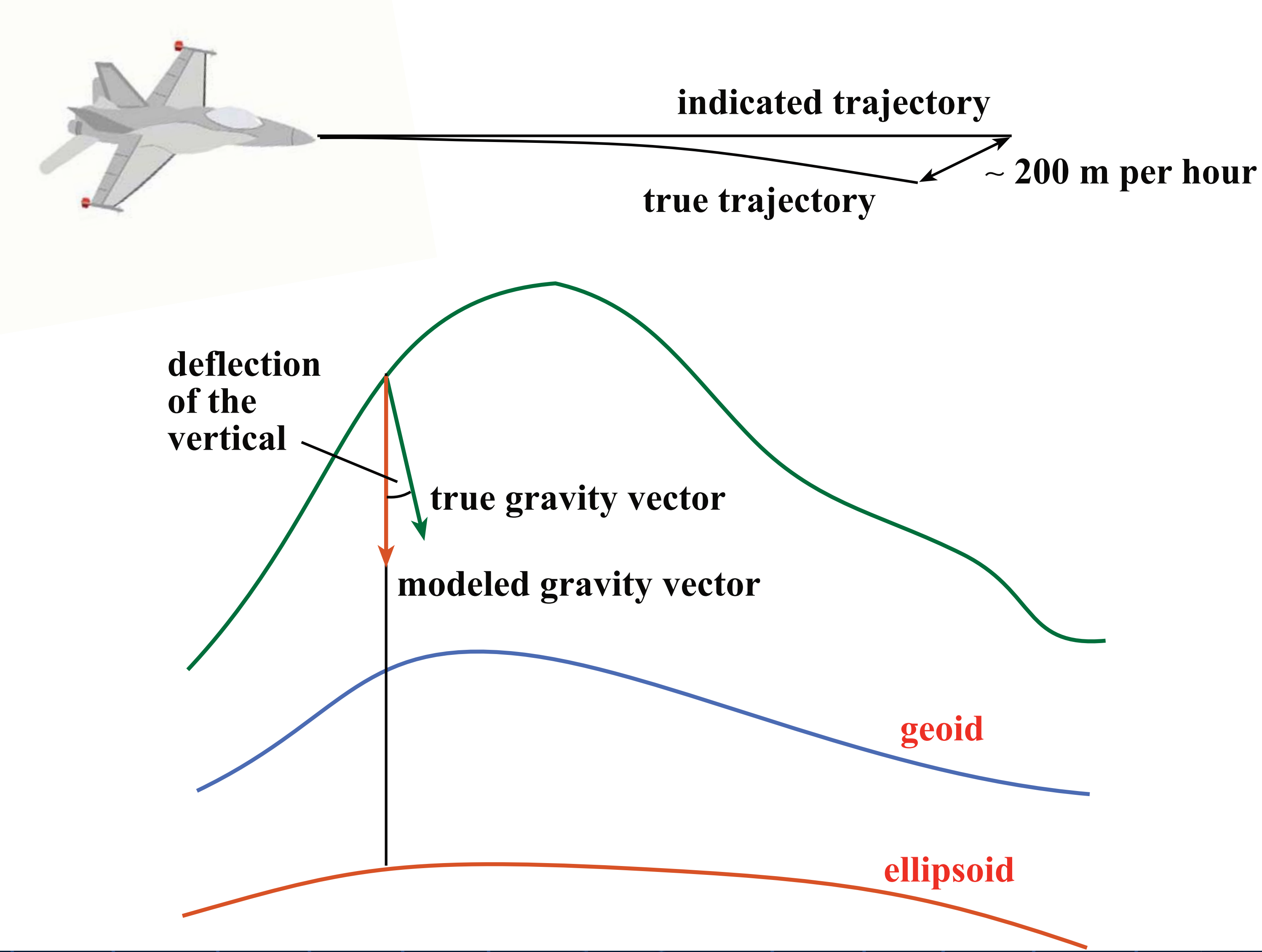
Gravity *deflection* is one of the largest uncompensated errors in INS



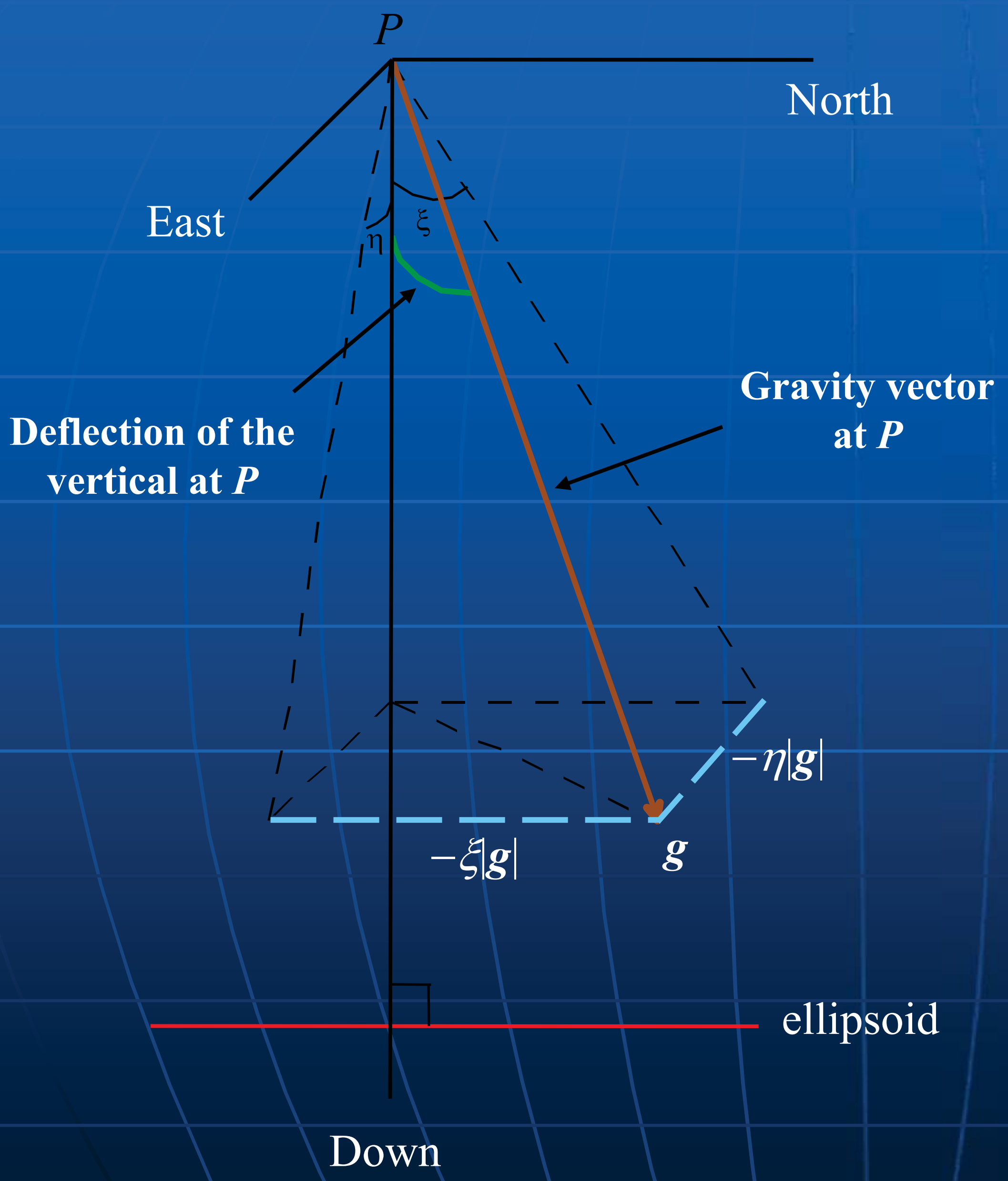
- Uncompensated INS integrates *indicated* accelerometer output and yields *erroneous* velocity and position.

- *Note*: Accelerometer does *NOT* sense mountain because mountain attracts accelerometer proof mass, accelerometer housing, and aircraft, all with the same gravitational acceleration.

Determine *direction of gravity* to enable precision inertial navigation



Deflection of the Vertical



ξ = *north deflection*

η = *east deflection*

$$\delta \mathbf{g}^n \approx \begin{pmatrix} -\xi g \\ -\eta g \\ \delta g \end{pmatrix}$$

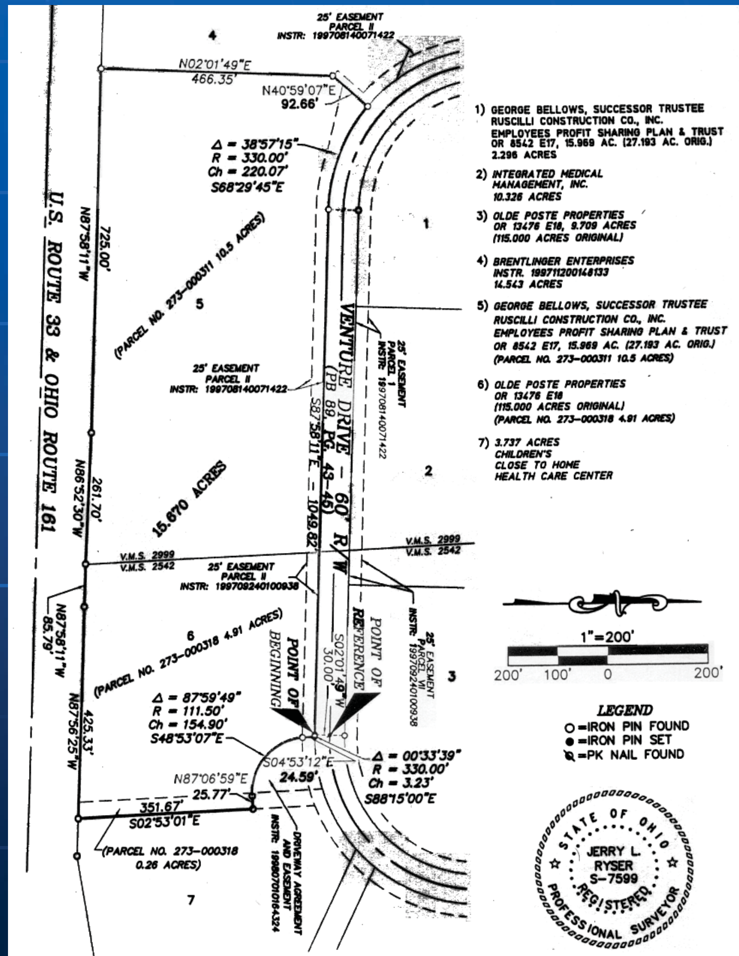
linear approximation

$$\delta g = |\mathbf{g}| - |\boldsymbol{\gamma}| \qquad g = |\mathbf{g}|$$

gravity disturbance

Types of Surveys

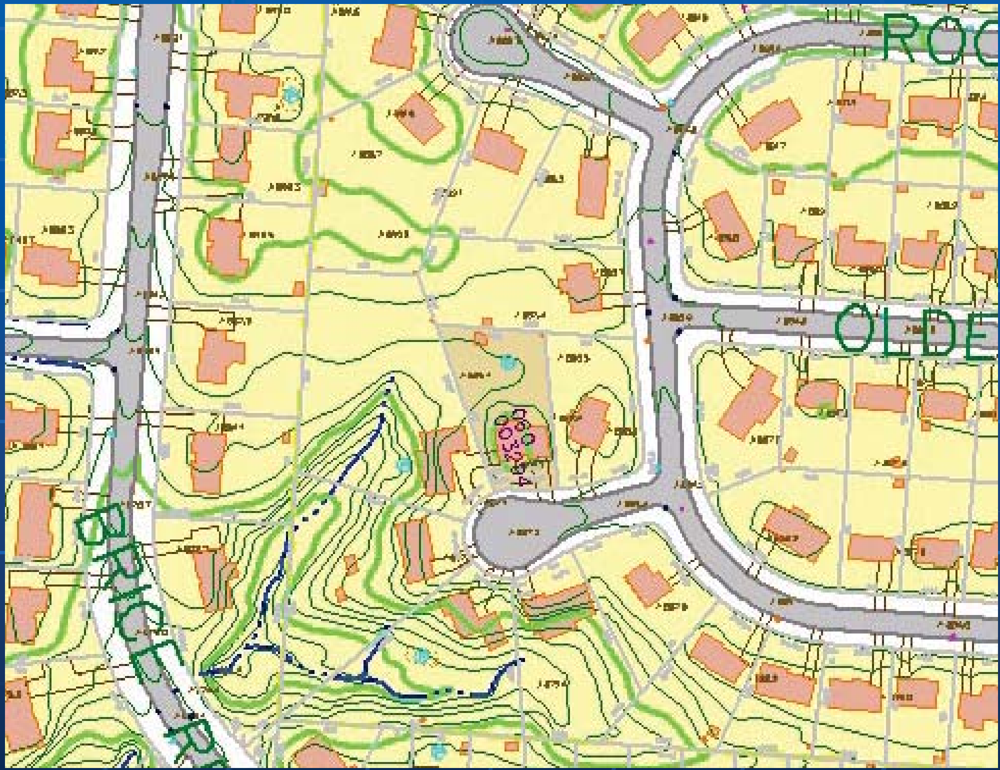
- **BOUNDARY:** Sometimes referred to as cadastral surveying. This survey for the purpose of determining evidence of boundary or property lines.



- Example types of Surveys
  - *Everything is based on position coordinate estimation*
  - Conventional methods (point-based surveying)
  - Remote sensing: position/georeference the sensor to recover information from the image (imagery, LiDAR (light detection and ranging)
  - Increasing importance of GPS

Types of Surveys

- **TOPOGRAPHIC:** Survey for the purpose of locating the position of physical features on, under or near the ground surface. Determining ground configuration (contours or elevations) - aerial or photogrammetric surveys may be used for this purpose.



Types of Surveys

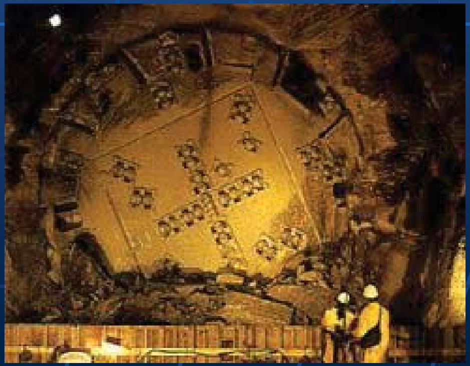
- **CONTROL: Survey for the purpose of establishing a network of points (horizontal and vertical position) to be used as a set of references for other surveys and mapping. This may for the basis for a boundary or topographic survey or for a right of way (route design) project.**

Types of Surveys

- **SITE PLAN:** This is a combination of boundary, site and sometimes control surveying to produce a complete site plan to be used as a basis for a future improvement such as an engineering, architectural, environmental or landscaping project.

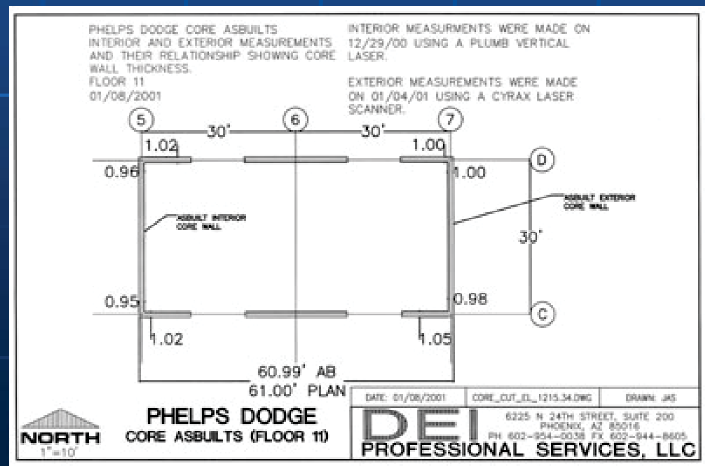
Types of Surveys

- **CONSTRUCTION:**
  - Survey for the purpose of establishing points for the construction of engineering, landscape or architectural projects.
  - Mine and tunneling surveys.



Types of Surveys

- CONSTRUCTION (continued):
  - Industrial surveys – optical tooling and/or alignment
  - "As-built" surveys for documenting conformance to acceptable dimensional tolerances.

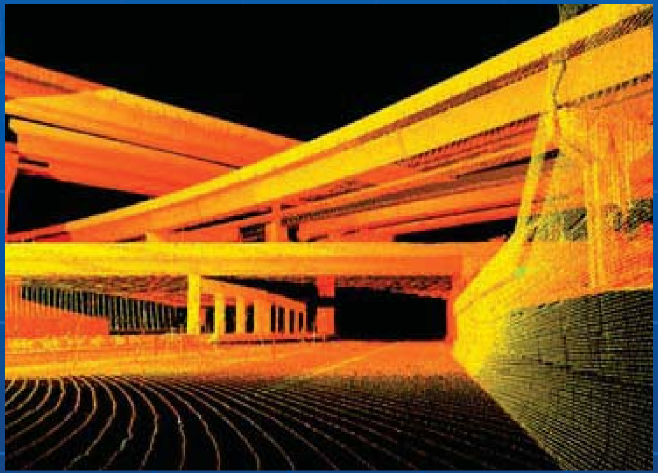


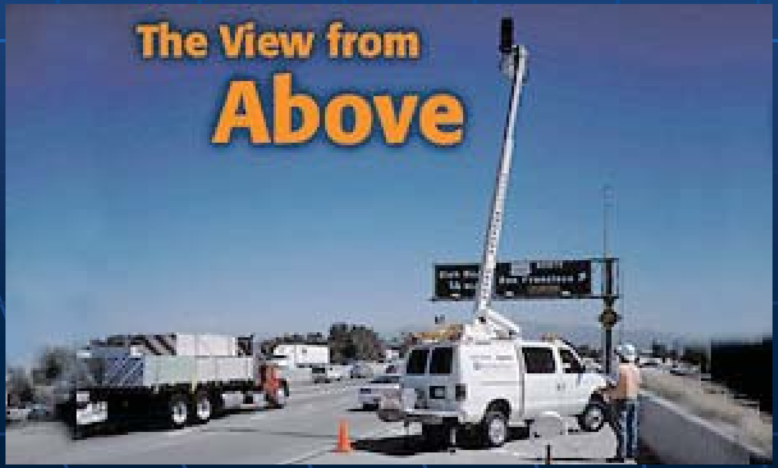
Types of Surveys

- **FORENSIC SURVEYING: Measurements taken for the purpose of re-construction of a crime scene.**

Types of Surveys

Route Surveying:
Combines both Data Collection and Construction Layout
Involves Boundary, Site, Control Surveys





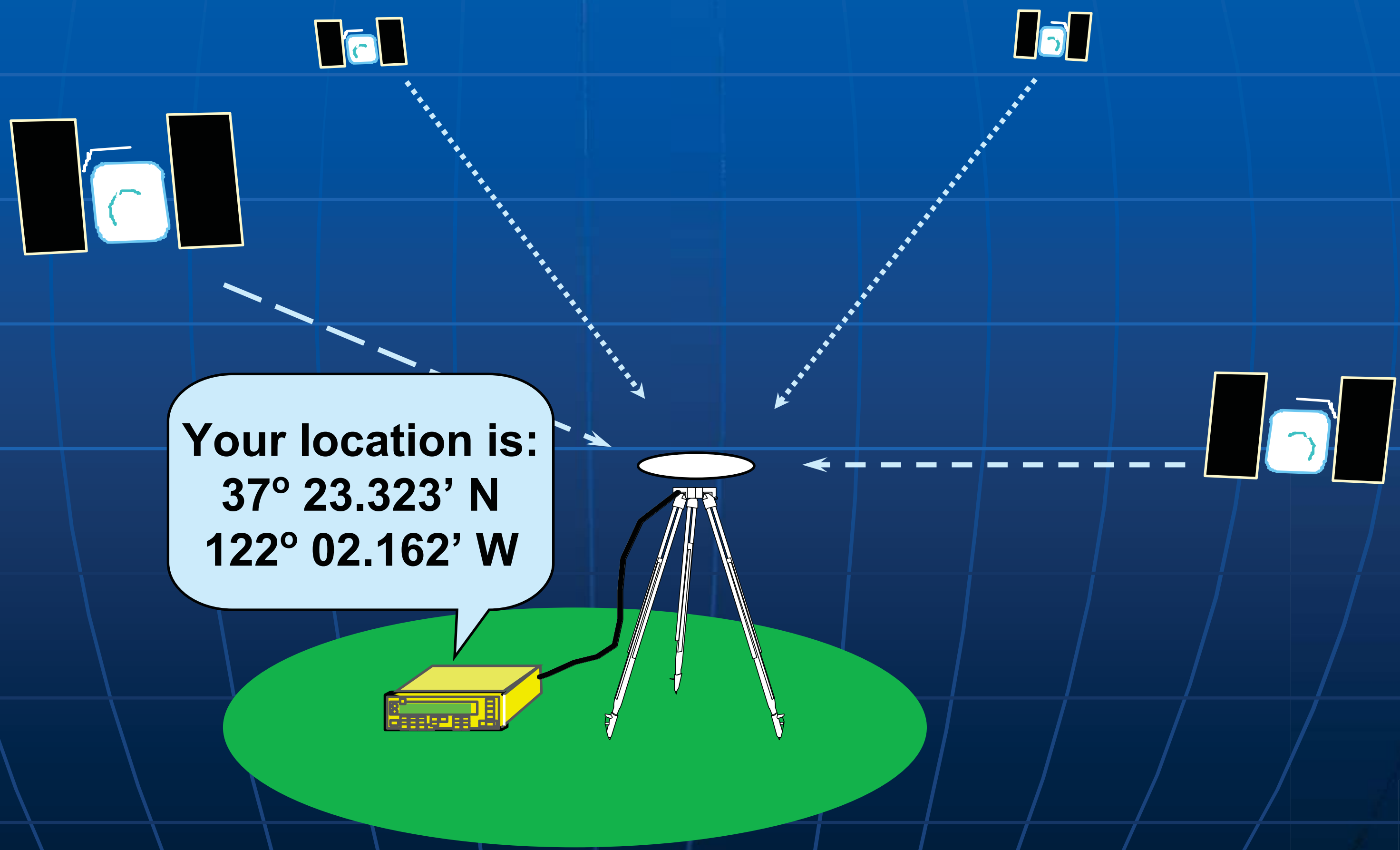
New and Emerging Technologies

Total Stations
Electronic Distance Measurement

New and Emerging Technologies

- Global Positioning Systems (GPS) Applications
  - Survey & Mapping~54%
  - Navigation~ 20%
  - Tracking & Comm~18%
  - Military~ 6%
  - Car Navigation~ 2%

New and Emerging Technologies

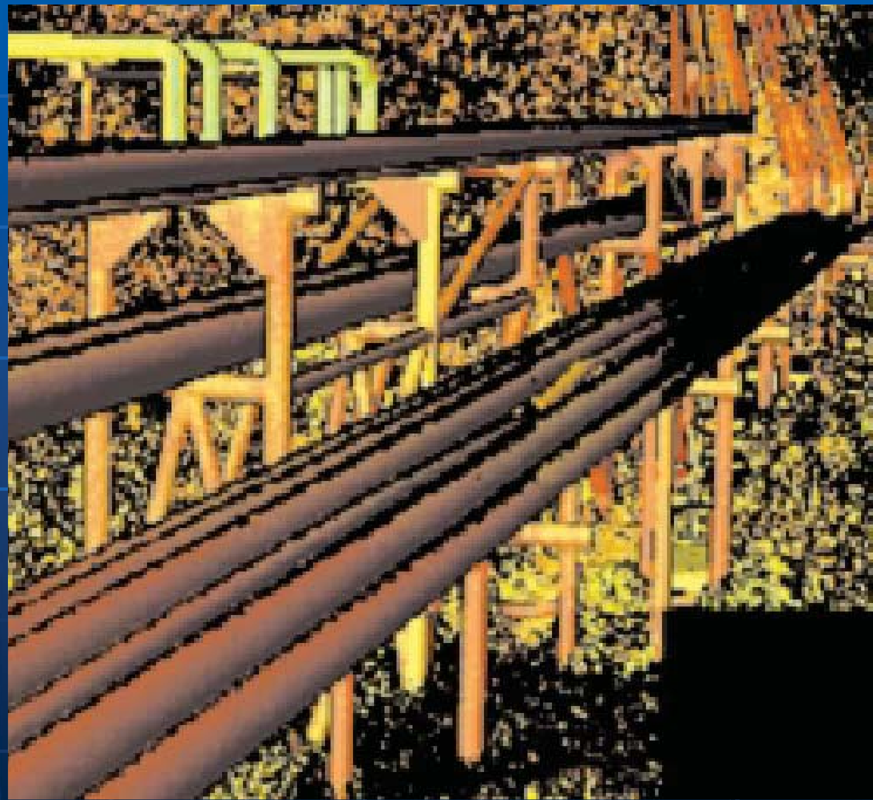


New and Emerging Technologies

Laser Scanning – Close in Remote Sensing

New and Emerging Technologies

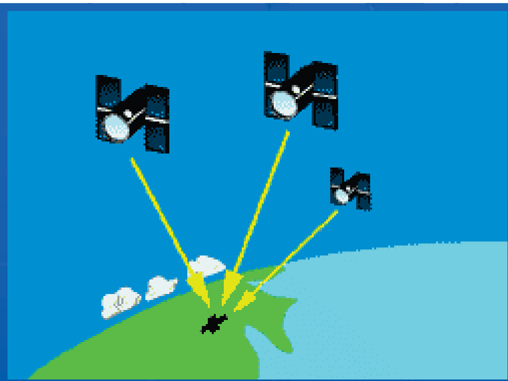
Laser Scanning – Close in Remote Sensing

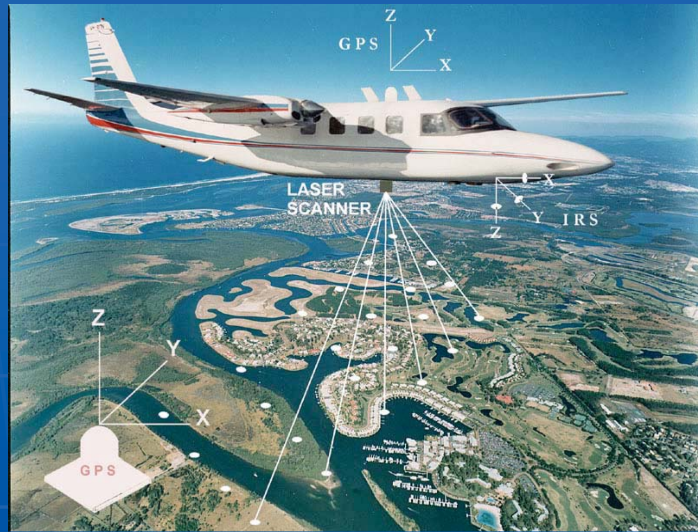


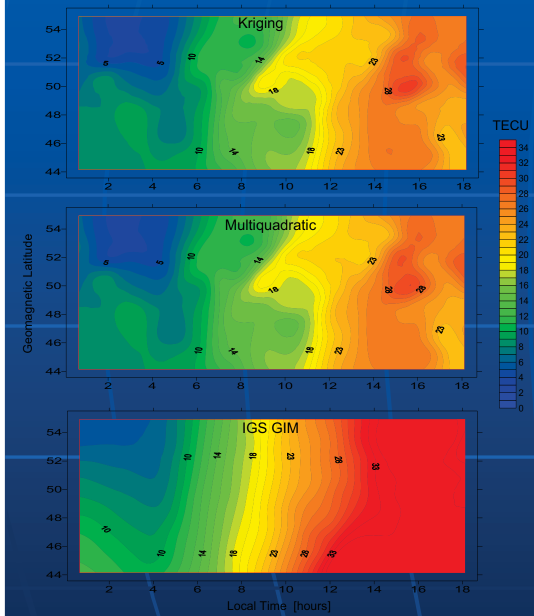
TO GO WHERE NO ONE WANTS TO GO!

New and Emerging Technologies

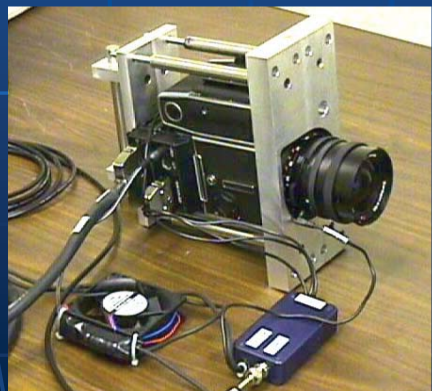
AERIAL
SURVEYING/MAPPING

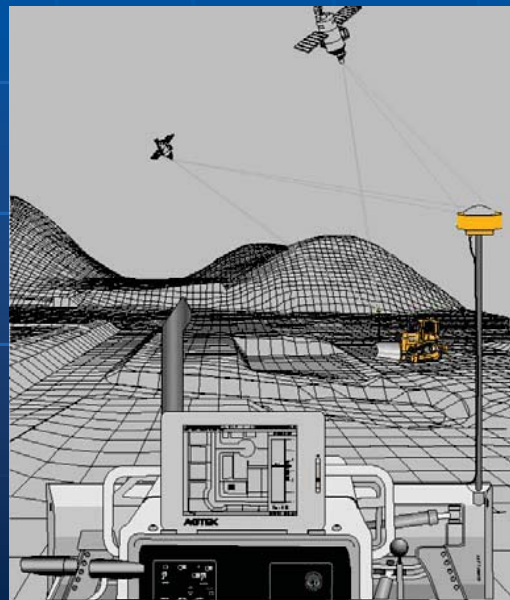



GPS
Z
Y
X
LASER SCANNER
IRS
GPS


Kriging
Multiquadratic
IGS GIM
TECU
Geomagnetic Latitude
Local Time [hours]


TRANSMAP ON-SIGHT

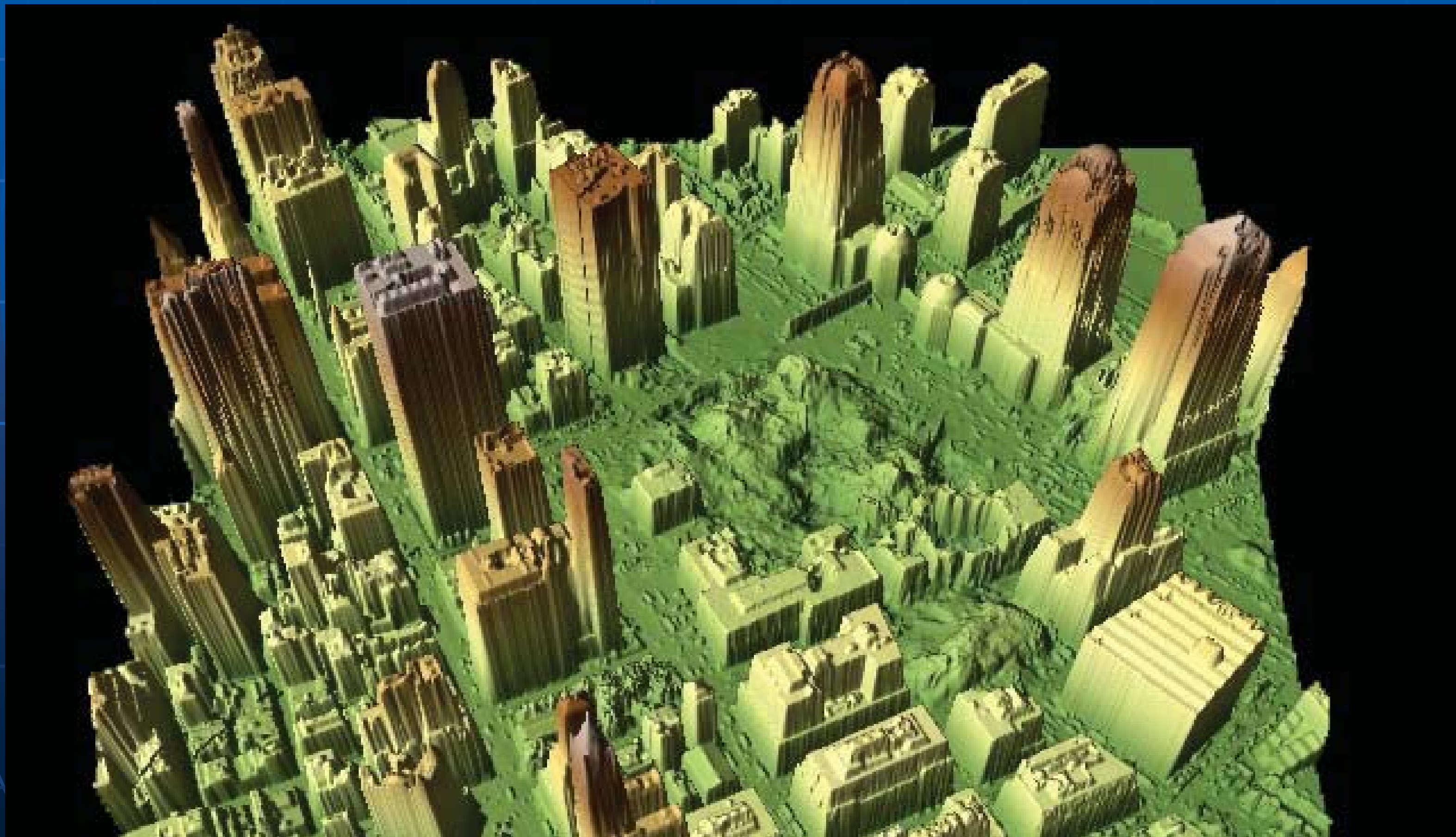





Vehicle 1

Light Detection and Ranging (LIDAR) Data

GPS and Inertial Measurement Unit (IMU) are necessary to georegister LiDAR data



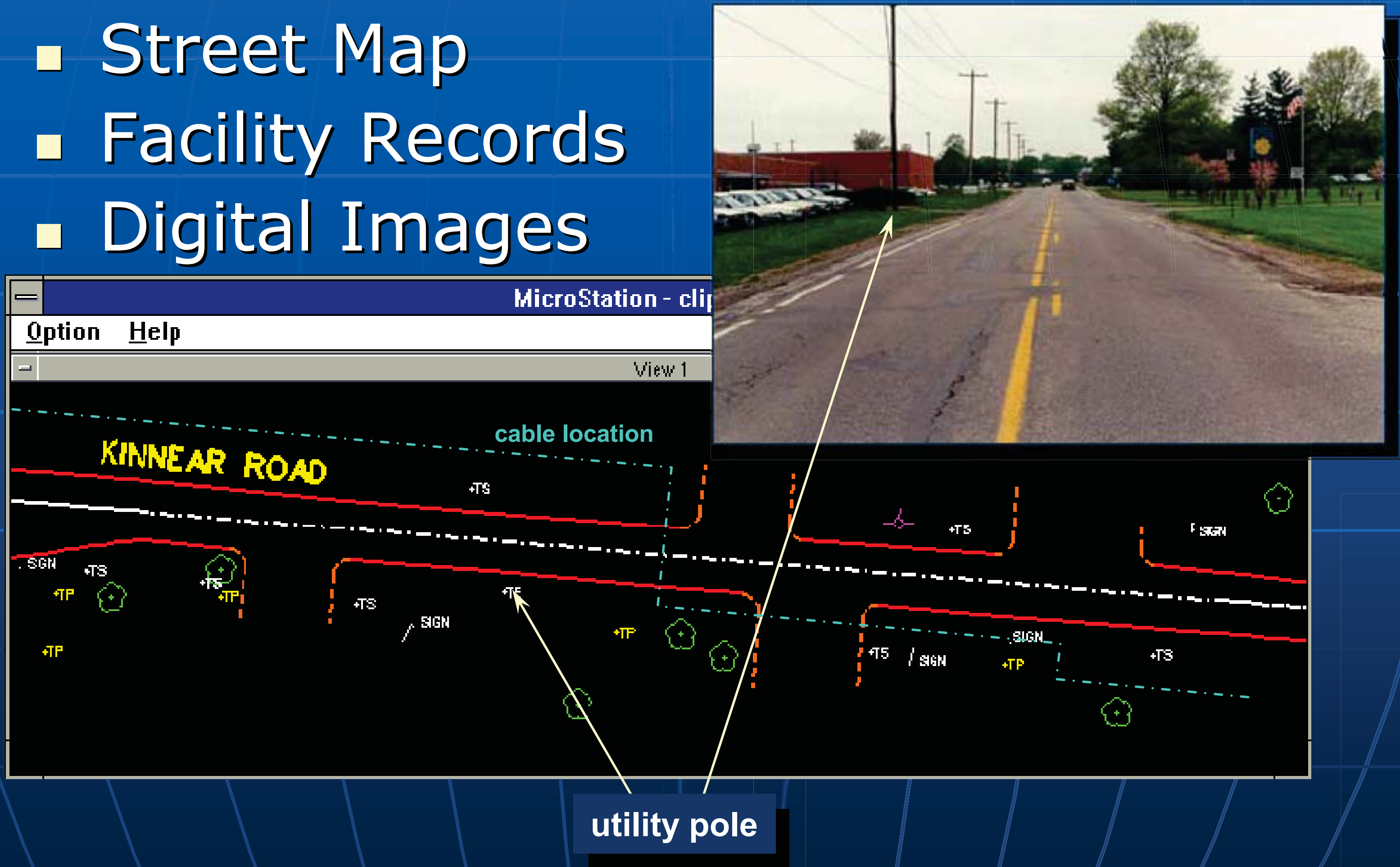
Mobile Mapping System (MMS)

