OSU Basics of GNSS Workshop February 2, 2012

Part 1. GPS and GNSS Basics

Mark L. Armstrong, PLS
NOAA/NGS Oregon State Advisor
mark.l.armstrong@noaa.gov

Prof. Michael Olsen, PhD
OSU Geomatics Engineering
michael.olsen@oregonstate.edu

79 slides

Introduction to GPS (USA) and GNSS

Overview of GPS

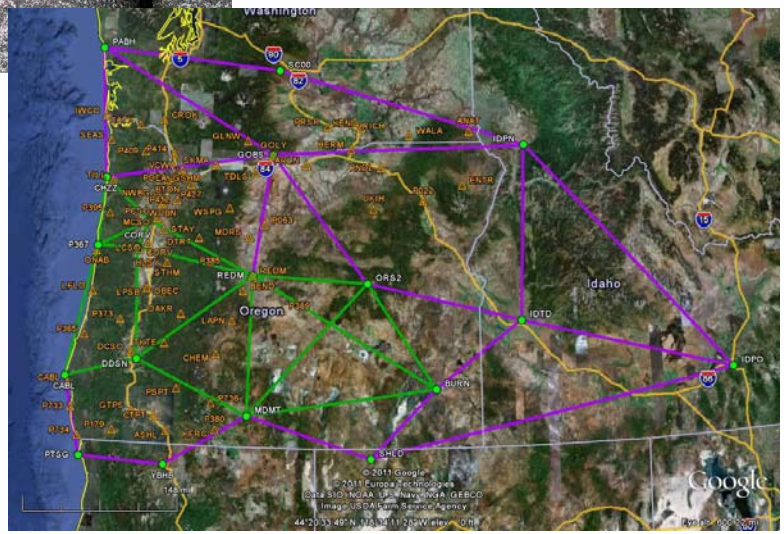
- GPS Satellite Constellation
- GPS Segments
- GPS Satellite Signals
- GPS Modernization
- GNSS

GPS Positioning Basics

- Pseudo-range Navigation
- Code-phase Tracking
- Carrier-Phase Measurements
- GPS Errors & Biases
- Atmospheric Corrections
- Differencing Methods

GPS Positioning Modes

- DGPS, RTK, PP



Overview of GPS

The Global Positioning System (GPS) is a satellite-based navigation system. What does GPS really mean?

Developed by U.S. DoD in the early 1970's for the military. **Why? What else to the SV's provide besides positioning, navigation, and timing.**

Now a dual-use system for both military & civilian users – **Free to all!**

Continuous positioning & timing information in any weather, any place

Unlimited users (passive ranging system)

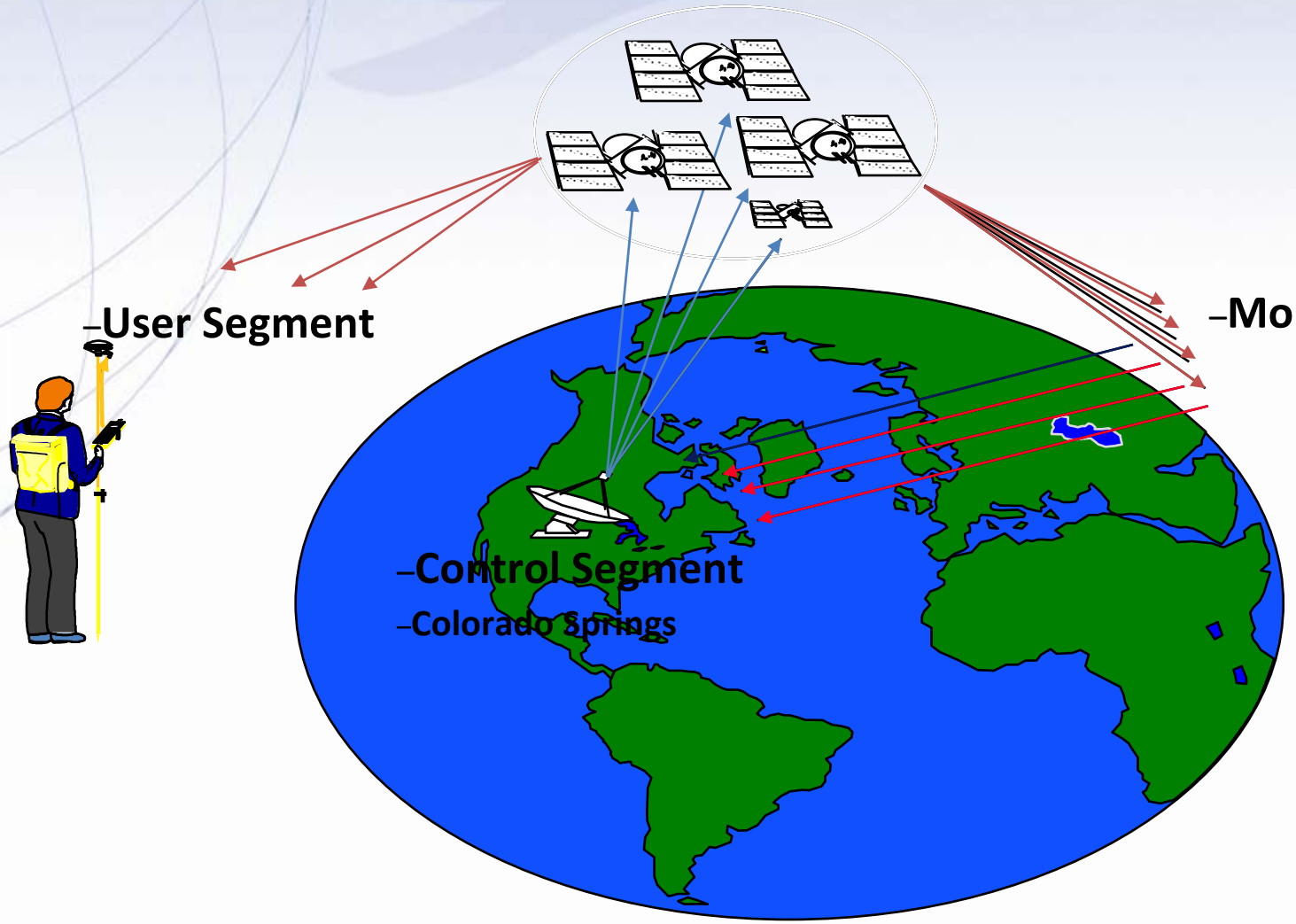
The GPS System

The Space Segment consists of a minimum of 24 operational satellites in six circular orbits 20,200 km (10,900 NM) above the earth at an inclination angle of 55 degrees with a 12 hour period. The satellites are spaced in orbit so that at any time a minimum of 6 satellites will be in view to users anywhere in the world. The satellites continuously broadcast position and time data to users throughout the world.

The Control Segment consists of a master control station in Colorado Springs, with five monitor stations and three ground antennas located throughout the world. The monitor stations track all GPS satellites in view and collect ranging information from the satellite broadcasts. The monitor stations send the information they collect from each of the satellites back to the master control station, which computes extremely precise satellite orbits. The information is then formatted into updated navigation messages for each satellite. The updated information is transmitted to each satellite via the ground antennas, which also transmit and receive satellite control and monitoring signals.

The User Segment consists of the receivers, processors, and antennas that allow land, sea, or airborne operators to receive the GPS satellite broadcasts and compute their precise position, velocity and time.

The Global Positioning System



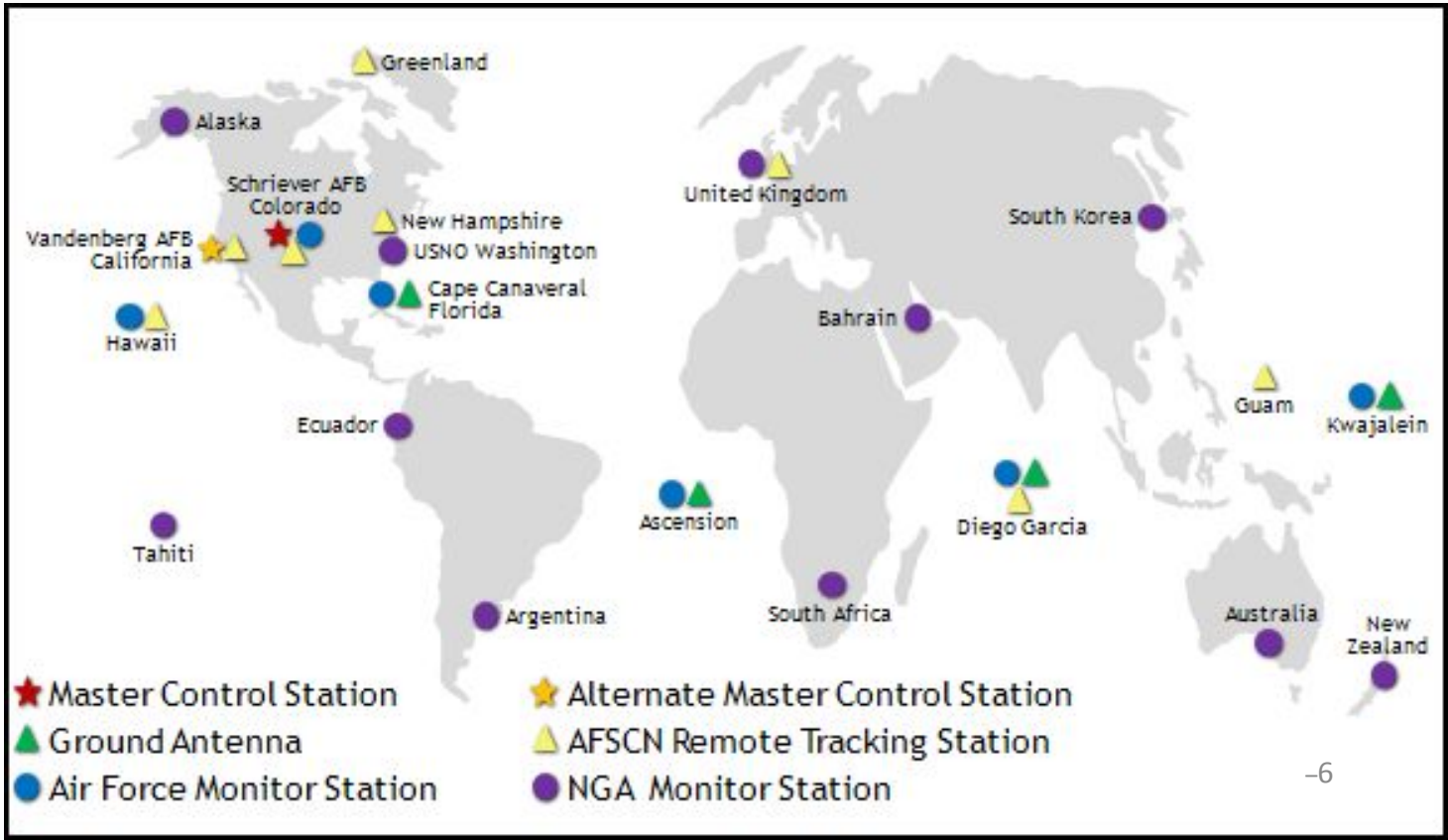
Control / Monitor Segment

Monitored by Department of Defense - All perform monitor functions

- Receive all satellite signals
- Collect Meteorological data (used for ionospheric modeling)
- Transmit data to MCS

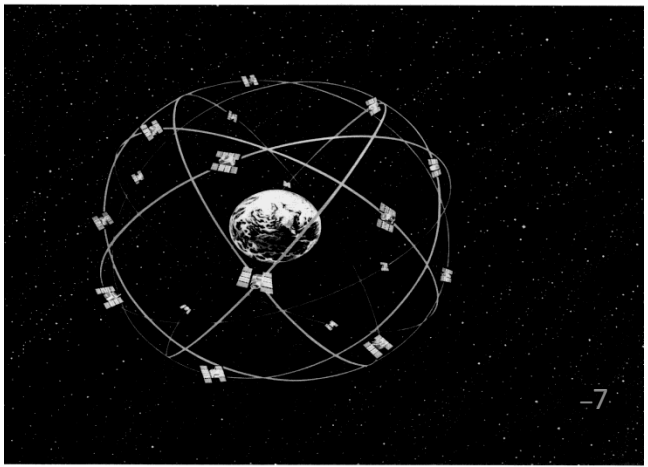
  Master Control Station -Upload to Satellites

  - Orbital prediction parameters
  - SV Clock corrections
  - Ionospheric models
  - SV commands



Space Segment

- 24 + 5 satellites in final constellation
  - 6 planes with 55° rotation
  - each plane has 4/5 satellites
- Very high orbit
  - 20,183 KM, 12,545 miles
  - approximately 1 revolution in 12 hours
  - for accuracy
  - survivability
  - coverage



User Segment

- Surveyor, engineer, GIS, military, public
- Anyone with GPS equipment!
  - Hardware and Software can be application specific

- Vehicle Tracking
- Navigation
- Mapping
- Hydrographics
- Aircraft Approach and Landing
- Dredging
- Sunken ship salvage
- Oil Exploration
- Cell phones

Ambulances
Police
Cruise Ships
Courier Services
Hikers

The GPS Constellation

Initial Operating Capability (IOC) 1993 w/ 24 satellites.

Final Operating Capability (FOC) 1995.