Utility Pole Inventory

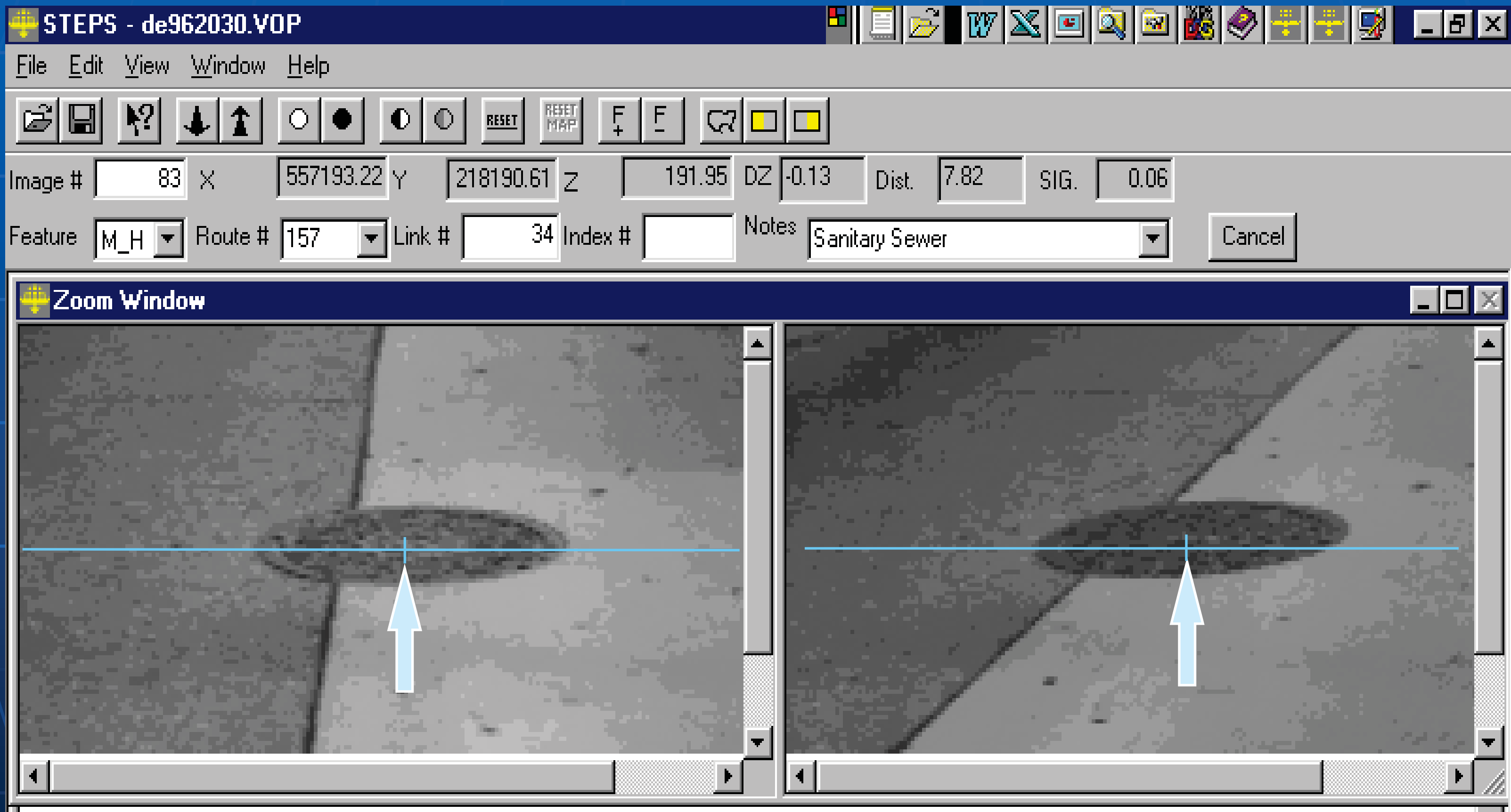
- type of pole
- height of conductors
- offset between cables
- coordinate locations
- image of feature

Visual Management of Assets

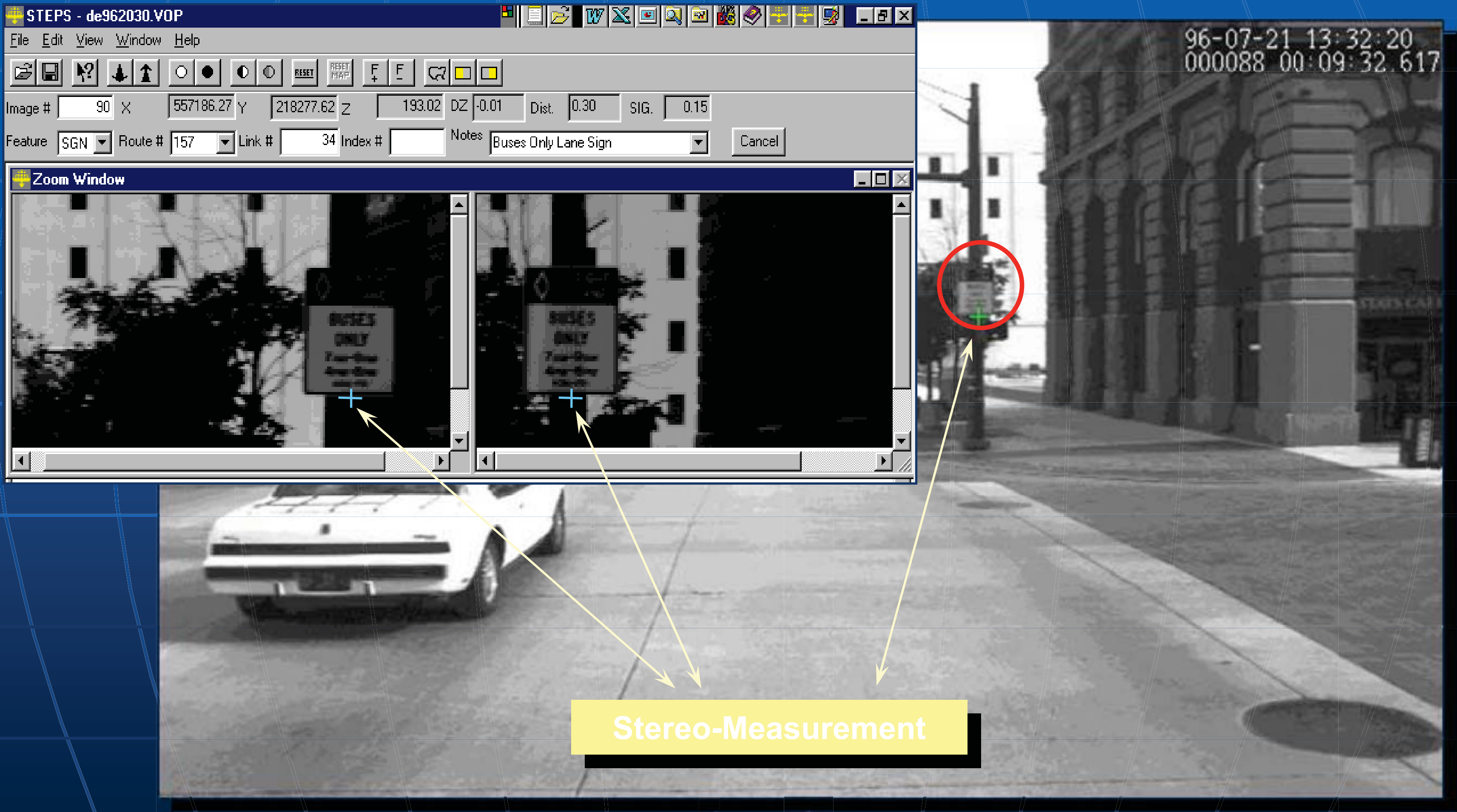
- Street Map
- Facility Records
- Digital Images



Asset Location & Inventory



STEreo Positioning System™



Newest MMS for ODOT: centerline mapping

MMS for Mapping the Highway Linear Features

- Designed for a high-accuracy near real-time mapping of highway centre and edge-lines, for ODOT
- Single down-looking camera
  - ✓ color digital, Pulnix TMC-6700, based on 644 by 482 CCD, with an image acquisition rate of up to 30 Hz (10 Hz currently used)
  - ✓ Consecutive time-offset images form a stereo pair
- Near real-time image processing supported by navigation data (under implementation)
- Post processing of GPS/INS data to refine the image orientation data

Sensor Configuration

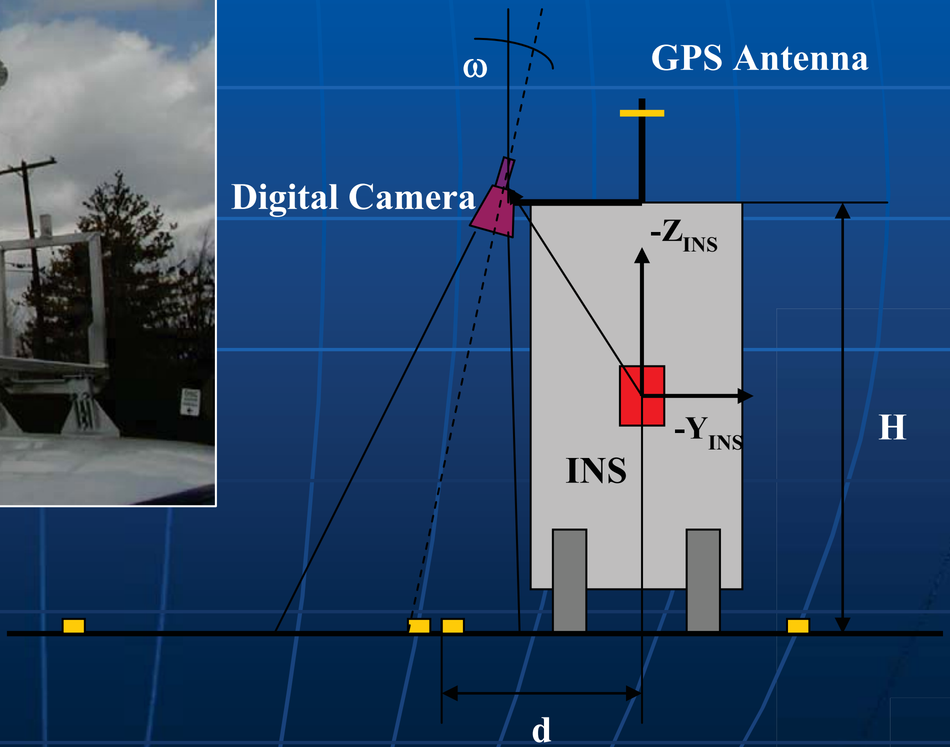
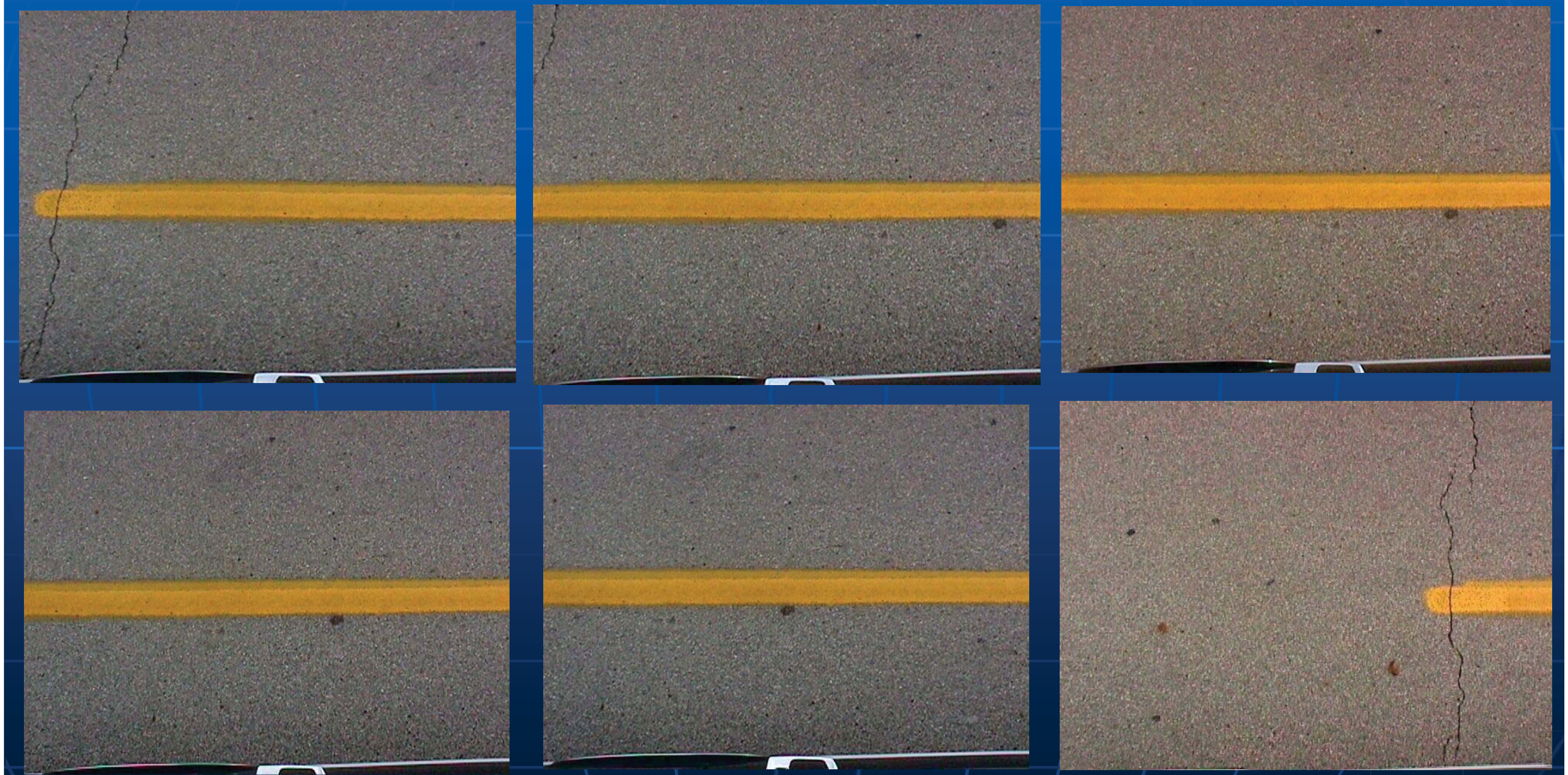


Image Sequence

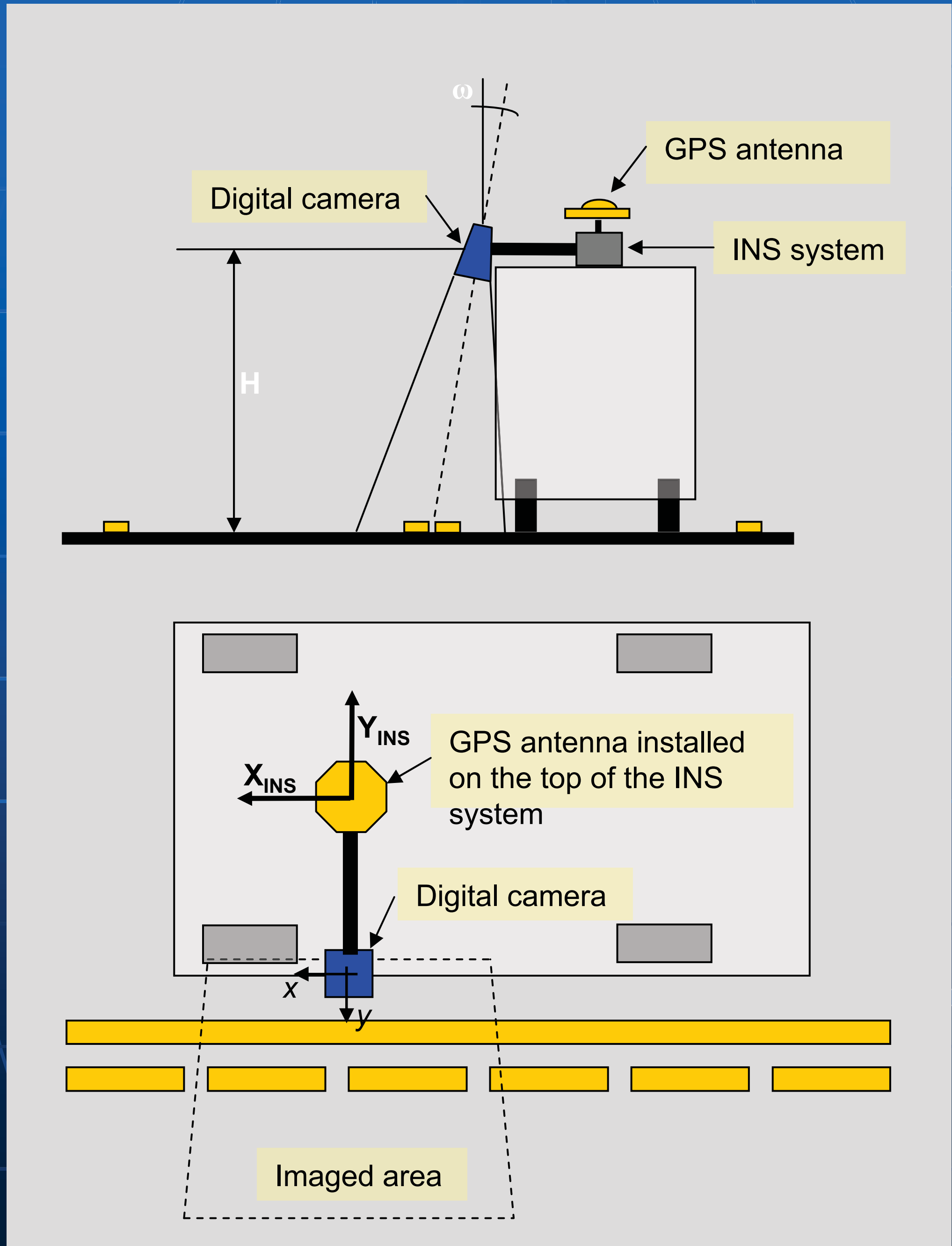




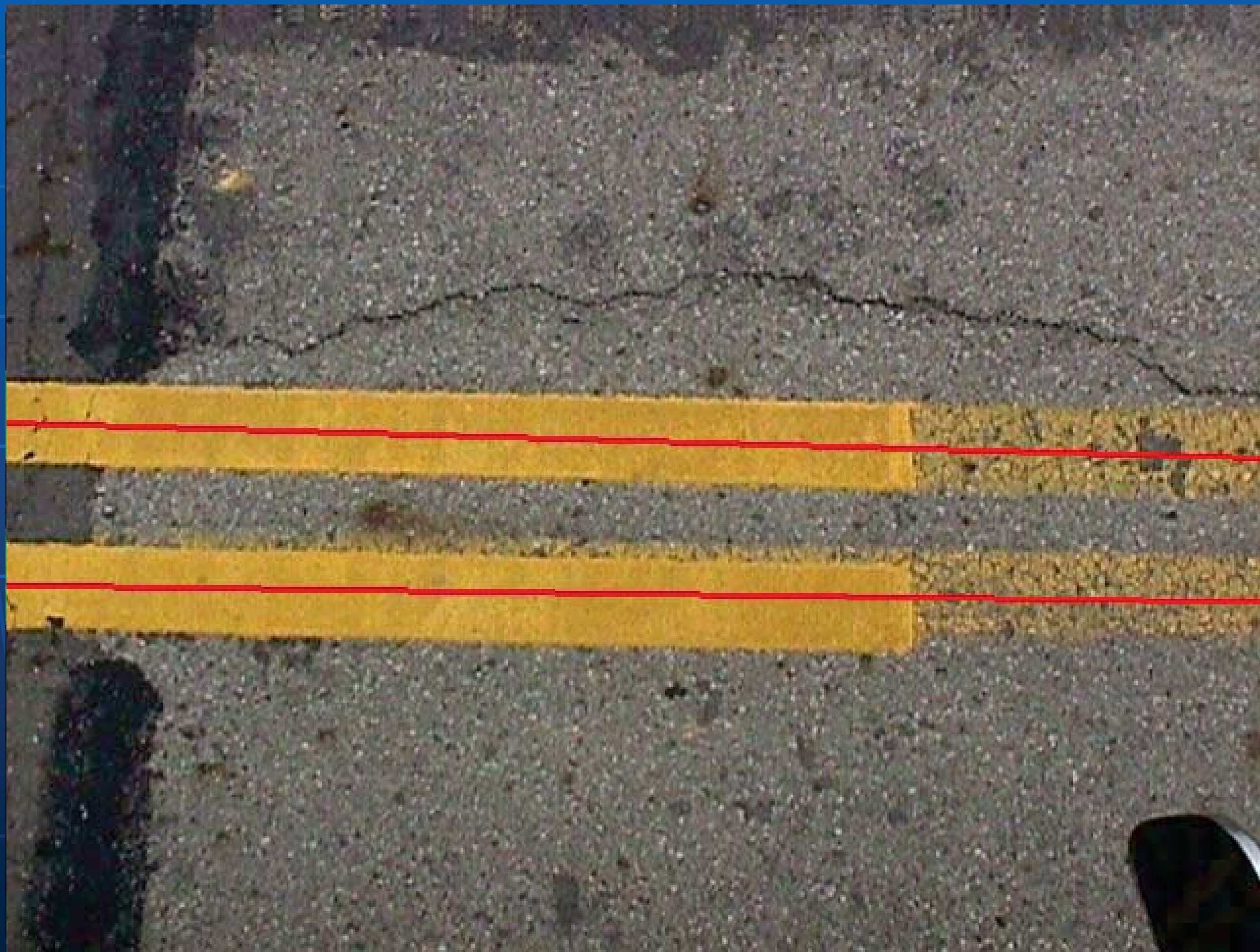




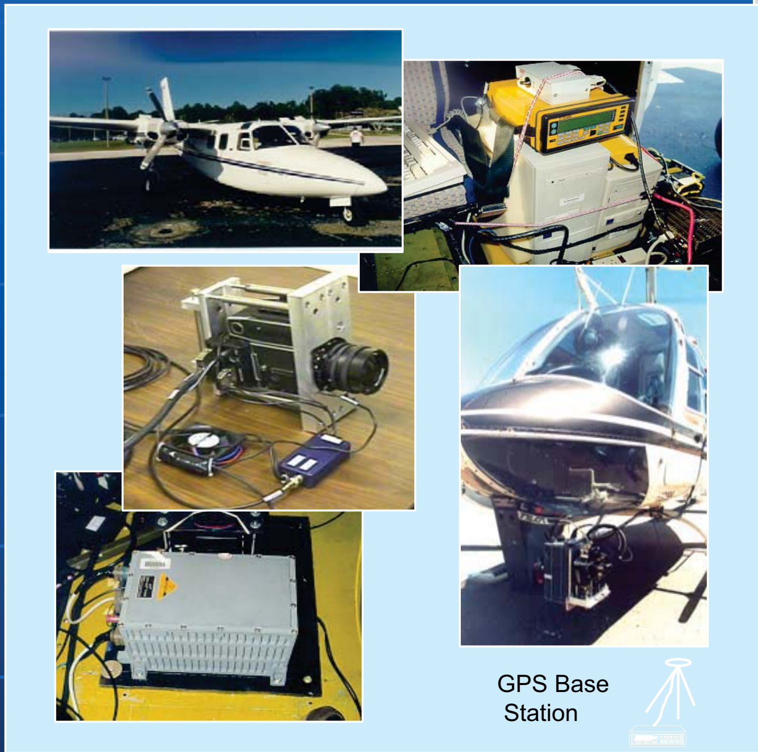




ω
GPS antenna
Digital camera
INS system
H
Y_{INS}
X_{INS}
GPS antenna installed on the top of the INS system
Digital camera
x
y
Imaged area

Centerline Extraction



Airborne Integrated Mapping System
AIMS™



AIMS™ Characteristics

- Fully digital airborne data acquisition system
- Single high-resolution imaging sensor
- Direct platform orientation by tightly coupled GPS/INS
- Typical fit to ground truth
  - 2-30 cm for flying height of ~ 300m

AIMS™ Applications

- Large-scale topographic mapping
- Corridor surveys of the transportation infrastructures
- Military reconnaissance
- Potential for real-time applications

New capabilities →

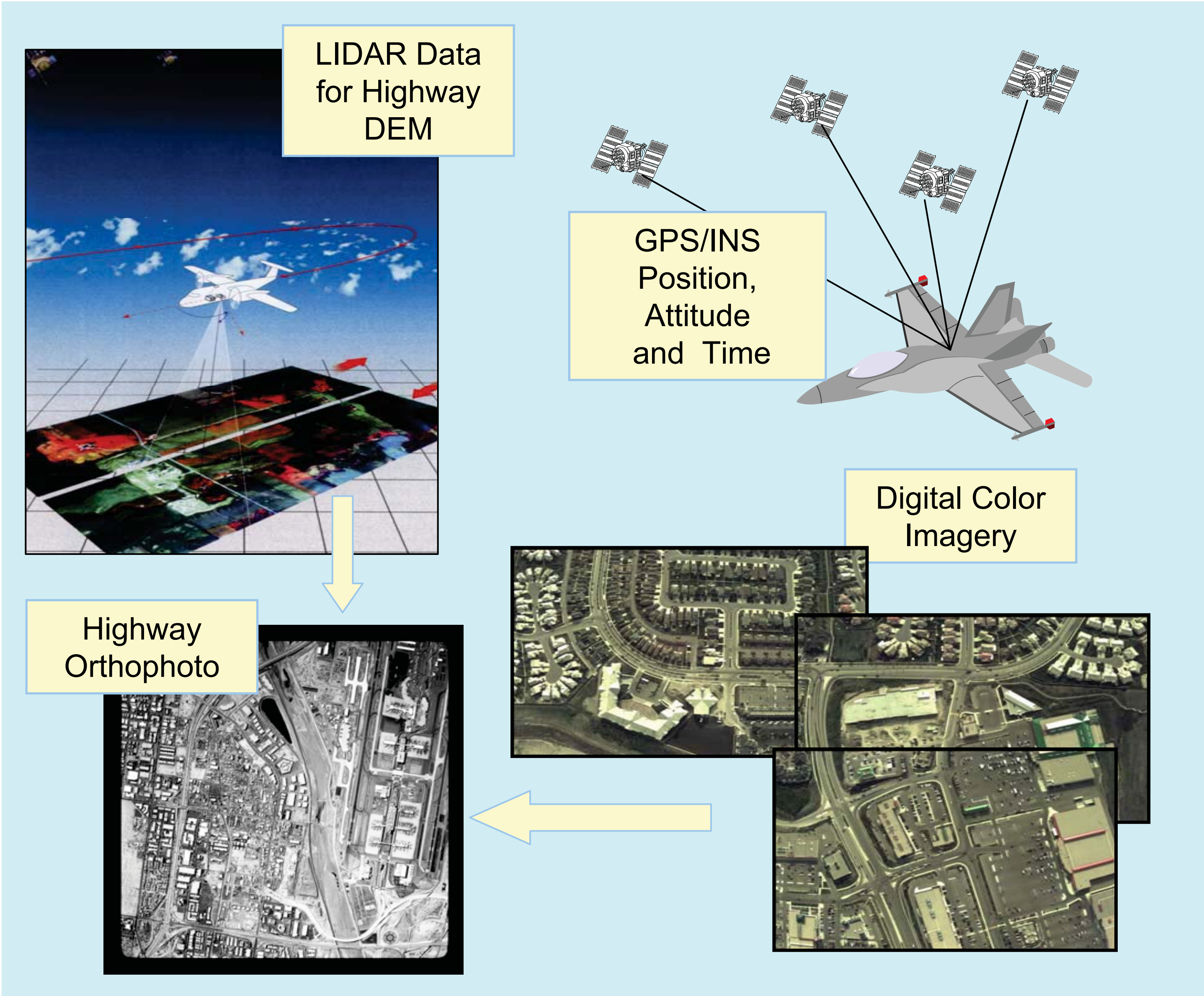
Near real-time processing power

High quality direct georeferencing and timing

Better and faster sensors

New sensors (LiDAR)

Multi-sensor fusion
New applications


LIDAR Data
for Highway
DEM
GPS/INS
Position,
Attitude
and Time
Digital Color
Imagery
Highway
Orthophoto

Enabling technological developments

GPS/INS-based direct georeferencing

Digital sensor/camera developments

Improved LIDAR electronics

Real-time processing capability

↓

Affordable mapping technology

Higher flying height

Increased data rate

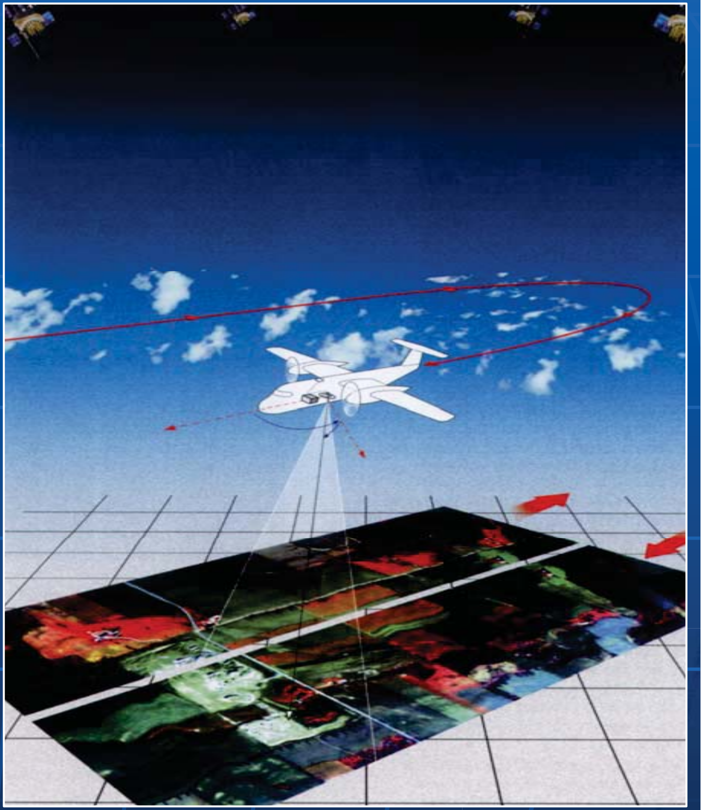
All-digital system design

↓

Sensor integration/Data fusion

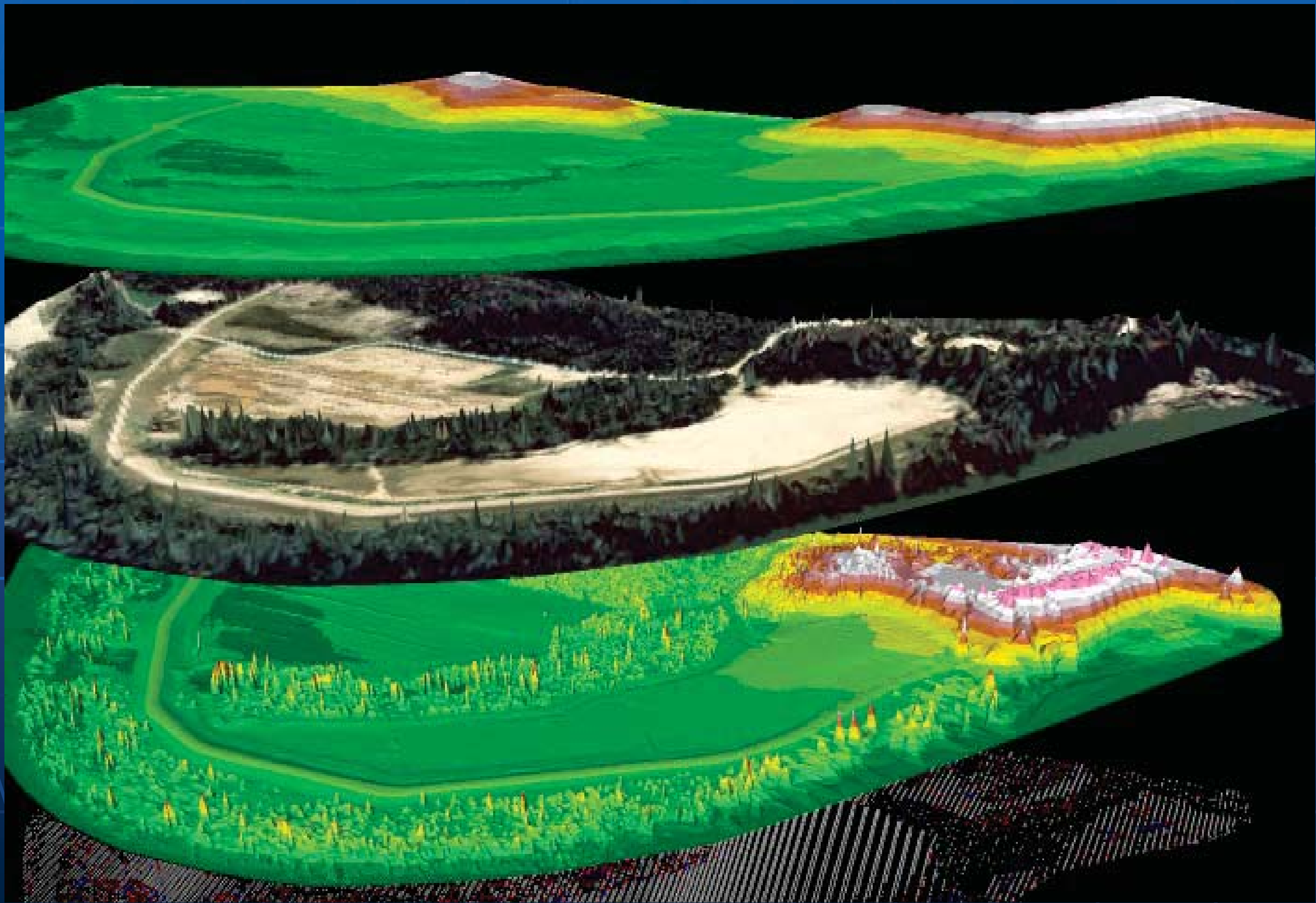
Vehicle Motion Between the Images

LIDAR: Light Detection and Ranging



- Scanning system, using a laser ranging device to measure a range to a target with the accuracy better than 5 cm
- The airborne laser data form 3D point clusters or lines, where the elevation has a unique value as a function of the horizontal location
- Requires direct orientation by GPS/INS
- Experimental applications of Airborne Laser Ranging (ALR) date back to the 1970s and 1980s
- First introduced to the mapping community - about a decade ago

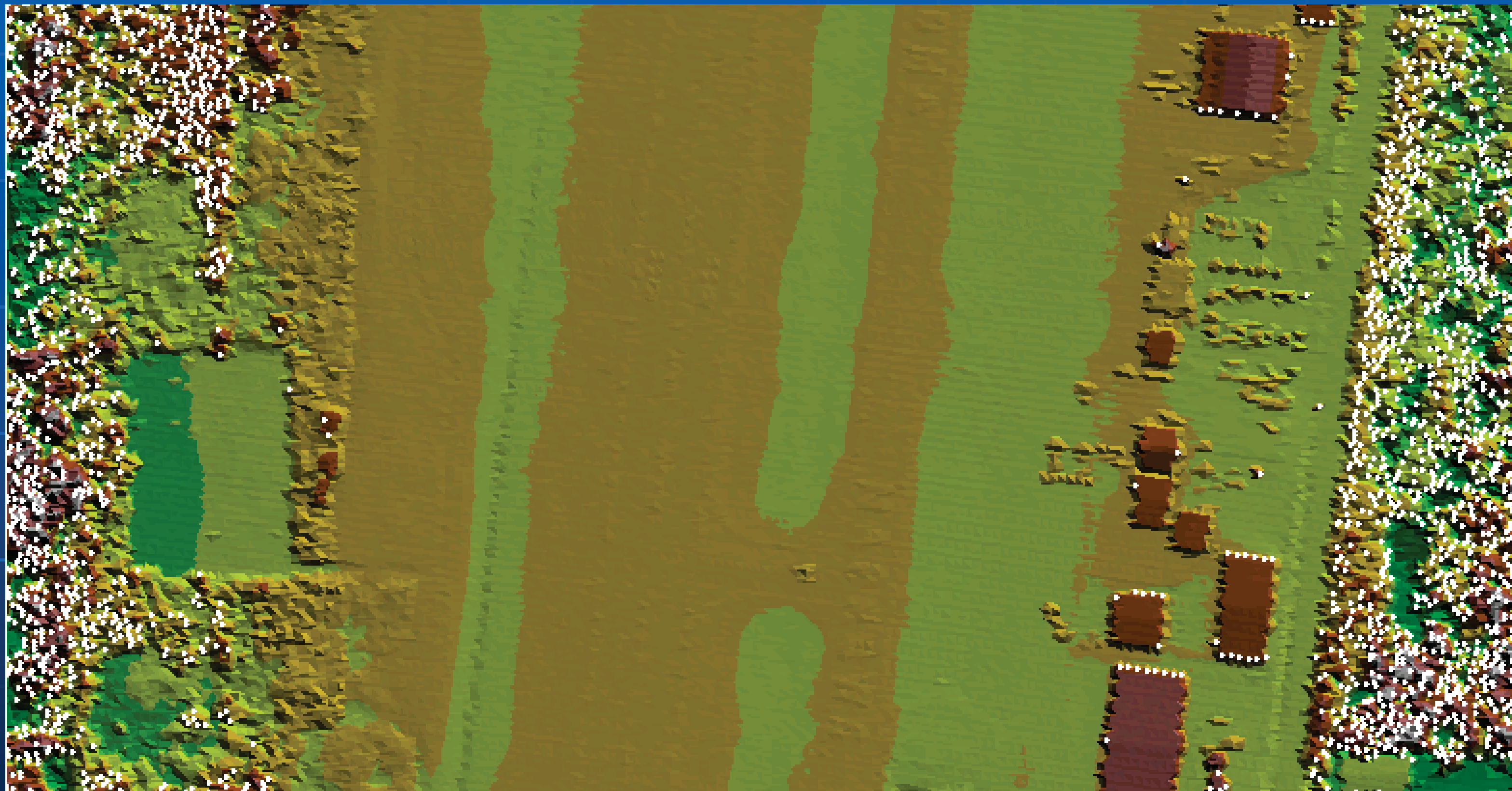
LIDAR DEM



Courtesy of EathData Technologies

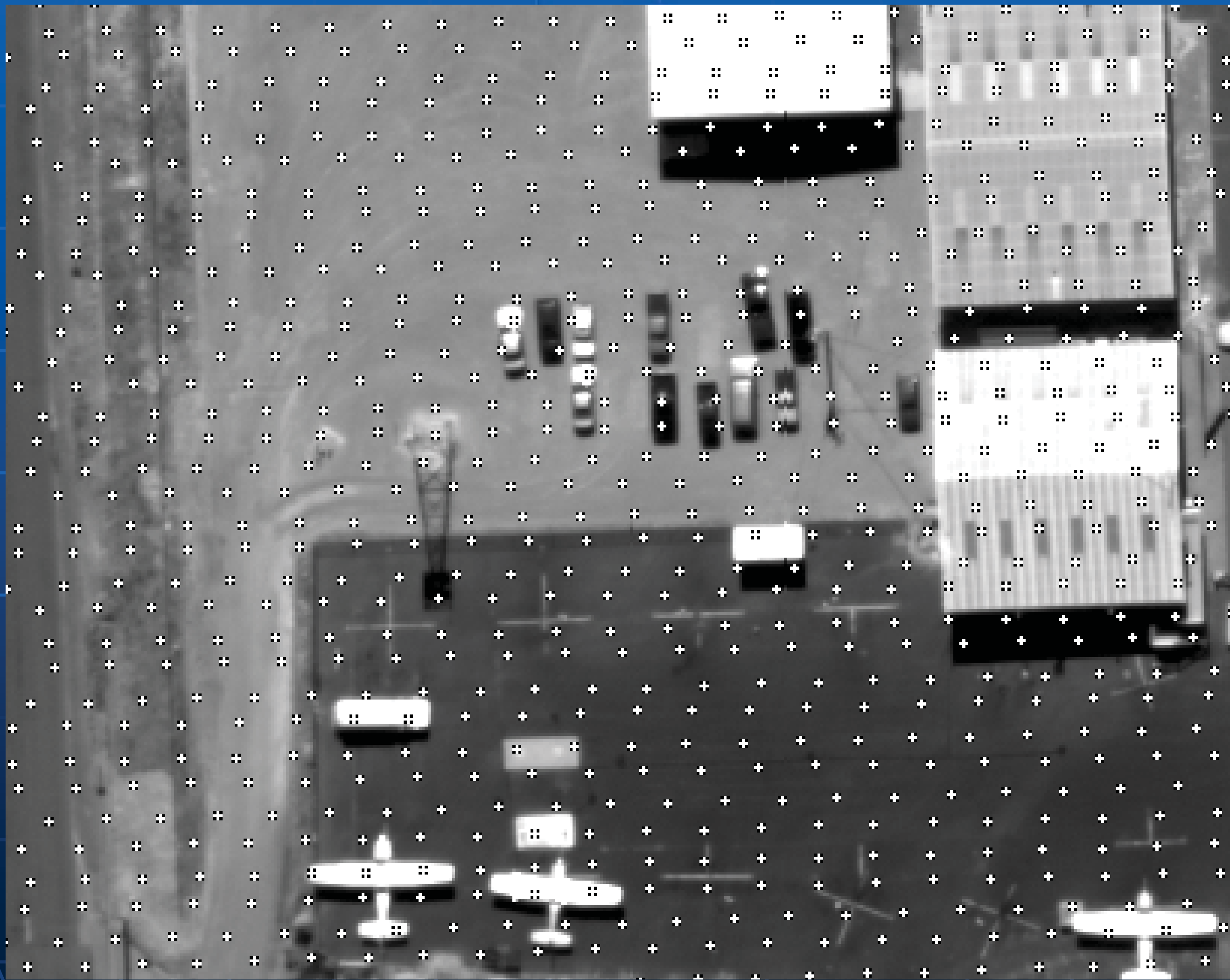
DEM – Digital Elevation Model

Multiple returns

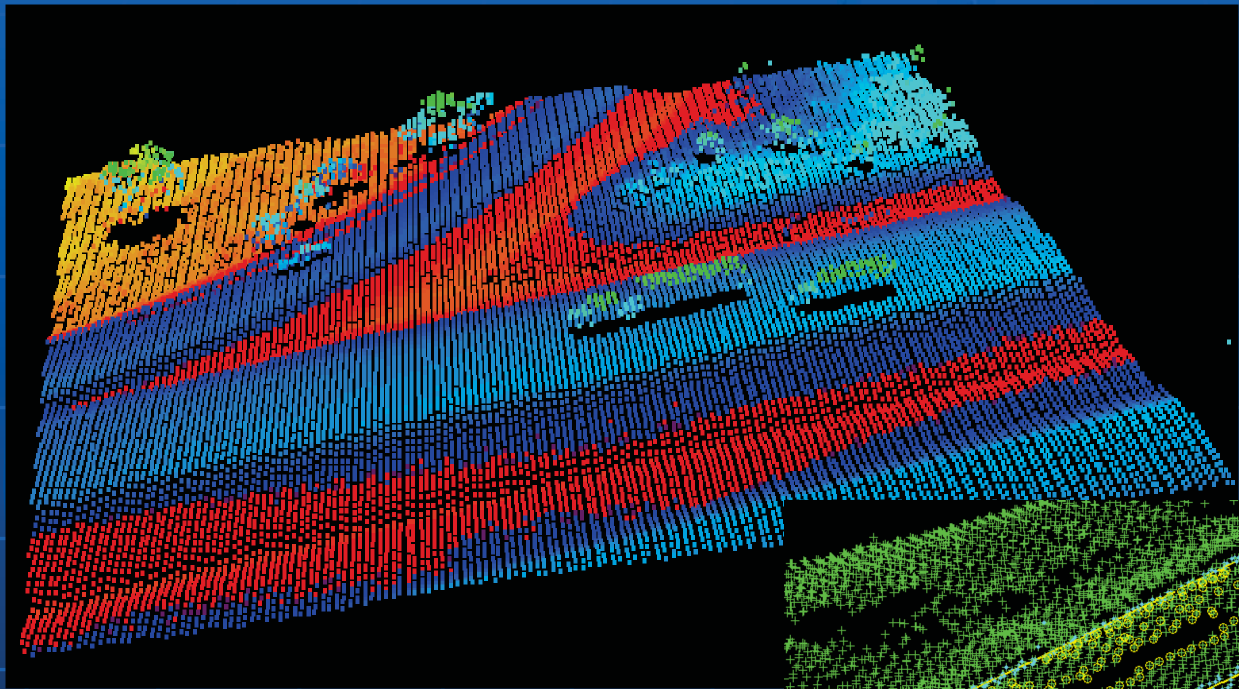


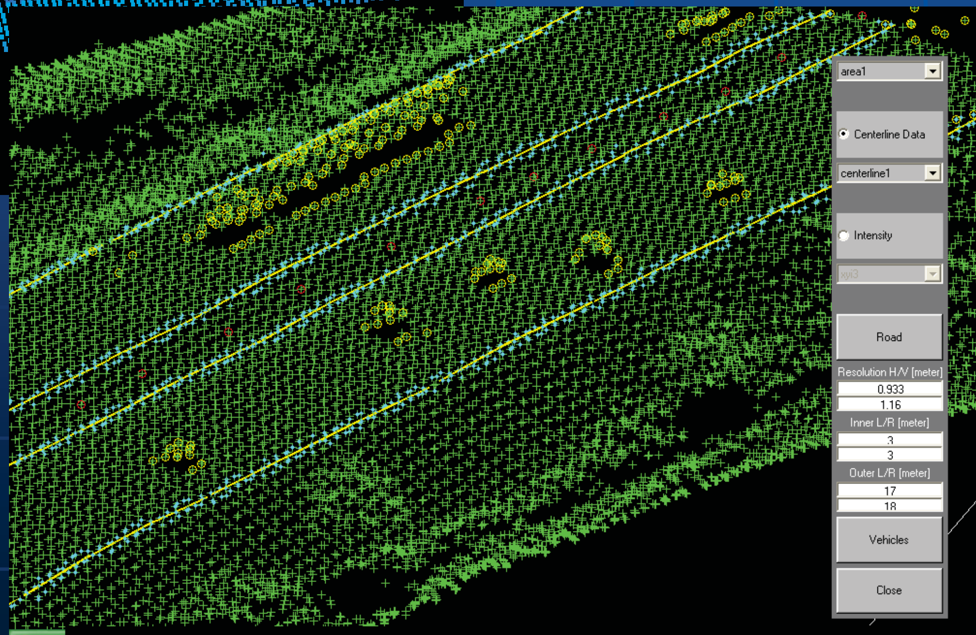
- \- **multiple returns**

LIDAR spots and image background

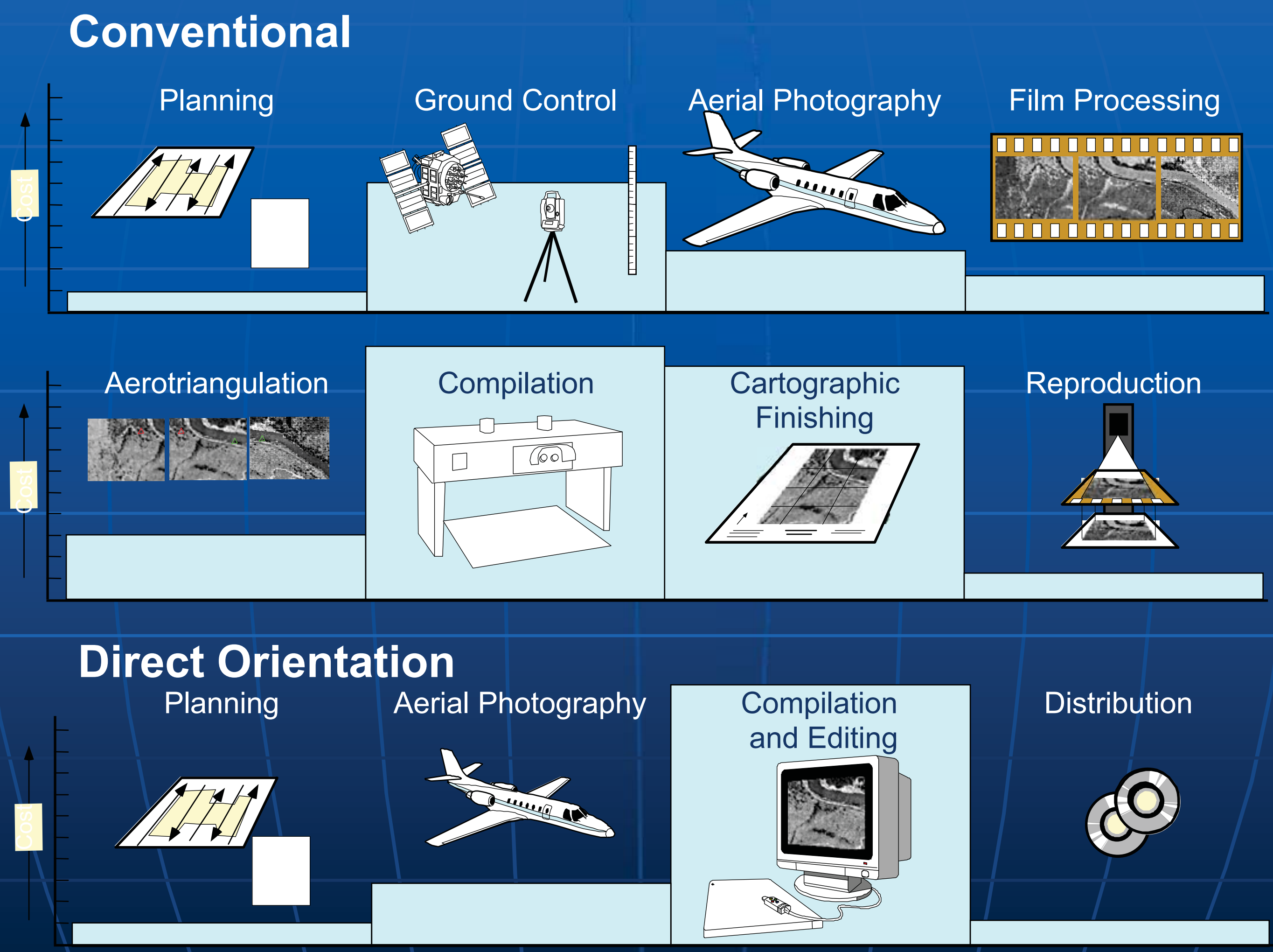


Sample LiDAR data: transportation





A Comparison of Mapping Scenarios

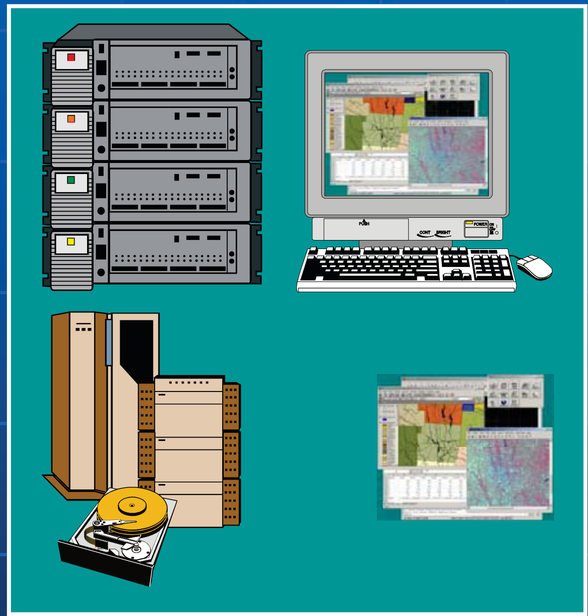


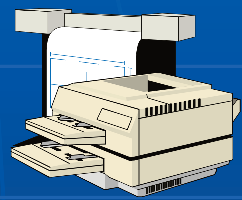
Geographic Information Systems

- Computer based system of layers (themes) of spatially-related information (common geographic reference framework
- Applications:
  - Natural resource management
  - Facilities siting & management
  - Land records modernization
  - Demographic & market analysis
  - Emergency response & fleet operations
  - Regional, national & global environmental monitoring

Geographic Information Systems

Input | **Management & Analytical Modules** | **Output**





Data Acquisition
- Global Positioning
- Remote Sensing
- Field Observations

Analog Data Conversion
- Scan
- Digitize

Management
- Data Storage
- Data Retrieval, Expand Edit, and Update
- Query

Analytical Modules
- Data Conversion
- Data Manipulation
- Modeling

Data Output
- Visual Presentation
- Analog Map Output
- Reports

Modern trends in mapping

Disaster management: societal changes

- Defense
  - Increased sensitivity to personnel life – use robots as soldiers (30% within the next decade)
  - War theater: training (simulations) or in situ
    - Up-to-date spatial data needed

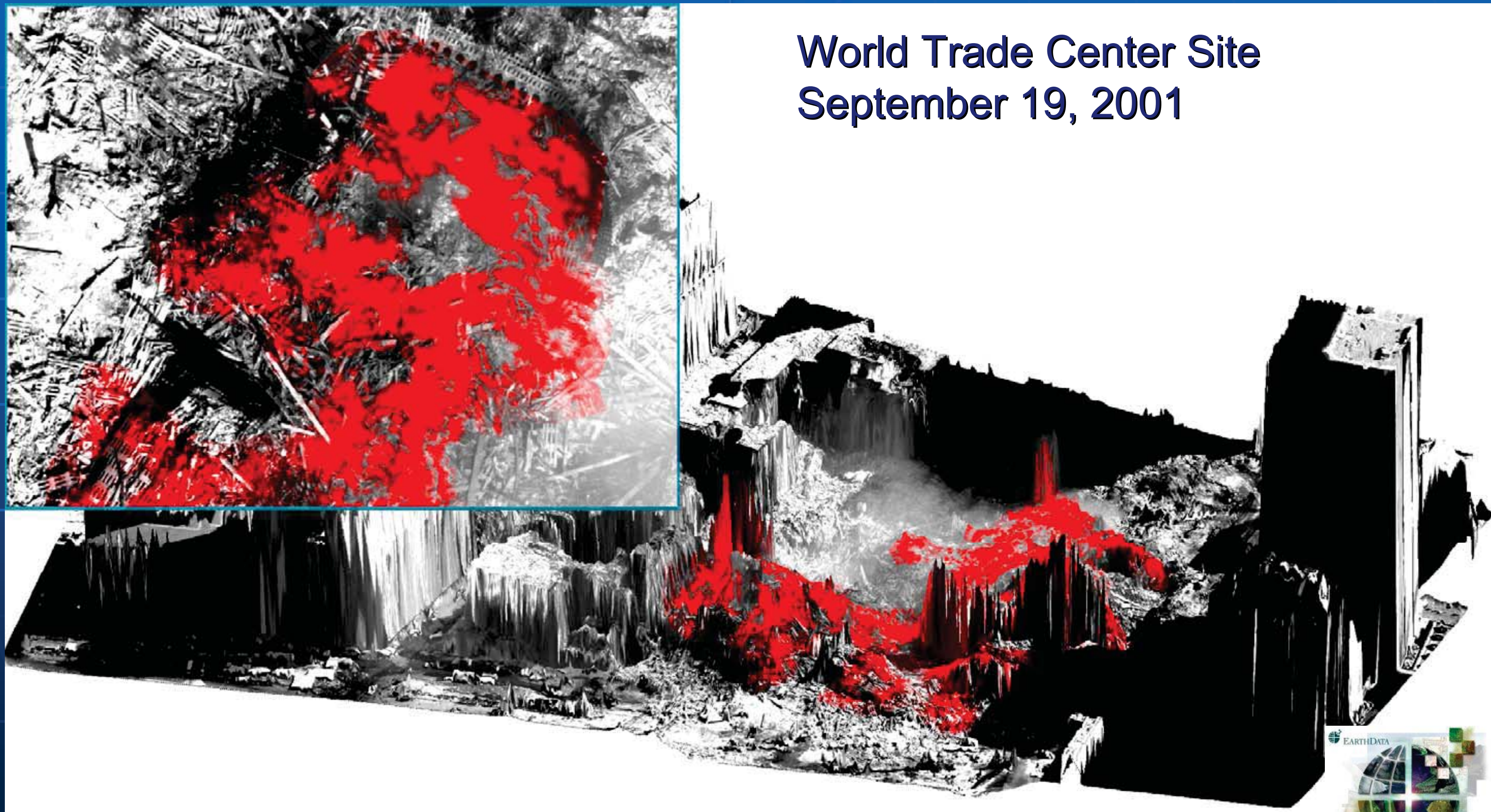
- Natural disasters
  - Improving prediction models needs up-to-date spatial data (sustained data acquisition)
  - If disaster struck, rapid mapping of the affected areas is needed to support rescue operations

- Terrorist threat to civilians
  - Increased demand for security requires better geolocation and tracking capabilities
  - Growing need for indoor/outdoor map data

Disaster management: societal changes

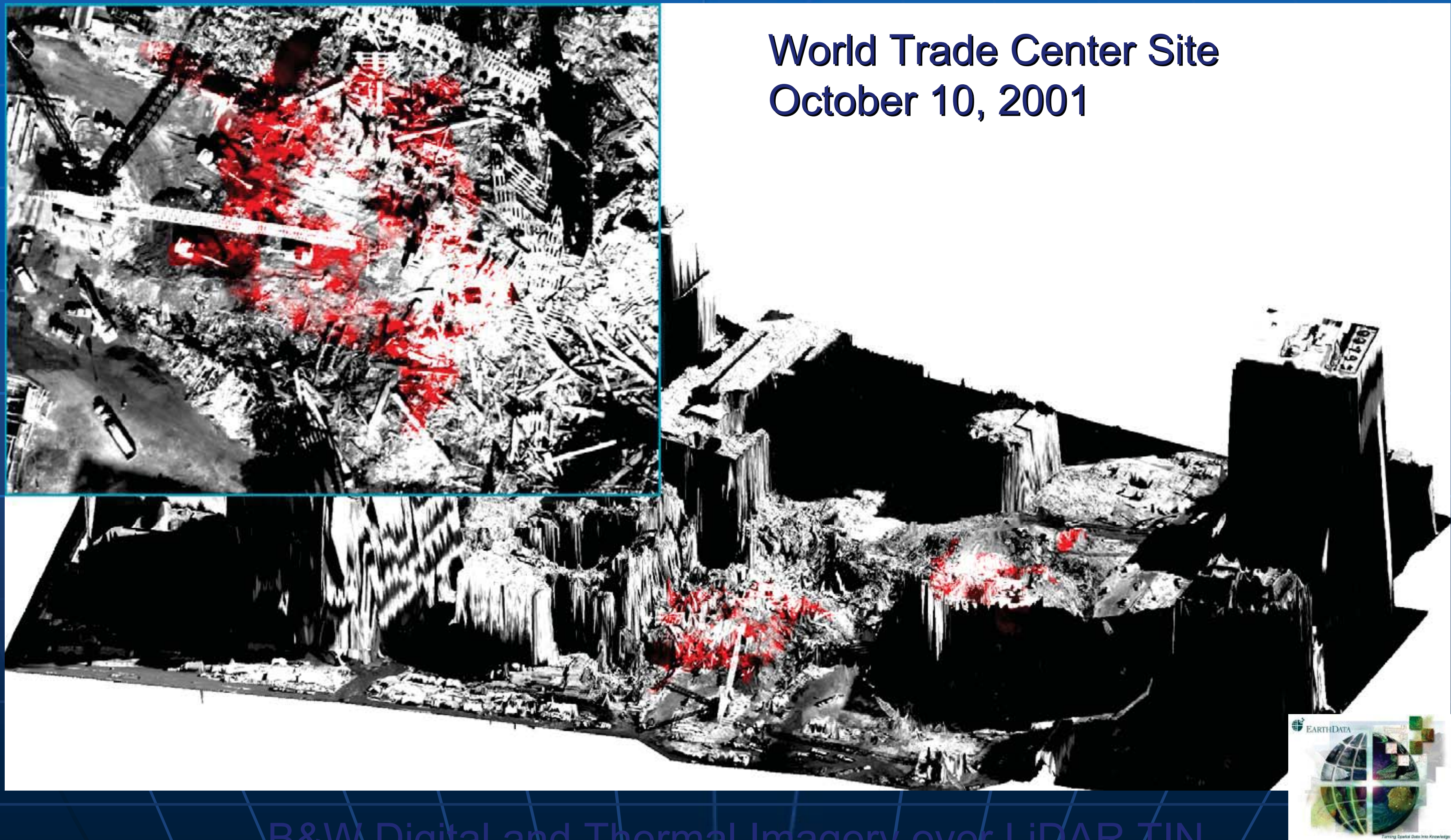
*Supporting **urgent needs** for imaging, mapping, and GIS*

Disaster management: Ground Zero



B&W Digital and Thermal Imagery over LiDAR TIN

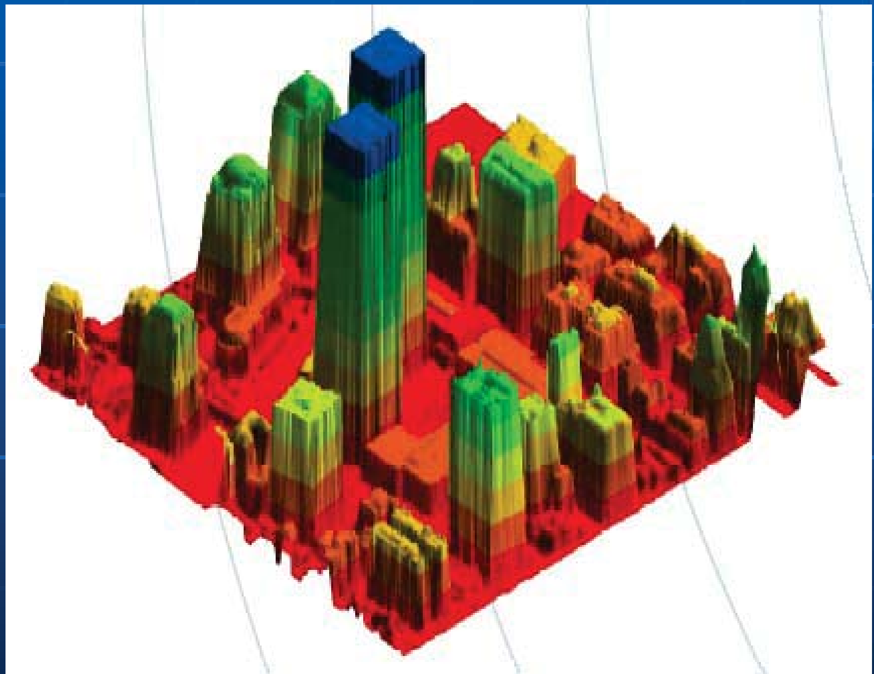
Disaster management: Ground Zero

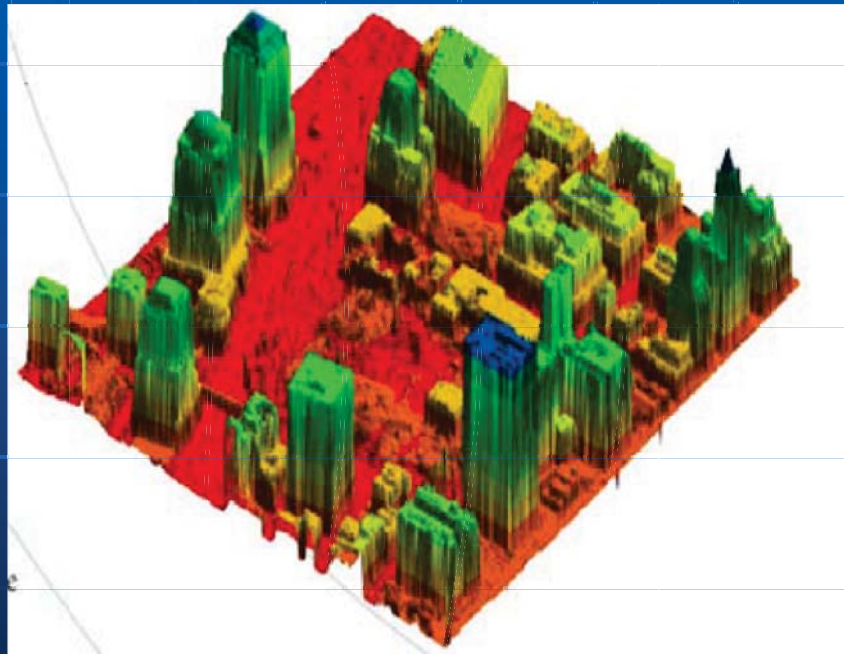


World Trade Center Site
October 10, 2001

B&W Digital and Thermal Imagery over LiDAR TIN

Disaster management: Ground Zero





Towards rapid mapping

- **Time elapsed between data acquisition and final mapping product**
  - Analog camera, aerial triangulation, map compilation, cartographic finishing, hardcopy — 6 months
  - Digital camera, LiDAR and GPS/IMU-based georeferencing, digital product preparation — 2-4 weeks
  - 9/11 Emergency Mapping by EarthData Group — 6-12 hours
  - Demonstration of ARIES (Airborne Rapid Imaging for Emergency Support) by various government agencies and EarthData Group — 1-2 hours

- **Autonomous platforms**
  - Airborne systems already exist – UAVs (difficult)
  - Land-based systems – Autonomous Vehicle Navigation (extremely difficult)

Airborne Rapid Imaging for Emergency Support – ARIES

1.25 Gb/s wireless link

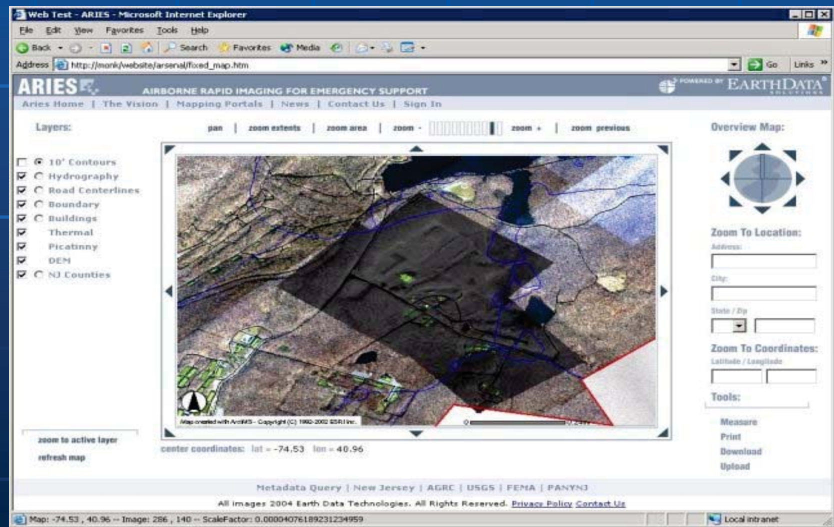
UHF, VHF, Video (YV) Links

Data

- **Optical Imagery**
- **Thermal imagery**
- **LiDAR**
- **GPS-IMU data**

Products

- **DEM**
- **Orthos**



Web-based Dissemination

PDA with GPS Tracking

Computer Systems

GPS Techniques Used in Mapping and Surveying

and

Their Accuracy Standards

GPS Data

- **Data File**
  - range (pseudorange) measurement
    - C/A code on L1 (and on L2 in Block IIR-M)
    - P(Y) code on L1 and L2
  - carrier phase on L1 and L2,
  - range rate (Doppler)

- **Navigation Message** (broadcast ephemeris) - provides information about satellite orbits, time, clock errors and ionospheric model to remove the ionospheric error from pseudorange observations

- ***Provided in binary-receiver dependent format***

- Usually converted to **RINEX** - Receiver Independent Exchange format (ASCII file)

GPS Navigation Message (RINEX)

```
 2              NAVIGATION DATA                                   RINEX VERSION / TYPE
DAT2RIN 1.00e       The Boss            29JUN98 17:59:25 GMT PGM / RUN BY / DATE
                                                                  COMMENT
    .1118D-07   .0000D+00  -.5960D-07   .0000D+00                             ION ALPHA
    .9011D+05   .0000D+00  -.1966D+06   .0000D+00                             ION BETA
   -.142108547152D-13 -.372529029846D-08    61440      159   DELTA-UTC: A0,A1,T,W
      12                                                          LEAP SECONDS
                                                                  END OF HEADER
 3 97 10 10 18  0  0.0  .605774112046D-04  .352429196937D-11  .000000000000D+00
    .760000000000D+02  .494687500000D+02  .448018661776D-08  .220198356145D+00
    .264309346676D-05  .244920048863D-02  .842288136482D-05  .515366117668D+04
    .496800000000D+06  .335276126862D-07 -.790250226717D+00 -.372529029846D-07
    .951777921211D+00  .211531250000D+03  .259765541557D+01 -.819891294621D-08
    .160720980388D-10  .100000000000D+01  .926000000000D+03  .000000000000D+00
    .700000000000D+01  .000000000000D+00  .139698386192D-08  .588000000000D+03
    .490320000000D+06
 6 97 10 10 15 59 44.0 -.358093529940D-06  .000000000000D+00  .000000000000D+00
    .220000000000D+02  .526250000000D+02  .438268255632D-08 -.281081720890D+00
```

GPS Observation File Header (RINEX)

```
 2                    OBSERVATION DATA                          RINEX VERSION / TYPE
DAT2RIN 1.00e         The Boss      29JUN98 17:59:19 GMT                 PGM / RUN BY / DATE
Mickey Mouse          CFM                                                OBSERVER / AGENCY
5137                            TRIMBLE 4000SSI    Nav 7.25 Sig 3. 7              REC # /
TYPE / VERS
0                     4000ST L1/L2 GEOD                                  ANT # / TYPE
____0001                                                                 MARKER NAME
____0001                                                                 MARKER NUMBER
  557180.9687 -4865886.9211  4072508.3413                                APPROX POSITION
XYZ
    0.0000       0.0000       0.0000                        ANTENNA: DELTA H/E/N
    1    1    0                                             WAVELENGTH FACT L1/2
    4   L1    C1    L2    P2                                 # / TYPES OF OBSERV
    1                                                       INTERVAL
 1997    10    10    15    13    5.000000                   TIME OF FIRST OBS
 1997    10    10    16    38    8.000000                    TIME OF LAST OBS
   8                                                        # OF SATELLITES
   3  1598  1603  1504  1504                                PRN / # OF OBS
   6  4051  4051  4051  4051                                PRN / # OF OBS
   9  4208  4212  4150  4150                                PRN / # OF OBS
  ………………………… (rest of the SV is given here)……………………………………        PRN / # OF OBS
                                                            END OF HEADER
```

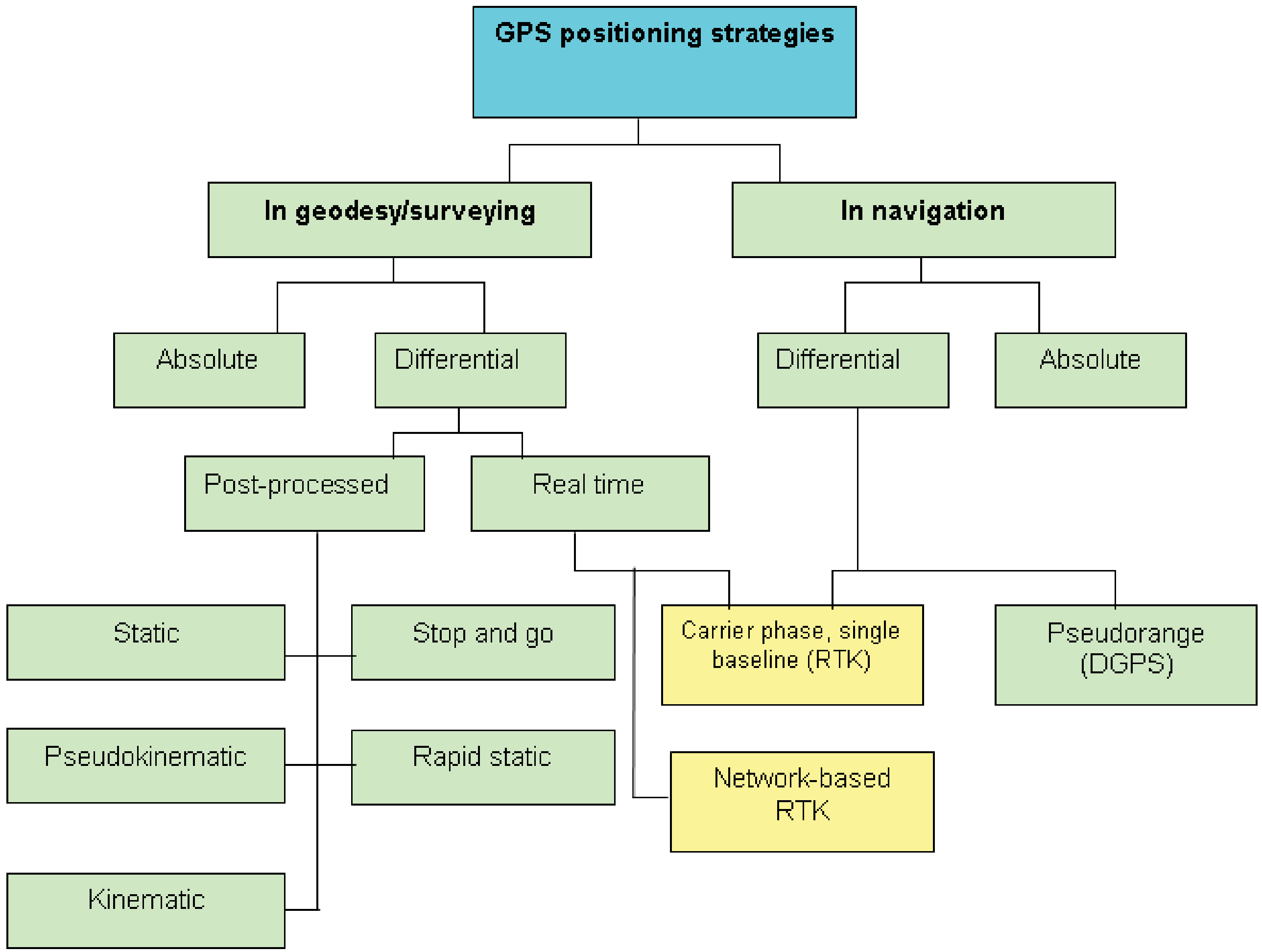
GPS Observation File (RINEX)

```
 97 10 10 15 13  6.000  0  5  6 10 17 23 26                  0.000215178
  -331628.90610  21627234.69600   -258412.19950  21627239.86440
  -330564.59210  23839375.76600   -264155.63150  23839382.29440
  -344922.28510  20838559.61800   -268770.84150  20838564.48140
  -344734.12710  22476960.02400   -268624.54850  22476965.59140
  -338016.17810  20319996.64100   -263389.71350  20320000.46240
 97 10 10 15 13  7.000  0  5  6 10 17 23 26                  0.000215197
  -329205.73500  21627695.91400   -256524.01640  21627700.98840
  -327788.16700  23839904.12500   -261992.18640  23839909.89140
  -346924.68000  20838178.43000   -270331.14940  20838183.24640
  -346674.25800  22476590.73400   -270136.33740  22476596.25440
  -337719.08000  20320053.10100   -263158.20940  20320056.88740
 97 10 10 15 13  8.000  0  5  6 10 17 23 26                  0.000215216
  -326782.19000  21628157.18700   -254635.54040  21628162.34340
  -325011.83600  23840432.60100   -259828.81640  23840438.14440
  -348926.80400  20837797.46000   -271891.24440  20837802.31240
  -348614.34600  22476221.42900   -271648.09340  22476226.99540
  -337421.42500  20320109.74100   -262926.27040  20320113.51540
```

.... continues

RINEX 2 description:

http://www.ngs.noaa.gov/CORS/Rinex2.html


GPS positioning strategies
In geodesy/surveying
In navigation
Absolute
Differential
Differential
Absolute
Post-processed
Real time
Static
Stop and go
Carrier phase, single baseline (RTK)
Pseudorange (DGPS)
Pseudokinematic
Rapid static
Network-based RTK
Kinematic

GPS Techniques Used in Surveying and Mapping

- Differential Static
  - Most accurate, centimeter or better
  - Requires long observation times (several hours)

GPS Techniques Used in Surveying and Mapping

- Differential Kinematic
  - Sampling rates up to 10Hz
- Differential Stop & Go
  - Collection times: 1 to 3 min
- Differential Rapid-static
  - Collection times: 10 to 20 min
- Achievable accuracies
  - cm to a few cm

Surveyor on the go using RTK (real time kinematic) procedures

Benchmark Survey System

- Sub-mm GPS only survey system
  - < 0.6 mm horizontal
  - < 1.0 mm vertical
- Improvements in throughput and resources
  - Throughput up over 400%
  - Human resources requirements down over 80%

National Geodetic Survey (NGS)

GPS ACCURACY STANDARDS

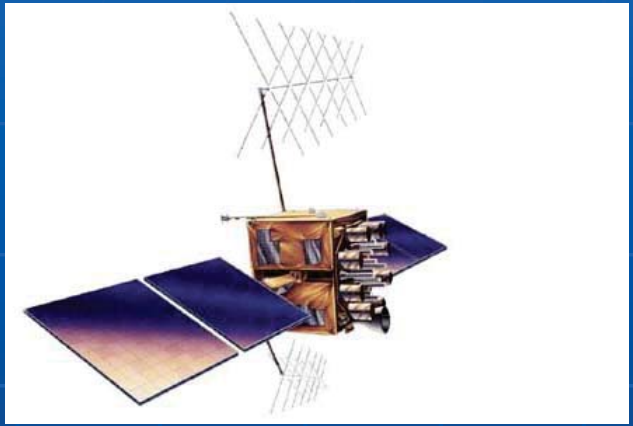
Classification	Minimum Geometric Accuracy Standard*
AA	0.3 cm + 1:100,000,000
A	0.5 cm + 1: 10,000,000
B	0.8 cm + 1: 1,000,000
First	1.0 cm + 1: 100,000
Second, Class I	2.0 cm + 1: 50,000
Second, Class I	3.0 cm + 1: 20,000
Third	5.0 cm + 1: 10,000

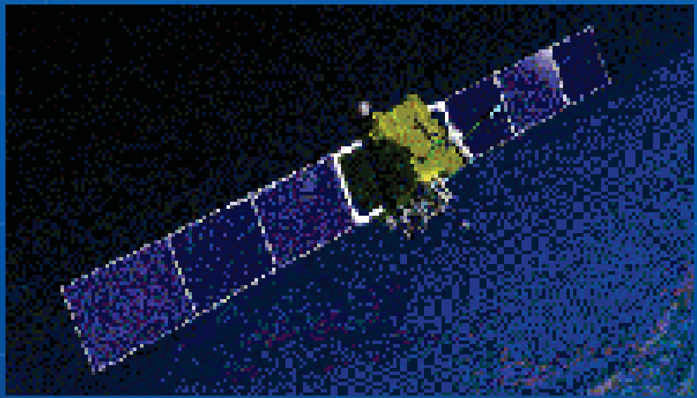
* Note: At the 95 Percent Confidence Level

Global Positioning Systems

Class AA Accuracy is achievable using post-processed static differential GPS using carrier phase measurements

Global Positioning Systems



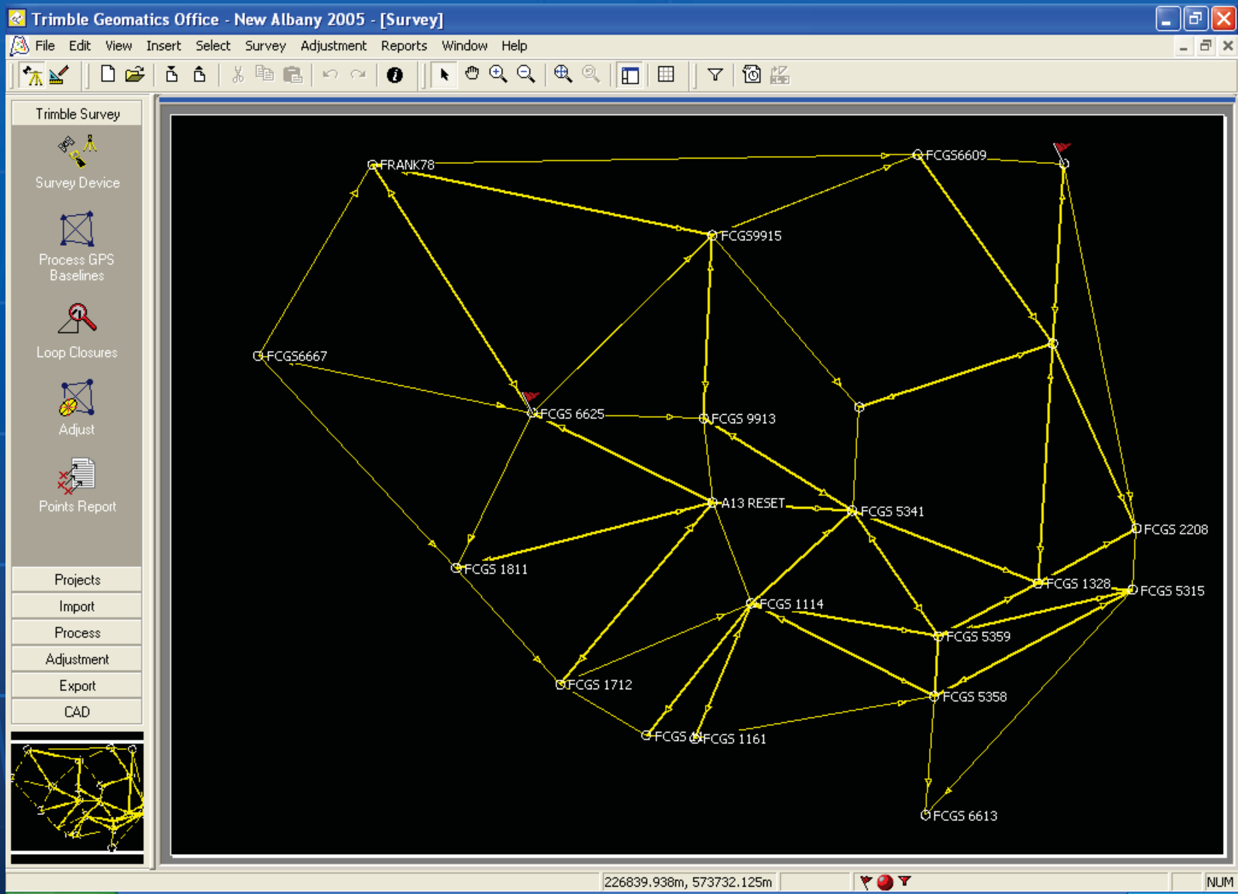


- NGS Blue Book Requirements:
  - Long observation (point occupation) times - usually 5 un-interrupted hours.
  - Observe two different GPS constellations – different day and different time of day.
  - Use NGS Software and Processing Procedures.