6 Orbits

- Inclined @ 55° with respect to the equator
- 20,200 km altitude
- Orbits identified as A thru F

At least 4 satellites per orbit

- 6 “slots” each, spaced ~60° apart
- Period is 12 sidereal hours (11hrs 58 mins)
  - So a satellites apparent rise time is about 4 minutes earlier every day
- 5 to 8 satellites visible to users from anywhere on earth

Current Constellation

Plane/Slot	1	2	3	4	5 (spare)
A	2A-21 (39)	2A-12 (25)	2A-28 (38)	2A-15 (27)	2-4 (19)
B	2A-18 (22)	2A-27 (30)	2-2 (13)	2A-22 (35)	2R-5 (44)
C	2A-24 (36)	2A-25 (33)	2A-19 (31)	2A-20 (37)	
D	2A-11 (24)	2R-3 (46)	2-5 (17)	2A-23 (34)	2-9 (15)
E	2R-4 (51)	2-8 (21)	2A-26 (40)	2R-7 (54)	2A-10 (23)
F	2R-6 (41)	2A-14 (26)	2R-2 (43)	2A-16 (32)	2A-17 (29)

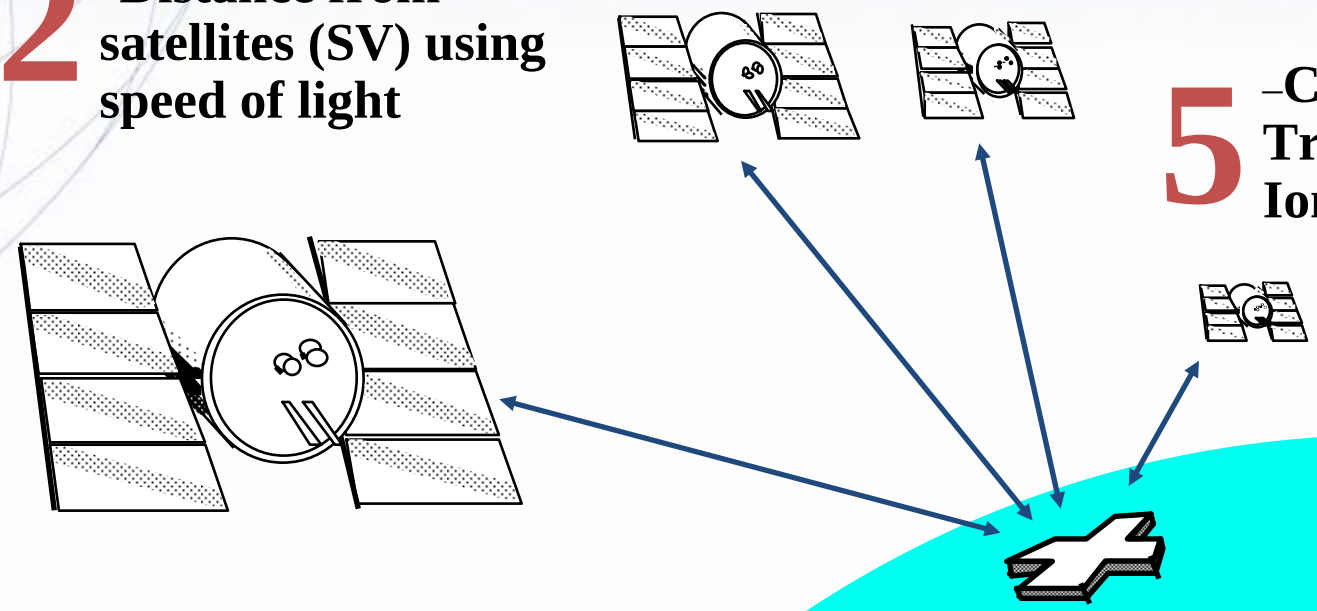
GPS position in 5 easy steps

3
- 4 SVs to solve
- for X,Y,Z,t

4
- Use message from satellite for its location

2
- Distance from satellites (SV) using speed of light

5
- Correct for Troposphere & Ionosphere



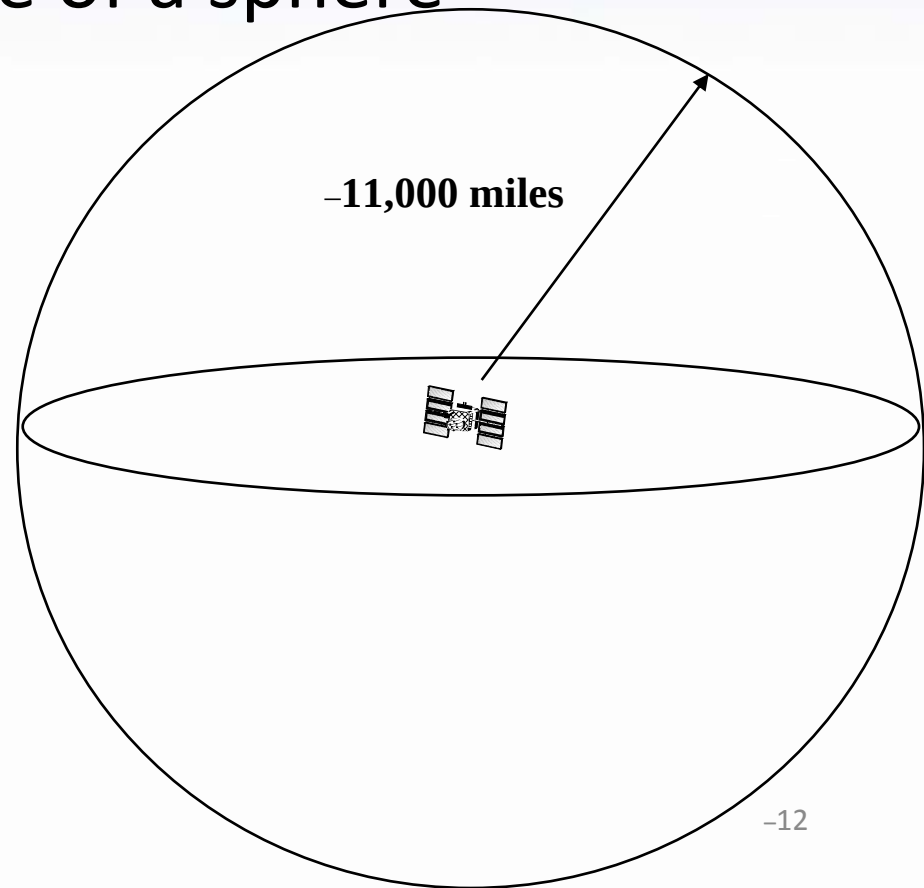
1
- Based on Trilateration

Trilateration

By measuring distance from several satellites you can calculate your position

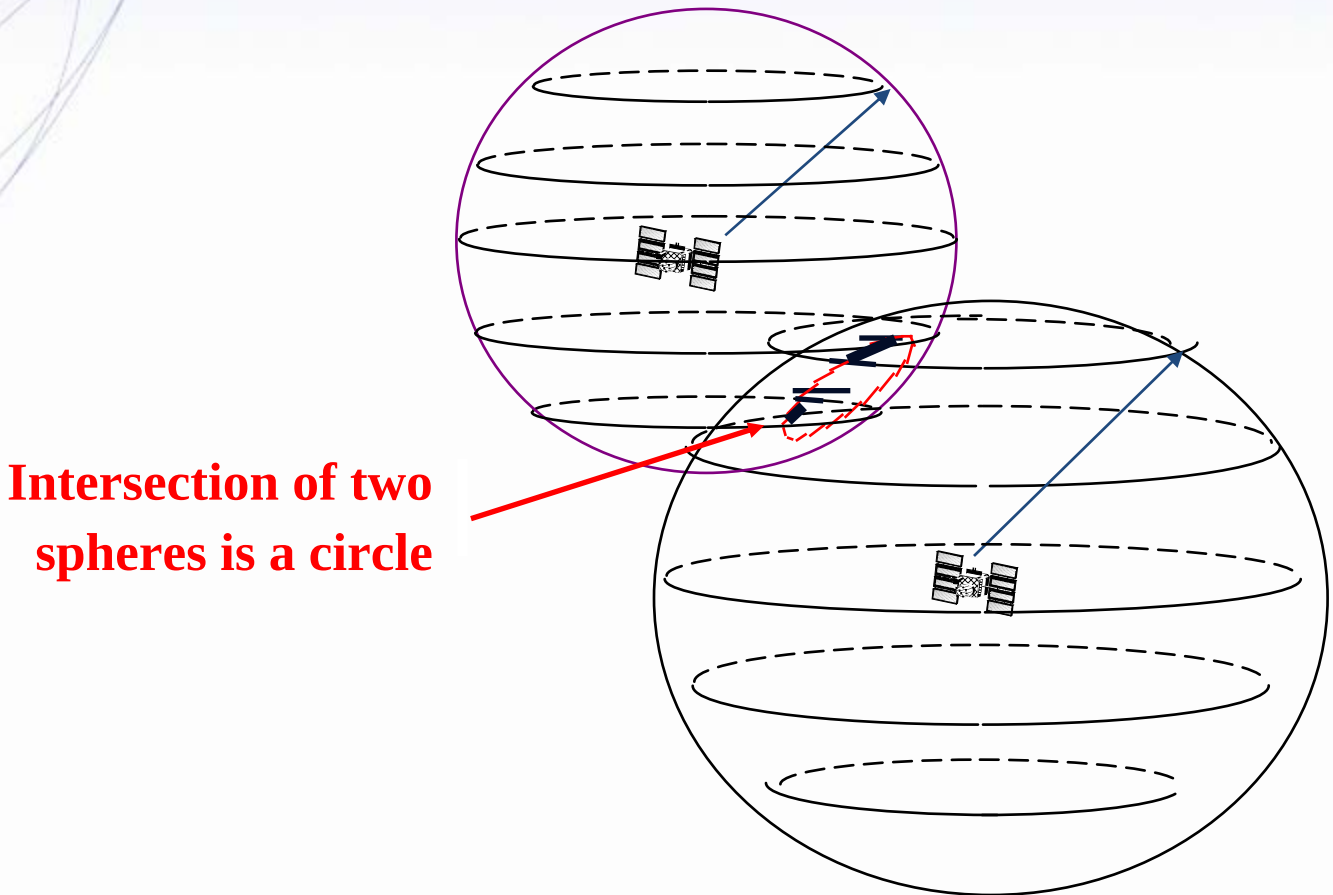
One measurement narrows down our position to the surface of a sphere

–**We're somewhere**
–**on the surface of**
–**this sphere.**



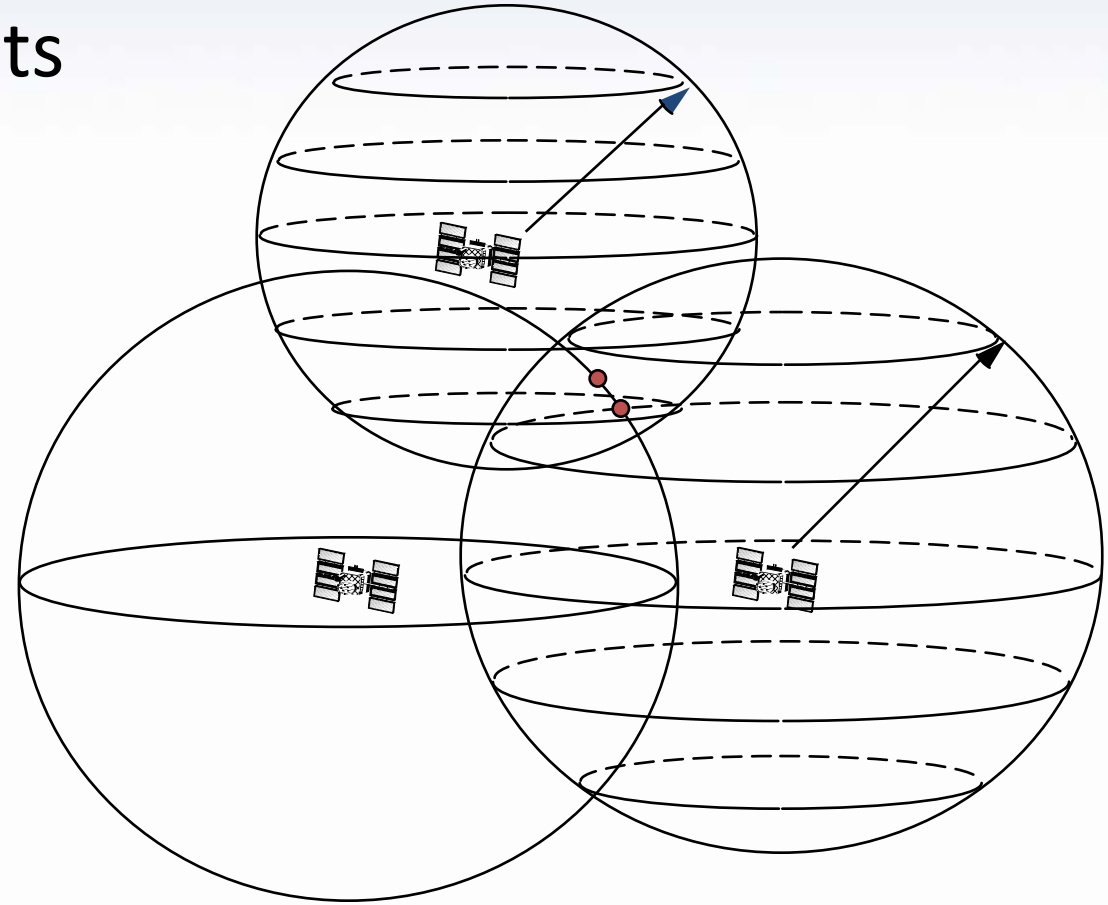
Trilateration

Second measurement narrows it down to–
intersection of two spheres



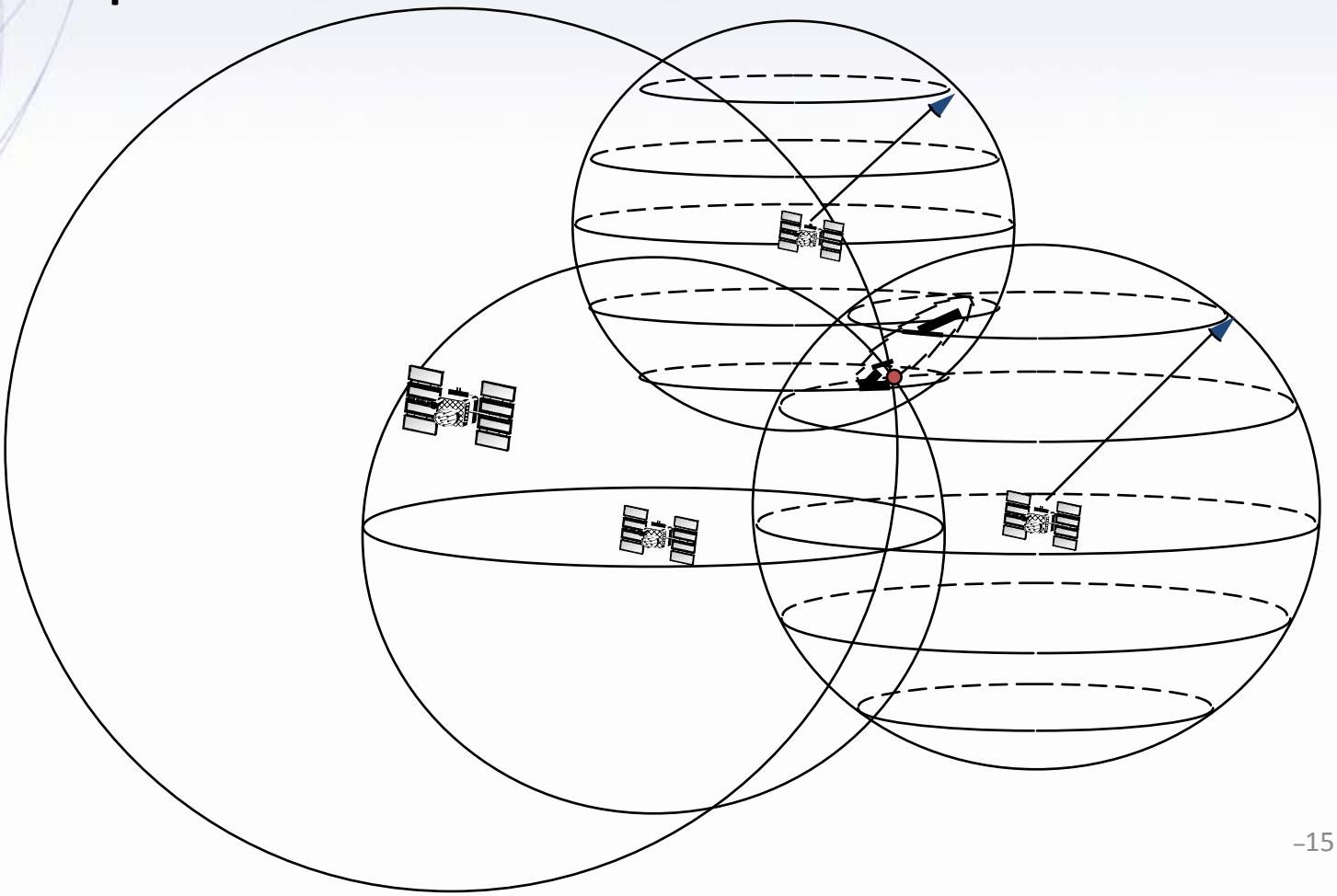
Trilateration

Third measurement narrows to just two points



Trilateration

Fourth measurement will decide between two points



Trilateration

In practice 3 measurements are enough because…

- We can discard one point because it will be a ridiculous answer
  - Out in space
  - Or moving at high speed
- <u>But we do need the 4th measurement to cancel out clock errors</u>