Global Positioning Systems

- Class B Accuracy is achievable using post-processed static differential post processing – carrier phase observations with 45 minute observation times.
- Usually two occupations of each point are recommended.

Global Positioning Systems



Static GPS Surveying – leapfrog technique.
Typically 3 units are used.
Used to establish high positional accuracy points.

Global Positioning Systems

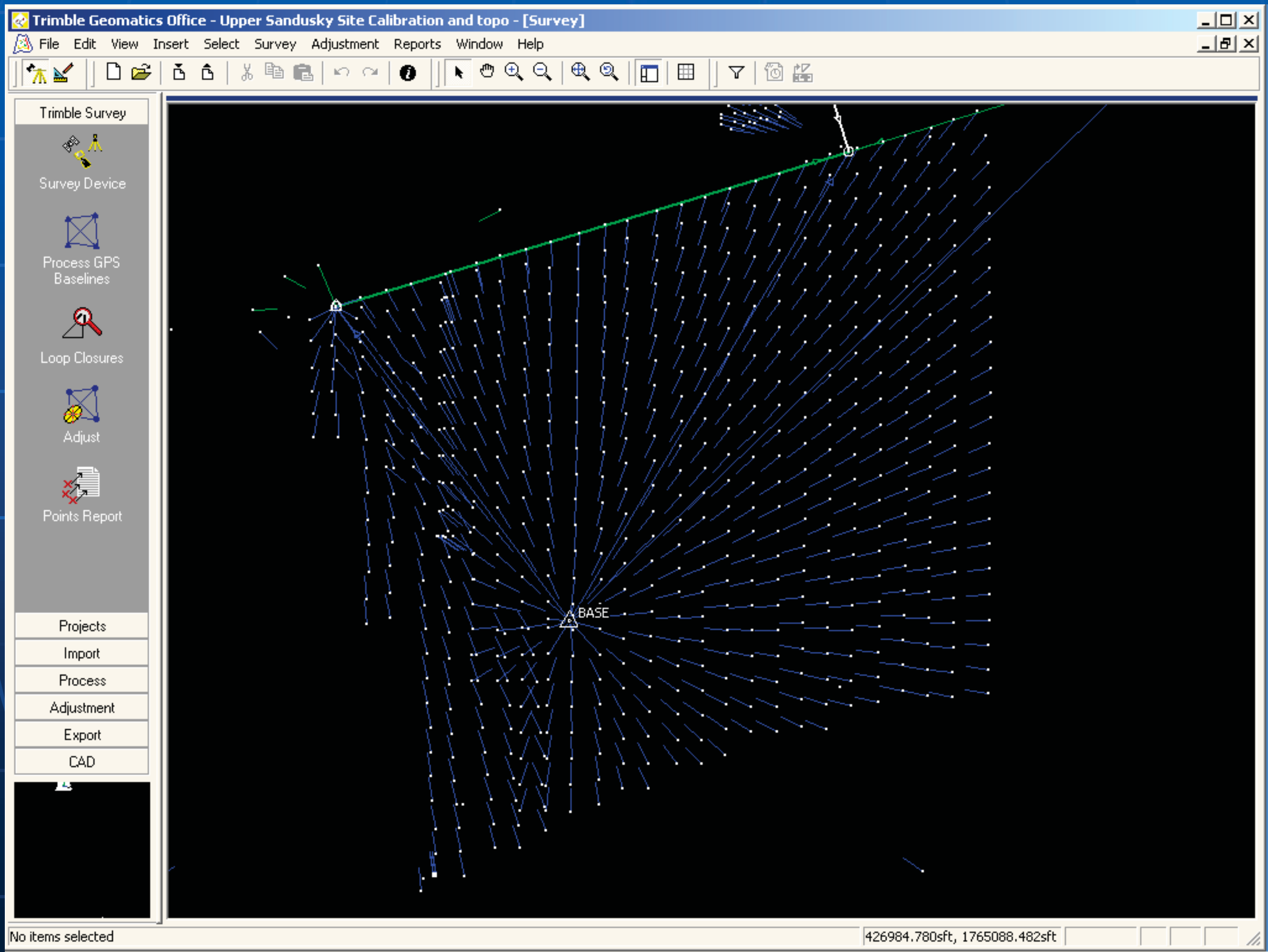
BASE UNIT

First Order Accuracy is achievable using Differential Real Time (or post-processed) Kinematic Technique with Carrier Phase Observations

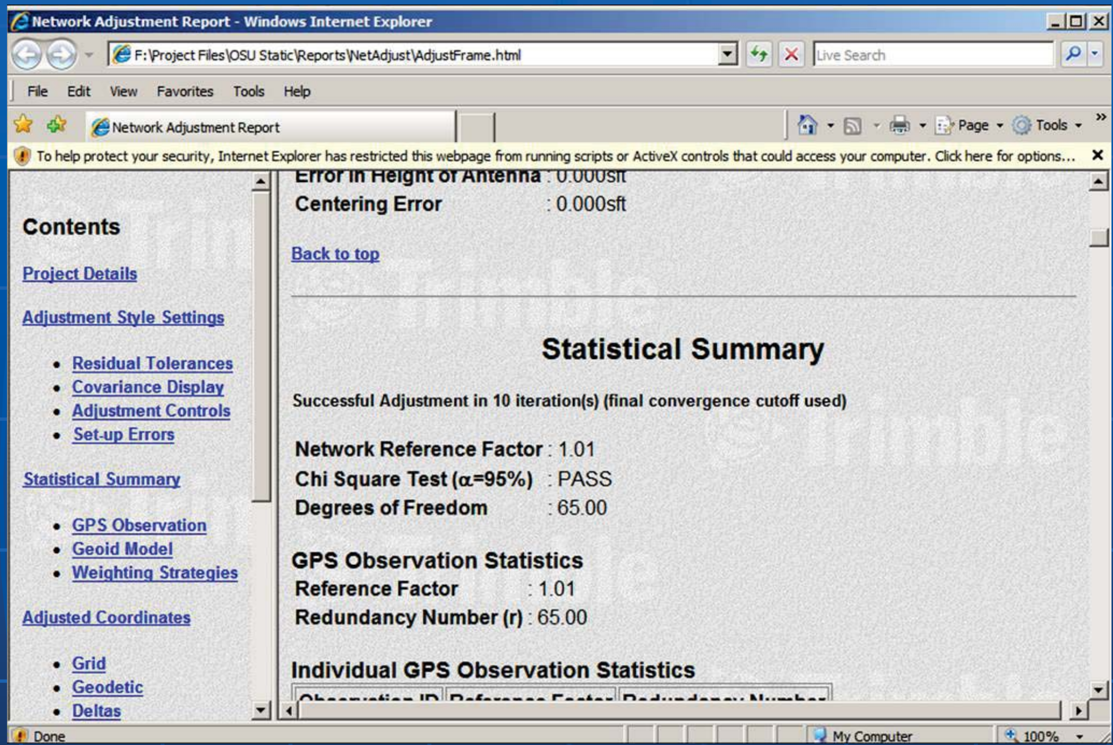
ROVER UNIT

Global Positioning Systems

REAL TIME KINEMATIC – TOPOGRAPHIC SURVEYS



Global Positioning Systems



The statistical accuracy required in GPS measurements is set at the two sigma (95%) confidence level.

Accuracy and geometric factor

- The errors affecting the GPS range measurement were discussed in detail in the earlier part of this workshop
- Here, only geometric aspect (dilution of precision factor) of the positioning accuracy is explained

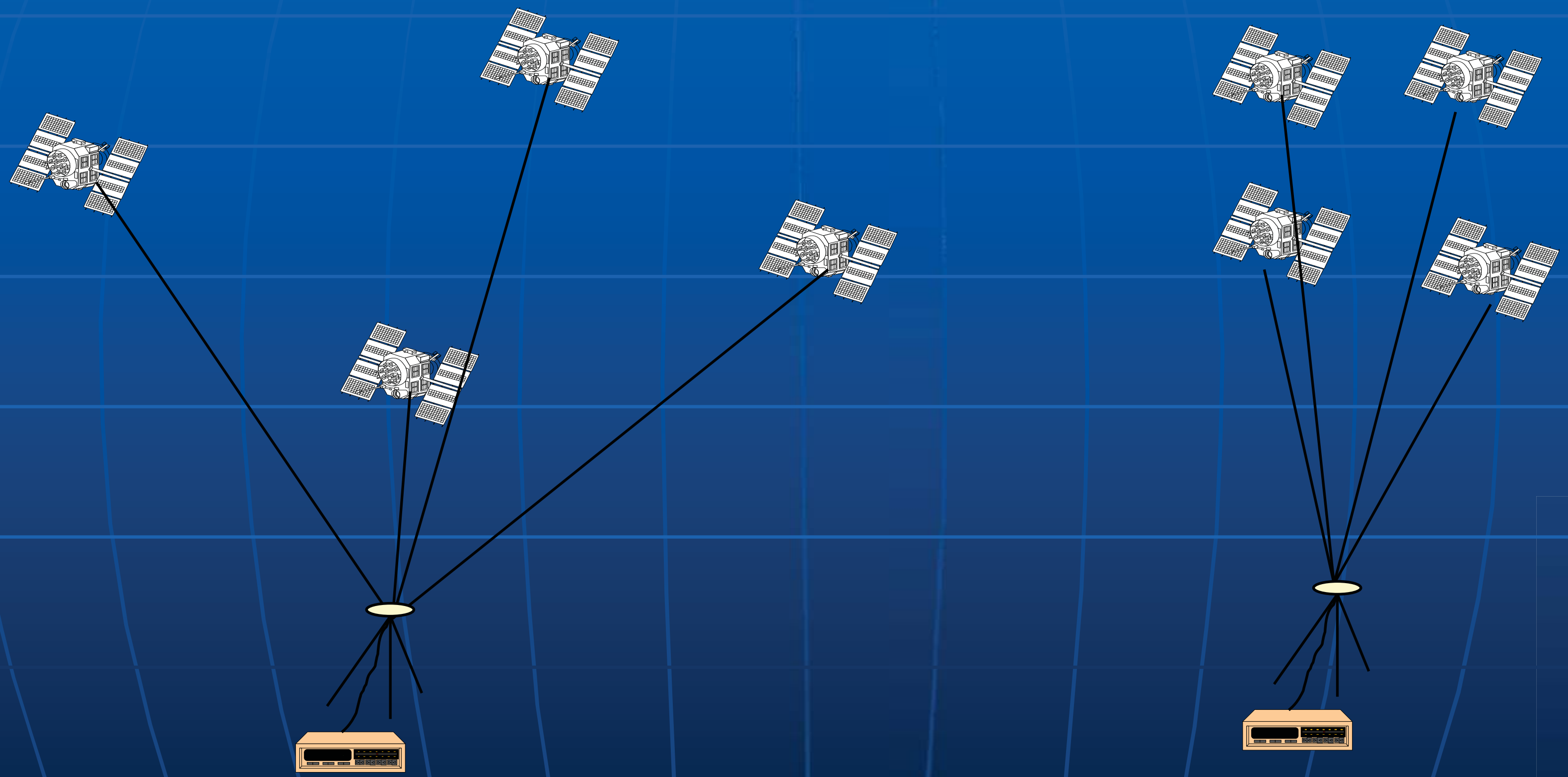
Dilution of Precision

- The two major factors that reflect the accuracy of GPS are
  - (1) error in the range measurement, σ
  - (2) geometric configuration between the receiver and the satellites.
- The two factors combined together define the ultimate positioning error as a product of σ and geometry factor, PDOP (position dilution of precision), namely, *standard deviation of 3D positioning* = PDOP $\times$ σ.

Dilution of Precision

- The geometric factor, PDOP, reflects the instantaneous geometry related to a single receiver, and is determined by the position of the GPS satellites with respect to the receiver.
- PDOP can be interpreted as the reciprocal value of the volume of a tetrahedron that is formed by the positions of the satellites and the user.
- The best geometry corresponds to a large volume and vice versa. Normally, more satellites yield smaller PDOP value, and PDOP of two and less indicates an excellent geometry; PDOP below six refers to a good geometry, while PDOP of seven and above indicates virtually useless data.

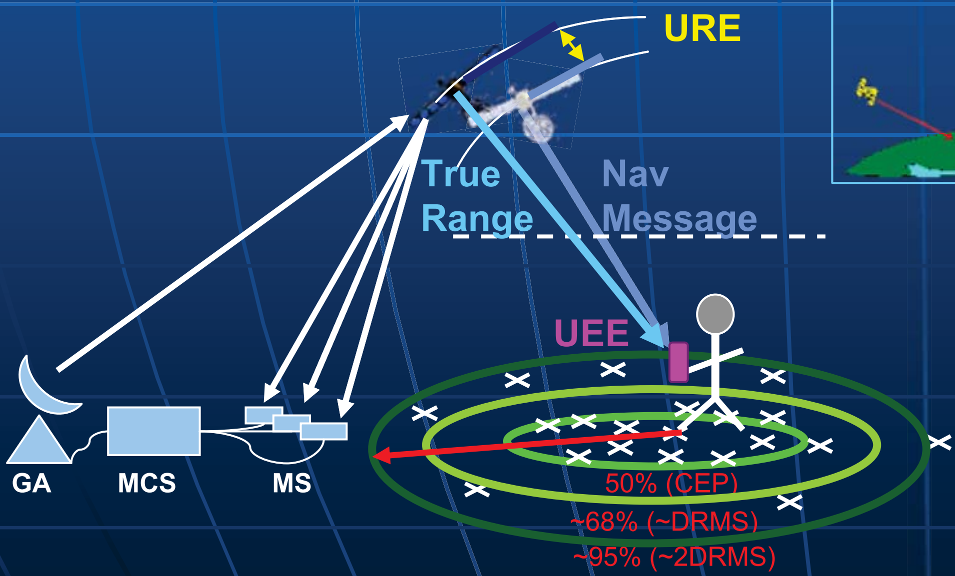
Good PDOP (left) and bad PDOP (right)

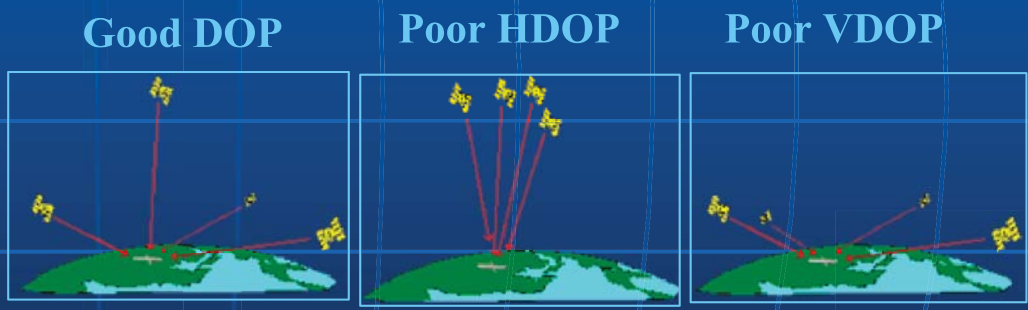


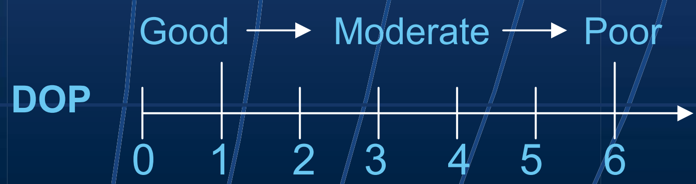
Accuracy equation

$$\text{Accuracy} = \text{Statistical Conversion} * \text{DOP} * \sqrt{\text{URE}^2 + \text{UEE}^2}$$

Accuracy: DOP is a big part of the accuracy equation



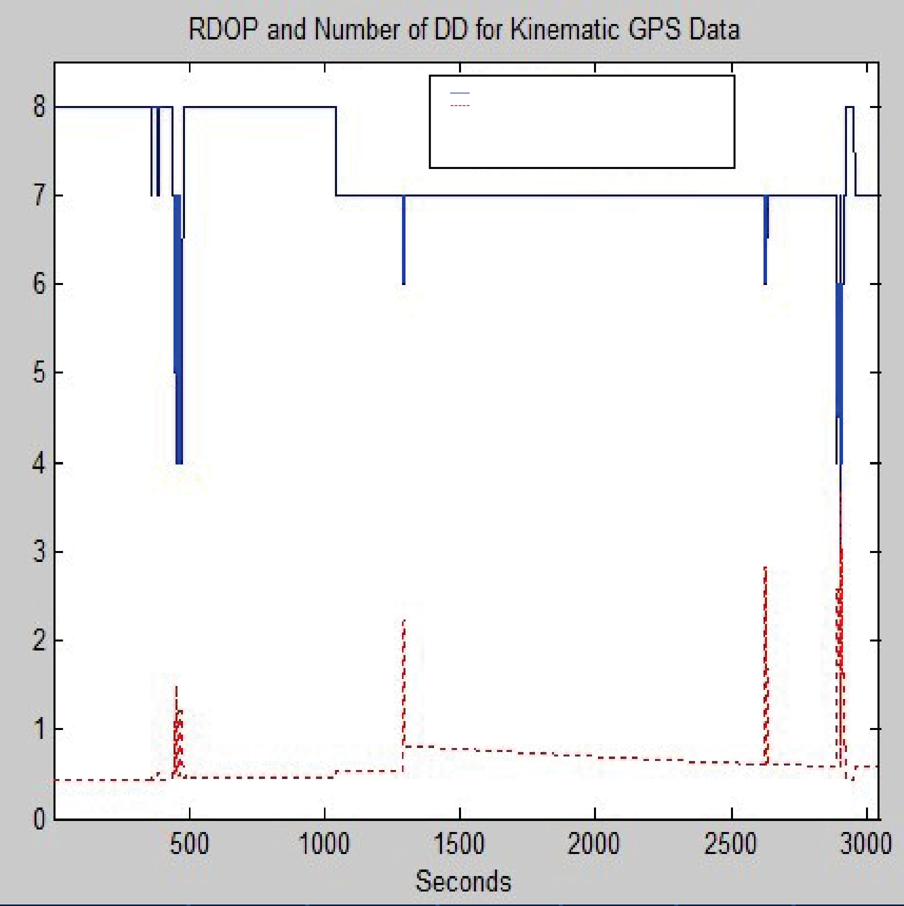


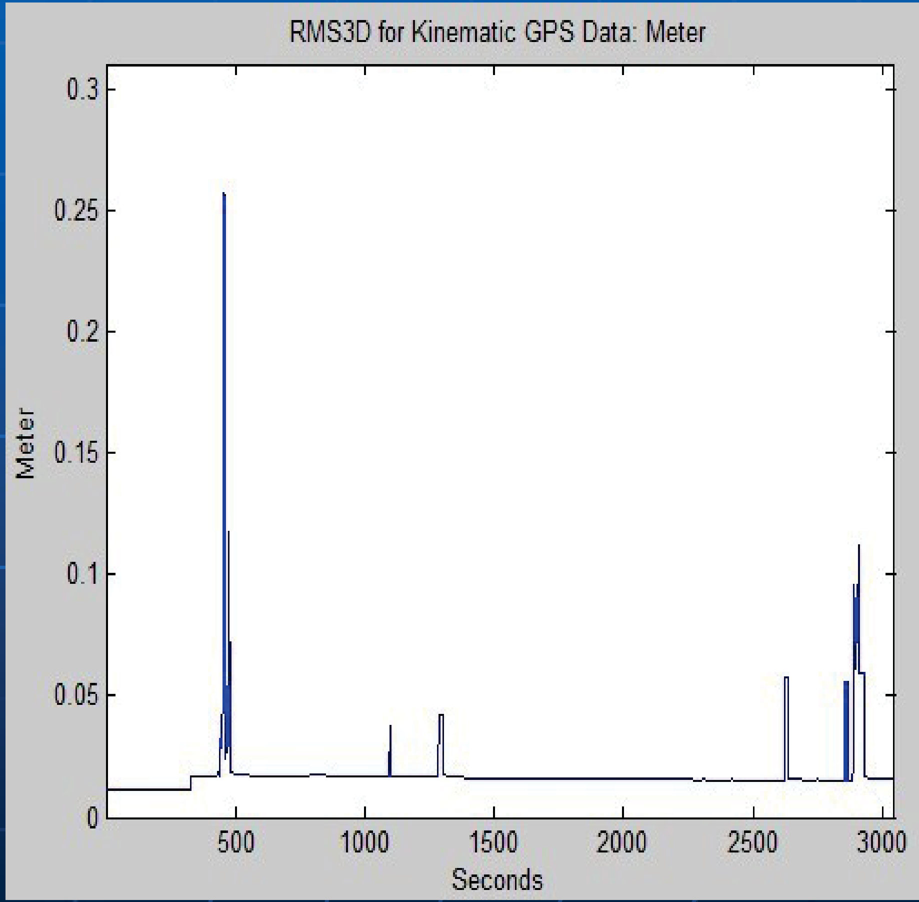


Relative DOP- Important in Kinematic Surveying

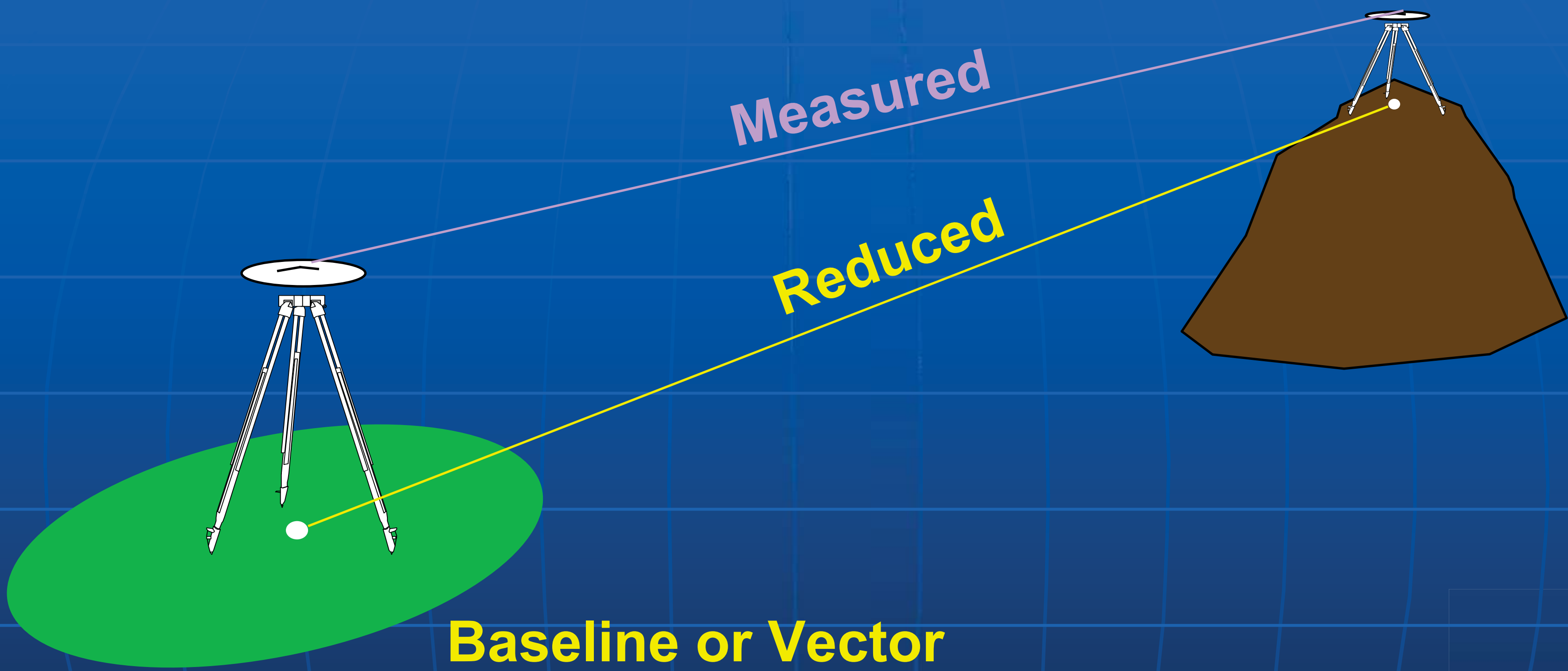
- A geometric factor related to a pair of receivers working in relative (differential) mode (e.g., a base and a rover) is called Relative DOP (RDOP).
- An example of varying geometry and partial loss of signal lock on GPS positioning accuracy is shown in the next slide for differential (relative) positioning
- PDOP/RDOP can be estimated using the approximated location of the user and the satellite broadcast ephemeris included in the satellite navigation message.

RDOP and the number of differential observations (left) and the corresponding 3D standard deviation for GPS relative positioning with carrier phase observations (right)





DGPS Vector (Baseline vector)



Baseline or Vector

(sub-cm precision)

Azi = 212° 42’ 49.8244”
Dist = 557.05307 m
ΔEll Ht = 4 .8751 m

OR

Δ X = -408.251 m
Δ Y = -84.830 m
Δ Z = -369.413 m

Regardless of the accuracy requirement and GPS technique used, each GPS mapping project consists of five basic steps

- *Mission Planning*: all the initial preparations that take place before GPS and geophysical sensor data are collected
- *Data Collection*: collecting GPS and geophysical sensor data in the field
- *Manipulation*: all the processing of GPS data that occurs between the collection period and data analysis, such as the downloading, export, quality control, and processing of GPS data
- *Analysis*: using GPS data as spatially referenced information in a research problem: here – geolocation of geophysical properties mapped
- *Application*: applying the results of the analysis phase in the real world.

Summary

- GPS results are in reference to an ECEF (earth-centered-earth-fixed) coordinate system and the WGS-84 ellipsoid.
- Errors in GPS can be minimized by planning and utilizing proper surveying techniques.
- At least 4 SVs are required to determine a position or survey with GPS after ambiguities have been fixed to their integer values
- At least 2 receivers are required to survey with GPS in differential (DGPS) mode.

Differential GPS (DGPS) in Surveying: How is it done?

DGPS - Benefits

Error source	Single Difference	Double Difference
Ionosphere	Reduced, depending on the baseline length	Reduced, depending on the baseline length
Troposphere	Reduced, depending on the baseline length	Reduced, depending on the baseline length
Satellite clock	Eliminated	Eliminated
Receiver clock	Present	Eliminated
Broadcast ephemeris	Reduced, depending on the baseline length	Reduced, depending on the baseline length
Ambiguity term	Present	Present
Noise level w.r.t. one-way observable	Increased by $\sqrt{2}$	Increased by 2

Introduction to Static GPS

Trimble 5800 Receiver
and
TSC2 Controller

OVERVIEW

- The system consists of the combination antenna and receiver (Trimble 5800) and a controller (TSC2).
- For Static Surveys, the 5800 Receiver mounts to a standard tribrach and tripod; a bracket is provided to mount the TSC2 Controller to one of the tripod legs.

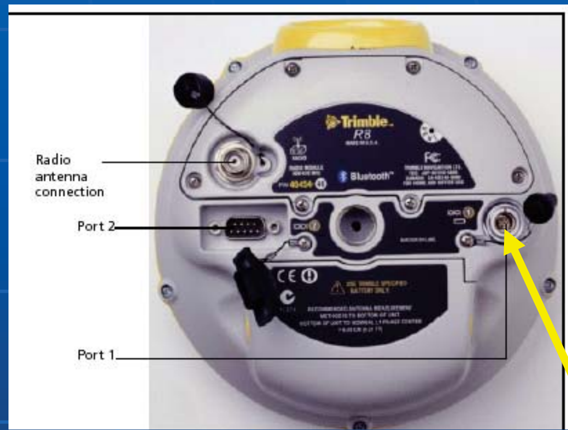
OVERVIEW

- The TSC2 Controller can communicate with the 5800 Receiver by one of two methods:
  - Cable.
  - Bluetooth wireless communication.
- Standard Cable is Recommended for Static Surveys

Standard Cable

Bluetooth

OVERVIEW



9 Pin Port

Controller

Receiver

Port 1

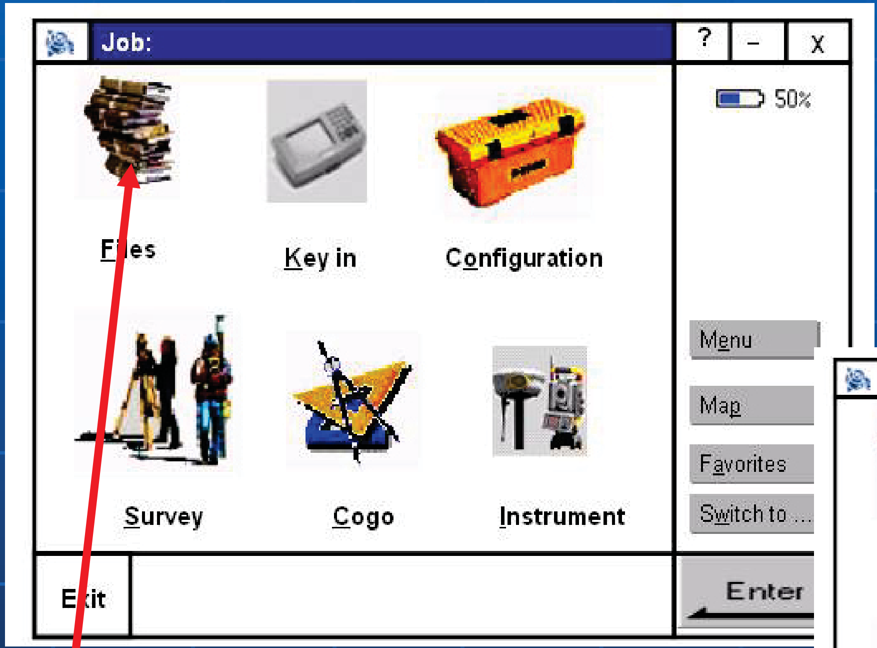
- For Static Surveys it is recommended that the standard nine (9) pin yellow cable (Controller End) be used and be connected to Port 1 on the receiver.

PROJECT SETUP

- Press the Green Key on the lower left hand corner of the controller keyboard.
- Use the stylus to double click (tap) on the Survey Controller Selection in the Menu.

Start Key

NEW JOB



Click on the **Files ICON.**

Click on **New job**

Introduction to Real Time Kinematic GPS

Trimble 5800 Receiver and TSC2 Controller

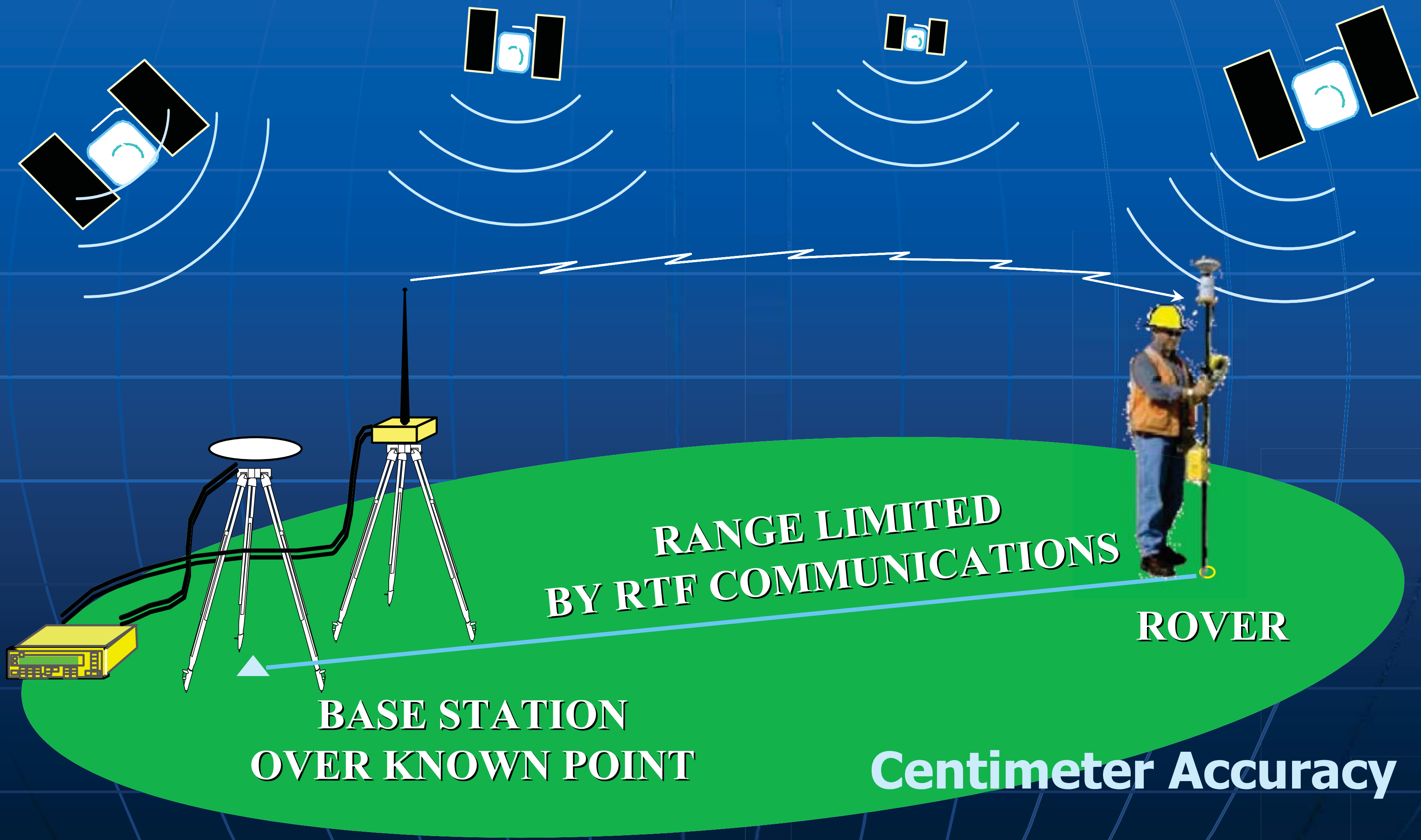
GPS Field Procedures

- Kinematic GPS surveys (Post Processed)
  - 1 receiver remains fixed on a known station while another receiver(s) roves from 1 position to another without losing lock on the satellites
- Real-time kinematic GPS surveys (Processed Real Time)

Base & Radio

Rover

Real Time Kinematic



OVERVIEW - RTK

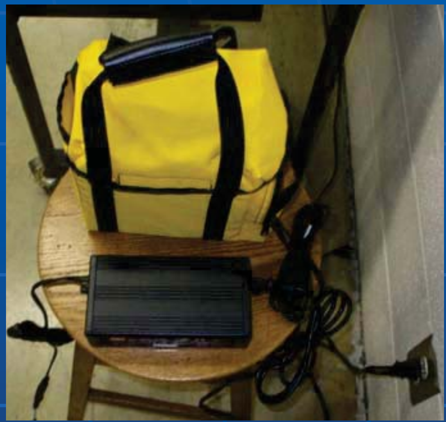
BASE UNIT

The system consists of a Base Station (Trimble 5800 Receiver and Pacific Radio Transmitter) and a Rover (Trimble 5800 Receiver & TSC2 Controller).

ROVER UNIT

OVERVIEW - BATTERIES

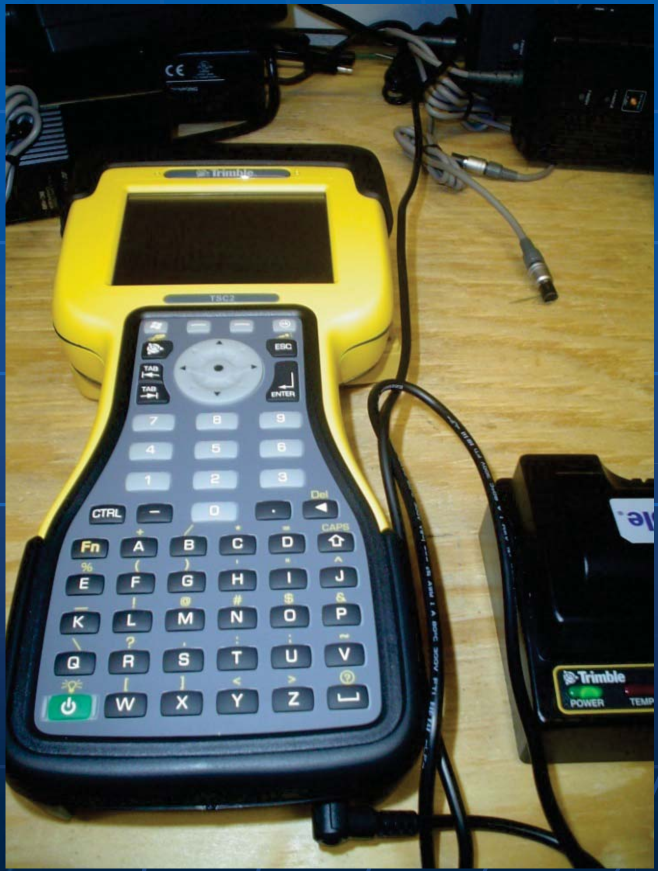
Amber lights are lit during charge cycle and will go out when fully charged.



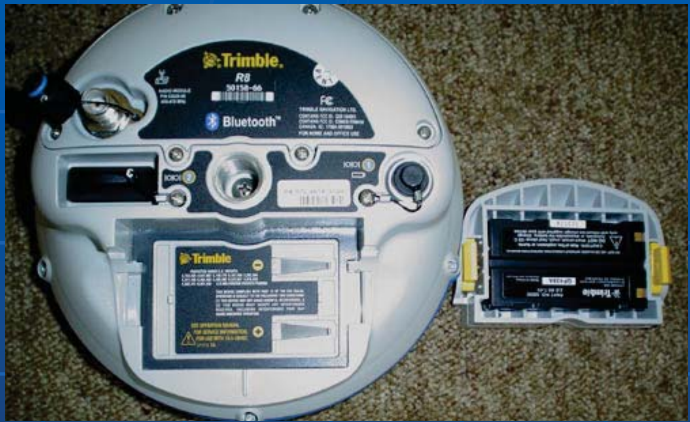
- The 5800 Base Receiver uses rechargeable external battery.
- The Pacific Radio uses a sealed lead/acid battery.
- Each battery has its own charger; batteries should be recharged immediately after use. Batteries should be fully charged prior to storage.

BATTERIES

- The TSC2 Controller batteries are contained within the units and can be recharged by means of a one pin plug.



BATTERIES



- The 5800 Receiver uses a small removable "cam-corder" battery.
- The 5800 Receiver has a detachable battery holder on the bottom of the unit.
- Make certain that the battery is properly aligned in the holder before attaching it to the receiver.

OVERVIEW
EQUIPMENT ASSEMBLY

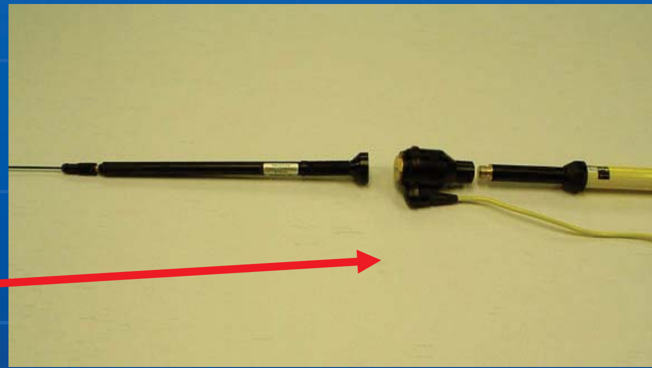
- The Base Station consists of a Trimble 5800 Receiver and Pacific Radio transmitter and antenna assembly.
- Maintain 7 feet (~2 Meters, minimum) between the Receiver and the Radio/Transmitter.

OVERVIEW
EQUIPMENT ASSEMBLY

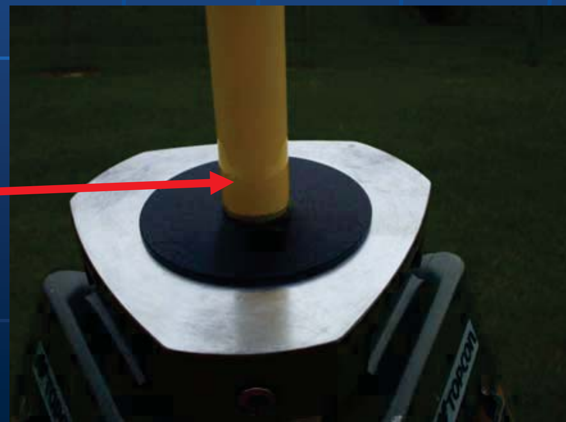
Antenna Assembly – Be Careful of Threads on the Antenna

OVERVIEW
EQUIPMENT ASSEMBLY

Antenna Assembly With Telescoping Extension; Extend Until the Black Button Clicks Into Place.



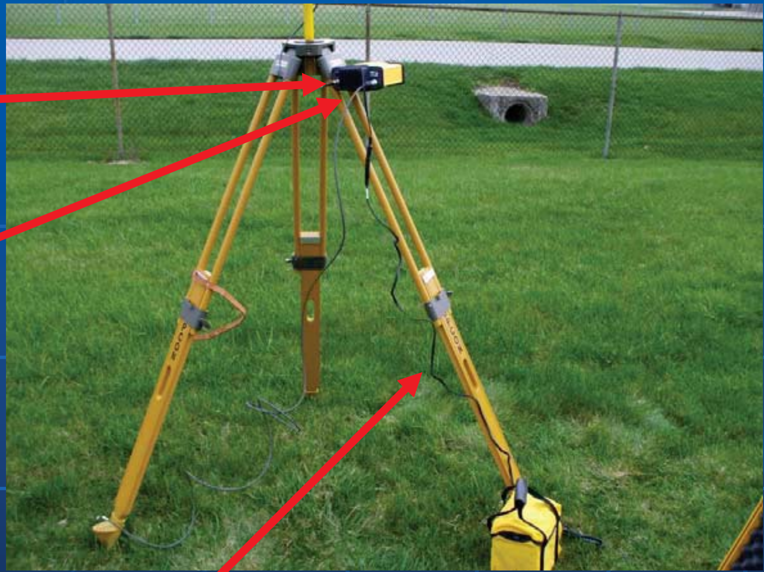
Extension Mounts Directly to a Tripod With a Washer Insert



OVERVIEW
EQUIPMENT ASSEMBLY

Antenna
Cable

Data
Cable



Power
Cable

Pacific
Radio Transmitter
Cable & Power Assembly

OVERVIEW
EQUIPMENT ASSEMBLY

Unit "4" Trimble 5800 Base Receiver On 0.25 Meter Extension

5800 Combination Power and I/O Cable

5800 Battery

OVERVIEW
EQUIPMENT ASSEMBLY

Trimble
5800 Base Receiver
On 0.25 Meter
Extension
Cable Hookups

Controller Cable

Data Cable to Radio

OVERVIEW
EQUIPMENT ASSEMBLY

Trimble 5800
Receiver and
TSC 2 Controller
Rover Assembly
Mounted on the
Range
Pole and
Bipod

Bluetooth
Wireless
Antenna
On Receiver

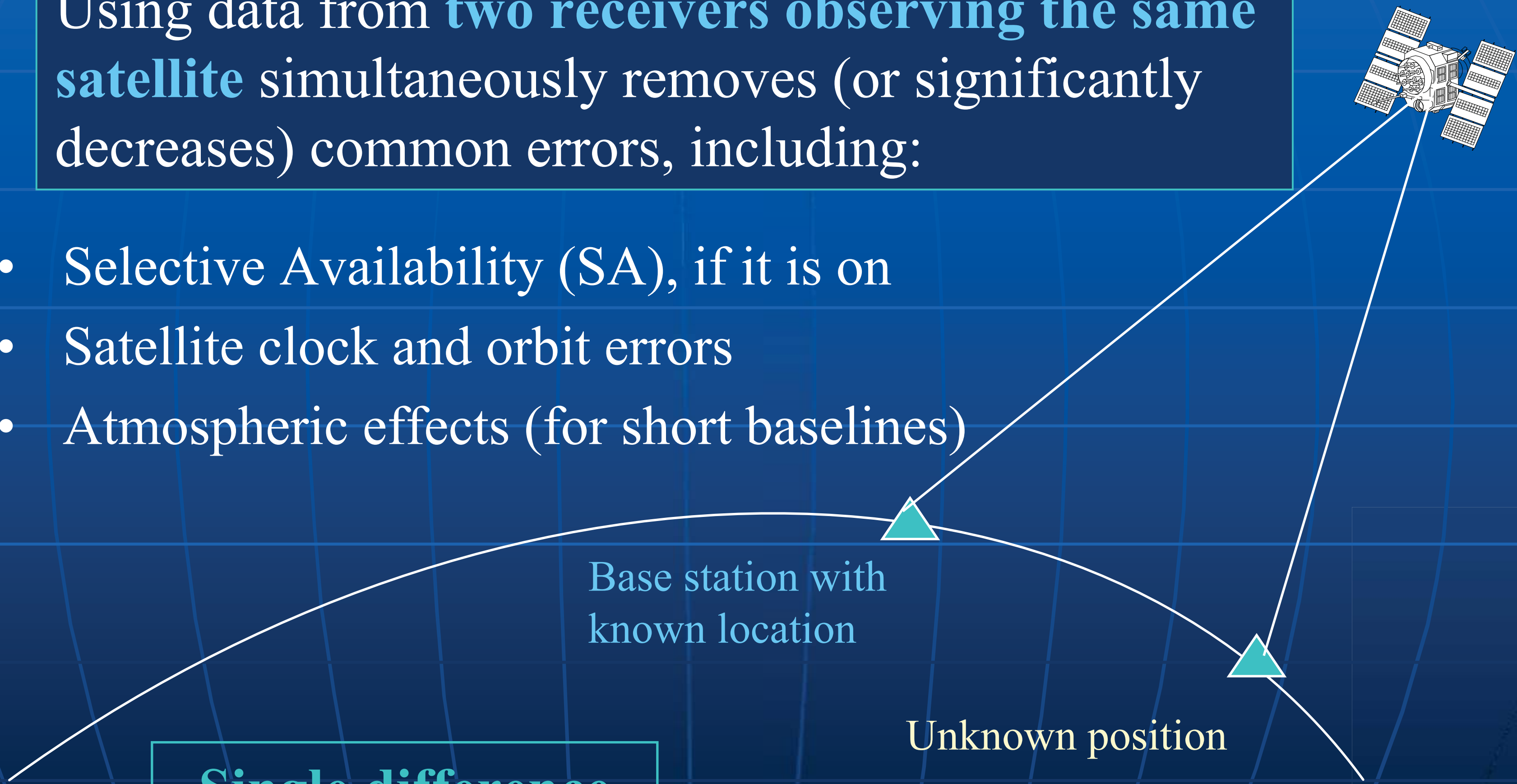
TSC 2 Controller
Has the Bluetooth
Internal to the
Controller

DGPS: Basic Algorithms

Differential GPS

Using data from **two receivers observing the same satellite** simultaneously removes (or significantly decreases) common errors, including:

- Selective Availability (SA), if it is on
- Satellite clock and orbit errors
- Atmospheric effects (for short baselines)

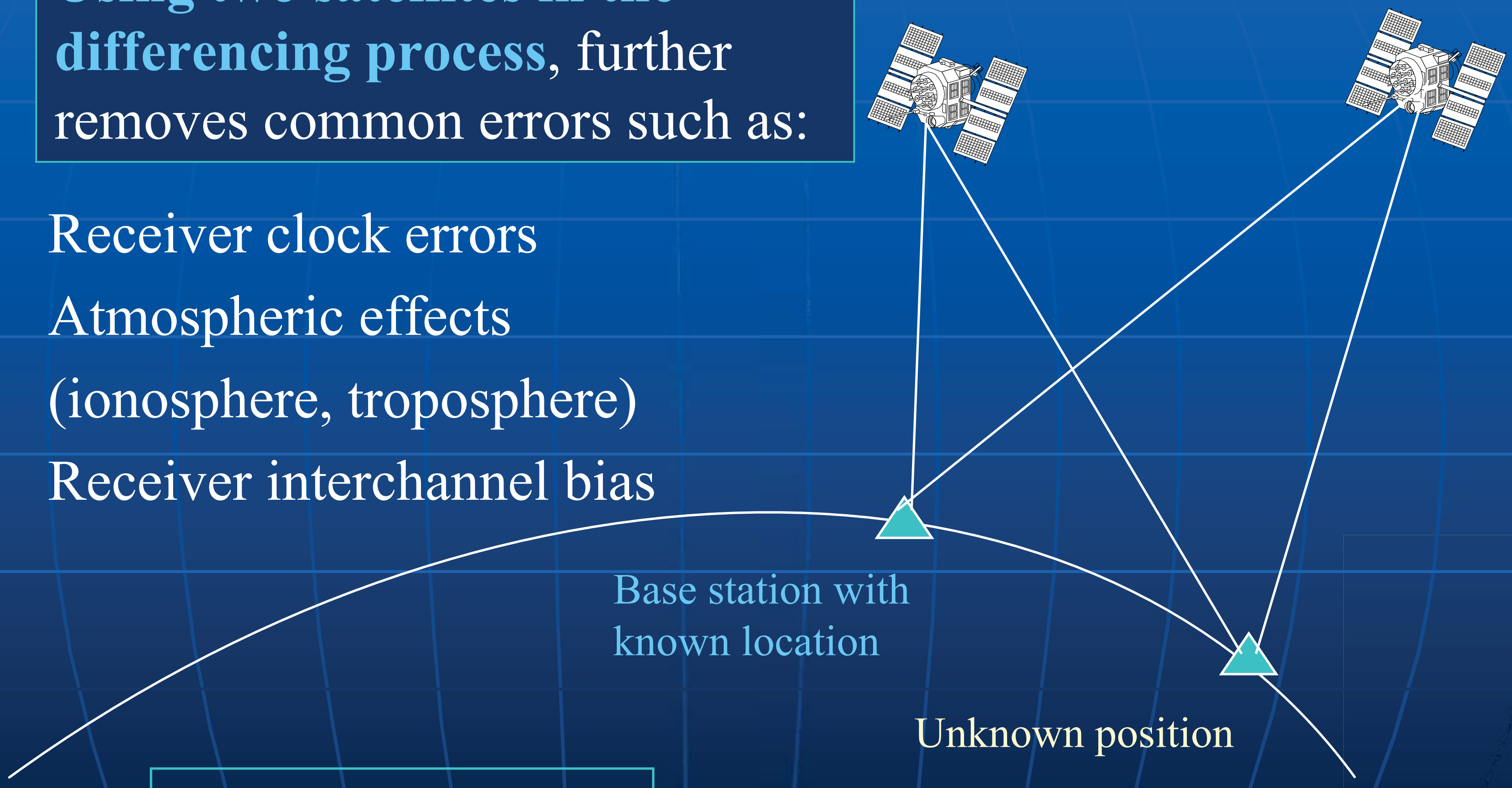


Single difference mode

Differential GPS

Using two satellites in the differencing process, further removes common errors such as:

- Receiver clock errors
- Atmospheric effects (ionosphere, troposphere)
- Receiver interchannel bias



Double difference mode

Basic GPS Observables

$$P_{i,1}^{k} = \rho_i^k + \frac{I_i^k}{f_1^2} + T_i^k + c(dt_i - dt^k) + b_{i,2} + M_{i,1}^k + e_{i,1}^k$$

$$P_{i,2}^{k} = \rho_i^k + \frac{I_i^k}{f_2^2} + T_i^k + c(dt_i - dt^k) + b_{i,3} + M_{i,2}^k + e_{i,2}^k$$

$$\Phi_{i,1}^{k} = \rho_i^k - \frac{I_i^k}{f_1^2} + T_i^k + \lambda_1 N_{i,1}^k + c(dt_i - dt^k) + \lambda_1\left(\varphi_{0,1}^k - \varphi_{i_0,1}\right) + m_{i,1}^k + \varepsilon_{i,1}^k$$

$$\Phi_{i,2}^{k} = \rho_i^k - \frac{I_i^k}{f_2^2} + T_i^k + \lambda_2 N_{i,2}^k + c(dt_i - dt^k) + b_{i,1} + \lambda_2\left(\varphi_{0,2}^k - \varphi_{i_0,2}\right) + m_{i,2}^k + \varepsilon_{i,2}^k$$

$$\rho_{i,0}^k = sqrt\left[\left(X^k - X_i\right)^2 + \left(Y^k - Y_i\right)^2 + \left(Z^k - Z_i\right)^2\right]$$

The primary unknowns are *Xi, Yi, Zi* – coordinates of the user (receiver)

1,2 stand for frequency on L1 and L2, respectively

i –denotes the receiver, while k denotes the satellite

Basic GPS Observables (cont.)

$P_{i,1}^{k}, P_{i,2}^{k}$ – pseudoranges measured between station i and satellite k on L1 and L2

$\Phi_{i,1}^{k}, \Phi_{i,2}^{k}$ – phase ranges measured between station i and satellite k on L1 and L2

$\varphi_{0,n}^{k}, \varphi_{i_0,n}$ – initial fractional phases at the transmitter and the receiver, respectively; $n = 1$ or 2, stands for the frequency

$N_{i,1}^{k}, N_{i,2}^{k}$ – ambiguities associated with L_1 and L_2, respectively

$\lambda_1 \approx 19$ cm and $\lambda_2 \approx 24$ cm are wavelengths of L_1 and L_2 phases

ρ_i^k - geometric distance between the satellite k and receiver i,

$\frac{I_i^k}{f_1^2}, \frac{I_i^k}{f_2^2}$ - ionospheric refraction on L1 and L2, respectively

T_i^k - the tropospheric refraction term

Basic GPS Observables (cont.)

dt_i - the *i-th* receiver clock error
dt^k - the *k-th* transmitter (satellite) clock error
f_1, f_2 - carrier frequencies
c - the vacuum speed of light

$e^k_{i,1}, e^k_{i,2}, \varepsilon^k_{i,1}, \varepsilon^k_{i,2}$ - measurement noise for pseudoranges and phases on L1 and L2

$M^k_{i,1}, M^k_{i,2}, m^k_{i,1}, m^k_{i,2}$ – multipath on phases and ranges

$b_{i,1}, b_{i,2}, b_{i,3}$ - interchannel bias terms for receiver *i* that represent the possible time non-synchronization of the four measurements

$b_{i,1}$ - interchannel bias between $\Phi^k_{i,1}$ and $\Phi^k_{i,2}$

$b_{i,2}, b_{i,3}$ – biases between $\Phi^k_{i,1}$ and $P^k_{i,1}$, $\Phi^k_{i,1}$ and $P^k_{i,2}$

Consider two stations i and j observing L1 pseudorange to the same two GPS satellites k and l:

$$P_{i,1}^{k} = \rho_i^k + \frac{I_i^k}{f_1^2} + T_i^k + c(dt_i - dt^k) + b_{i,2} + M_{i,1}^k + e_{i,1}^k$$

$$P_{i,1}^{l} = \rho_i^l + \frac{I_i^l}{f_1^2} + T_i^l + c(dt_i - dt^l) + b_{i,2} + M_{i,1}^l + e_{i,1}^l$$

$$P_{j,1}^{k} = \rho_j^k + \frac{I_j^k}{f_1^2} + T_j^k + c(dt_j - dt^k) + b_{j,2} + M_{j,1}^k + e_{j,1}^k$$

$$P_{j,1}^{l} = \rho_j^l + \frac{I_j^l}{f_1^2} + T_j^l + c(dt_j - dt^l) + b_{j,2} + M_{j,1}^l + e_{j,1}^l$$

Consider two stations i and j observing L1 phase range to the same two GPS satellites k and l:

$$\Phi_{i,1}^{k} = \rho_i^k - \frac{I_i^k}{f_1^2} + T_i^k + \lambda_1 N_{i,1}^k + c(dt_i - dt^k) + \lambda_1\left(\varphi_{0,1}^k - \varphi_{i_0,1}\right) + m_{i,1}^k + \varepsilon_{i,1}^k$$

$$\Phi_{i,1}^{l} = \rho_i^l - \frac{I_i^l}{f_1^2} + T_i^l + \lambda_1 N_{i,1}^l + c(dt_i - dt^l) + \lambda_1\left(\varphi_{0,1}^l - \varphi_{i_0,1}\right) + m_{i,1}^l + \varepsilon_{i,1}^l$$

$$\Phi_{j,1}^{k} = \rho_j^k - \frac{I_j^k}{f_1^2} + T_j^k + \lambda_1 N_{j,1}^k + c(dt_j - dt^k) + \lambda_1\left(\varphi_{0,1}^k - \varphi_{j_0,1}\right) + m_{j,1}^k + \varepsilon_{j,1}^k$$

$$\Phi_{j,1}^{l} = \rho_j^l - \frac{I_j^l}{f_1^2} + T_j^l + \lambda_1 N_{j,1}^l + c(dt_j - dt^l) + \lambda_1\left(\varphi_{0,1}^l - \varphi_{j_0,1}\right) + m_{j,1}^l + \varepsilon_{j,1}^l$$

DGPS in Geodesy and Surveying

• The ***single-differenced*** measurement is obtained by differencing two observables of the satellite *k* , tracked simultaneously by two stations *i* and *j:*

$$\Phi_{ij,1}^{k} = \rho_{ij}^{k} - \frac{I_{ij}^{k}}{f_1^2} + T_{ij}^{k} + \lambda_1 N_{ij,1}^{*k} + c \cdot dt_{ij} + m_{ji,1}^{k} + \varepsilon_{ij,1}^{k}$$

$$P_{ij,1}^{k} = \rho_{ij}^{k} + \frac{I_{ij}^{k}}{f_1^2} + T_{ij}^{k} + c \cdot dt_{ij} + b_{ij,2} + M_{ji,1}^{k} + e_{ij,1}^{k}$$

$$N_{ij,1}^{*k} = N_{ij,1}^{k} + (\varphi_{t_0 i,1} - \varphi_{t_0 j,1})$$

Non-integer ambiguity !

DGPS Concept, cont.

- By differencing one-way observable from two receivers, *i* and *j*, observing two satellites, *k* and *l*, or simply by differencing two single differences to satellites *k* and *l*, one arrives at the **double-differenced (DD)** measurement:

$$P_{ij,1}^{k} = \rho_{ij}^{k} + \frac{I_{ij}^{k}}{f_1^2} + T_{ij}^{k} + c \cdot dt_{ij} + b_{ij,2} + M_{ji,1}^{k} + e_{ij,1}^{k}$$

$$P_{ij,1}^{l} = \rho_{ij}^{l} + \frac{I_{ij}^{l}}{f_1^2} + T_{ij}^{l} + c \cdot dt_{ij} + b_{ij,2} + M_{ji,1}^{l} + e_{ij,1}^{l}$$

Two single differences

$$P_{ij,1}^{kl} = \rho_{ij}^{kl} + \frac{I_{ij}^{kl}}{f_1^2} + T_{ij}^{kl} + M_{ji,1}^{kl} + e_{ij,1}^{kl}$$

Double difference

- In the actual data processing the differential tropospheric, ionospheric and multipath errors are neglected; the only unknowns are the station coordinates

Differential Carrier Phase Observations

$$\Phi_{ij,1}^{k} = \rho_{ij}^{k} - \frac{I_{ij}^{k}}{f_1^2} + T_{ij}^{k} + \lambda_1 N_{ij,1}^{*k} + c \cdot dt_{ij} + m_{ji,1}^{k} + \varepsilon_{ij,1}^{k}$$

$$\Phi_{ij,1}^{l} = \rho_{ij}^{l} - \frac{I_{ij}^{l}}{f_1^2} + T_{ij}^{l} + \lambda_1 N_{ij,1}^{*l} + c \cdot dt_{ij} + m_{ji,1}^{l} + \varepsilon_{ij,1}^{l}$$

Two single differences

$$\Phi_{ij,1}^{kl} = \rho_{ij}^{kl} - \frac{I_{ij}^{kl}}{f_1^2} + T_{ij}^{kl} + \lambda_1 N_{ij,1}^{kl} + m_{ji,1}^{kl} + \varepsilon_{ij,1}^{kl}$$

Double difference

Single difference ambiguity

$$N_{ij,1}^{*k} = N_{ij,1}^{k} + (\varphi_{t_0 i,1} - \varphi_{t_0 j,1})$$

DGPS in Geodesy and Surveying

- By differencing one-way observable from two receivers, *i* and *j*, observing two satellites, *k* and *l*, or simply by differencing two single differences to satellites *k* and *l*, one arrives at the ***double-differenced*** measurement:

$$\Phi_{ij,1}^{kl} = \rho_{ij}^{kl} - \frac{I_{ij}^{kl}}{f_1^2} + T_{ij}^{kl} + \lambda_1 N_{ij,1}^{kl} + m_{ji,1}^{kl} + \varepsilon_{ij,1}^{kl}$$

$$P_{ij,1}^{kl} = \rho_{ij}^{kl} + \frac{I_{ij}^{kl}}{f_1^2} + T_{ij}^{kl} + M_{ji,1}^{kl} + e_{ij,1}^{kl}$$

Differential Phase Observations

- **Double differenced (DD)** mode is the most popular for carrier phase data processing in Surveying applications
- In DD the unknowns are station coordinates and the integer ambiguities
- In DD the differential atmospheric and multipath effects are very small and are normally neglected
    - Atmospheric errors become important for longer baselines
- The achievable accuracy is cm-level for short baselines (below 10-15 km); **for longer distances, DD ionospheric-free combination** is used
- **Single differencing** is also used, however, the problem there is non-integer ambiguity term (see previous slide), which does not provide such strong constraints into the solution as the integer ambiguity for DD

Useful linear combinations

- Created usually from double-differenced phase observations
- Ion-free combination based on L1 and L2 observable eliminates ionospheric effects (actually, the first order only)
- Ion-only combination based on L1 and L2 observable, (useful for cycle slip tracking) eliminates all effects except for the ionosphere, thus can be used to estimate the ionospheric effect
- Widelane – its long wavelength of 86.2 cm supports ambiguity resolution; based on L1 and L2 observable

Ionosphere-free combination

- **ionosphere-free** carrier phase measurement

$$\alpha_1 = \frac{f_1^2}{f_1^2 - f_2^2}$$

$$\alpha_2 = -\frac{f_2^2}{f_1^2 - f_2^2}$$

$$\begin{aligned}\Phi_{1,2} &= \alpha_1\Phi_1 + \alpha_2\Phi_2 \\ &= \rho + T + \alpha_1\lambda_1 N_1 + \alpha_2\lambda_2 N_2 + \alpha_1\varepsilon_1 + \alpha_2\varepsilon_2\end{aligned}$$

- similarly, ionosphere-free pseudorange can be obtained

$$R_{1,2} = R_1 - \frac{f_2^2}{f_1^2} R_2$$

- The conditions applied are that sum of ionospheric effects on both frequencies multiplied by constants to be determined must be zero; second condition is for example that sum of the constants is 1, or one constant is set to 1 (verify!)

Ionosphere-free combination

Take the ionospheric terms on L1 and L2 and assume that they meet the following conditions (where **α_1 and α_2** are the coefficients defining the iono-free combination:

$$\alpha_1 \frac{I}{f_1^2} + \alpha_2 \frac{I}{f_2^2} = 0$$

$$\alpha_1 + \alpha_2 = 1$$

thus

$$\alpha_1 \frac{I}{f_1^2} - \alpha_1 \frac{I}{f_2^2} + \frac{I}{f_2^2} = 0$$

However, we only considered the 1st order ionospheric term here!

simplifying:

$$\alpha_1 \left(\frac{f_2^2 - f_1^2}{f_1^2 f_2^2} \right) = -\frac{1}{f_2^2}$$

finally:

$$\alpha_1 = \frac{f_1^2}{f_1^2 - f_2^2}$$

$$\alpha_2 = -\frac{f_2^2}{f_1^2 - f_2^2}$$

Other useful linear combinations

- ***widelane*** $\varphi_w = \varphi_1 - \varphi_2$ where φ is in cycles

the corresponding wavelength $\lambda_w = \lambda_1 \lambda_2 / (\lambda_2 - \lambda_1) = 86.2\,cm$

$$\Phi_{ij,w}^{kl} = \rho_{ij}^{kl} + \frac{I_{ij}^{kl}}{f_1^2}\frac{f_1}{f_2} + T_{ij}^{kl} + \lambda_w \left(N_{ij,1}^{kl} - N_{ij,2}^{kl} \right) + \varepsilon_{ij,w}^{kl}$$ [meter]

ionospheric-only (geometry-free) combination is obtained by differencing two phase ranges [m] belonging to the frequencies L_1 and L_2

$$\Phi_{ij,iono-only}^{kl} = \Phi_{ij,1}^{kl} - \Phi_{ij,2}^{kl} = I_{ij}^{kl}\left(\frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right) + \lambda_1 N_{ij,1}^{kl} - \lambda_2 N_{ij,2}^{kl} + \varepsilon_{ij,iono-only}^{kl}$$ [meter]

Non-integer ambiguity!

Widelane

• **Difference between phase observable on L1 and L2 (in cycles)**

$$\varphi_1 - \varphi_2 = \frac{\rho}{\lambda_1} + N_1 - \frac{1}{\lambda_1}\frac{I}{f_1^2} + \frac{T}{\lambda_1} - \frac{\rho}{\lambda_2} - N_2 + \frac{1}{\lambda_2}\frac{I}{f_2^2} - \frac{T}{\lambda_2} =$$

$$= \rho\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) + (N_1 - N_2) + T\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) + \frac{I}{f_1^2}\left(\frac{f_1^2}{f_2^2}\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) =$$

$$= \rho\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) + (N_1 - N_2) + T\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) + \frac{I}{f_1^2}\left(\frac{\lambda_2^2}{\lambda_1^2}\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) =$$

$$= \rho\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) + (N_1 - N_2) + T\left(\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right) + \frac{I}{f_1^2}\frac{\lambda_2}{\lambda_1}\left(\frac{\lambda_2 - \lambda_1}{\lambda_2\lambda_1}\right) =$$

$$\Phi_{12,w} = \rho + \lambda_w(N_1 - N_2) + T + \frac{I}{f_1^2}\frac{f_1}{f_2}$$

Widelane in [m]

$$\lambda_w = \lambda_1\lambda_2 / (\lambda_2 - \lambda_1) = 86.2\,cm$$

Widelane wavelength

Kinematic GPS Positioning

What is kinematic GPS?

- In kinematic mode the so-called rover receiver is moving with respect to the base (reference receiver at known location), or maybe multiple rover receivers are moving with respect to each other and a base (or multiple base) station
- Kinematic positioning is usually associated with real-time operation, however, the data collected in kinematic mode can be processed in the post-mission mode for higher accuracy
- Thus, kinematic GPS positioning is performed either in real-time or post-processing

Kinematic GPS Positioning

- Real-time kinematic (RTK) GPS can be performed based on DGPS (WADGPS = Wide Area DGPS) services, thus, based on pseudoranging, as discussed in earlier sessions at this workshop, or
- Can be performed based with respect the user's own base station, which usually supports precise, carrier phase-based differential positioning
- In real-time mode, the rover must communicate with the base via radio modem
- In any case, the positioning can be performed only after the integer ambiguities have been resolved
- For very long baselines, kinematic positioning can be performed based on real-valued ambiguities, if the integers cannot be resolved due to a high noise level
  - results in the loss of accuracy (up to 10 cm per coordinate for baselines > 20 km, and more for baselines > 100 km)

Real-time Precise Kinematic GPS Positioning (RTK)

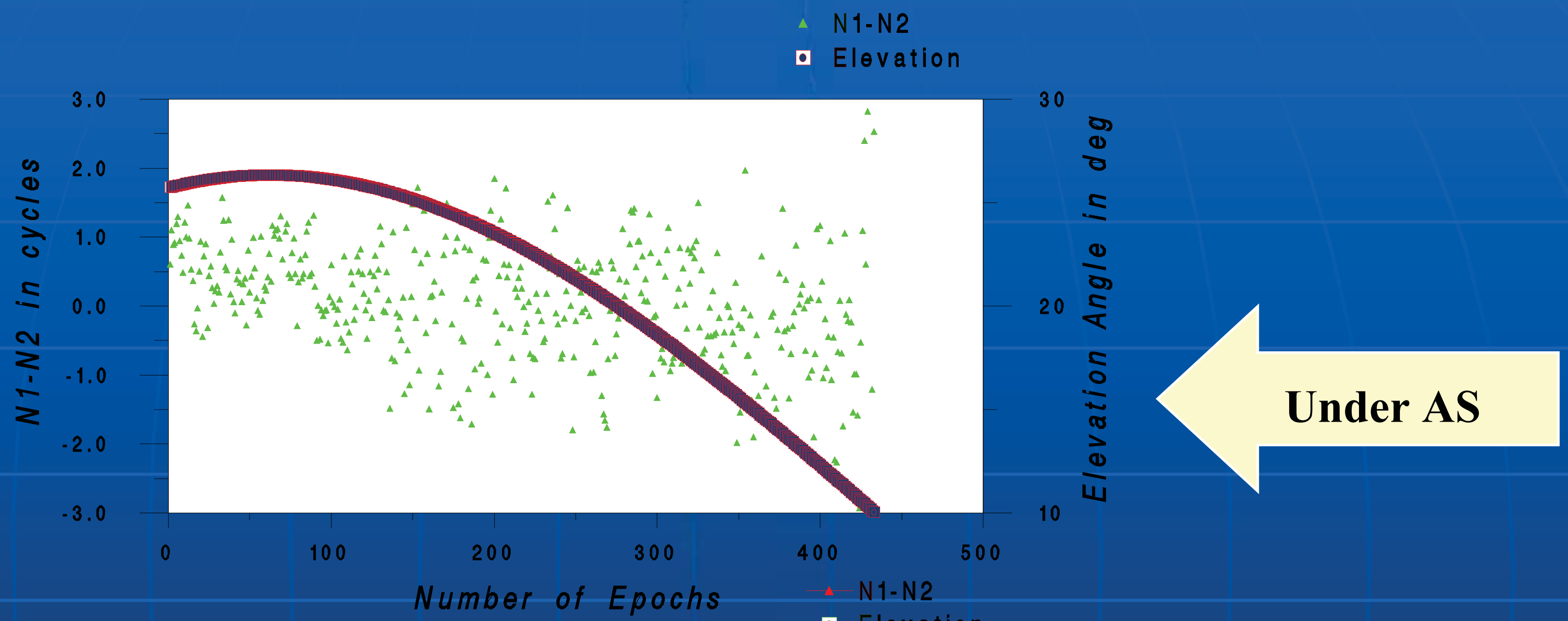
- Requires real-time data transfer (radio link) – thus limited to shorter distanced, 10-20 km, depending on radio communication (limited reliability of data transfer)
- Limited also due to the increasing atmospheric effects that prevent reliable ambiguity resolution (applies to any long-range GPS)
- Requires use of carrier phase measurements (millimeter-level noise)
- **Exact determination of integer ambiguities is critical**
  - In the static scenario, the changing satellite geometry allows for separation of the ambiguities from the constant station geometry
  - In the kinematic scenario ambiguity resolution is more difficult due to the motion of the station and the satellites (even more challenging for real-time)

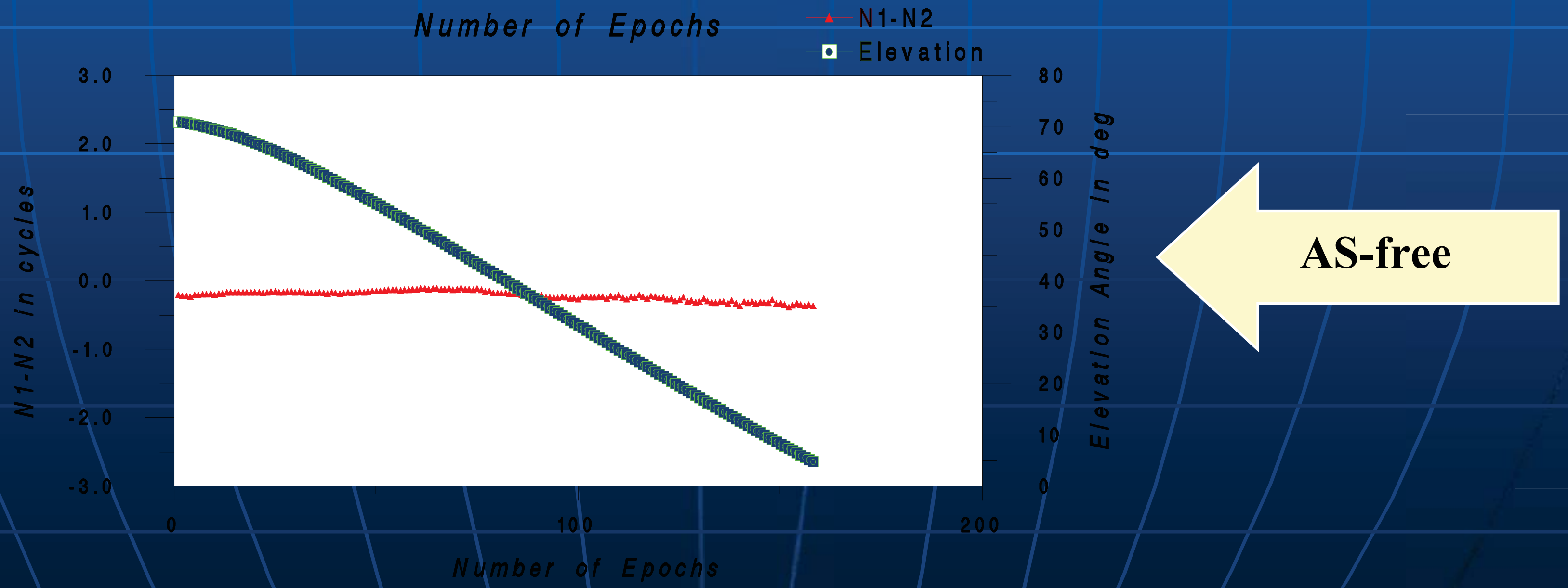
Real-time Precise Kinematic GPS Positioning

• **Exact determination of integer ambiguities is critical** (continued)

- It must be done On-The-Fly (OTF)
- It must be done fast
- Presence of Anti Spoofing (AS) may not allow for instantaneous ambiguity resolution using four-measurement filter (i.e. two carrier phase and two range observations) – longer and uninterrupted tracking is required to smooth the larger noise or some alternative techniques must be applied

Epoch-by-epoch widelane ambiguity N_1-N_2 combination





Real-time Precise Kinematic GPS Positioning

Solution strategy/conditions:

- Real-time ambiguity resolution
- Minimum of four satellites must be tracked (after ambiguities are solved)
- Least-squares batch solution
- Kalman filtering
- Uses data up to the epoch of observation
- Processes data only once

Post-processing of Kinematic GPS Data

Solution strategy/conditions:

- Minimum of four satellites must be tracked (after ambiguities are solved)
- Typically processes data twice
  - first run through the data determines integer ambiguities
  - second run estimates the rover positions
- Can directly use the real-time algorithms
- Least-squares batch solution
- Kalman filtering/smoothing
  - uses data up to the epoch of observation (filtering)
  - uses the whole dataset (smoothing)

Kinematic GPS positioning accuracy

Baseline length/multipath conditions		PDOP	
		Low (below 3)	High (3-5)
Long baseline 15-20 km	Low multipath	1-2 cm	2-4 cm
Short baseline <10 km	Medium multipath	1-2 cm	2-3 cm
Short baseline	Low multipath	mm-level	cm-level

Comparison of real-time and post-processing scenarios.