Satellite Ranging

Measuring the distance from a satellite…

- Done by measuring travel time of radio signals at the speed of light (nearly)

Measure how long it takes the GPS signal to get to us…

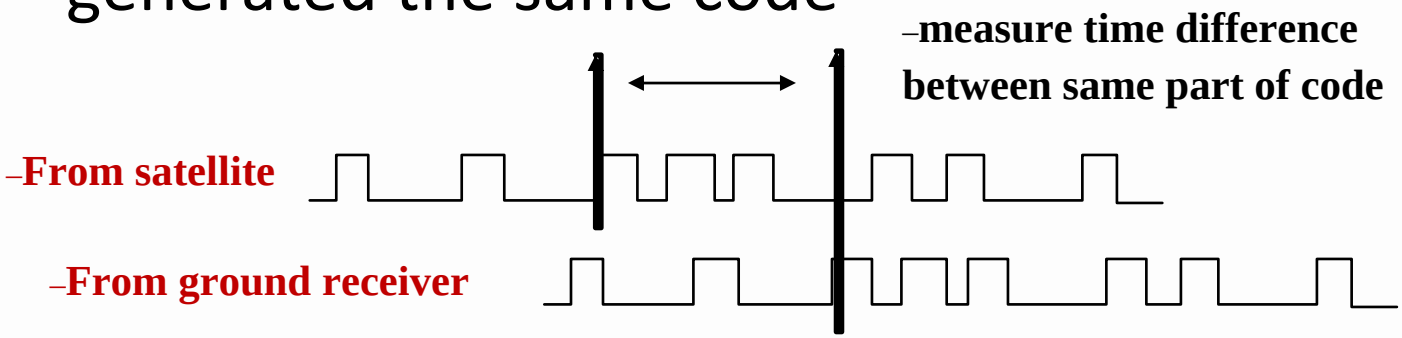
- Multiply that time by 300,000 km/sec
  - Time (sec) x 300,000 = km

- <u>If you've got a good clock in the receiver, all you need to know is exactly when signal left satellite.</u>

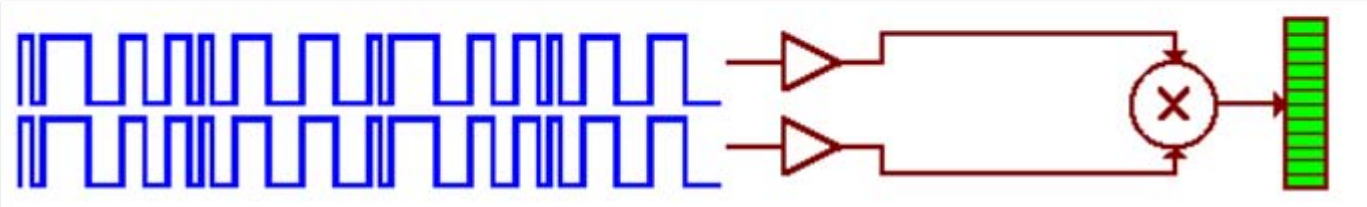
How Do We Know When the Signal Left the Satellite?

One of the Clever Ideas of GPS:

- Use same code at receier and satellite
- Synchronize satellites and receivers so they're generating same code at same time
- Then we look at the incoming code from the satellite and see how long ago our receiver generated the same code



Correlation Animation



From Peter H. Dana, http://www.colorado.Edu/geography/gcraft/notes/gps/gps_f.html

Why a Code?

Code lets you jump in anywhere…

- Code lets many satellites operate on same frequency
- Code gives us a way to increase signal-to-noise ratio

Accurate Clocks

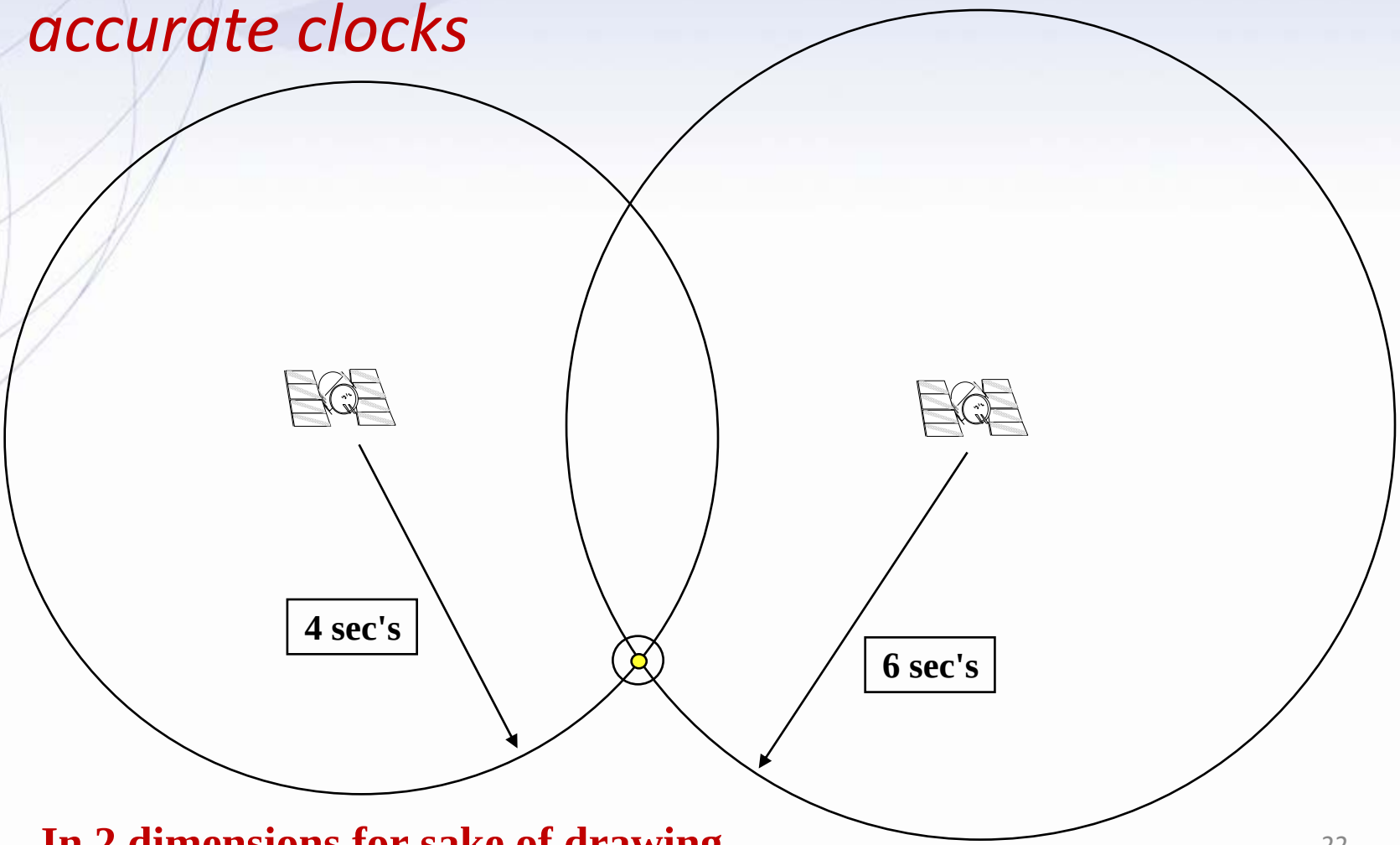
Necessary to measure travel time…

- Making sure both receiver and satellite are synchronized
- Whole system depends on very accurate clocks
- Satellites have atomic clocks… accurate but expensive
- Ground receivers just need consistent clocks