Positioning mode/attribute	Accuracy	Time	Navigation	Cost	Remote Locations	Portability
Post-processing	Advantage			Advantage		Advantage
Real time		Advantage	Advantage		Advantage	

Achievable DGPS accuracy compared to static and RTK GPS accuracy

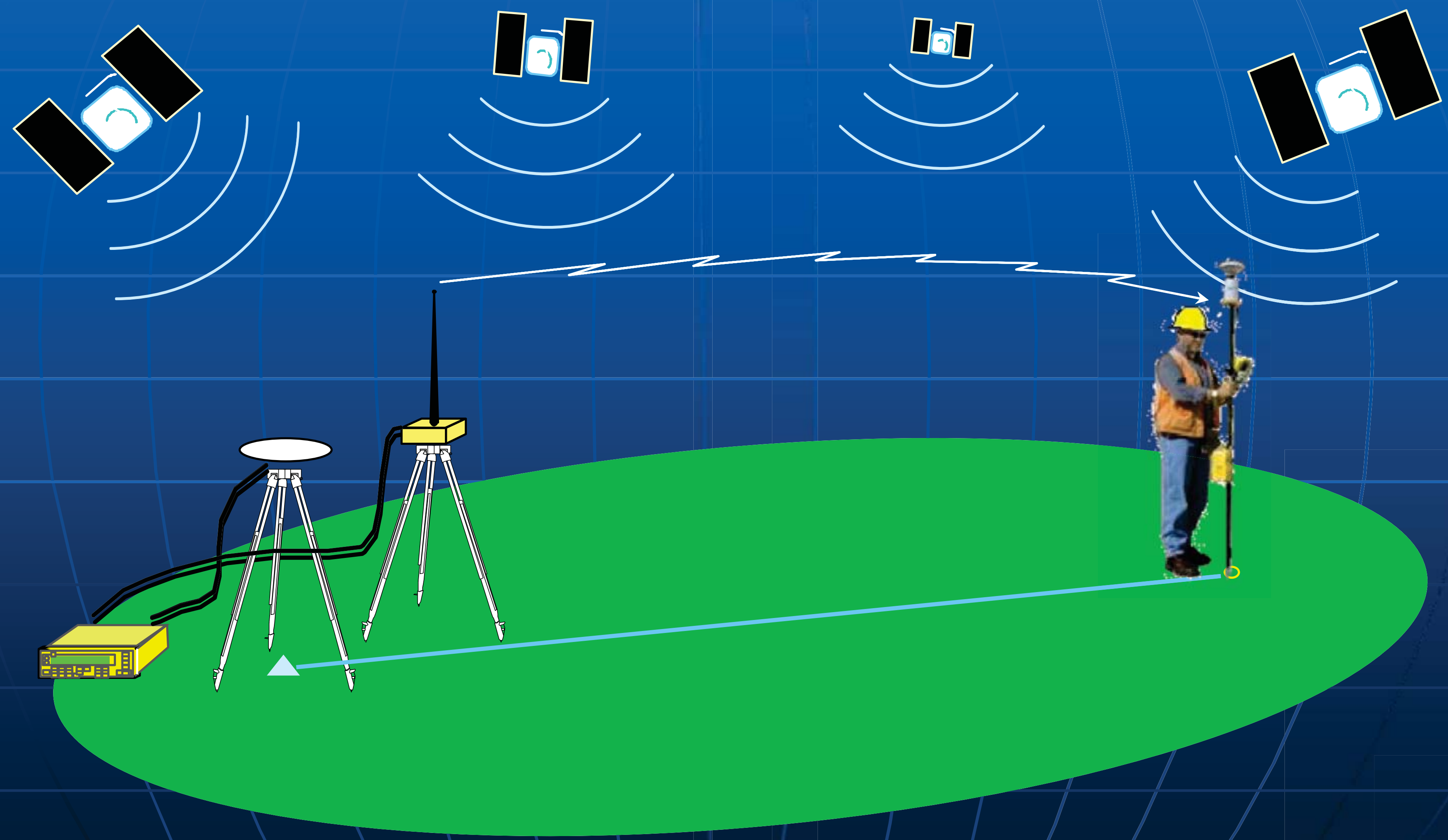
Correction type	Horizontal accuracy	Vertical accuracy
Single frequency WAAS	3-7 m*	3-7 m*
Dual frequency WAAS	< 50 cm	< 70 cm
StarFire™ (dual frequency)	< 10 cm	< 15 cm
IGDG (dual frequency)	< 50 cm	< 70 cm
Static (using NGS CORS)	5 mm**	5 mm**
Static (using base and rover)	5 mm**	5 mm**
RTK	1 cm**	2 cm**
Network-based RTK	5 mm**	10 mm**

*according to the WAAS specifications; however, much better accuracies (< 2m, even up to 30-70 cm) were reported, as explained in Section 8.7.2.1

** increases with the baseline length

Network-Based RTK GPS and Precise Point Positioning

Single-baseline RTK



Differential (relative) positioning

- Predominantly uses a single baseline solution
- Can be performed in post-processing
  - Highest accuracy (forward and backward processing possible)
  - Precise orbits and clocks from IGS* can be used
- Can be performed in real time = Real Time Kinematic (RTK)
  - Requires base-user (rover) communication
  - One-way data processing only (forward)
  - Usually radio modems are used
  - Limited to 10-20 km
    - To assure ambiguity resolution
    - To assure radio-communication
- Differential errors become significant with increasing base-rover separation
  - Ionosphere – 5-10 km cut-off
  - Troposphere – few tens of km cut-off (depends on the atmospheric conditions at both ends of the baseline)
  - Orbital errors – a few tens of km to ~100 km cut-off
  - Acceptable positioning error level depends on the application

* International GNSS Service

Network RTK – Concept and Benefits

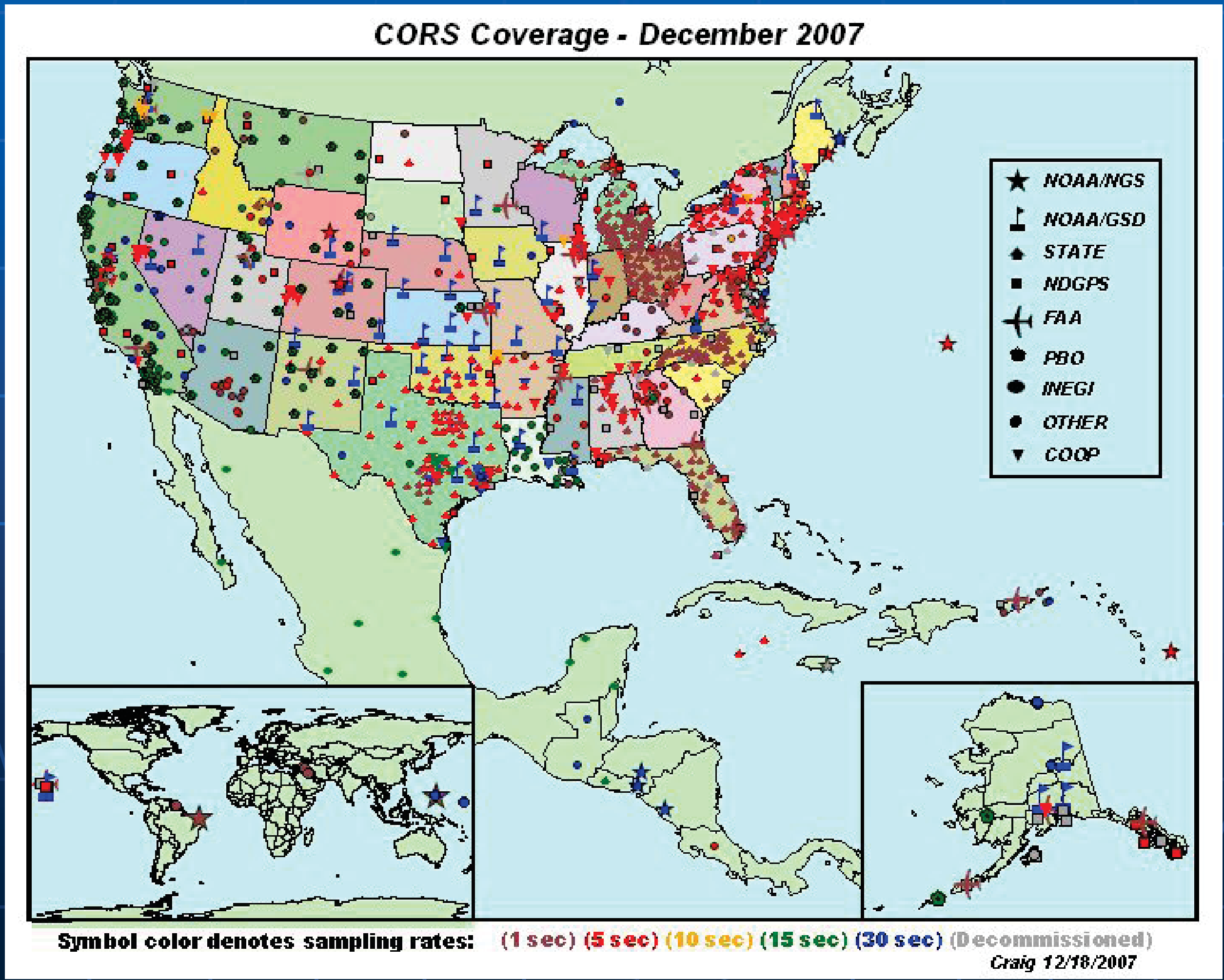
Traditional RTK (single baseline): limitations

- Limited to short distances (~10 km)
- Local reference station required
- Rover/Reference distance is limited due to error growth with the baseline length
  - Ionospheric and tropospheric refraction are the main error sources
- Reliability and performance decrease with the increasing distance from the reference base

Network RTK

- Atmospheric corrections are evaluated in the network and broadcast to the user receiver location
  - Speed up ambiguity resolution in the user's positioning solution
- Single or multi-baseline instantaneous rover solution
- Long distances – over 100 km
- Centimeter-level accuracy
- Suitable for geodetic, surveying and navigation applications
- Takes advantage of already available network GPS infrastructure
- Takes advantage of the IGS orbital products, in particular for long baselines (over 100 km)

CORS: Continuously Operating Reference Station Network



CORS in Ohio

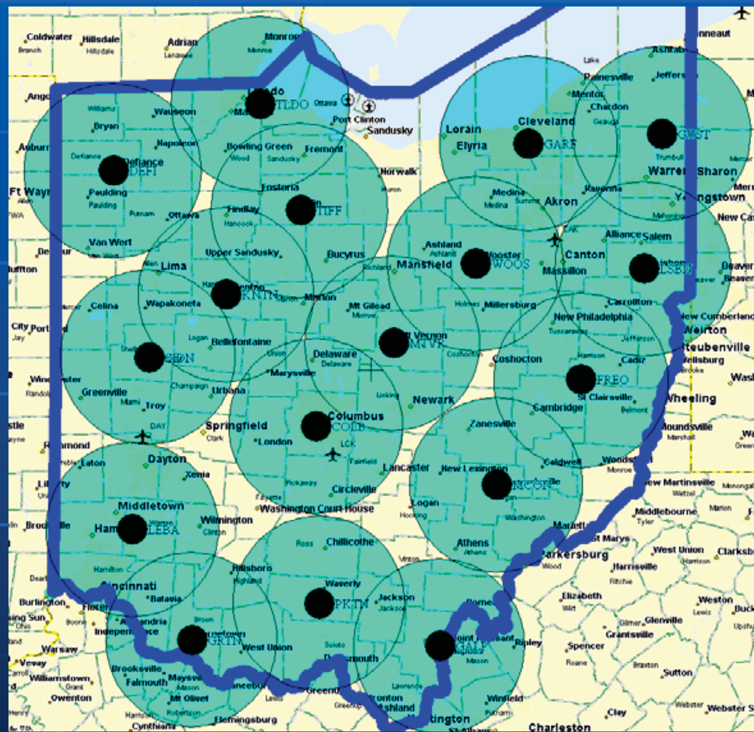

SIBY
MIDD
ADRI
MICW
MIHD
MIMO
OHAS
OHLU
TLDO
OHMH
OHCD
GUST
OHWI
OHFN
BGOH
GARF
ZOB1
DEFI
OHHU
OHLO
OHPO
OHHA
TIFF
GVFD
OHMN
STRS
SCSO
OHVW
OHAL
OHRI
WOOS
MASS
WPCC
LSBN
KNTN
OHMR
OHJE
OHTU
MTVR
SIDN
OHUN
OHCO
FREO
OHDR
OHCL
COLB
OHLI
OHMO
OHDT
OHMD
OHPR
MCON
LEBA
OHFA
OHWA
OHRO
STKR
OHAT
GALB
OHHI
PKTN
GSSP
KYBO
ERLA
GRTN
OHAD
GALP
WVRA
LOYE
KYTI
KYAS
WVHU

Ohio Department of Transportation (ODOT)

- Closest – Designation Columbus CORS (COLB).
- USGS Quadrangle Map – Southwest Columbus (1995).
- It is a CORS "Classic" Station.

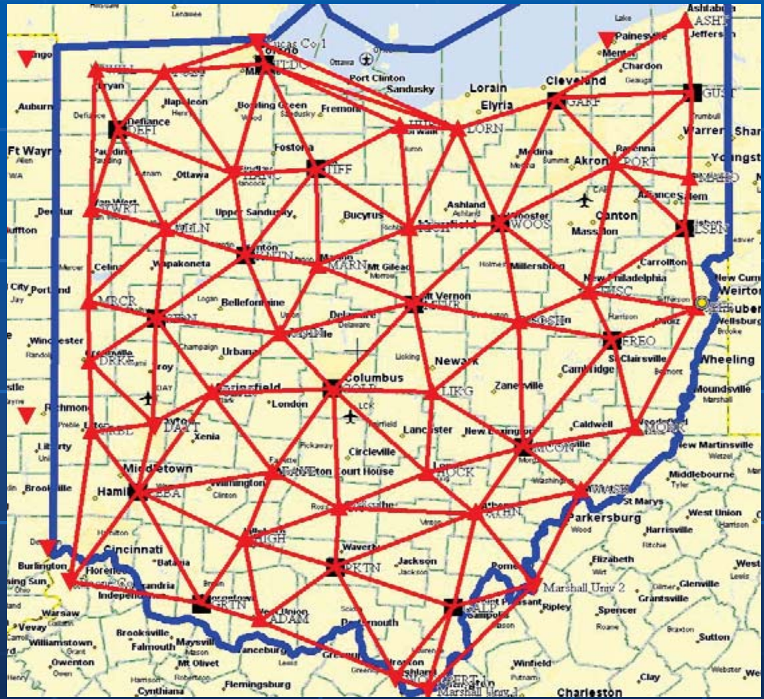
ODOT Phase 1 & 2 CORS

- 17 Stations scattered across the State all located at ODOT facilities.
- Concrete Antenna Pillar.
  - 8 ft. tall
  - 10 to 12 ft deep base
  - 36” diameter below grade
  - Steel reinforced throughout



CORS Classic

ODOT Phase 3 & 4 CORS



CORS "Light" – 29 Additional Stations
Installed Throughout the State – Full Coverage

Network RTK – Basic characteristics

- Three distinct steps in Network RTK
  - Ambiguity fixing within reference network
    - Only observations with fixed integers can be used for precise modeling of the distance-dependent errors
    - Station coordinates are precisely known
    - Station separation 100-200 km*
  - Correction (error model) estimation
    - Ionospheric and orbit biases must be modeled for each satellite
    - Tropospheric errors are modeled for each station
    - Ionospheric errors show largest temporal variations
    - Formation of synthetic reference observations (virtual reference station (VRS) approach) using the estimated corrections, and transmitting them to the user, or
    - Transmitting the corrections and one (or multiple) reference station data to the user
  - Rover (user) positioning solution performed by the user receiver

* In the OSU solution

The Available IGS products

IGS Product Table [GPS Broadcast values included for comparison]					
		Accuracy	Latency	Updates	Sample Interval
GPS Satellite Ephemerides/ Satellite & Station Clocks					
Broadcast	orbits	~160 cm	real time	--	daily
	Sat. clocks	~7 ns			
Ultra-Rapid (predicted half)	orbits	~10 cm	real time	four times daily	15 min
	Sat. clocks	~5 ns			
Ultra-Rapid (observed half)	orbits	<5 cm	3 hours	four times daily	15 min
	Sat. clocks	~0.2 ns			
Rapid	orbits	<5 cm	17 hours	daily	15 min
	Sat. & Stn. clocks	0.1 ns			5 min
Final	orbits	<5 cm	~13 days	weekly	15 min
	Sat. & Stn. clocks	<0.1 ns			5 min

Note 1: IGS accuracy limits, except for predicted orbits, based on comparisons with independent laser ranging results. The precision is better.
Note 2: The accuracy of all clocks is expressed relative to the IGS timescale, which is linearly aligned to GPS time in one-day segments.

http://igscb.jpl.nasa.gov/components/prods.html

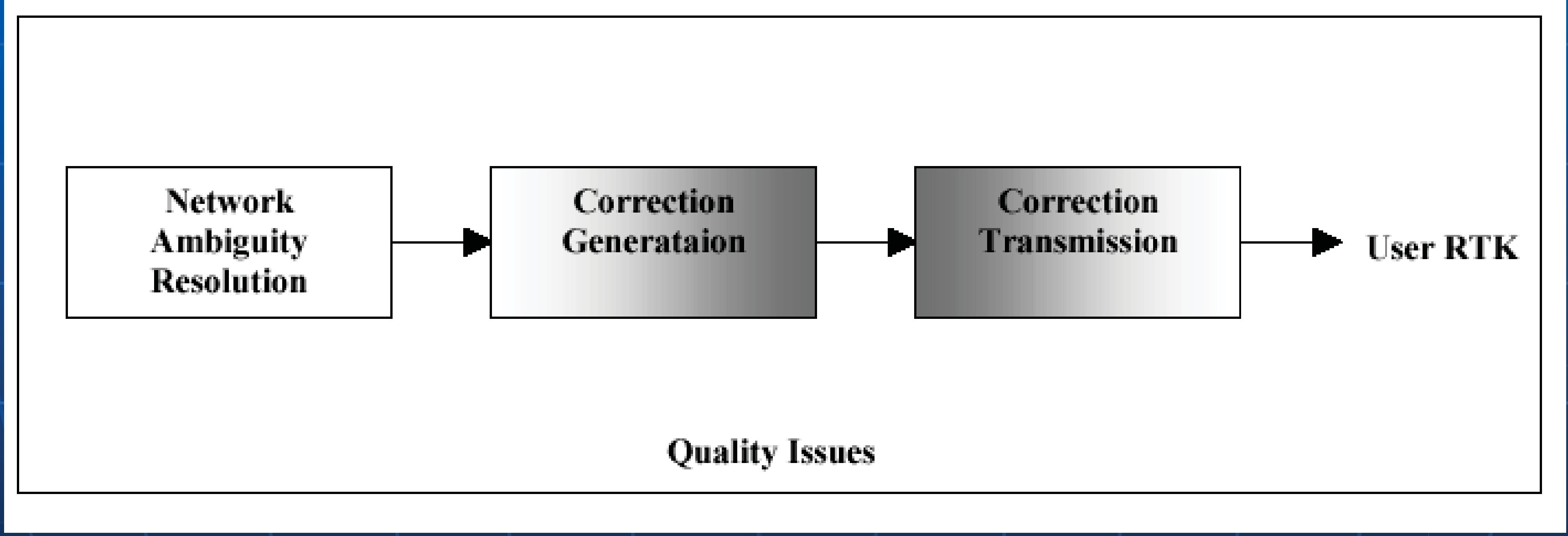
The Available IGS products

	Accuracy	Latency	Updates	Sample Interval
Atmospheric Parameters				
Final tropospheric zenith path delay	4 mm	< 4 weeks	weekly	2 hours
Ultra-Rapid tropospheric zenith path delay	6 mm	2-3 hours	every 3 hours	1 hour
Final Ionospheric TEC grid	2-8 TECU	~11 days	weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)
Rapid Ionospheric TEC grid	2-9 TECU	<24 hours	daily	2 hours; 5 deg (lon) x 2.5 deg (lat)

- IGS also provides GLONASS orbits
- Earth Rotation Parameters (ERPs): polar motion (PM)+rate (PM rate), and length-of-day (LOD)
- Geocentric coordinates of IGS sites (~130)

http://igscb.jpl.nasa.gov/components/prods.html

Multi-reference station modules for RTK positioning



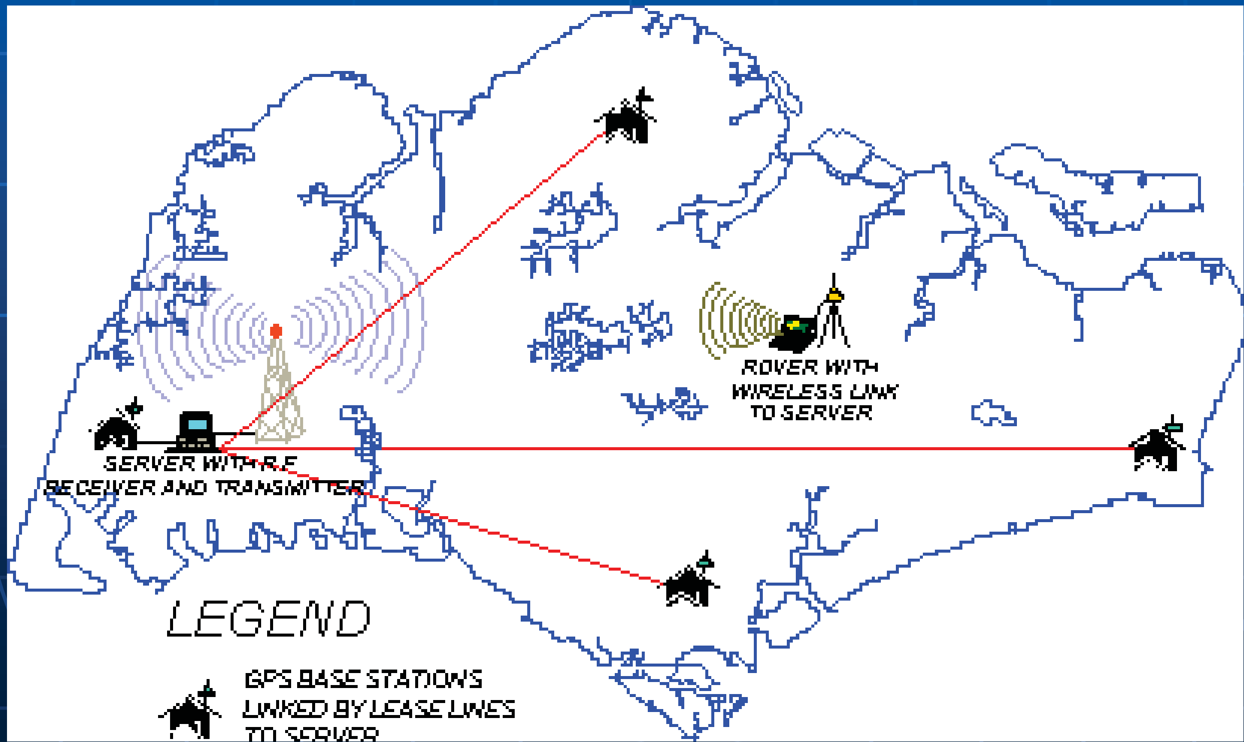
Network-RTK: data management system and data communication system

Three possible architectures:

(1) Generation of VRS and its correction/synthetic data

(2) Generating and broadcasting network-RTK corrections

(3) Broadcasting raw data for all the reference stations



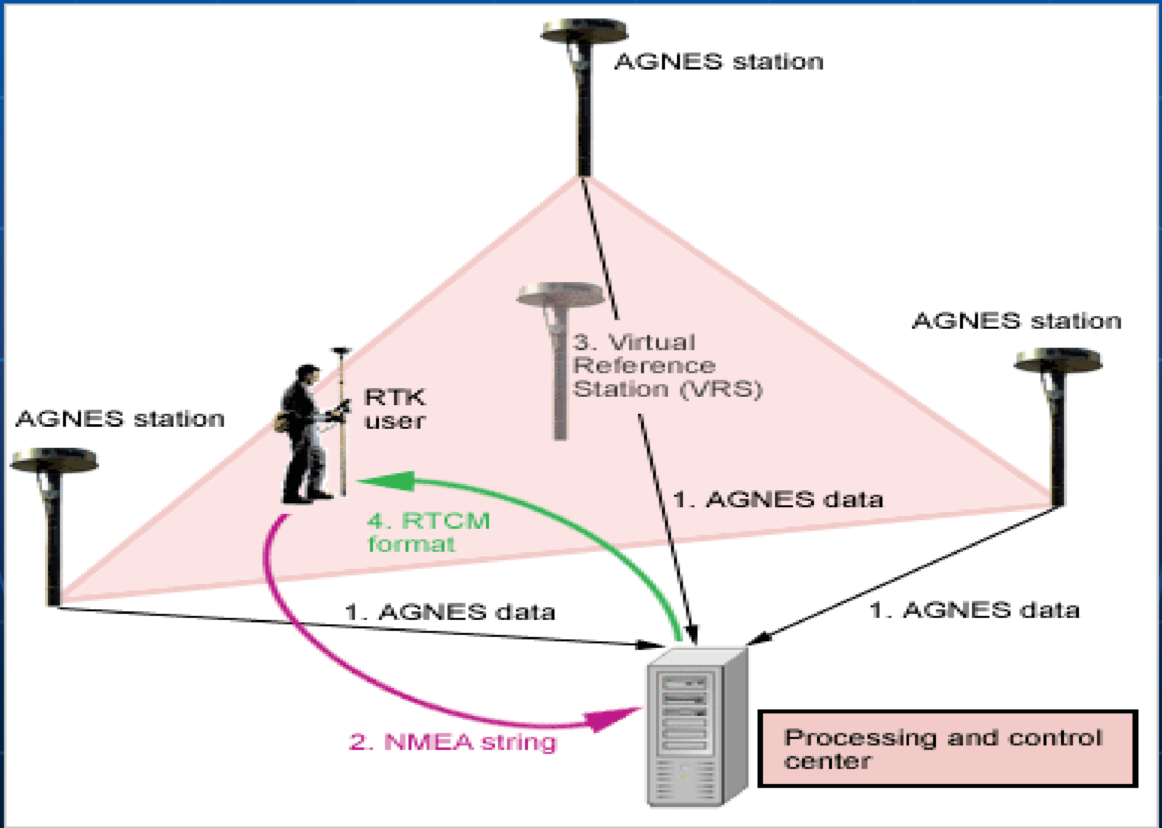
VRS- virtual reference station

Network-RTK: data management system and data communication system

- Virtual Reference Station
  - VRS can be generated when the server knows where the user is
  - Two-way communication is required
  - Limitation on the number of simultaneous users
- Correction Broadcasting
  - Corrections for each satellite at each reference stations are generated
  - One-way communication is sufficient
  - No limit on the number of users
  - Requires a new data format, the volume of transmitted data is substantial
- Raw Data Broadcasting
  - Broadcast raw measurements (either server or multiple reference stations)
  - Generate VRS, or corrections at rover site
  - One-way communication is sufficient
  - No limit on the number of users
  - Rover is completely independent of the reference station network provider

VRS definition

- A virtual reference station is an imaginary, unoccupied reference station, which is only a few meters away from the RTK users
- Observation data are created from the data of the surrounding reference stations as though they had been observed on that position by a GPS receiver



The National Marine Electronics Association (NMEA) has developed a specification that defines the interface between various pieces of marine electronic equipment.

Radio Technical Commission for Maritime Services (RTCM), a committee that governs standards for passing data between different equipment used in the Marine Electronics Industry. The RTCM Special Committee No. 104 established "Recommended Standards for Differential Navstar GPS Service (http://www.rtcm.org/)

RTCM, CMR and CMR+ are formats for broadcast RTK data

VRS - How does it work?

- Uses observations from multiple reference stations
- Continuously monitors integrity of reference station data
- Models systematic errors including:
  - ionosphere
  - troposphere
  - satellite orbit errors
  - multipath
- Creates a unique virtual reference station for each user's location
- Delivers the data in RTCM*/CMR+ format to the rover

* Radio Technical Commission for Maritime Services (RTCM), a committee that governs standards for passing data between different equipment used in the Marine Electronics Industry. The RTCM Special Committee No. 104 established "Recommended Standards for Differential Navstar GPS Service (http://www.rtcm.org/)

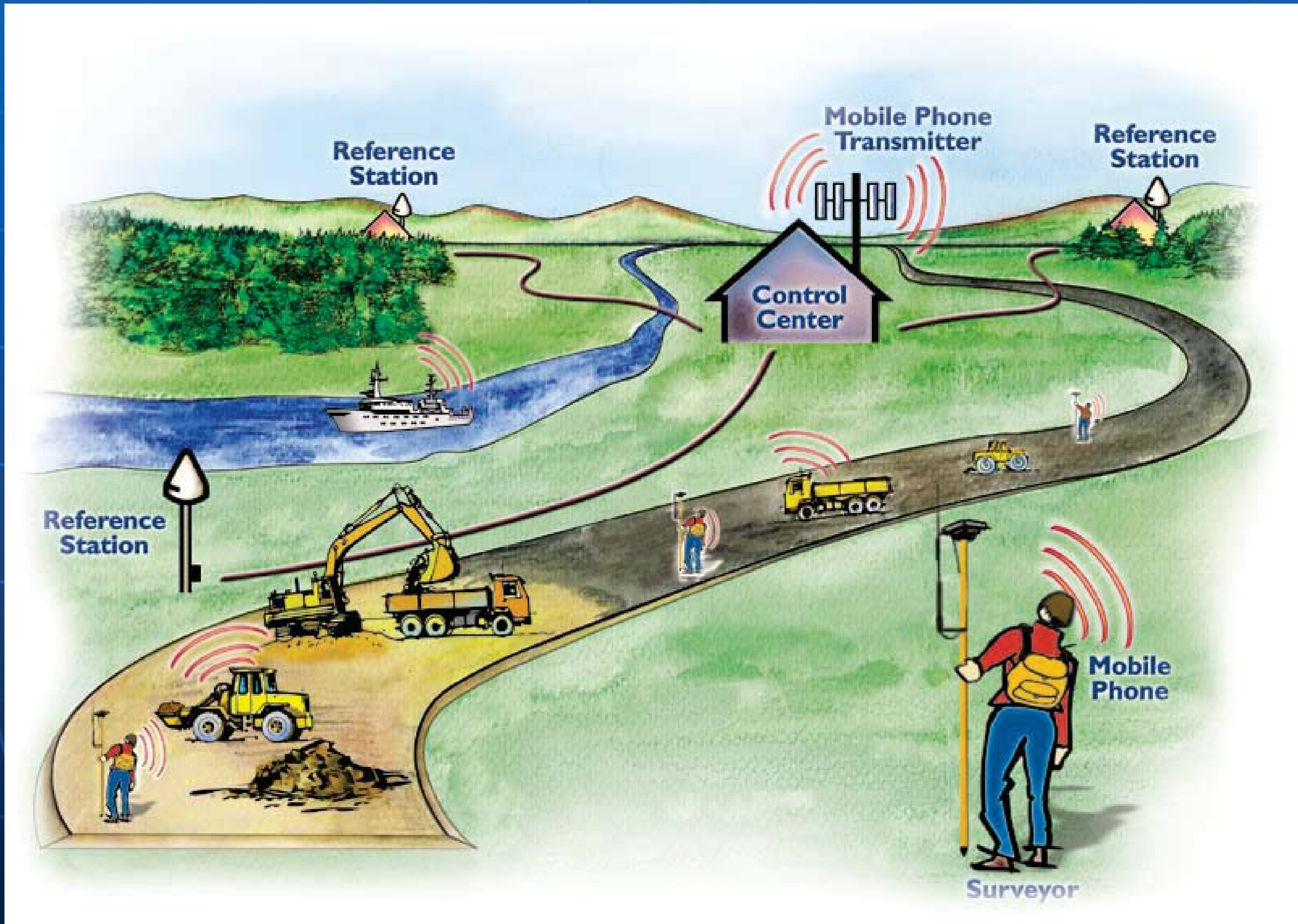
RTCM, CMR and CMR+ are formats for broadcast RTK data

Why use VRS?

- Extended operating range with improved initialisation and accuracy
- Increased productivity
- Eliminates need to establish reference station
  - Set-up, power, physical security become non-issues
- Provides integrity monitoring
- All users in common, established coordinate frame
- Eliminates dependency on single reference station
- Uses established communications

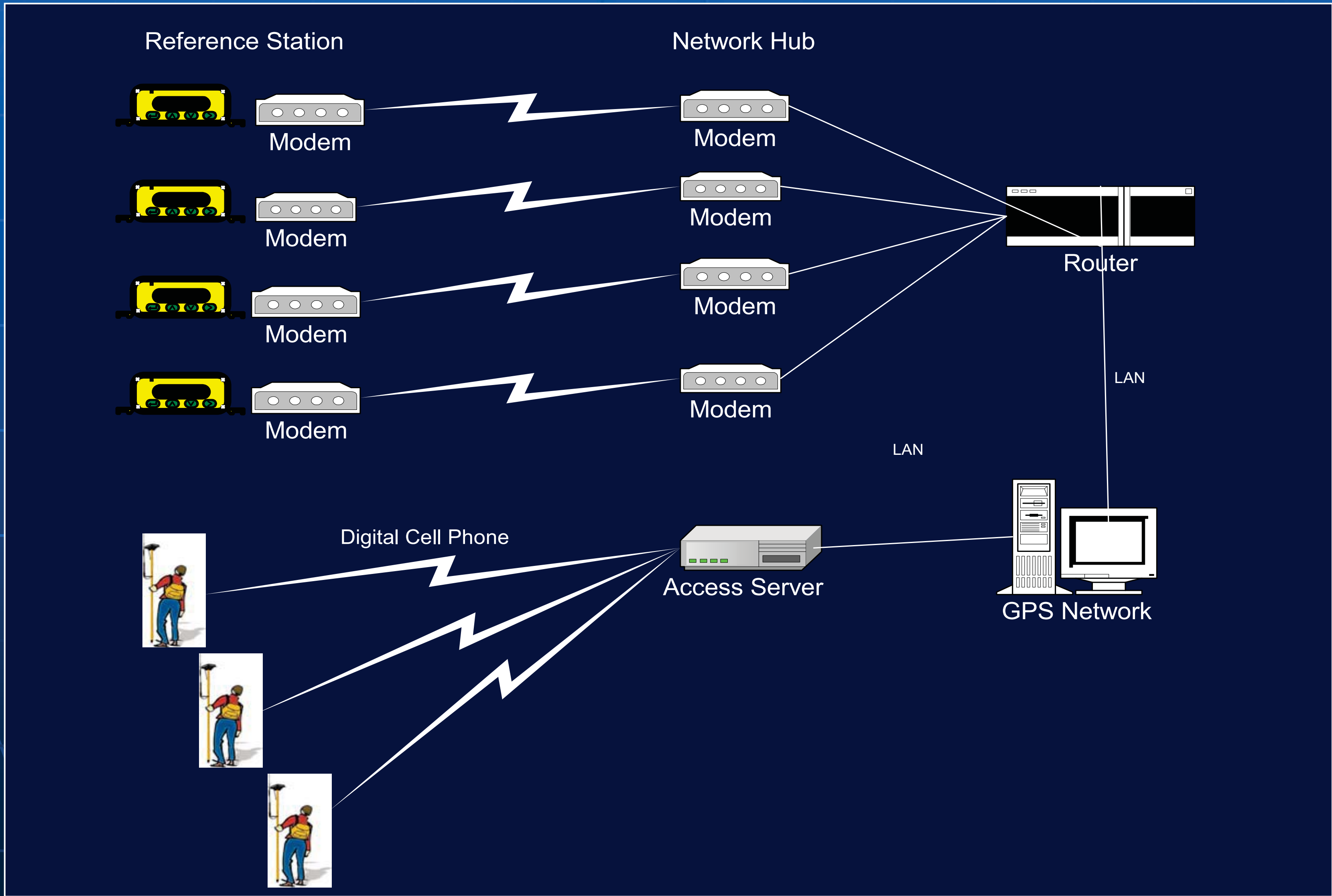
Courtesy: Trimble Navigation Ltd.