The secret is in the extra satellite measurement that adjusts the receiver clock

The Ideal Situation

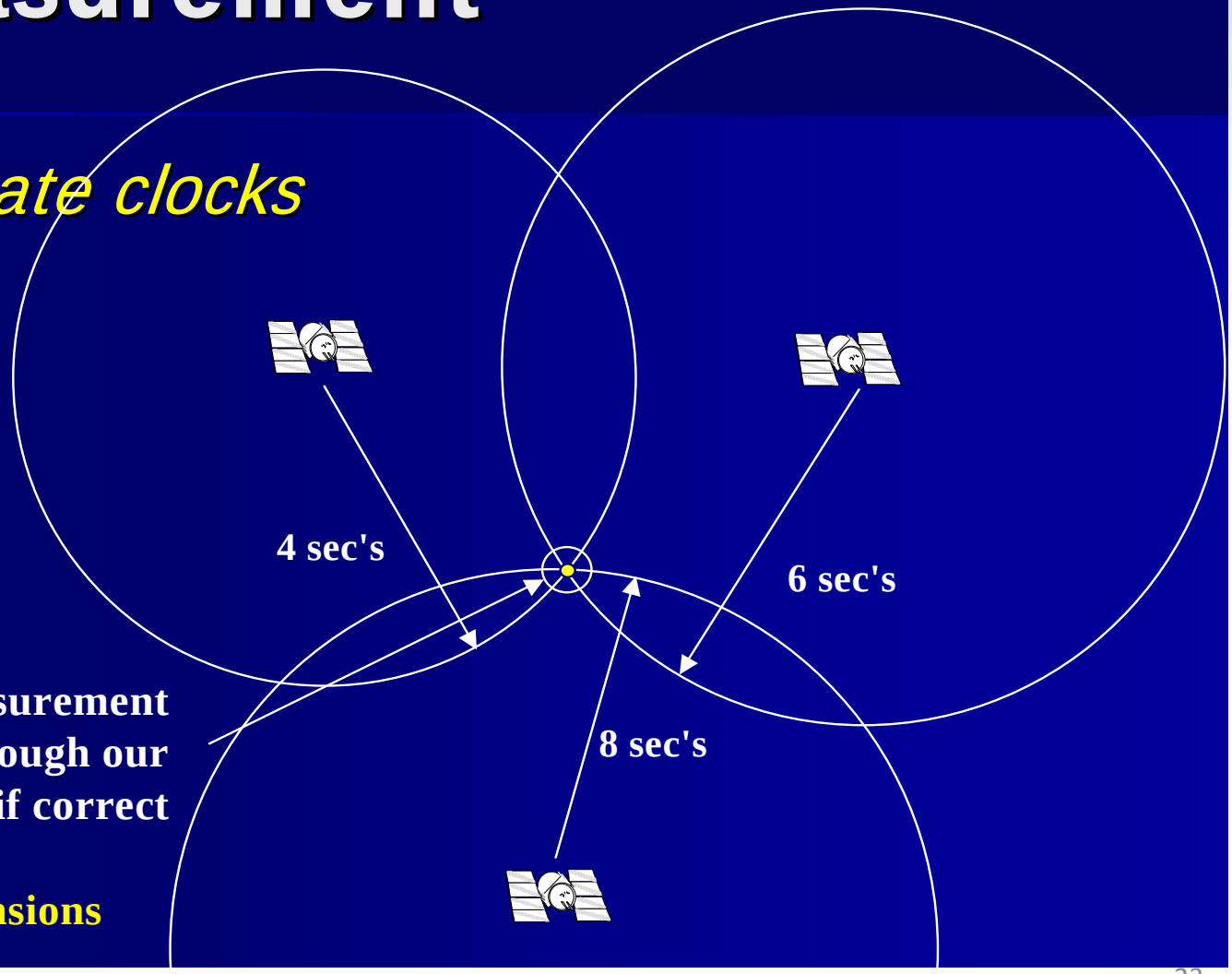
accurate clocks



–In 2 dimensions for sake of drawing

Adding a Fourth Measurement

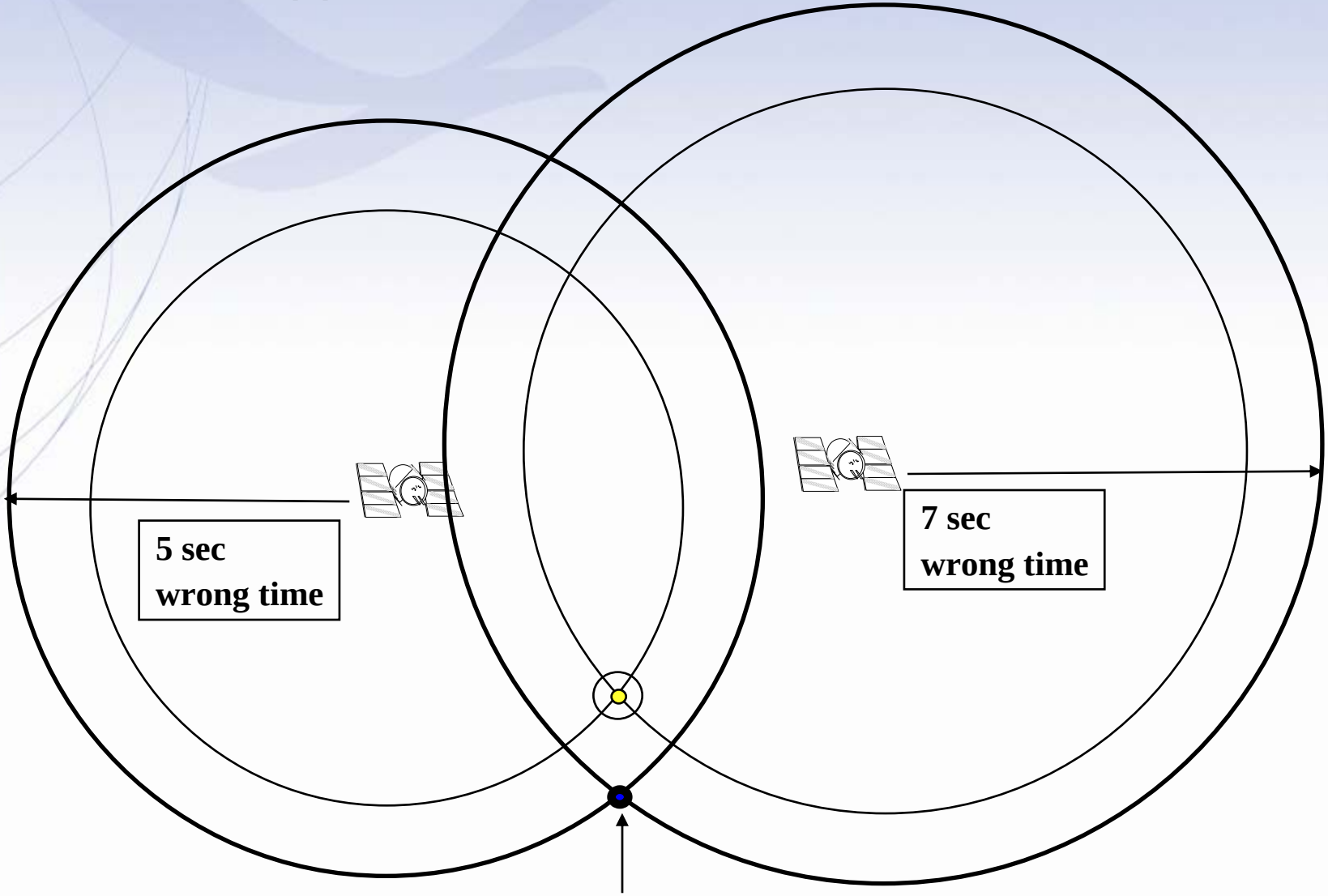
accurate clocks



Fourth measurement would go through our position if correct

In 2 dimensions

With Fast Clock

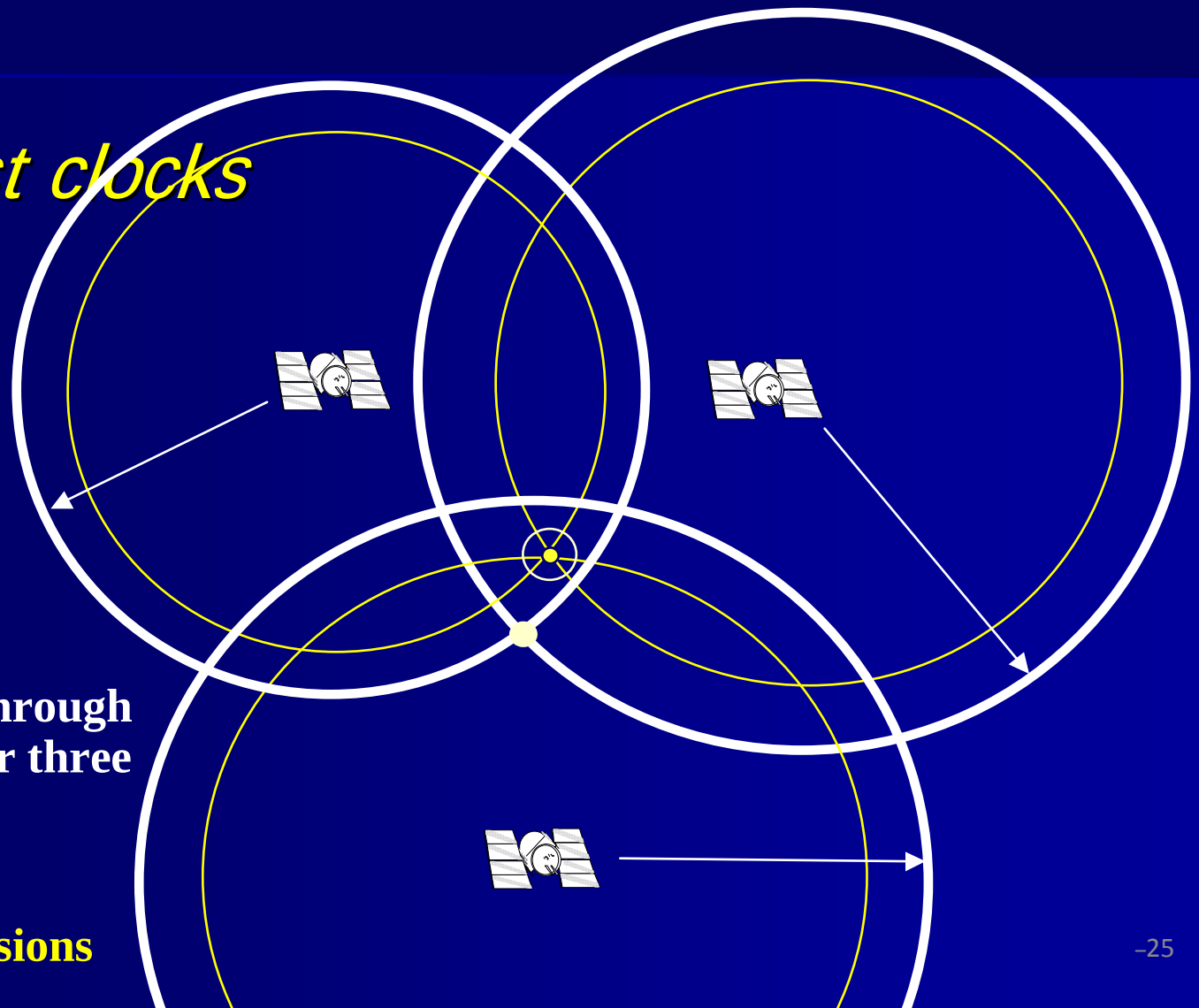


–Bad position because clock is off by one second

–In 2 dimensions

Fourth Measurement

fast clocks



Won't go through the other three

In 2 dimensions

Need 4 Satellites for 3D Position

If we are looking at the previous slides in 3d then we need

- 4 satellites for 3d position (X, Y, Z, time)
- 3 satellites for 2d position (X, Y, time) - user must enter Z value
  - Problem - if user enters poor Z, then X and Y will be incorrect!
  - **Solution - work only in 3D!**

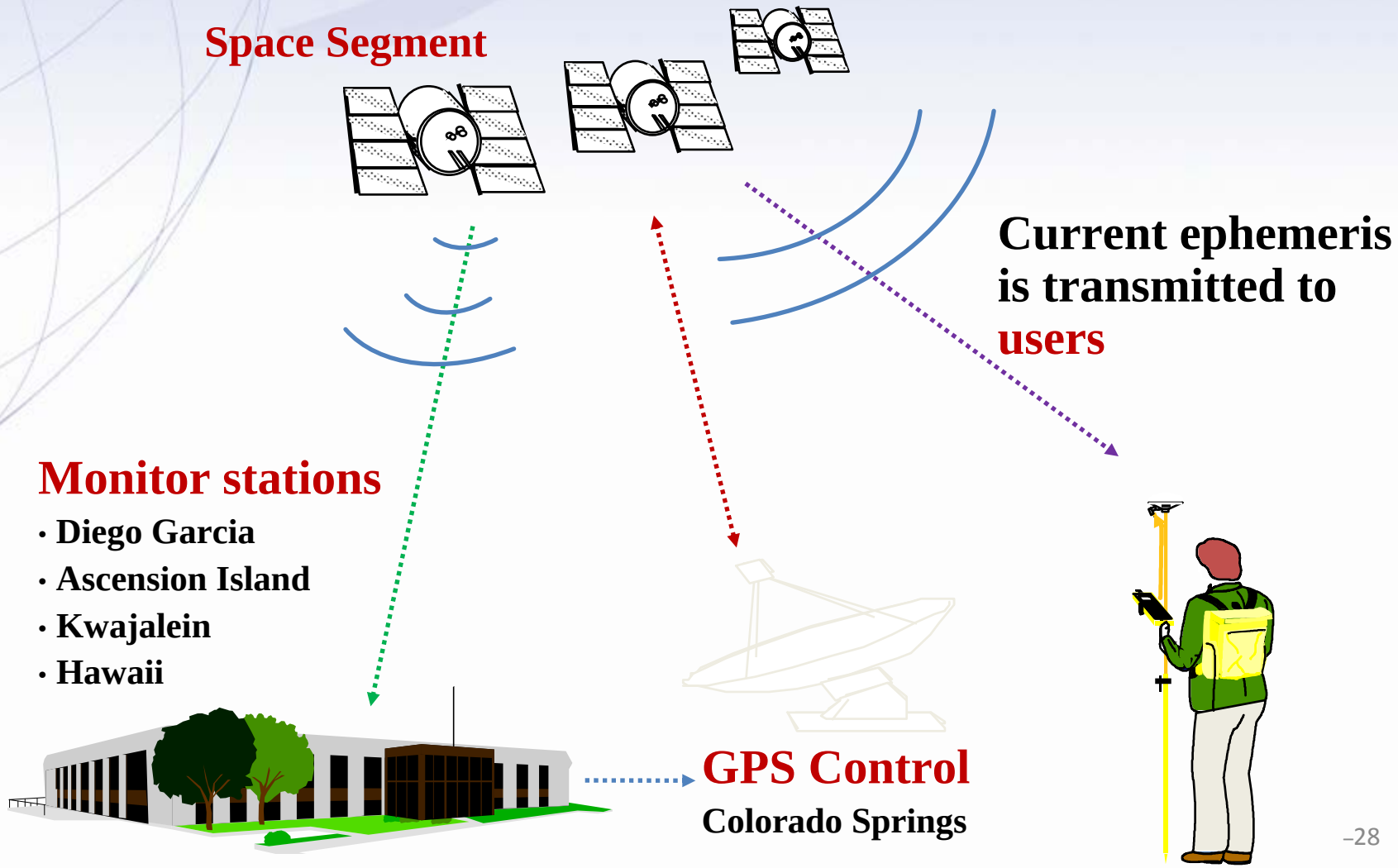
Knowing where the satellites are…

After all, they're 20,000 km up

- High orbit
  - Very stable orbits
  - No atmospheric drag
  - Survivability
  - Earth coverage
- Monitored by US Defense Department
  - DOD transmits corrections back to satellite
- Corrections transmitted from satellites to us
  - Status message

Current ephemeris is transmitted to users

Knowing where the satellites are - *Ephemeris*



The Navigation Message Ephemeris – Almanac

- **The Navigation Message** = A receiver needs to know detail info about each SV position and the network. This info is modulated on top of the C/A and P(Y) ranging codes. GPS day and time plus SV health.
  - **Ephemeris** = Orbital data allowing the receiver to calculate the position of the SV.
  - **Almanac** = Course orbit and status for each SV plus ionospheric model and GPS time coordinated to UTC time. The Almanac assists in acquisition of SV at power up – a prediction of where each SV at that time in the sky.

Ephemerides

GPS Orbits

NGS Home | About NGS | Data & Imagery | Tools | Surveys | Science & Education

GPS Orbits

Orbits Home
Orbit Naming Convention
Analysis Strategy
Orbit Data
Contact Us

GPS Orbit Data

IGS Orbit Availability
IGS Product Information

Ultra-rapid (iguWWWWD.sp3)
6-hour latency
constrained (no-net rotation, no-net translation) 24-hour file – sp3

Rapid (igrWWWWD.sp3)
13-hour latency
constrained (no-net rotation, no-net translation) 24-hour file – sp3

Final (igsWWWWD.sp3)
12 to 14 day latency
minimally constrained (no-net rotation) 24 hour file - sp3

files named by GPS Week number and Day of Week

GPS Satellite Generations

Block I

Design life span 4.5 yrs

Now defunct, last operational in 1995

Launched between 1978 – 1985

63° inclination

Mainly for experimentation/concept validation

Block II/IIA

14/180-day navigation message data storage capability

Added selective availability (SA) & anti-spoofing

7.5 yr design life span, but typically longer

28 satellites launched between 1989 & 1997

Block IIR

180-day autonomous navigation

210-day ephemeris & clock data

Replenish Block II/IIA

10 yr design life

Launches between 1997 & 2004 (about 21 satellites)

Block IIF

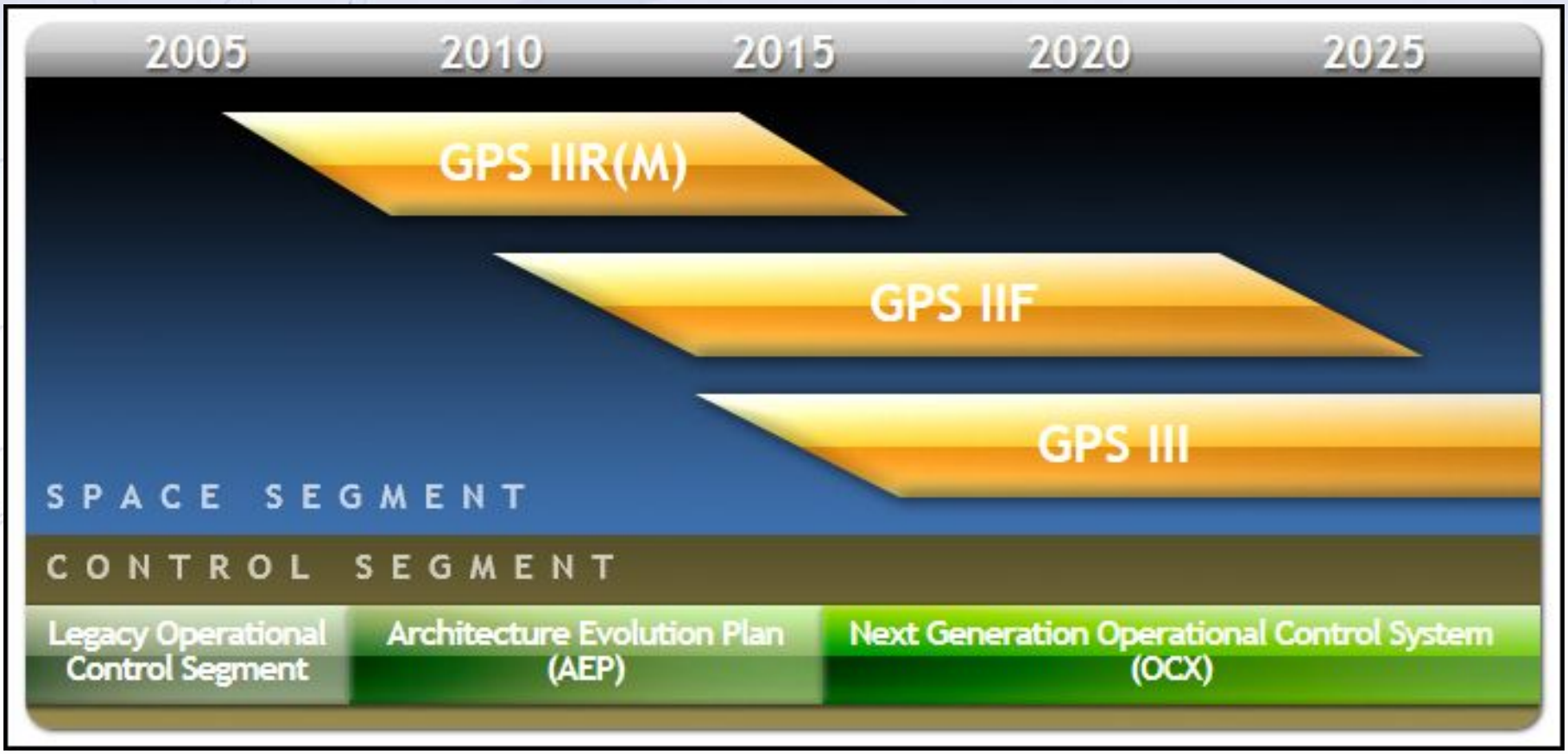
Launched after 2006…

GPS Modernization

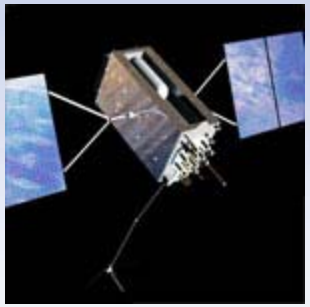
Block IIR-M and Block IIF satellites

- **L2CM (civil moderate length) code**
  - 511.5 Kbps chip rate, 10,230 chips long, 20 ms period
- **L2CL (civil long) code**
  - 511.5 Kbps chip rate, 767,250 chips long (75x), 1.5 s period
- **$D_c(t)$ new navigation message**
- **M (military) codes**
  - Binary offset carrier (BOC) modulation to get around bandwidth limitations
  - Transmit on both L1 & L2
- **Block IIF adds a 3rd frequency**
  - L5 @ 1176.45 MHz
  - 10.23 MHz chip rate, 10,230 chips long, 1 ms period

GPS Program Schedule



GPS Block III



(SVN-74 and up)

Key Improvements:

Fourth civilian GPS signal (L1C) for international interoperability.

15-year design lifespan.

Future: Distress Alerting Satellite System (DASS) for search and rescue.

Future: Satellite cross-links for rapid command and reduced age of data.

Update On January 12, 2012, the Air Force awarded Lockheed Martin a contract for production of the third and fourth GPS III satellites.

GPS Satellites Today

NANUs … (Notice Advisory to Navstar Users)

Find out the health of each SV and other notifications

See the US Coast Guard webpage:

http://www.navcen.uscg.gov/?pageName=gpsAlmanacs

GPS Signals

•The Coarse Acquisition (C/A) Code - Modulated on the L1 carrier onlyCode looks like noise, but is generated mathematically, hence "PRN Code" (pseudorandom noise)… available to all users. **SPS – Standard Positioning Service – Autonomous reception**

•Precision (P) Code - Modulated on both L1 and L2 carriers. **PPS - Precise Position Service**

Encrypting the P code w/ secret W code results in Y code. Referred to as anti-spoofing (A-S) Also called P(Y) code.

•Navigation (telemetry) data messages are modulated on both L1 and L2 carriers

Navigation message includes:

Coordinates of the GPS satellites in time

Satellite health, clock correction, almanac & atmospheric data

Info about other satellites

GNSS integrating: GPS, GLONASS, and GALILEO

- GNSS – Global Navigation Satellite System
  - Consists of:
    GPS (US) >24
    GLONASS (RUSSIA) 31 (full constellation)
    GALILEO (EUROPE) 2 (?????)
    COMPASS (CHINA) 19 so far
- Advantage: Many more satellites
- **Many newer receivers are GNSS enabled.**

GLONASS (Russia)

- http://www.glonass-center.ru/en/

–Used extensively in the US by surveyors and GIS professionals.

–The additional number of SV's allows for improved RTK work in trees, and urban canyons.

–Free to use at the moment with GNSS receiver and antenna.

COMPASS (China)

- 19 SV so far – Not free for anyone to use??

- China continues to deploy its Beidou-Compass constellation, which ultimately is scheduled to include 35 satellites — five in geostationary orbit, three in inclined-geostationary orbit and 27 in medium Earth orbit.

Antenna Phase Center Variation

The antenna phase center does not coincide perfectly with the physical center of the antenna's active element.

-In fact, the phase center can vary with SV elevation and azimuth.

-Antenna phase center errors typically on order of a few mm.

Relative vs. Absolute Antenna Models

- **Background**

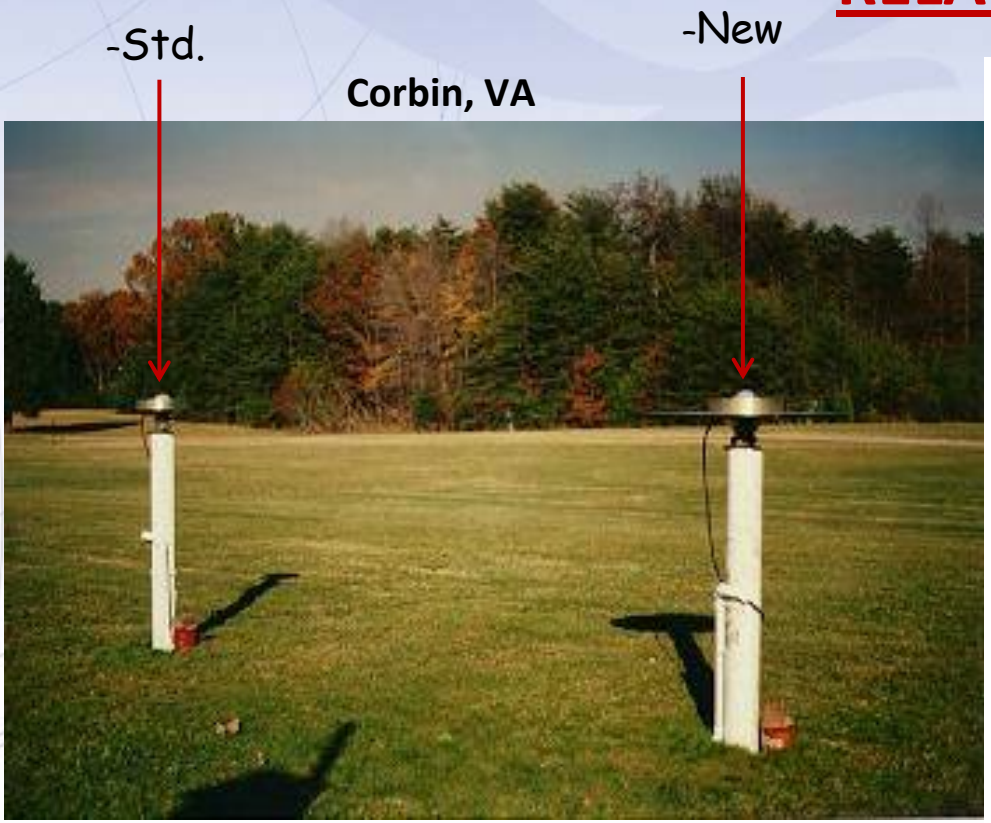
–The IGS started to use absolute antenna phase center variation (PCV) patterns with GPS week 1400.

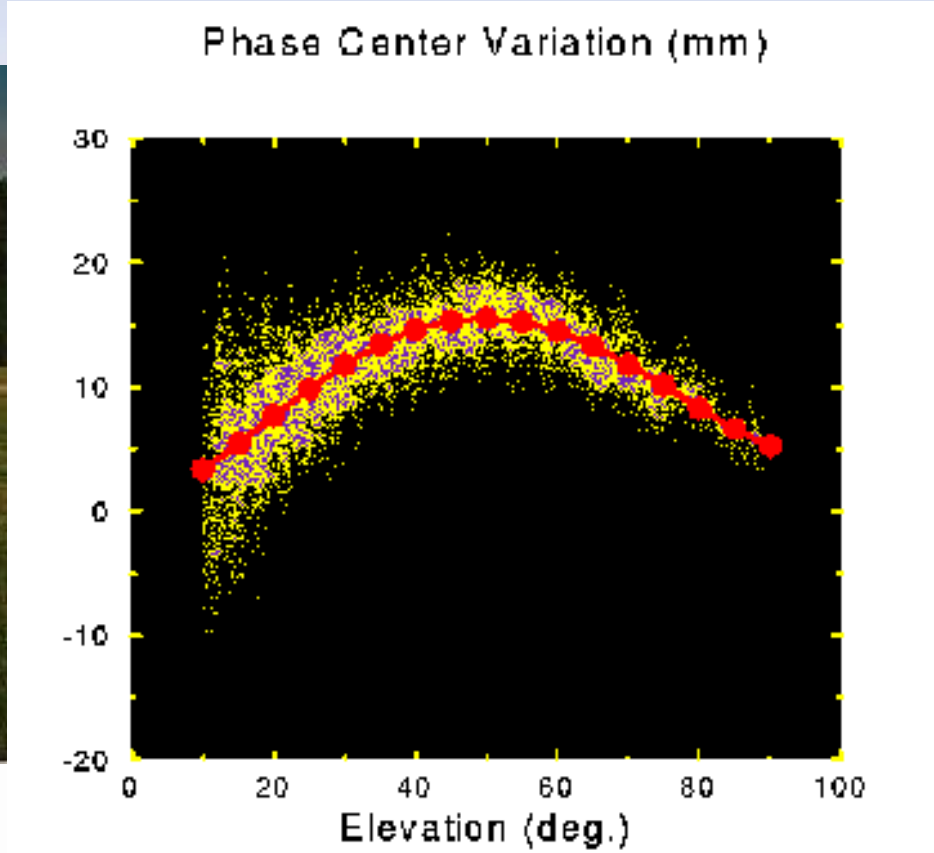
–Coordinates of IGS reference stations are consistently based on the official IGS absolute PCVs.

–As a consequence, a user should use the identical pattern for these sites as used by the IGS in order to get a consistent tie to the reference frame.

Relative vs. Absolute GNSS Antenna Calibration

RELATIVE



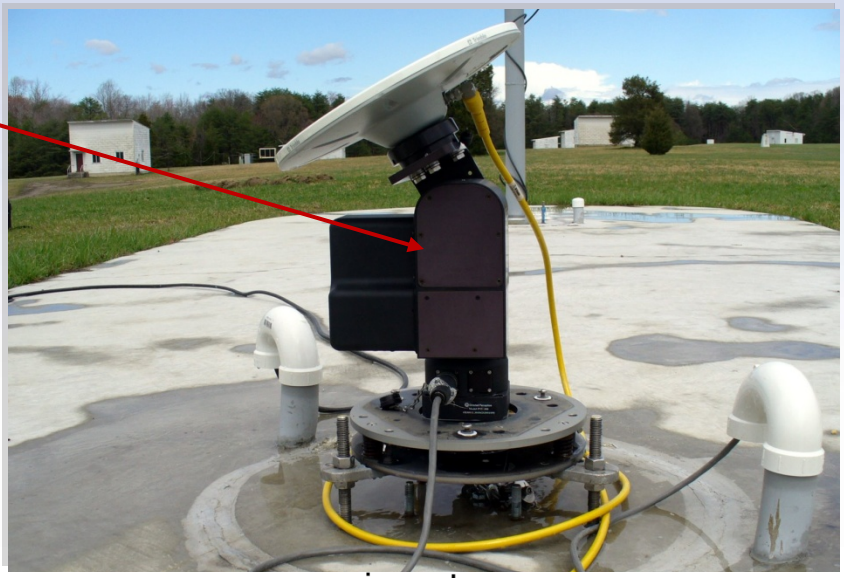


–Relative means all new antennae compared with the standard reference antenna Dorne Margolin Type, e.g. AOAD/MT. The standard being the "ZERO" fixed mean offset.

Relative vs. Absolute GNSS Antenna Calibration

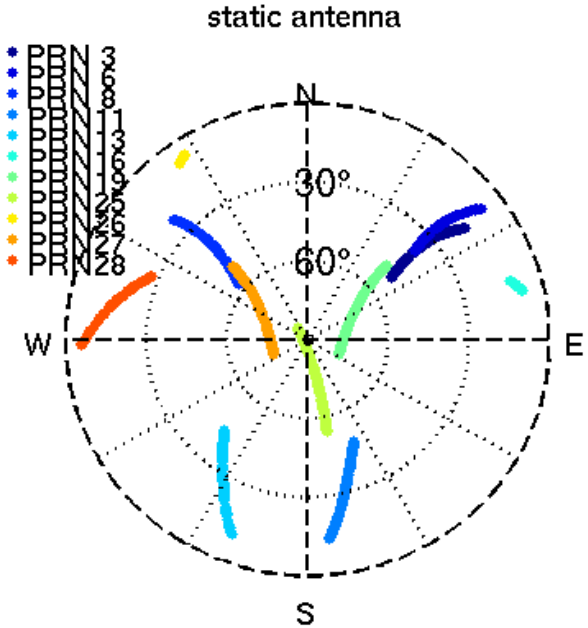
ABSOLUTE

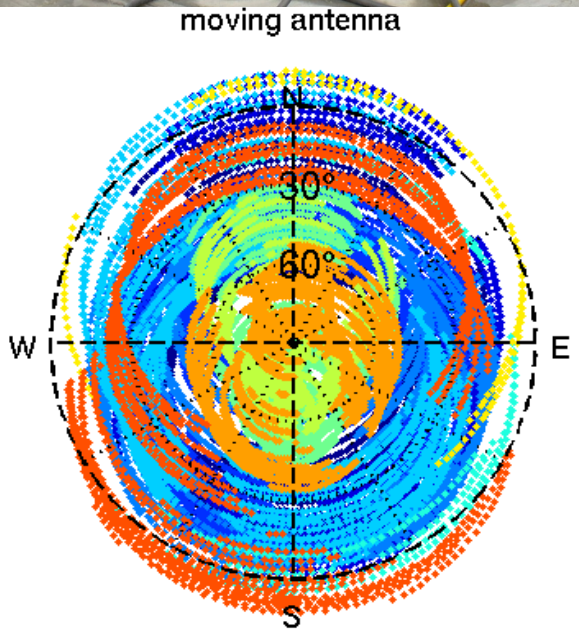
Robotic Arm



rotation introduces angle changes for time difference of single difference (TDSD) phase observables.