Example Setup for Construction Site



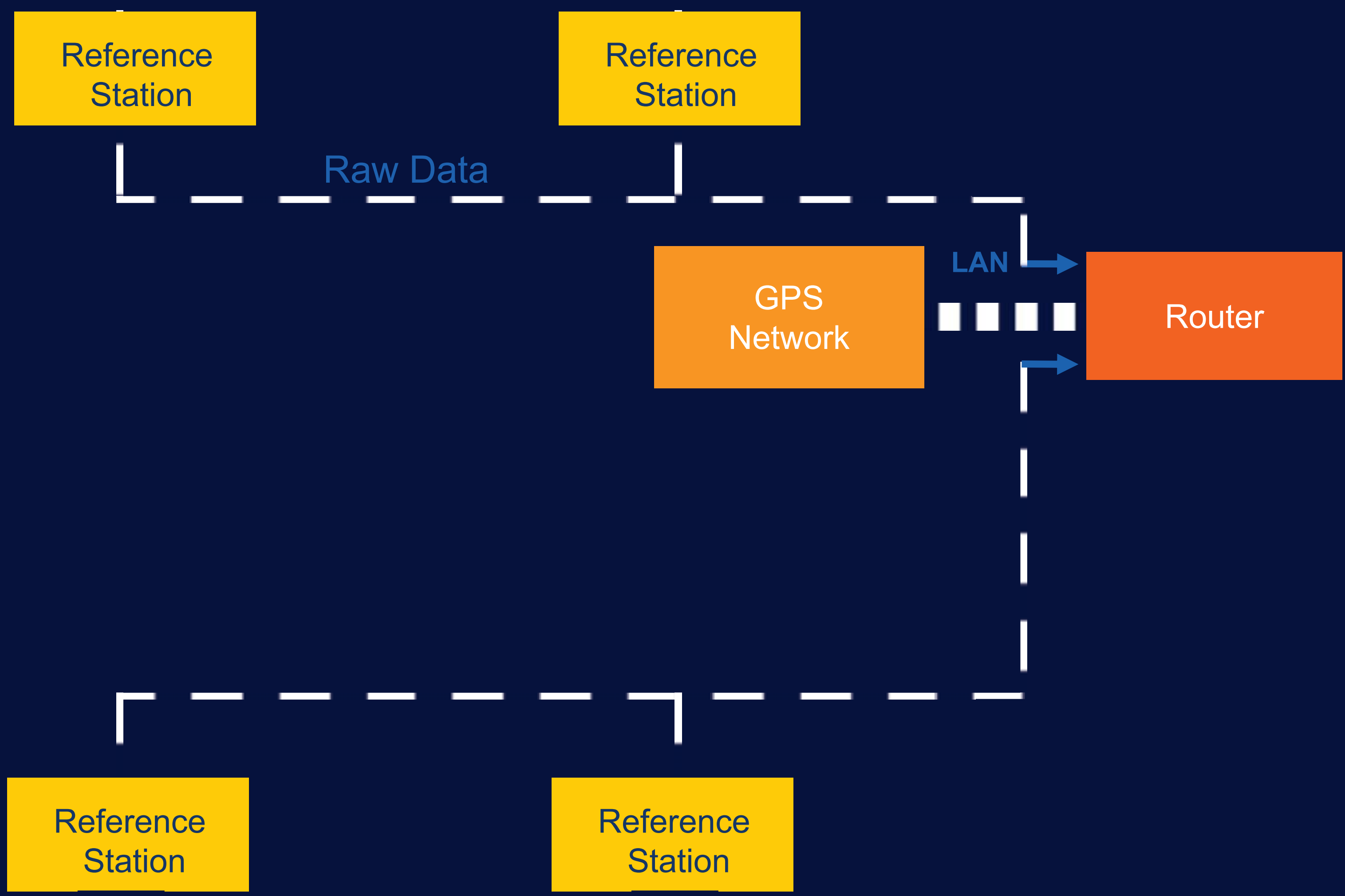
Courtesy: Trimble Navigation Ltd.

Data Communication



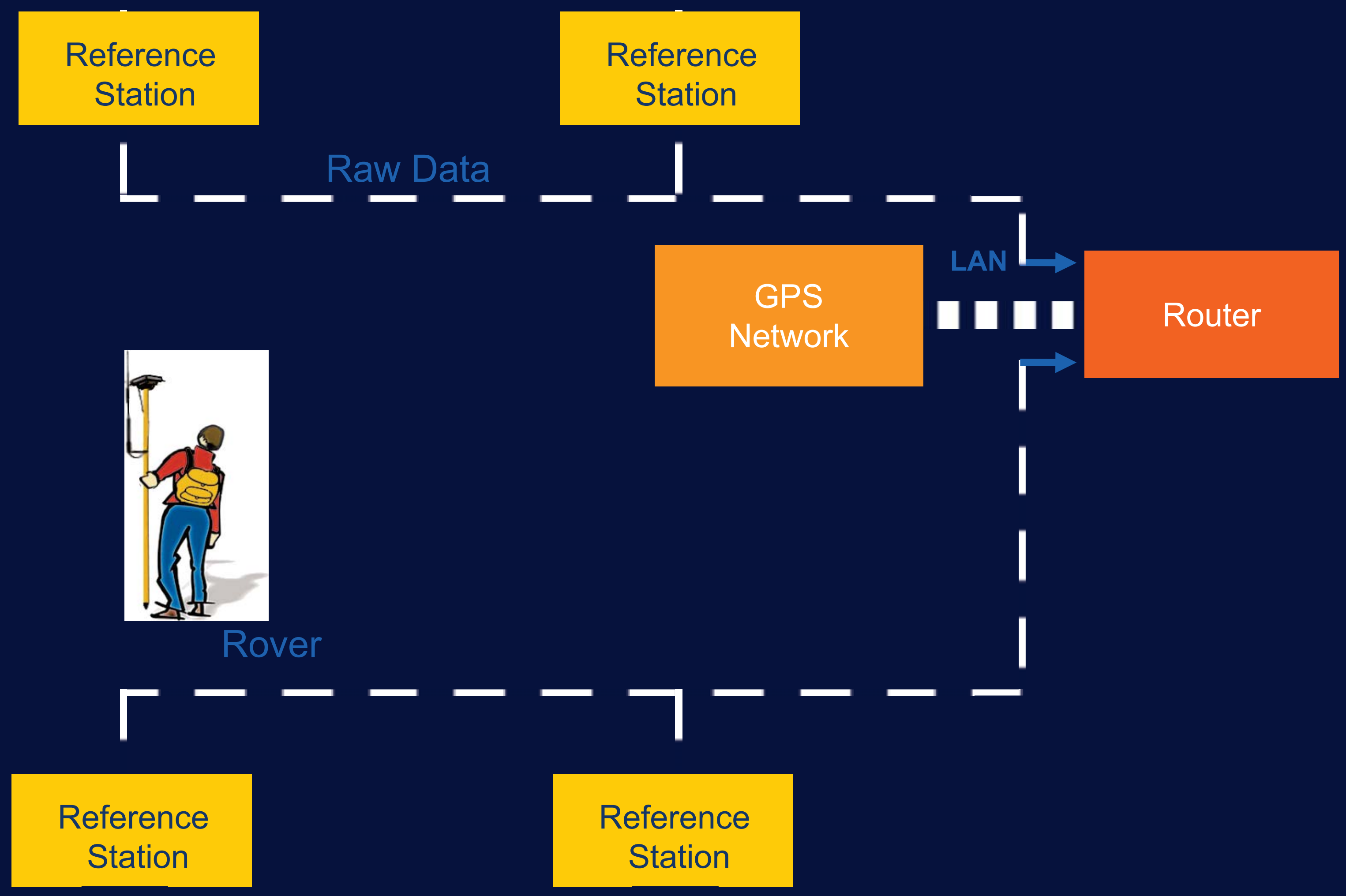
Courtesy: Trimble Navigation Ltd.

Data Flow in Network using digital cell phone



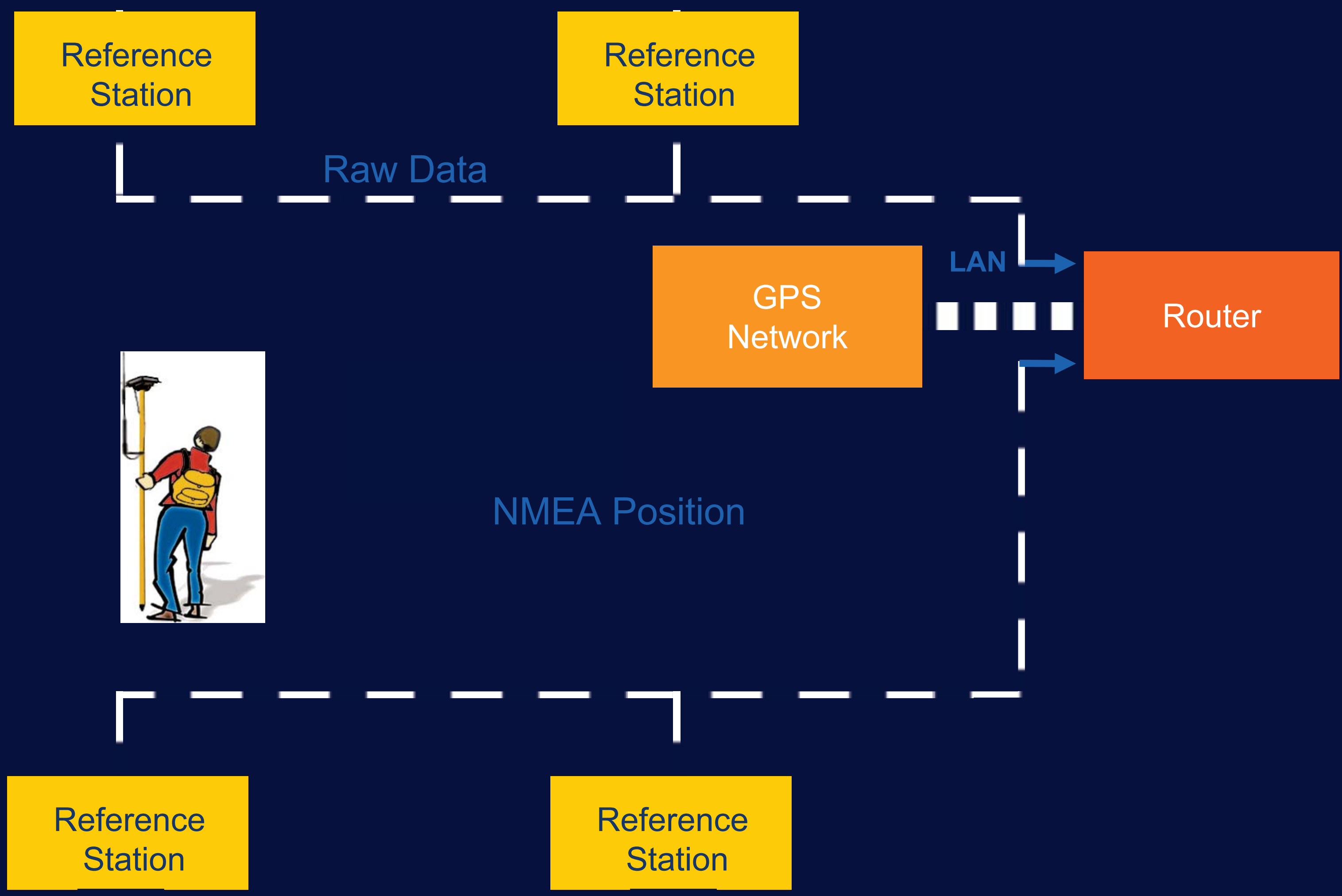
Courtesy: Trimble Navigation Ltd.

Data Flow in the Network



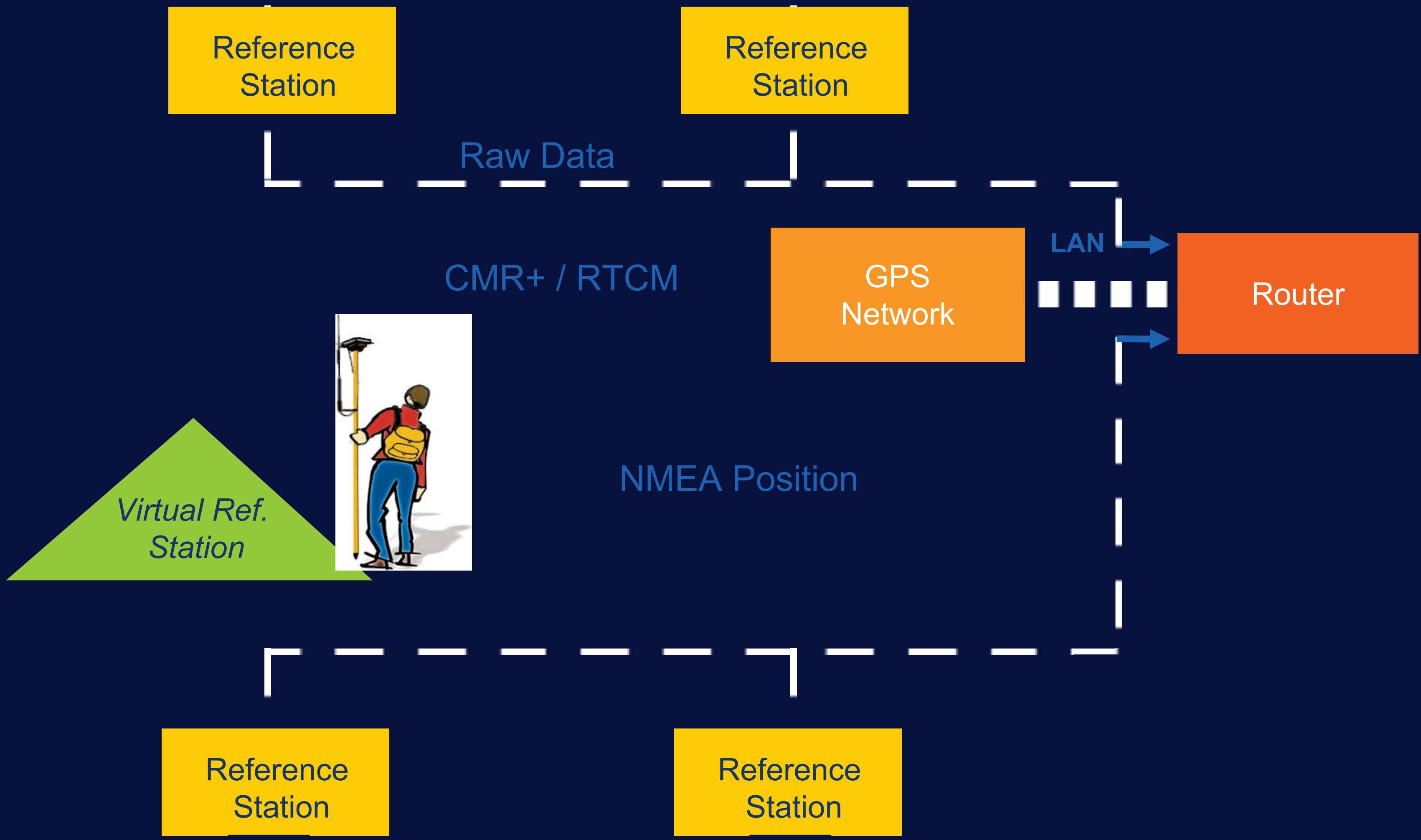
Courtesy: Trimble Navigation Ltd.

Data Flow in the Network



Courtesy: Trimble Navigation Ltd.

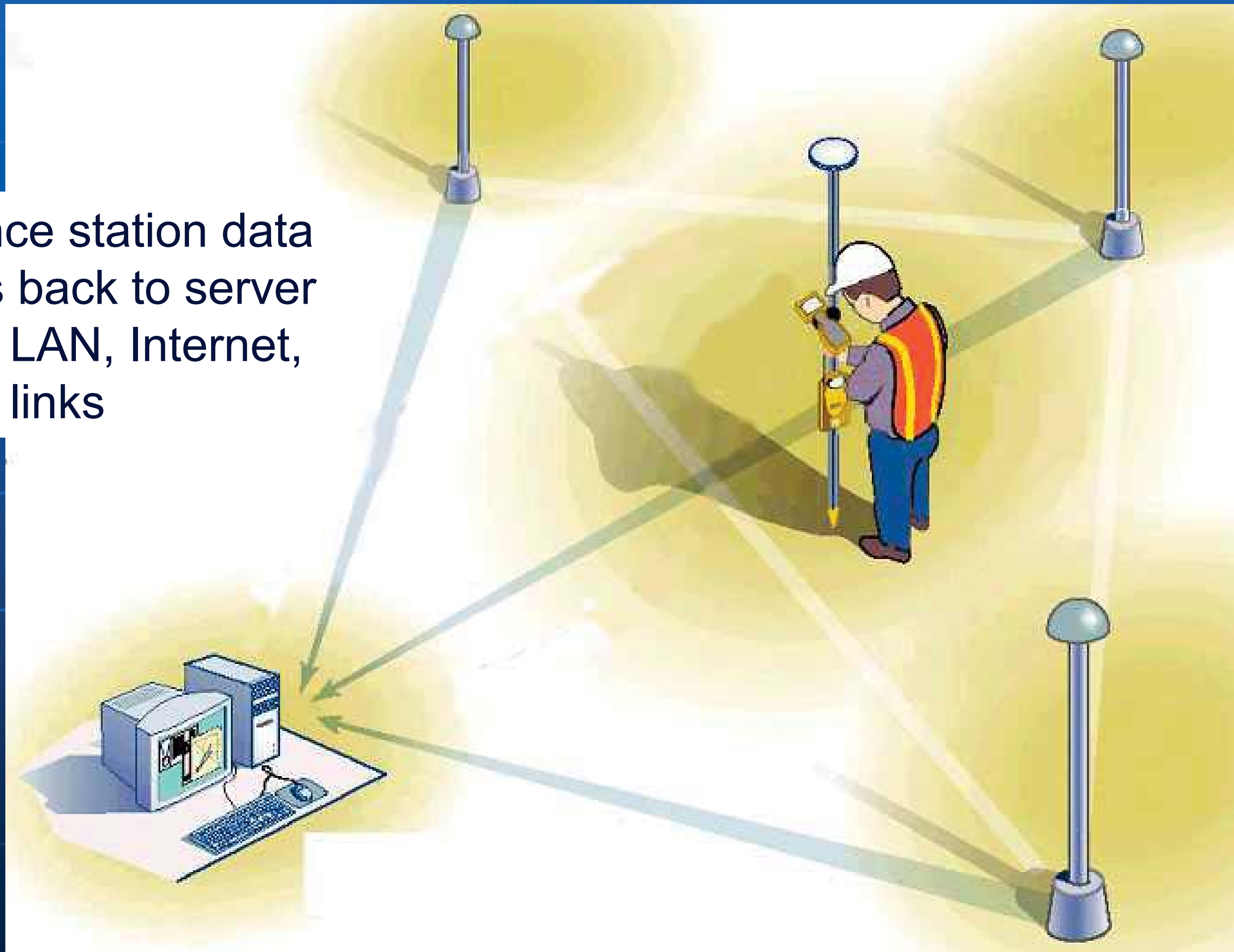
Data Flow in the Network



Courtesy: Trimble Navigation Ltd.

VRS Data Flow

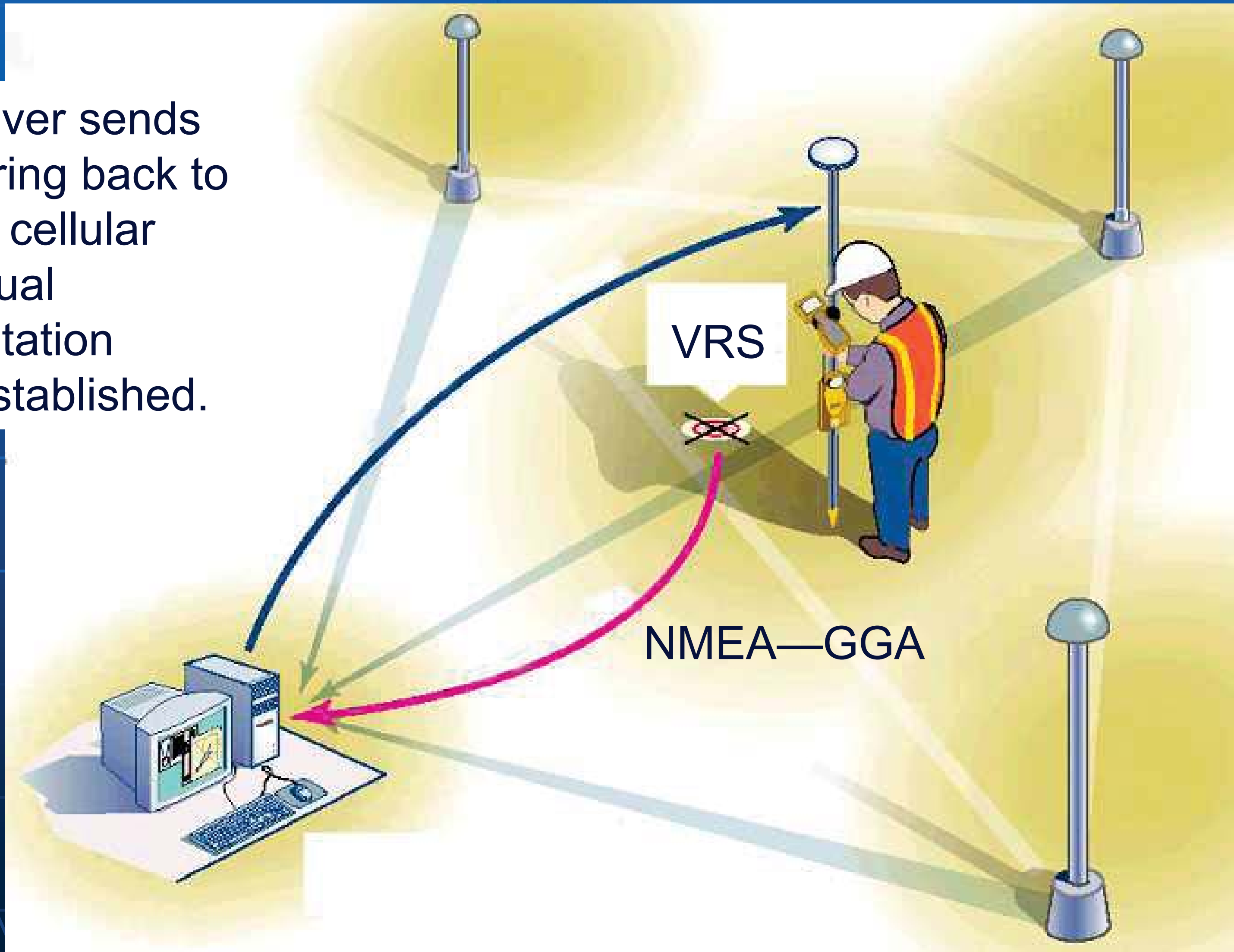
Reference station data streams back to server through LAN, Internet, or radio links



Courtesy: Trimble Navigation Ltd.

VRS Data Flow

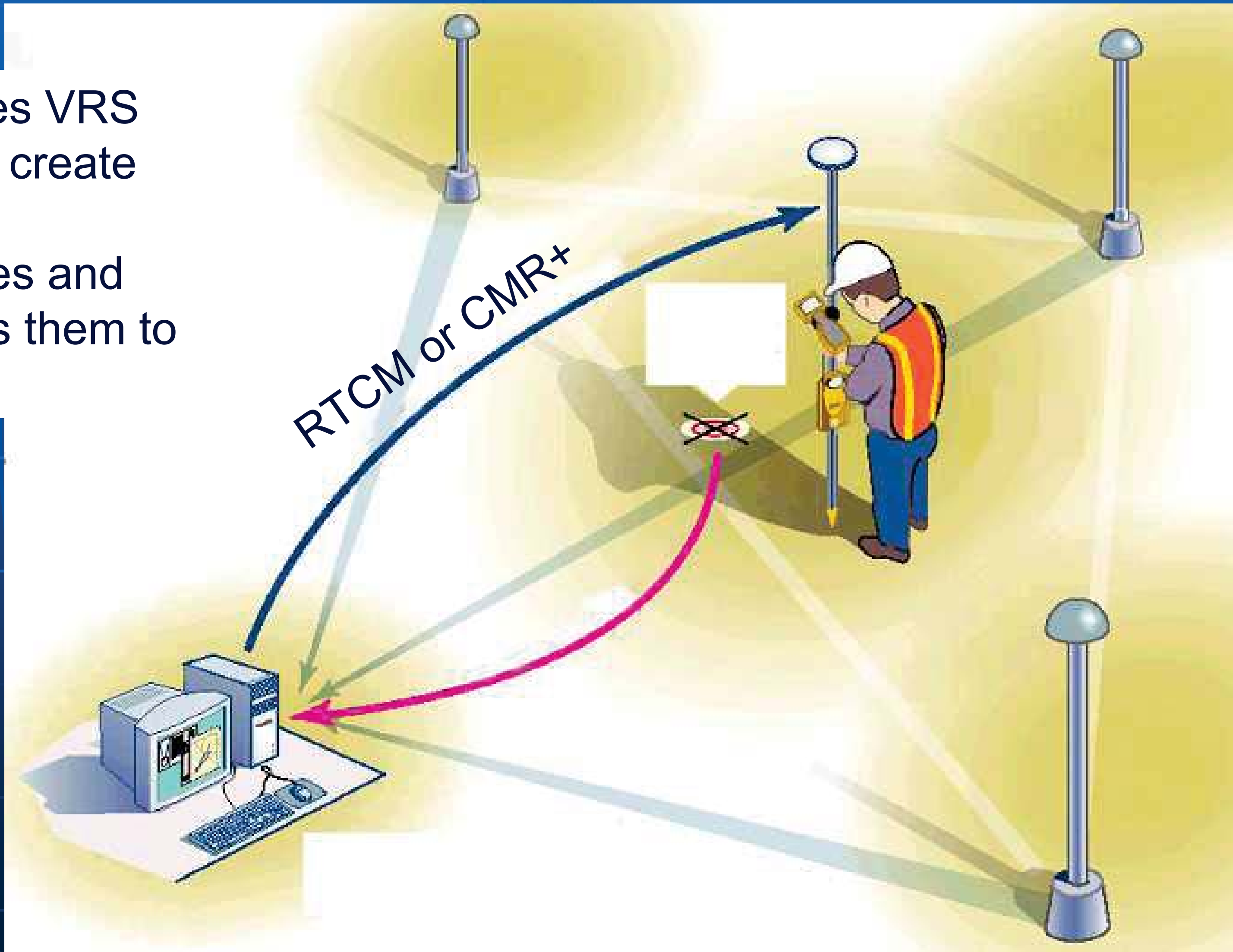
Roving receiver sends an NMEA string back to server using cellular modem. Virtual Reference Station position is established.



Courtesy: Trimble Navigation Ltd.

VRS Data Flow

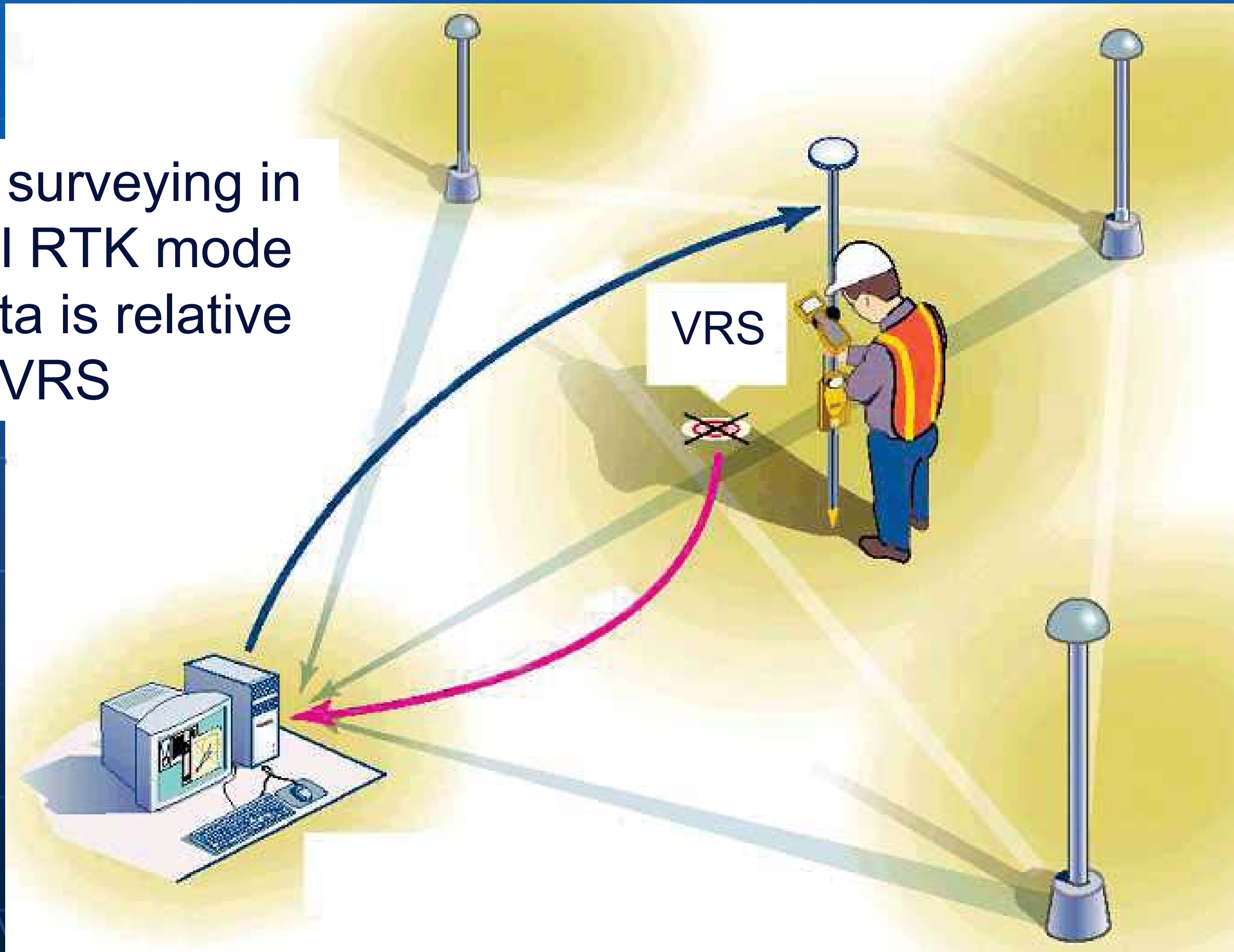
Server uses VRS position to create corrected observables and broadcasts them to the rover



Courtesy: Trimble Navigation Ltd.

VRS Data Flow

Rover surveying in normal RTK mode but data is relative to the VRS



Courtesy: Trimble Navigation Ltd.

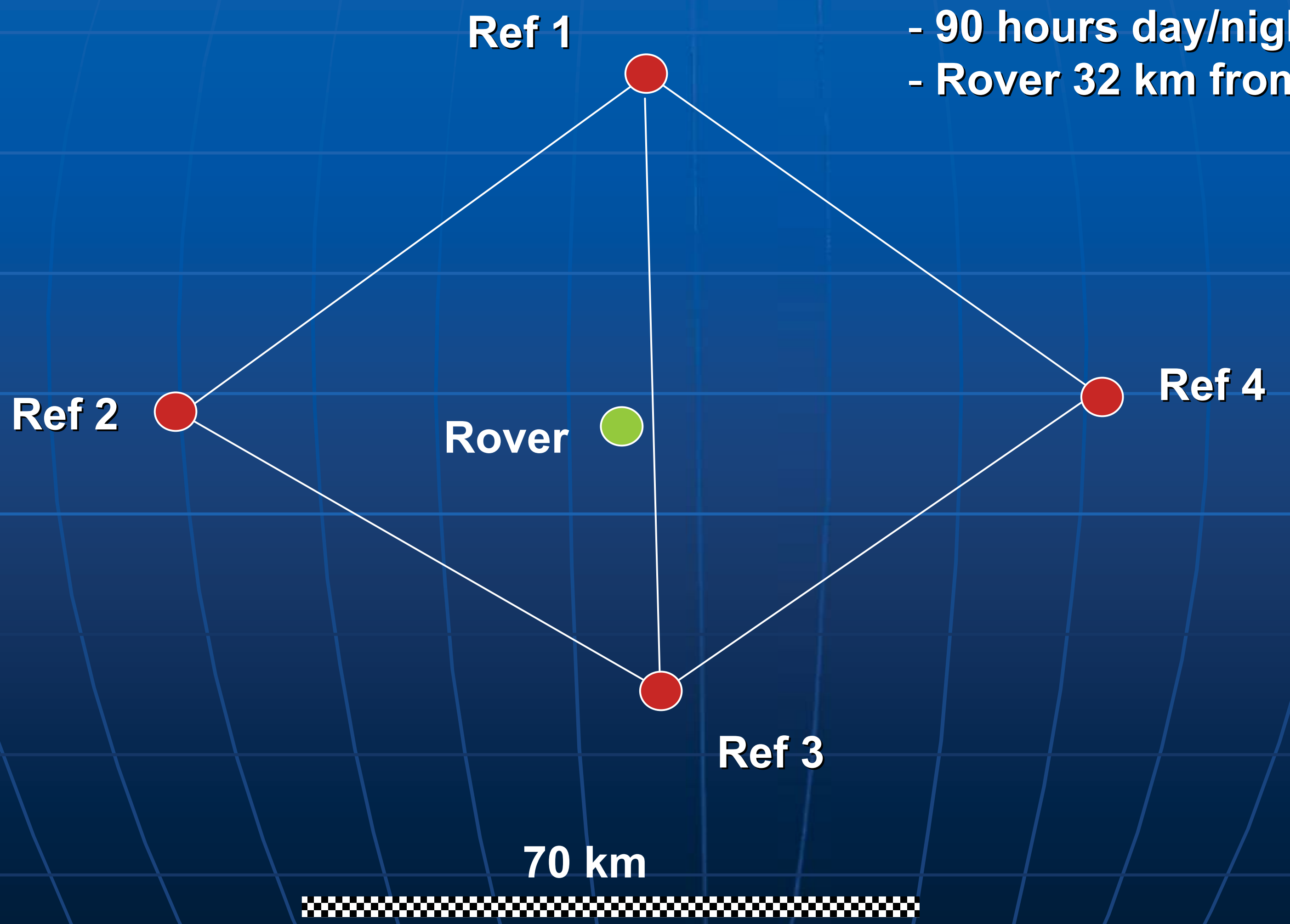
Example Hardware at Reference Station

- Dual Frequency GPS Receiver – e.g. Trimble NetRS™ or 5700 CORS GPS receivers
- Zephyr Geodetic™ Antennas
- Power supply with UPS (Uninterruptible Power Supply)
- Trimble GPSNet Software
- Trimble RTKNet Software
- Real-time continuous communication line to Control Center (min 9600 baud, max 1 second latency)

Courtesy: Trimble Navigation Ltd.

http://www.trimble.com/vrs.shtml

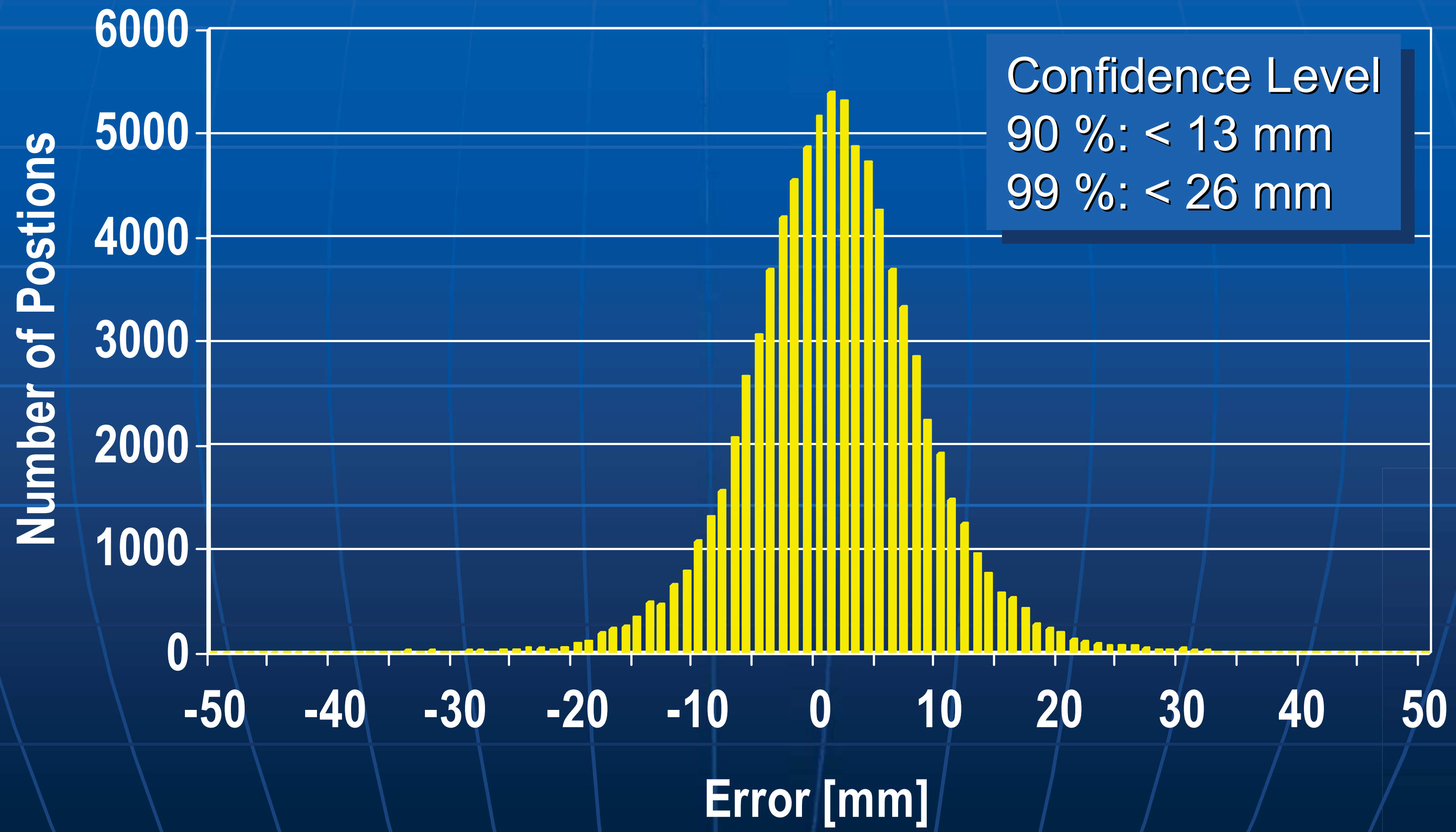
VRS Performance Analysis: Trimble example



- 90 hours day/night
- Rover 32 km from Ref 3

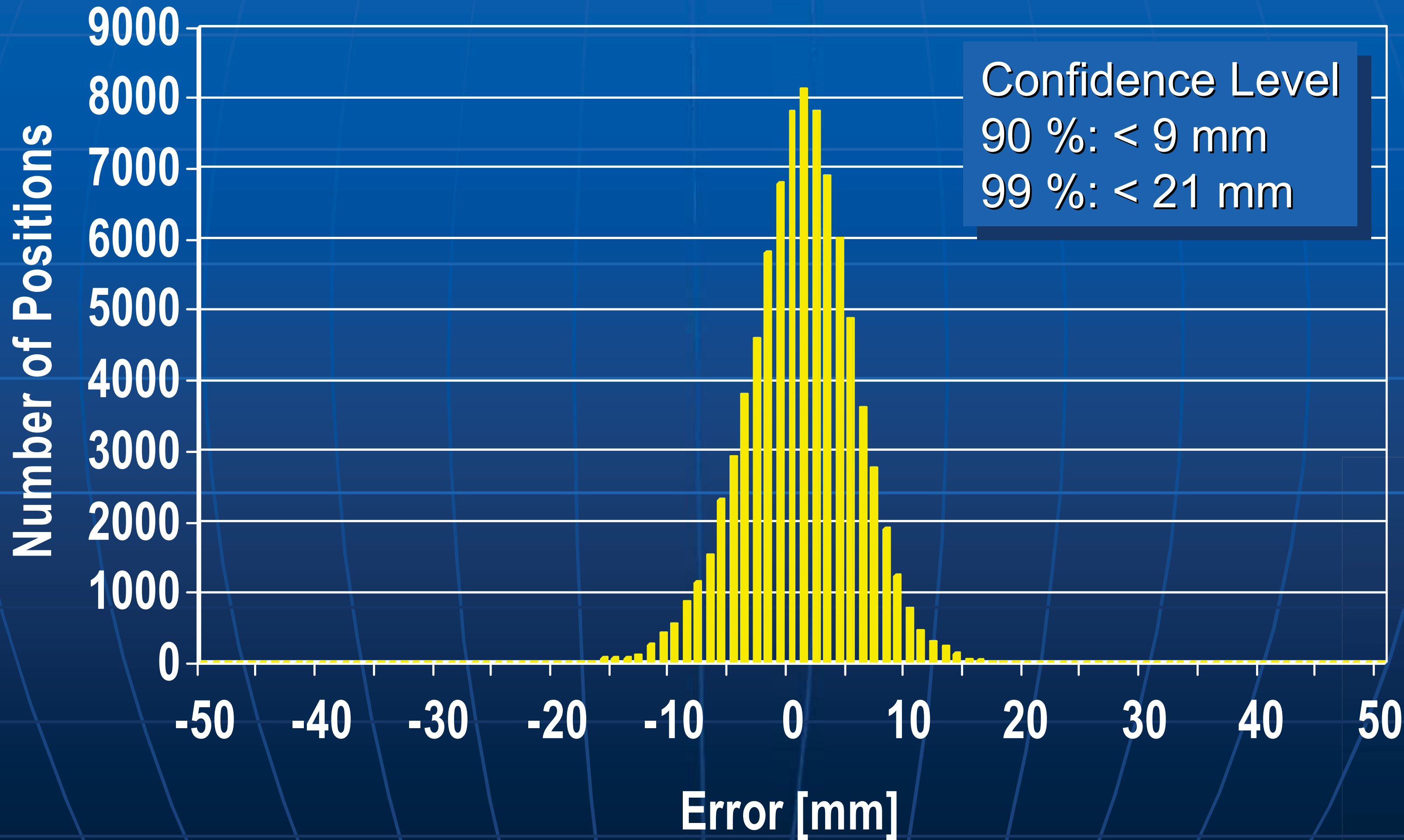
Courtesy: Trimble Navigation Ltd.