Speeds up the process!





Advantages of the absolute antenna calibration

- The robot carries out fast rotations on different axes
- Saves time

– absolute 3D-offset and PCV

– high resolution and precision (sub mm)

– free of multipath

– PCV from 0°-90° elevation, also azimuthal PCV

– site and location independent

Influence of the antenna dome

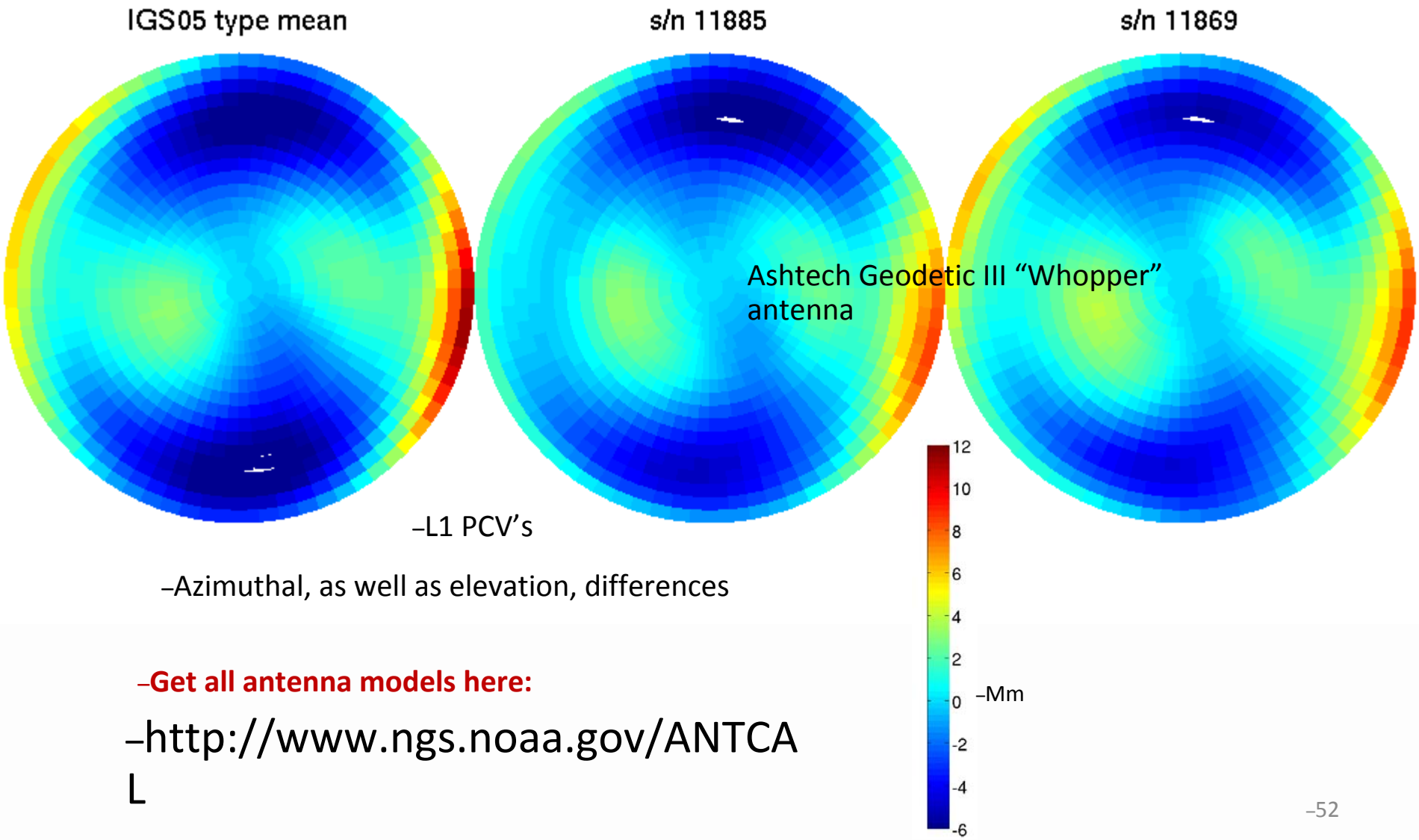
Site AB24 - Alaska

- 1st model antenna model without dome. (absolute)
- 2nd model with dome relative to model without dome.

- Studies have shown that domes can affect network horizontal change in position < 5 mm… and vertical network changes can be as large as < 3 cm.

- **The position error caused by domes is not a constant but depends on the satellite geometry observed at the specific site.** **(CH. Volken, F. Menge, Impact of Differenent GPS Antenna Calibr Models on EUREF)**

NGS Calibrations compared to IGS type mean



Ashtech Geodetic III "Whopper" antenna

–L1 PCV's

–Azimuthal, as well as elevation, differences

–Get all antenna models here:

–http://www.ngs.noaa.gov/ANTCAL

Receiver Measurement Noise

Limitations inherent in the receiver's electronics

Higher-end receivers have minimum noise

Buy the best GNSS receiver suitable for your mission!

Ionospheric Delay

The ionosphere is…

-A region of earth's atmosphere where uv and x-ray radiation from sun cause gas ionization.

-Extends from 50 km to ~1,000 km altitude

Ionosphere is a dispersive medium – it bends GPS signals and changes propagation speed of signal.

-Bending (signal refraction) causes negligible range errors

-Propagation speed changes cause significant range errors

-Speeds up carrier phase beyond speed of light, so ranges appear short

-Slows down PRN code, so ranges appear long

Ionosphere is not homogenous – described in layers within which electron densities vary.

Total Electron Count (TEC) varies with time of day, time of year, 11-year solar cycle, geographic location,

Ionospheric Delay

Ionospheric delay is frequency dependant

- L2 (1227.6 MHz, 24.4 cm) is greater than L1 delay (1575.42 MHz, 19 cm)
- Range errors on the order of 5 to 15 meters, but can be as high as 150 m during extreme solar events at midday and near the horizon.

Differencing techniques over <u>short baseline distances</u> can effectively remove much of the ionospheric delay.

Dual-frequency receivers combine L1 & L2 carrier phase measurement for iono-free solutions

- But increases measurement noise, so not always reliable
- Loose integers of cycle ambiguities

Single frequency receivers must use empirical models in post-processing or from real-time sources.

Tropospheric Delay

The troposphere extends from earth's surface up to about 50 km altitude

-It is considered electrically neutral

-Non-dispersive medium for RF below 15 GHz

Varies with temperature, pressure, and humidity

-So minimized at receiver's zenith (~2.3 m error), maximum at low elevations (~20-28 m error at 5° elevation)

Separated into dry (90%) and wet component

-Dry component can be predicted ok.

-Wet component cannot be predicted that well

Tropospheric delay cannot be removed with differencing techniques – must have model!

Use standard meteorological data as default.

1010 mb, 20° C, 50% rel humidity

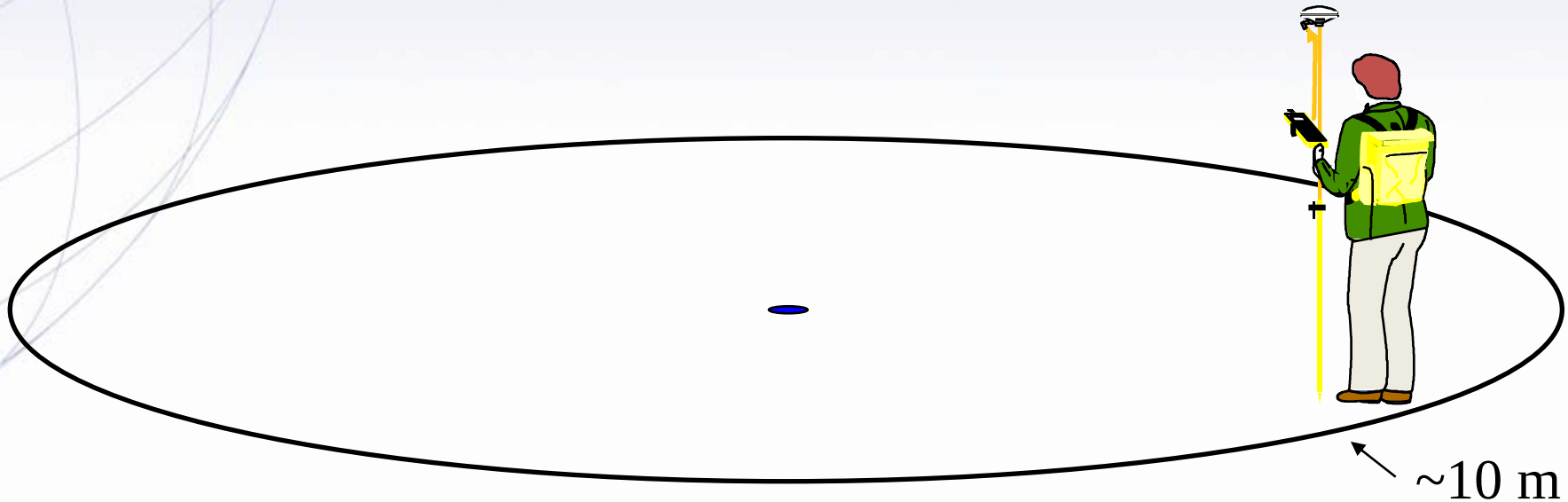
Many Accuracies Can Be Achieved

These depend on some variables

- Design of receiver
- Relative positions of satellites
- Time spent on measurements
- Use of Differential techniques

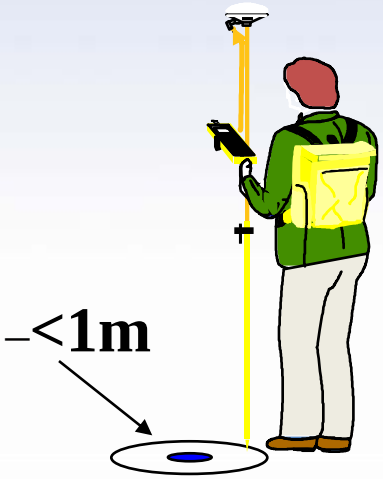
The following slides are horizontal RMS (Root Mean Square - 95th percentile)

Standard Positioning Service - SPS (C/A-Code) – Autonomous GPS



High Quality Mapping Receiver SPS-DGPS

Base Station



Survey Grade GPS
Dual frequency RTK or PP

Base Station

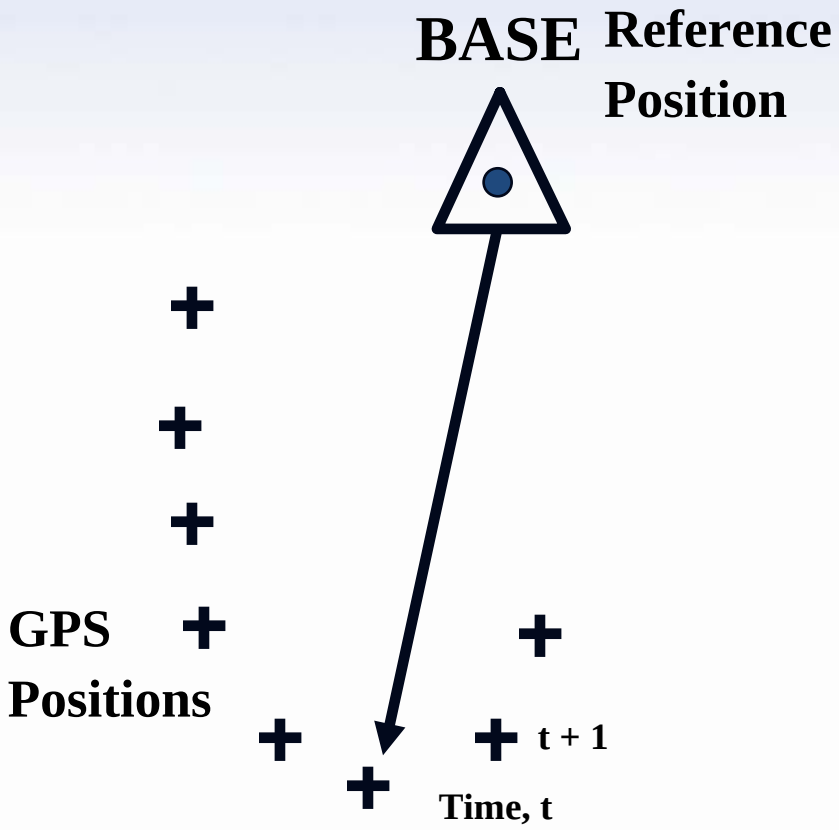
<1 to 2 cm
(precision of measurement)

Differential Correction

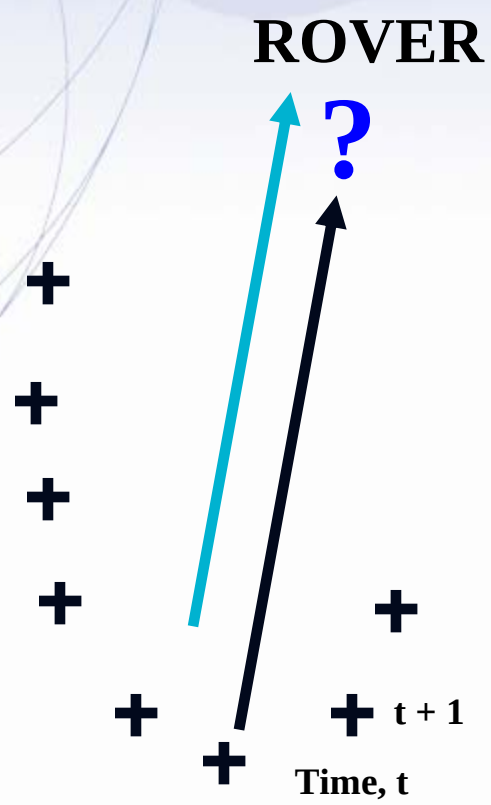
1. Base Station generates corrections for all satellites in view
2. A roving GPS receiver uses these corrections to remove correctable errors
3. Differential correction can be performed in either real-time or post processed mode

Differential Correction (Simplified)

- If you collect data at one location, there will be position errors
- Each of these errors are tagged with GPS time

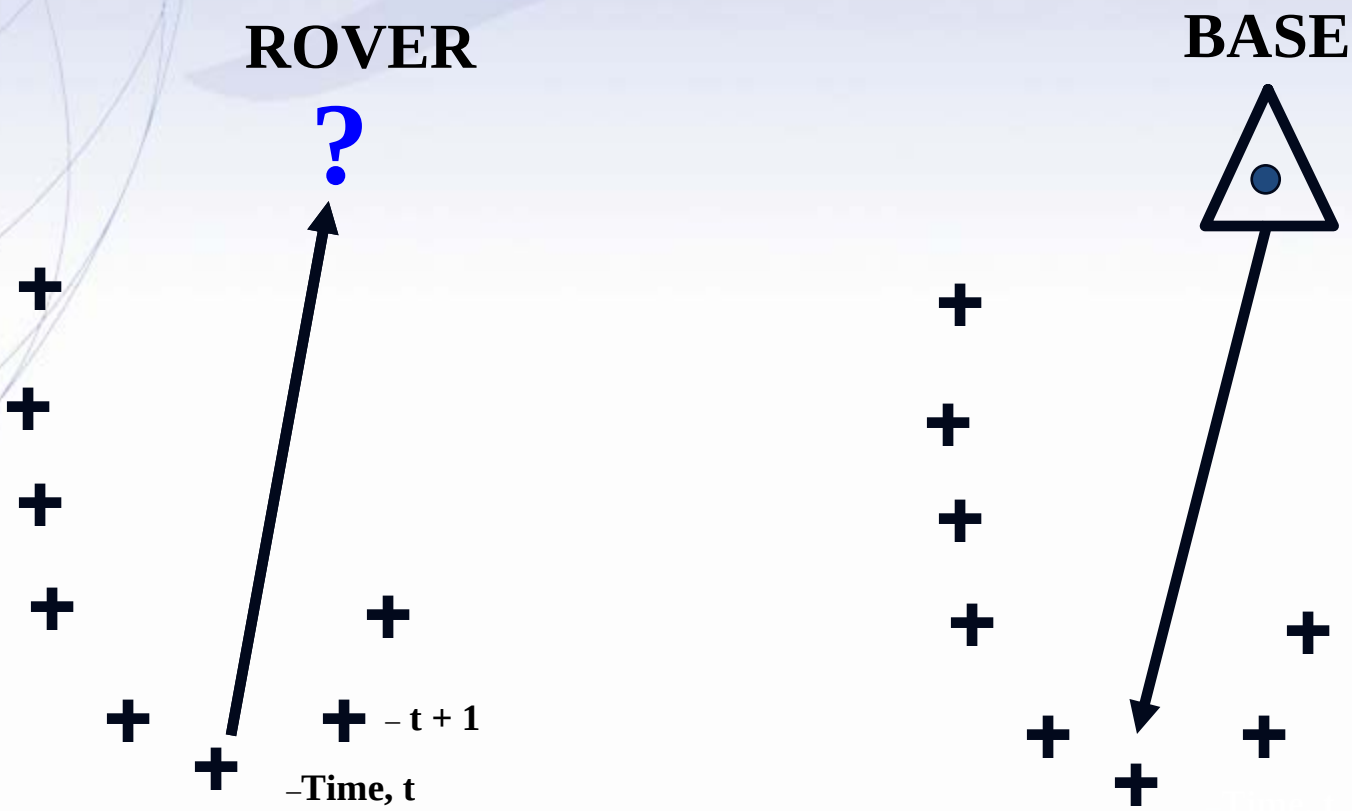


Differential Correction (Cont.)



- At the same time, the errors occurring at one location are occurring everywhere within the same vicinity

Differential Correction (Cont.)



Satellites Used

1 2 3 4

1 3 5 6

Any Combination of Base satellites

Satellites Seen

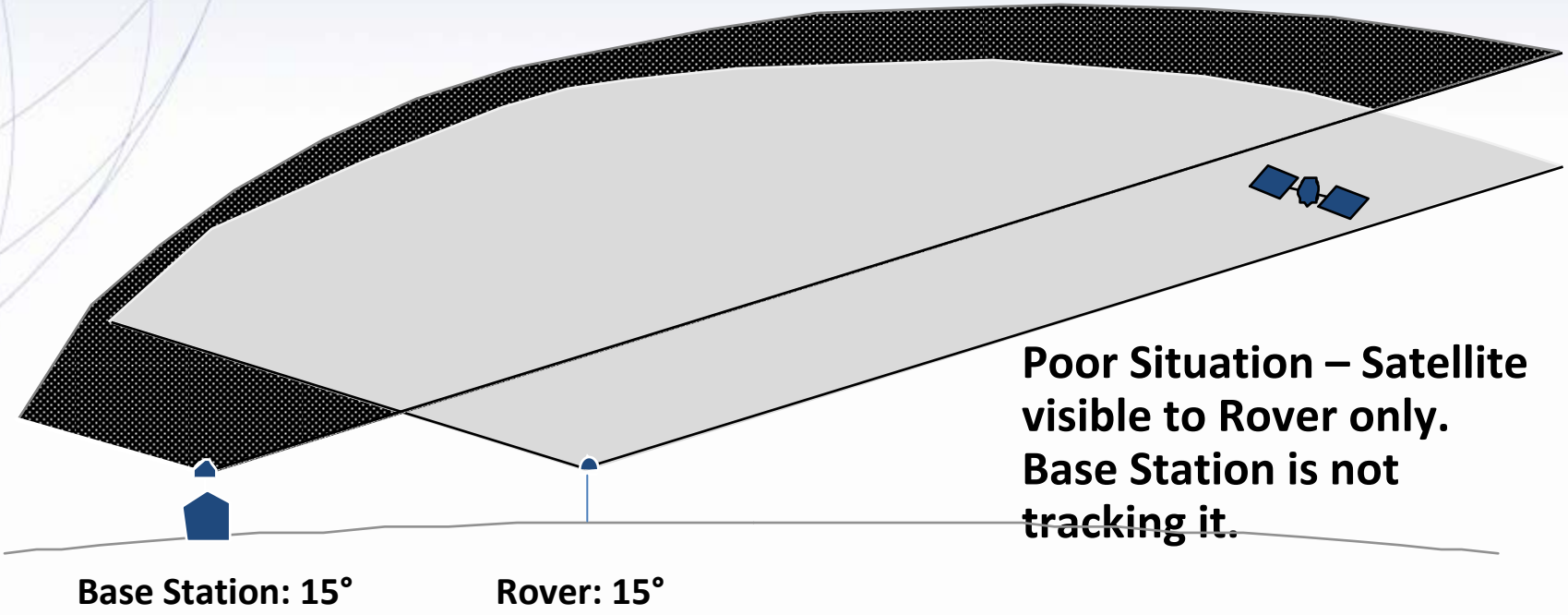
1 2 3 4 5 6 7 8

Base Station Site Requirements

- Clear view to satellites
- Autonomous or seeded coordinates
- Clear of transmitters (TV, radar)
- Line of site to rover is not necessary
- Close to where you are surveying (the further away you are the more error)
- **Read the manufacturer specifications for the receiver**

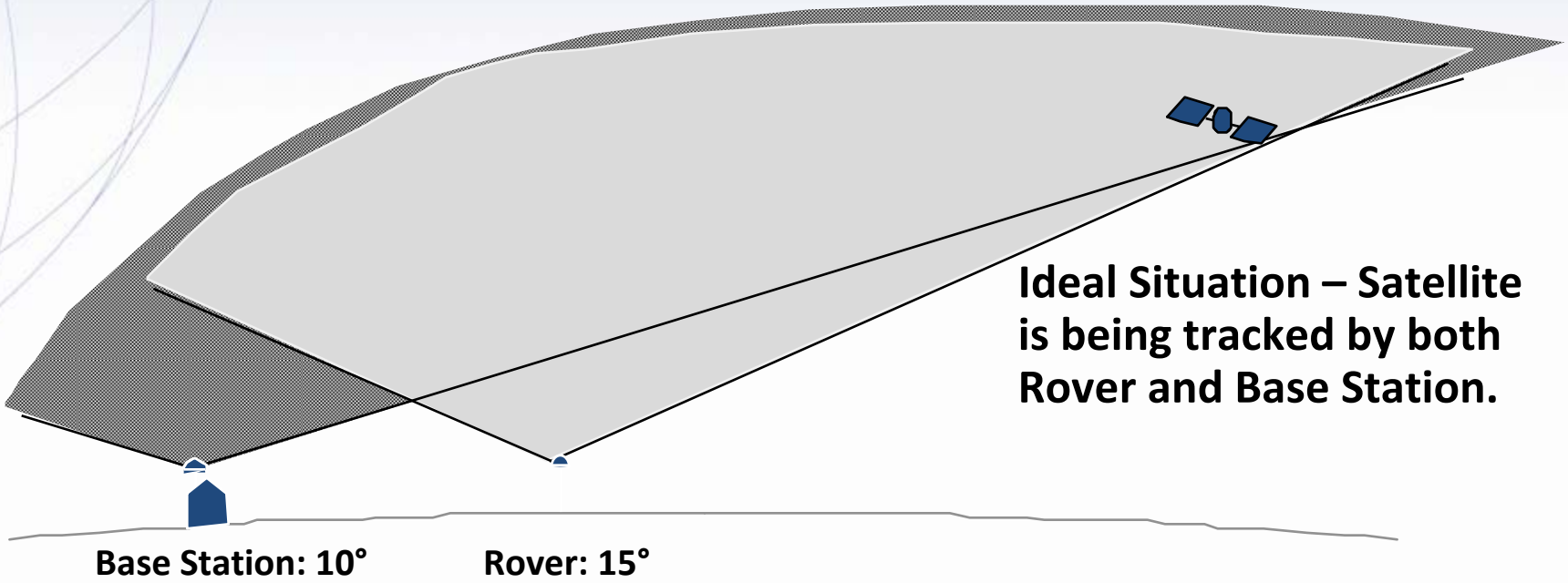
Possible Problem…

setting the elevation masks



Solution…

Set base elevation mask less than rover



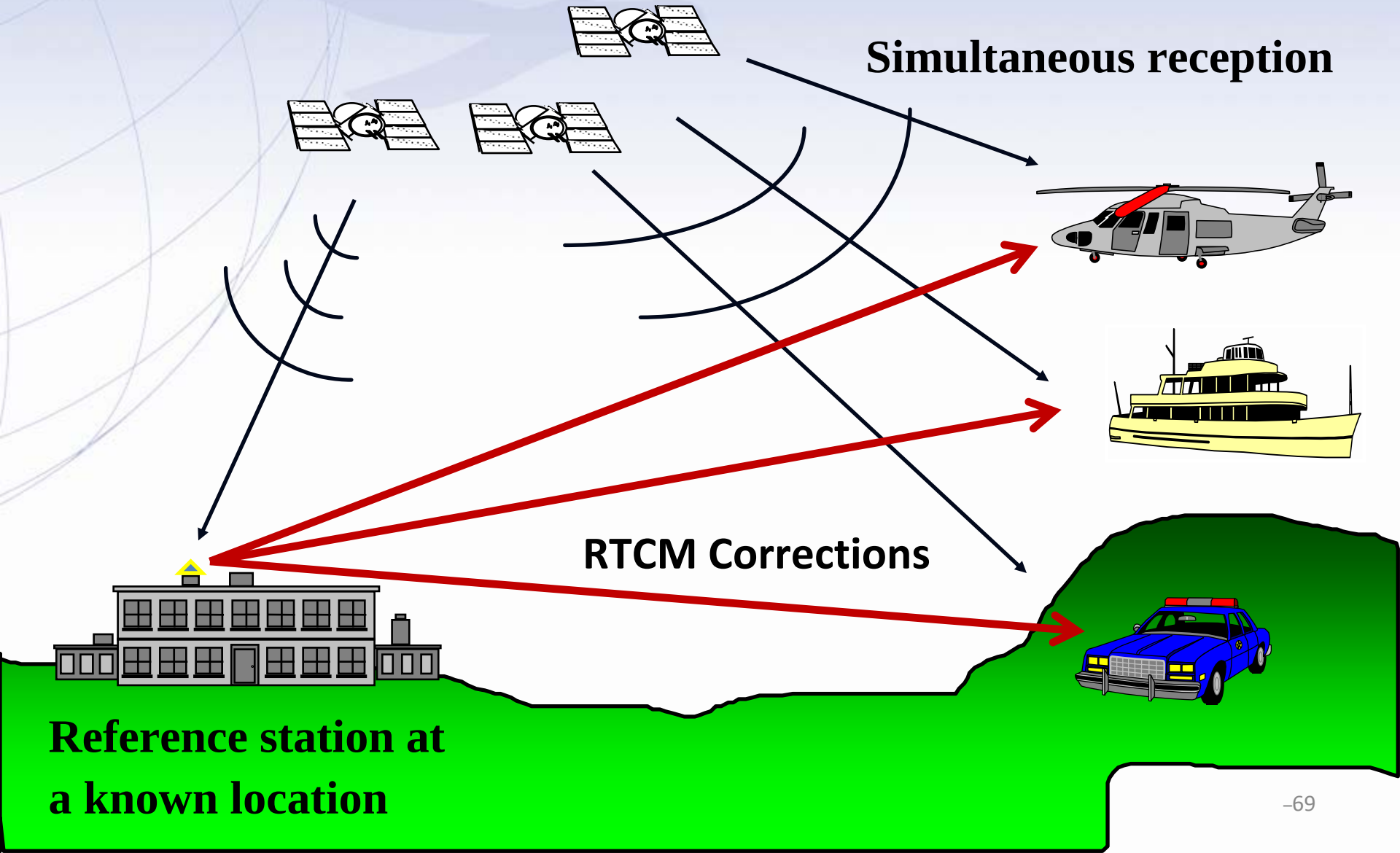
1° per 100 km distance between base and rover

Sources of Base Data for Post-processed DGPS

Where does one get differential GPS base station data?

- Community Base Stations (CBS)
  - government, commercial or public (universities)
  - NGS CORS
- BBS and Internet Access
- Set up your own
  - GPS Pathfinder CBS
  - Universal Reference Stations (URS)
  - Trimble rover units can be used as a base

Real-Time Differential GPS



Sources of Real-Time Corrections

Where does one get real-time differential GPS base station data?

Commercial Real-time DGPS providers

Government

- Coast Guards
- Mapping Agencies
- RTN (ie; ORGN, WSRN)

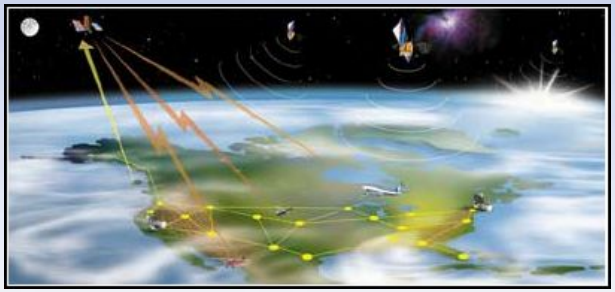
Set up your own real-time DGPS

- Required

  A source of DGPS correction in RTCM-SC-104 format

  A data link, for example, a data radio (modem and transmitter, cell phone, wifi)

WAAS (Wide Area Augmentation System)



- Satellite based augmentation system
- Developed by FAA & DOT for precision flight approaches
- Approximately 25 ground reference stations across the US that monitor GPS satellite data.