Error in North – 32 km Baseline



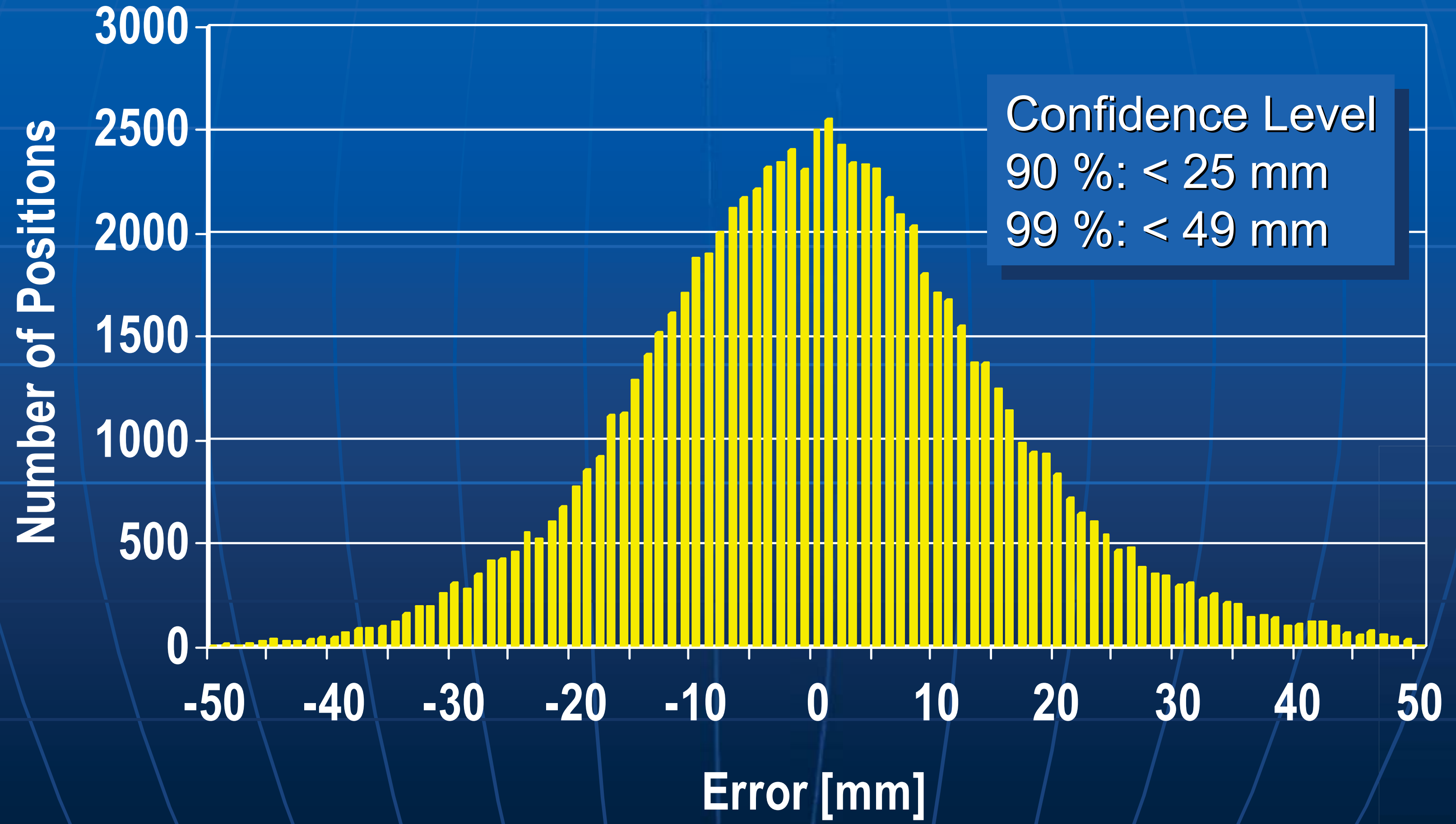
Courtesy: Trimble Navigation Ltd.

Error in East – 32 km Baseline



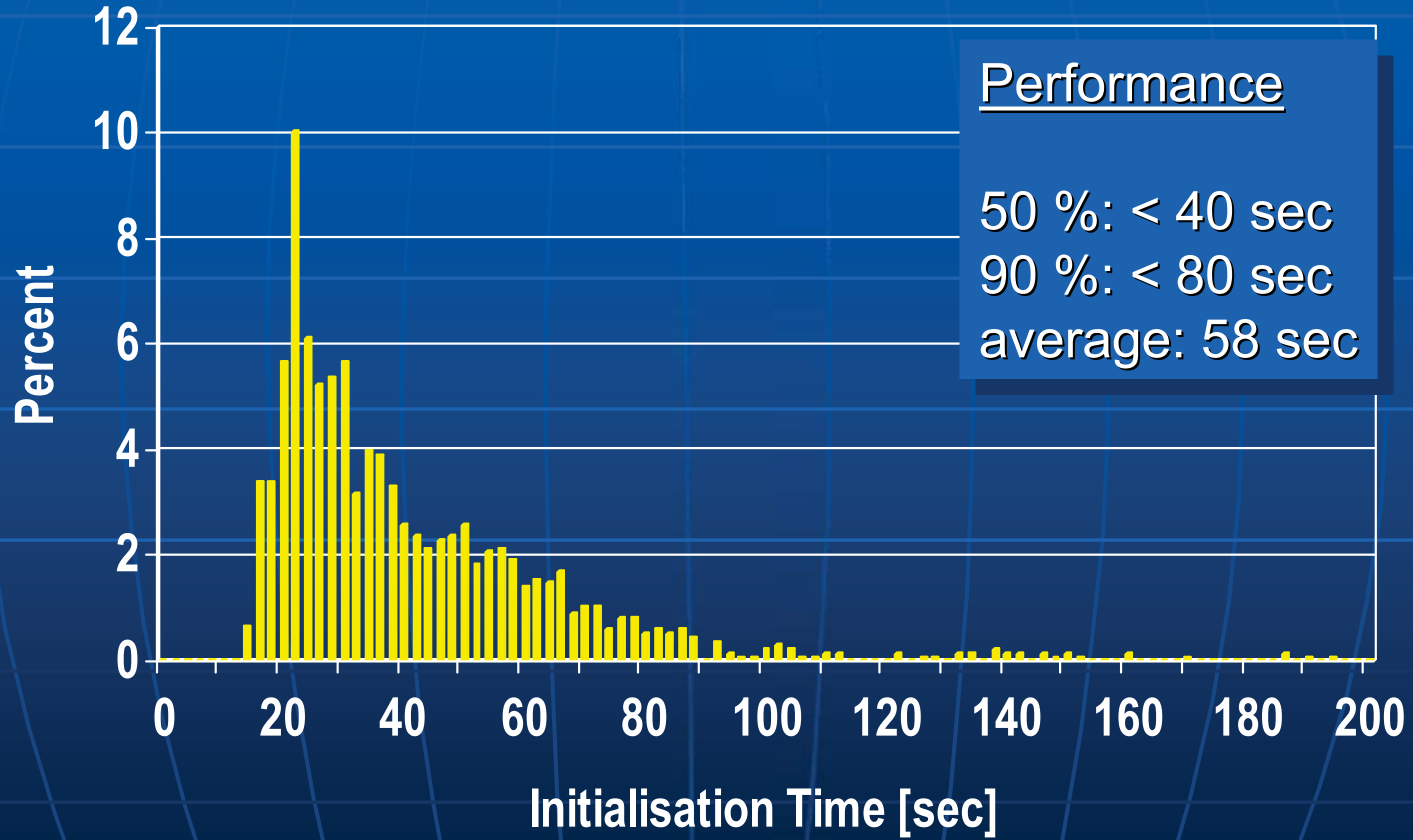
Courtesy: Trimble Navigation Ltd.

Error in Height – 32 km Baseline



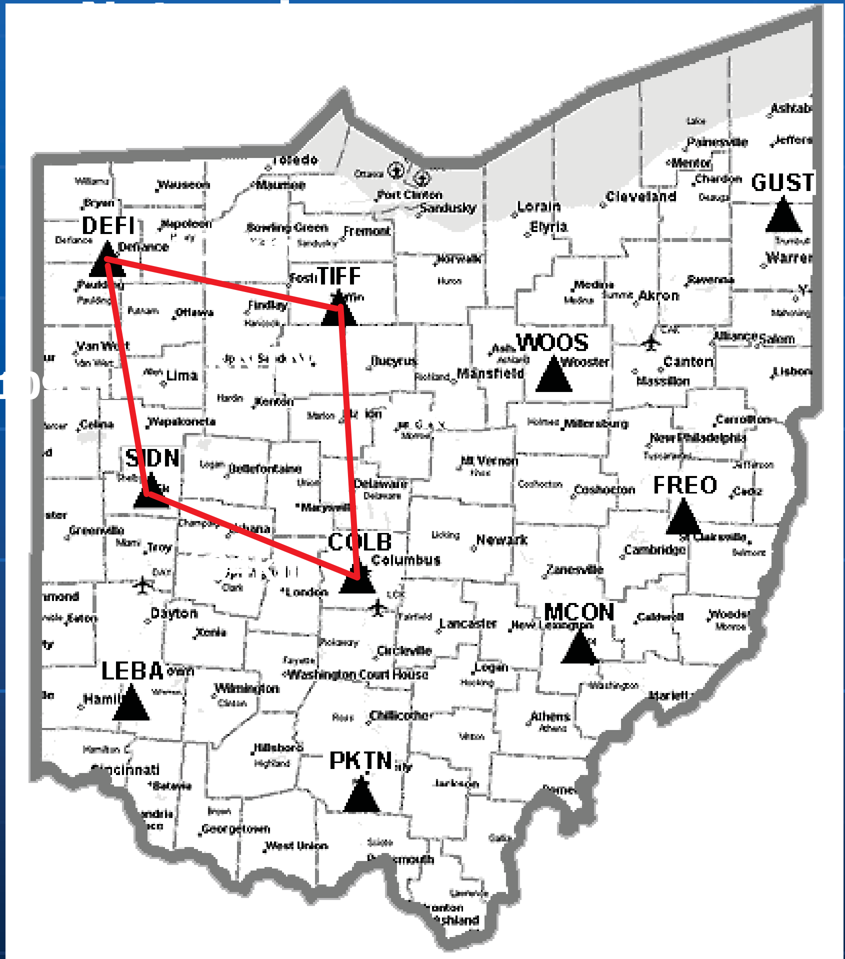
Courtesy: Trimble Navigation Ltd.

RTK Initialization – 32 km Baseline



Courtesy: Trimble Navigation Ltd.

OSU Experiments and Test Results: MPGPS software



Network solution
atmospheric corrections

Rover
baseline solution

Test area maps (Ohio CORS)

Position residuals with respect to the known reference coordinates: summary statistics, OSU Network-Based Solution

	Residuals in [m]					
	mean			std		
	n	e	u	n	e	u
KNTN-SIDN (~60 km) 4-6 UTC	0.002	0.002	-0.034	0.009	0.007	0.025
KNTN-SIDN (~60 km) 18-20 UTC	0.000	0.001	-0.004	0.008	0.006	0.024
KNTN-DEFI (~100 km) 4-6 UTC	0.013	0.007	-0.048	0.014	0.008	0.027
KNTN-DEFI (~100 km) 18-20 UTC	0.005	0.000	-0.003	0.007	0.007	0.022

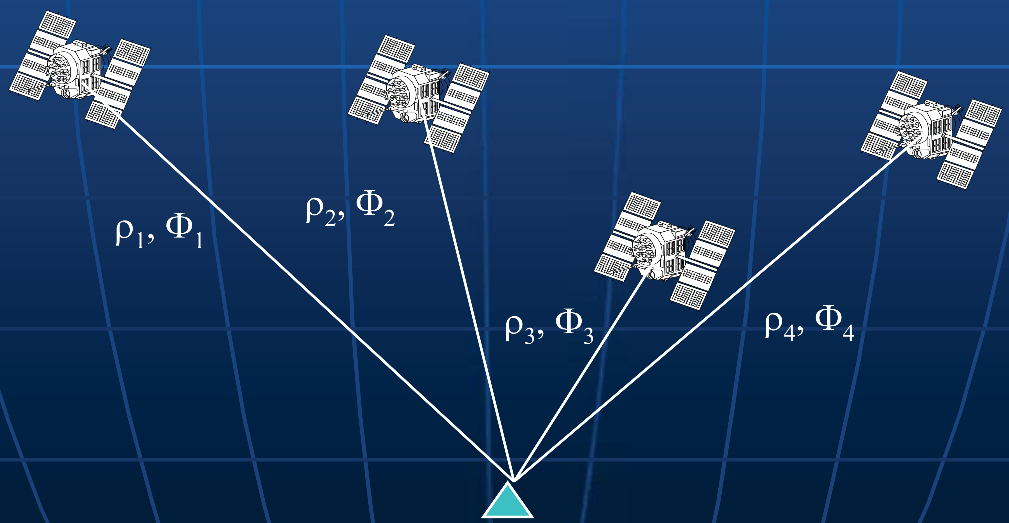
Precise Point Positioning: concept and example performance based on the OSU implementation

Point Positioning

- Standard:
  - Based on pseudorange measurements
  - Error sources
    - Orbital and satellite clock errors
    - Atmospheric errors: ionospheric and tropospheric delays
    - Receiver clock error, multipath, receiver noise
    - Accuracy ranges from a few meters to 100 meters, depending on the error level, mode of data collection and processing, and Selective Availability policy (currently turned off to zero)
- Precise:
  - The goal is to achieve accurate position solution using un-differenced carrier phase and pseudorange data, together with precise IGS orbits and clocks, and externally provided atmospheric corrections (or ionosphere-free linear combination is formed if dual-frequency observations are available)
  - Potentially centimeter-level accuracy is possible
  - Primary parameters: station 3D coordinates, receiver clock correction, tropospheric zenith delay, carrier phase ambiguities (non-integer)

Benefits of PPP

- Single receiver operation (low-cost)
- Can be applied anywhere and anytime under different dynamics (remote areas, space applications, etc)
- Not limited by baseline length as relative techniques
- Independence on GPS reference stations
- Can be applied for static and kinematic platforms



Error sources in PPP

- Orbits and clock
- Receiver clock and measurement noise
- Ionosphere and troposphere
- Multipath
- Relativistic effects (neglected in standard PP and DGPS)
  - Special and General relativity
  - Sagnac delay (caused by earth rotation during the signal propagation)
- Satellite attitude effects
  - Phase center offsets
  - Phase wind-up
- Site displacement effects
  - Solid earth tides
  - Ocean tides
  - Earth rotation parameters (only if working in inertial frame)

Methodology
PPP correction model

- ✓ Satellite orbit and clock corrections, (provided by IGS)
  - accuracy < 5 cm and <0.1 ns (3 cm)
- ✓ Relativistic effects (included in the IGS orbits, except for the periodic relativity, which is modeled in MPGPS™)
  - periodic relativity - up to 30 ns (~9 m)
- ✓ Receiver and satellite antenna phase center offsets (provided by IGS or NGS)
  - satellites - up to 1.023 m, receiver up to - 0.2 m
- ✓ Satellite P1–P2 and P1-C1 differential code biases (DCBs) (provided by IGS)
  - up to 2 ns (0.6 m), accuracy 0.1 ns (3 cm)
- ✓ Receiver DCB (GPS receiver calibration in MPGPS™ or IGS)
  - up to 20 ns (6 m), accuracy 0.1 ns (3 cm)
- ✓ Phase wind-up
  - up to 1 cycle (~0.2 m) of carrier phase data

Methodology

PPP correction model

Errors affecting the GPS observations (cont.)

- ✓ Ionospheric refraction
  - Ranges from <1 m to >100 m
- ✓ Tropospheric refraction
  - TZD = ~ 2.3 m (for standard atmosphere)

Errors affecting the station coordinates

- ✓ Atmospheric loading
  - correction: vertical < 1 cm
- ✓ Ocean loading
  - corrections : horizontal < 2 cm, vertical < 5 cm
- ✓ Solid Earth tides
  - correction: horizontal < 5 cm, vertical < 30 cm
- ✓ Earth Rotation Parameters, i.e., pole position and UT1-UTC (included in the IGS orbits)

International GNSS Service (IGS) products

Orbits	Accuracy (cm)
Ultra-Rapid (predicted half)	~10
Ultra-Rapid (observed half)	< 5
Rapid	< 5
Final	< 5

Clocks	Accurac y (ns)	Accuracy (cm)
Ultra-Rapid (predicted half)	~5.0	~ 150
Ultra-Rapid (observed half)	~0.2	~ 6
Rapid	0.1	3
Final	<0.1	<3

Final – 13-day delay, updated weekly

Rapid – 17-hour delay, updated daily

Ultra-rapid predicted – real time, updated four times a day

Ultra-rapid observed – 3 hour delay, updated four times a day

http://igscb.jpl.nasa.gov/components/prods.html

Experiments and test results
Data Source

- **Four stations, IGS/EPN (EUREF permanent network)**
  - ✓ Three stations were used to derive LIM and TZD (BOR1, GOPE, KRAW)
  - ✓ One station was selected as a rover (WROC)
- **Two three-hour sessions**
  - ✓ 01 - 04 UTC (nighttime - lowest TEC level)
  - ✓ 13 - 17 UTC (daytime - highest TEC level)
- 30-second sampling rate (i.e., 360 epochs per session)
- Carrier-phase data
- Distances between permanent stations ~330 km (average)
- Distances to the rover ~130–230 km (no DGPS solution, only PPP shown here)

Experiments and test results

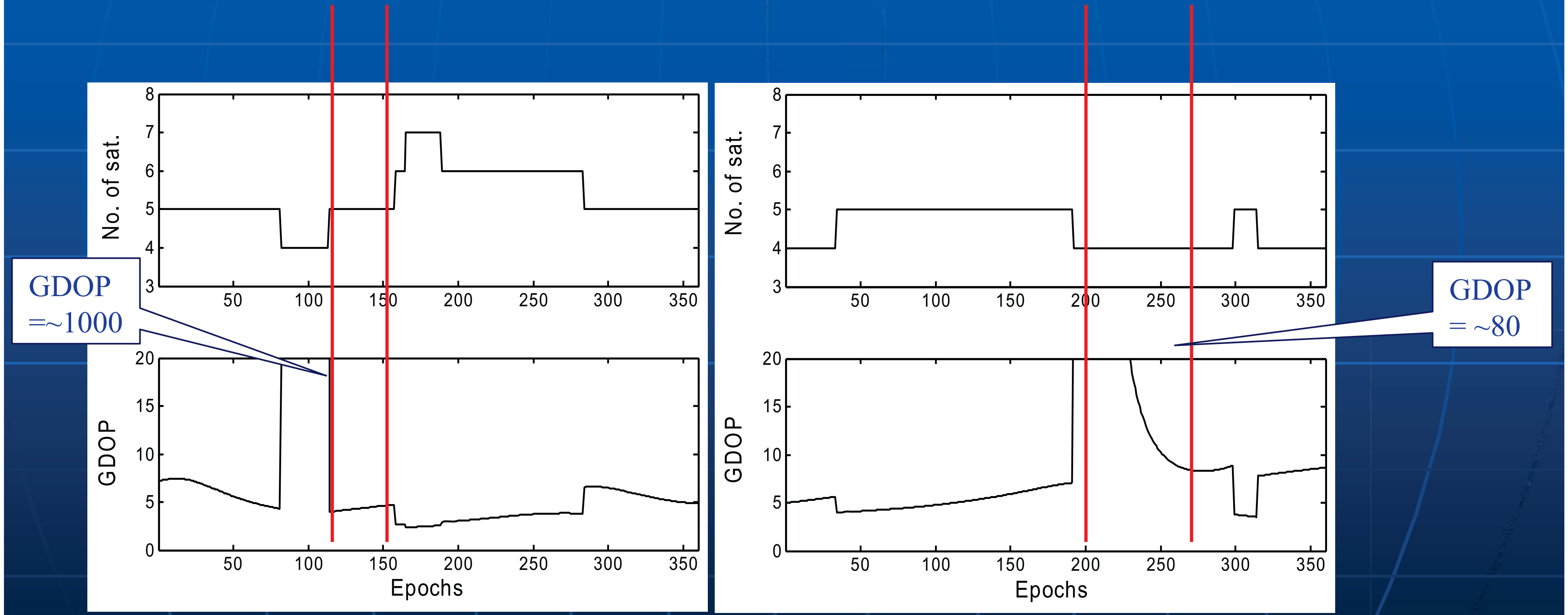
Test Area Map

Experiments and test results

Satellite Geometry - Station WROC

01-04 UTC nighttime
4-7 satellites

13-17 UTC daytime
4-5 satellites



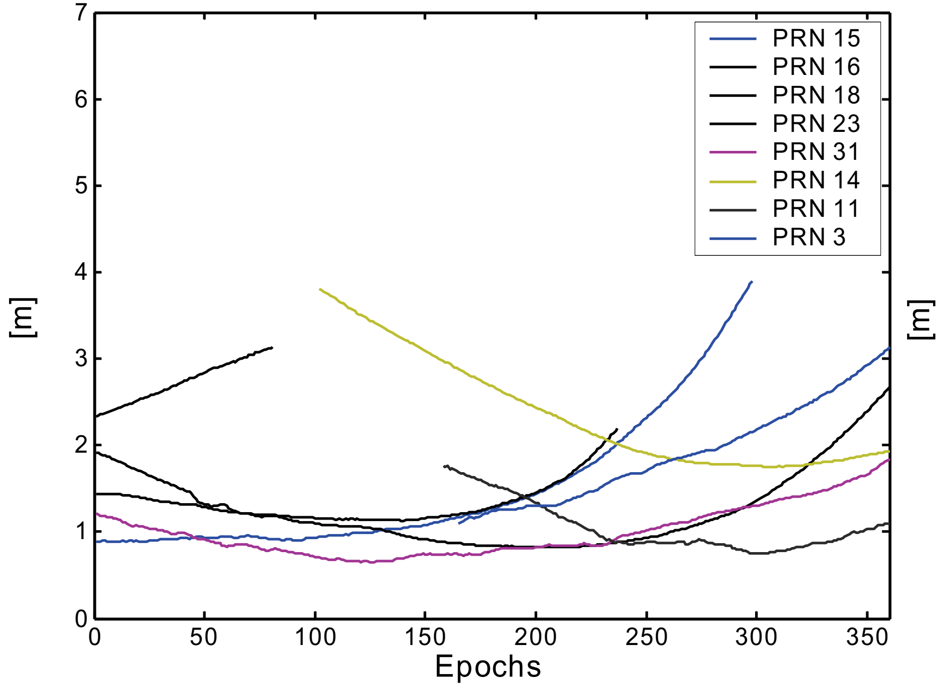
Poor satellite geometry, high GDOP - usually over 5
A short period with very poor geometry occurred in both sessions

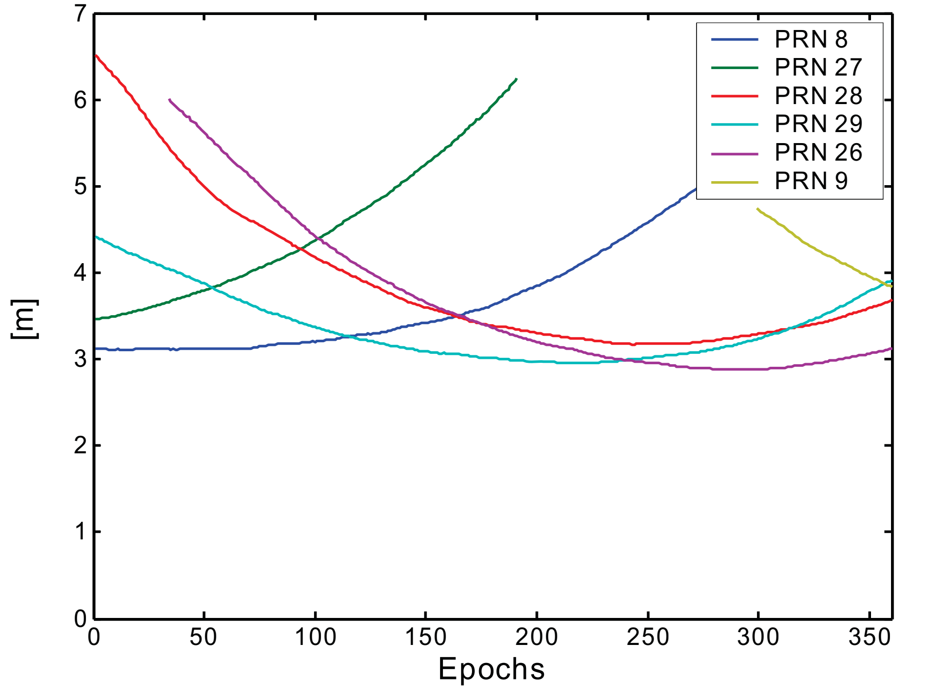
Experiments and test results

Example LIM-derived ionospheric delays (LIM- local ionospheric model)

01-04 UTC nighttime
lowest TEC

13-17 UTC daytime
highest TEC

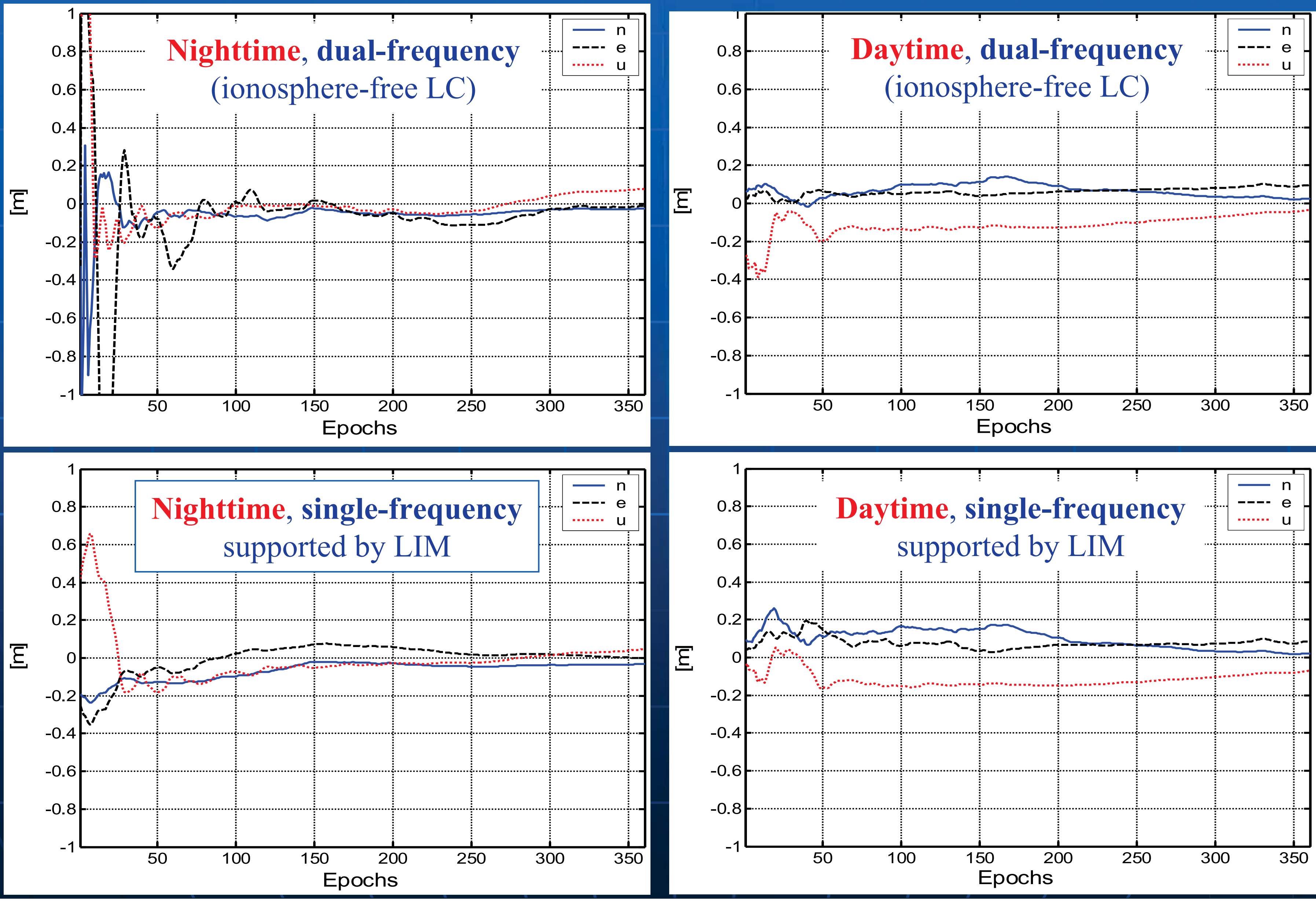




Station WROC (rover)

Experiments and test results

Static PPP Analysis – Station WROC



Experiments and test results

Static PPP Analysis – Station WROC

- **Ionosphere-free solution**
  - Horizontal - sub-decimeter-level position accuracy
  - Vertical - decimeter-level
  - Nighttime - convergence after 40 minutes
  - Daytime - convergence after 25 minutes

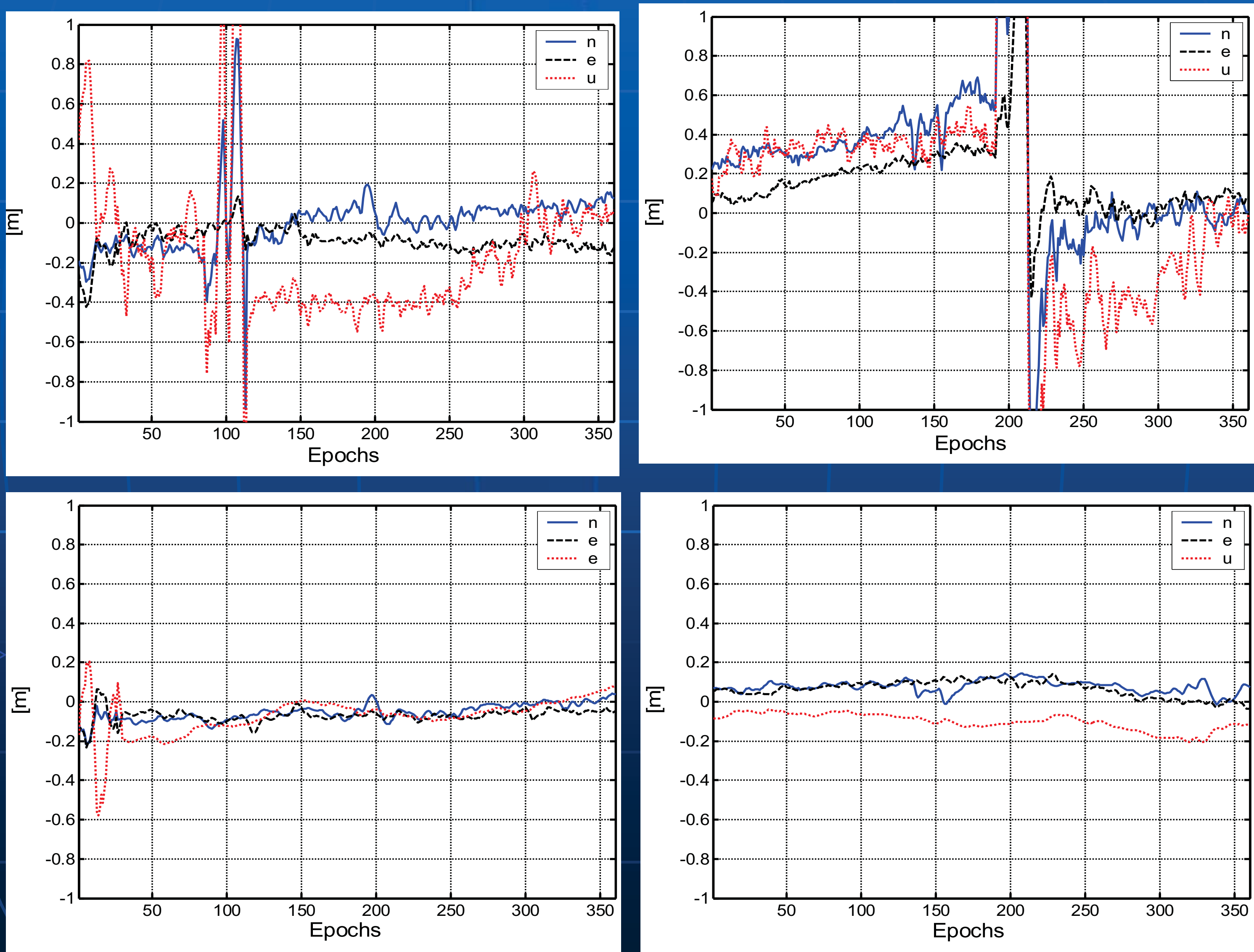
- **Single-frequency solution supported by Local Ionosphere Model**
  - Good agreement with its ionosphere-free counterpart
  - Similar accuracies and convergence times
  - LIM proved to be efficient in removing the ionospheric delays

Experiments and test results
Kinematic PPP Analysis – Station WROC

01-04 UTC (**nighttime**) | 13-17 UTC (**daytime**)

Unfiltered single-frequency supported by LIM

Filtered single-frequency supported by LIM



Experiments and test results

Kinematic PPP Analysis – Station WROC

- The unfiltered solutions are very noisy in both sessions
- In the filtered solution the large residuals were smoothed out after a few iterations (3-4)
- The filtered kinematic solutions show similar accuracies as obtained in the static case
- Sub-decimeter horizontal and decimeter-level vertical position accuracy was achieved
- Convergence time ranges from 25-40 minutes, depending on the level of ionospheric activity

Current and future trends in Network-Based RTK and PPP

- GNSS rather than GPS only: more data, multiple frequencies
- Large number of useful linear combinations – more options for improved algorithms
  - Faster, more reliable ambiguity resolution
  - Increased single-epoch AR accuracy and reliability
  - Tropospheric error estimation
  - Extended baseline length within the networks
  - Extended baseline length for a single baseline solution
  - Etc.
- New algorithms for PPP ambiguity resolution
  - Based on the observation that uncalibrated phase delay (fractional, at zero epoch) is very stable and can be estimated precisely and applied to ambiguity-fixing for PPP (94%)
    - Used as between-satellite wide-lane (and narrow-lane) difference
  - Increased positioning accuracy
  - Improved convergence speed, but still may pose a problem

Modern trends in Mapping Data Acquisition

- Reflect current trend: *Paradigm shift: static → kinematic, point → image, post-processing → real-time*
- Data and sensor fusion → increased automation and autonomous navigation
- Exploration of new/available “signals of opportunity”, and their integration with GNSS/inertial navigation technology
- Seamless navigation algorithms for indoor/outdoor navigation

Some on-line resources based on GPS networks in US and Canada

- **Real-Time and Daily Ionospheric Maps**
  - http://www.ngdc.noaa.gov/stp/IONO/USTEC/home.html
  - http://iono.jpl.nasa.gov/

- **Real Time Integrated Atmospheric Water Vapor and TEC from GPS**
  - http://www.gst.ucar.edu/gpsrg/realtime.html

- **Online Positioning User Service (Static and Rapid Static)**
  - http://www.ngs.noaa.gov/OPUS/
  - OPUS allows users to submit their GPS data files to NGS, where the data will be processed to determine a position using NGS computers and software. Each data file that is submitted will be processed with respect to 3 CORS sites. The sites selected may not be the nearest to your site but are selected by distance, # of obs, site stability, etc. The position for your data will be reported back to you via email in both ITRF and NAD83 coordinates as well as UTM, USNG and State Plane Coordinates (SPC) northing and easting. OPUS takes only L1/L2 data.
- **CSRS-PPP (Precise Point Positioning) Service**
  - http://ess.nrcan.gc.ca/2002_2006/gnd/csrs_e.php
  - CSRS-PPP allows GPS users to submit single or dual frequency, static or kinematic GPS raw observation data (in RINEX format) over the Internet. CSRS-PPP uses precise GPS orbit and clock information to determine very accurate positions in relation to the national reference frame, NAD83 or the global reference frame, ITRF.

Commercially available systems

- Trimble's VRS™ (Virtual Reference Station)
  - Trimble NetRS™ or 5700 CORS GPS receivers
  - Zephyr Geodetic™ Antennas
  - Trimble GPSNet Software
  - Trimble RTKNet Software
- Topcon's Net-G3 receivers
  - Track GPS and Glonass
  - CR-G3 choke ring antennae
  - TopNet-V software
    - encompasses Single-Base RTK and CORS functionality
- Leica's GRX1200 Series, also GMX900 Series and System 500 GNSS receivers
  - Track GPS and Glonass
  - AT504 (GG) choke ring antenna or AX1202 GG geodetic antenna
  - SpiderNET or SpiderWeb software