Two master stations, located on either coast, collect data from the **Reference** stations and create a GPS correction message.

This correction accounts for GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere.

The corrected differential message is then broadcast through one of two geostationary satellites, or satellites with a fixed position over the equator.

The information is compatible with the basic GPS signal structure, which means any WAAS -enabled GPS receiver can read the signal.

Better than 3 m error 95% of the time.

Positioning Basics

Raw position - The receiver provides latitude and longitude and height in the World Geodetic System (WGS-84), and may be transformed with data collector or office software to NAD 83 (plate fixed at a particular reference frame and epoch) or other datum available .

Velocities of crustal motion maybe computed from change of ground positions observed over time in 3D. CORS stations provide good velocity data.

Understanding GPS Time - GPS Time is derived from the Master Control Clock (USNO) and SV clocks (Cesium &/or Rubidium radioactive elements).

GPS Time is in weeks and seconds from 24:00:00, January 5, 1980.

GPS Time is steered to within 1 µs of UTC, but no leap seconds.

GPS Time today is ahead of UTC by 13 s.

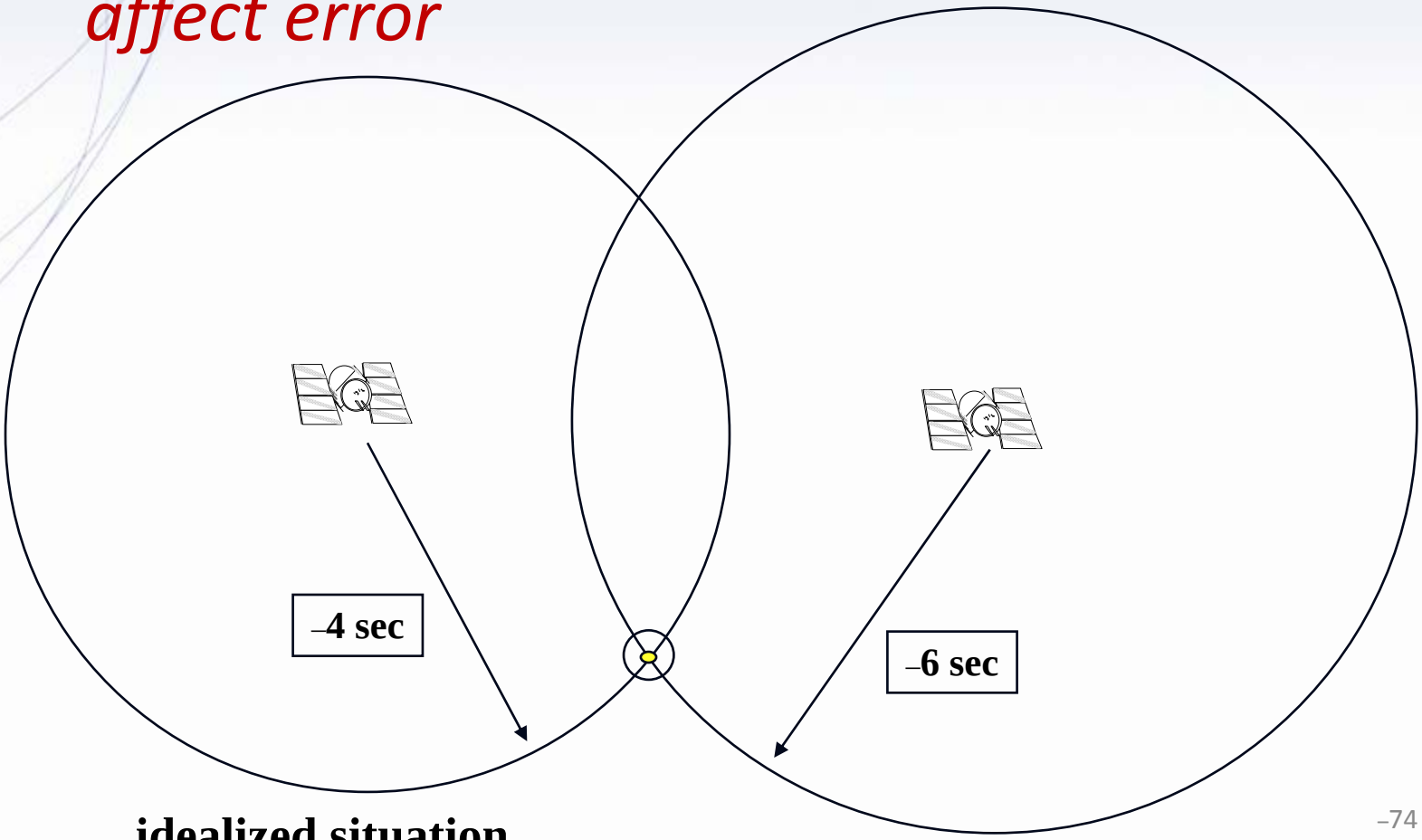
Dilution of Precision (DOP)

- A measure of Satellite geometry
- Indicates the quality of position fix

- Can be expressed in different dimensions
  - for example: PDOP, HDOP, VDOP, TDOP

Dilution of Precision (DOP)

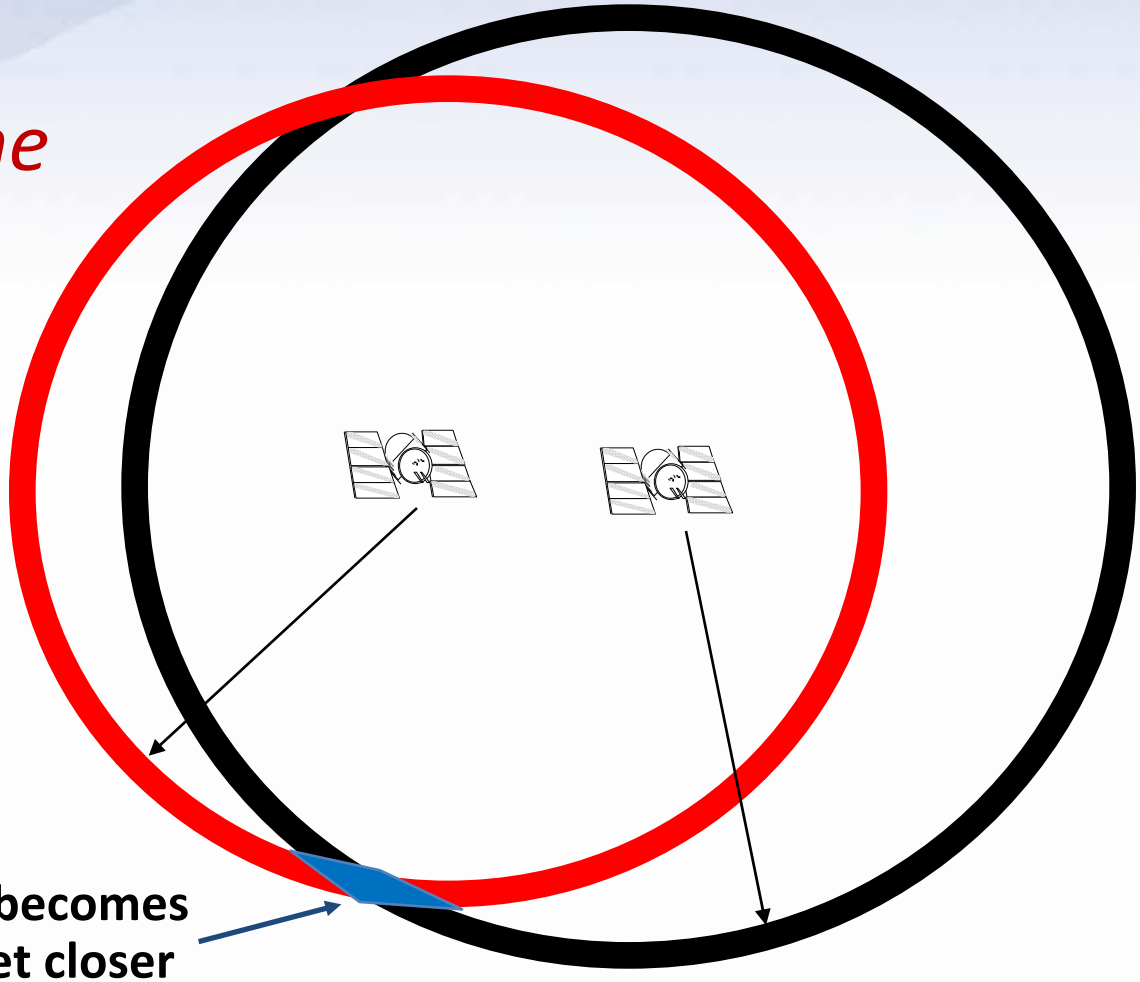
Relative position (geometry) of satellites can affect error



idealized situation

Dilution of Precision (DOP)

Even worse at some angles



Area of uncertainty becomes larger as satellites get closer together

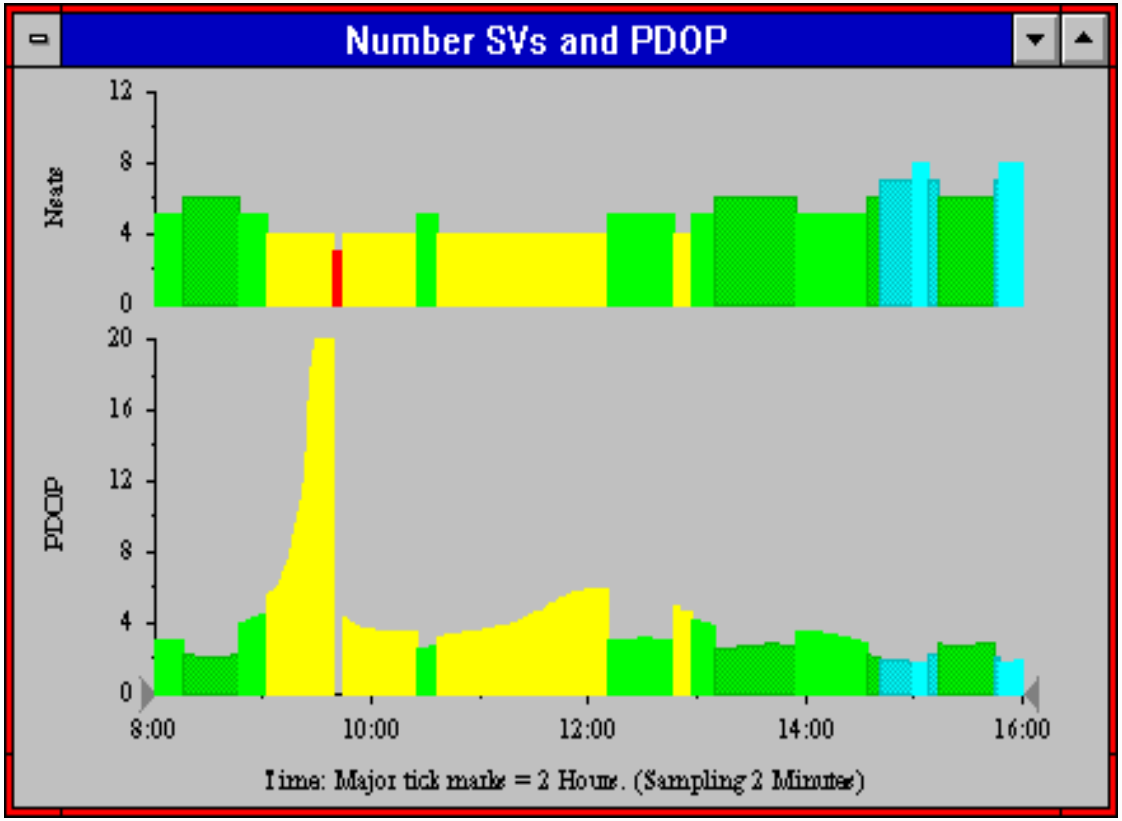
Dilution of precision (DOP)

Can be expressed in different dimensions

- GDOP - Geometric dilution of precision
- PDOP - Position dilution of precision
- HDOP - Horizontal dilution of precision
- VDOP - Vertical dilution of precision
- EDOP - East dilution of precision
- NDOP - North dilution of precision
- TDOP - Time dilution of precision
  - $GDOP^2 = PDOP^2 + TDOP^2$
  - $PDOP^2 = HDOP^2 + VDOP^2$
  - $HDOP^2 = EDOP^2 + NDOP^2$

Satellite Visibility and PDOP

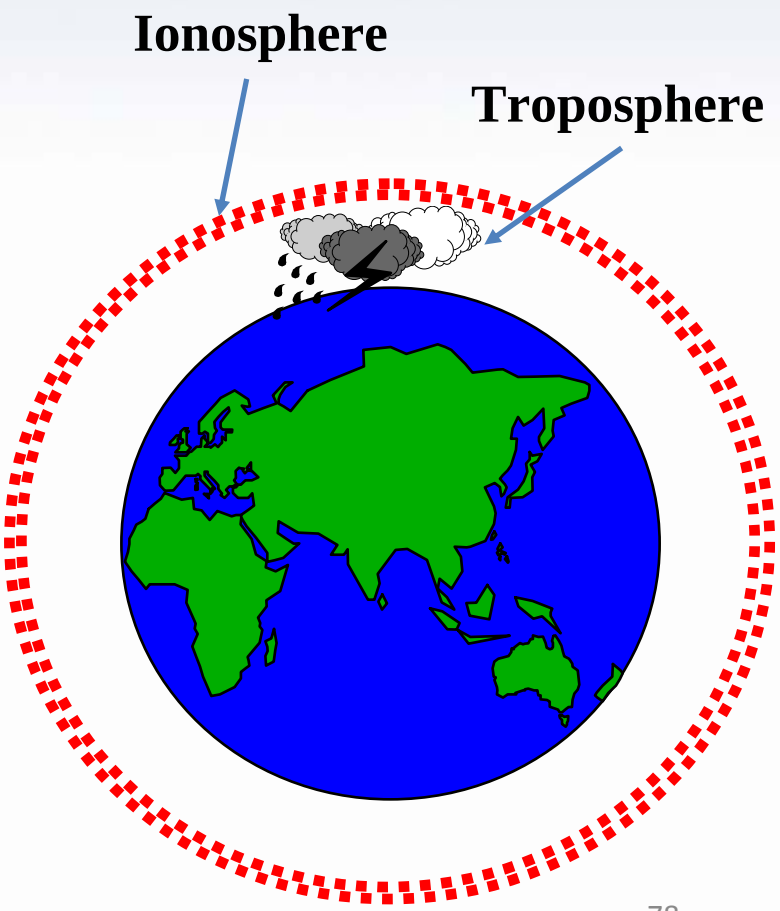
- Use an almanac from a GPS receiver to calculate the best times of the day for GPS.



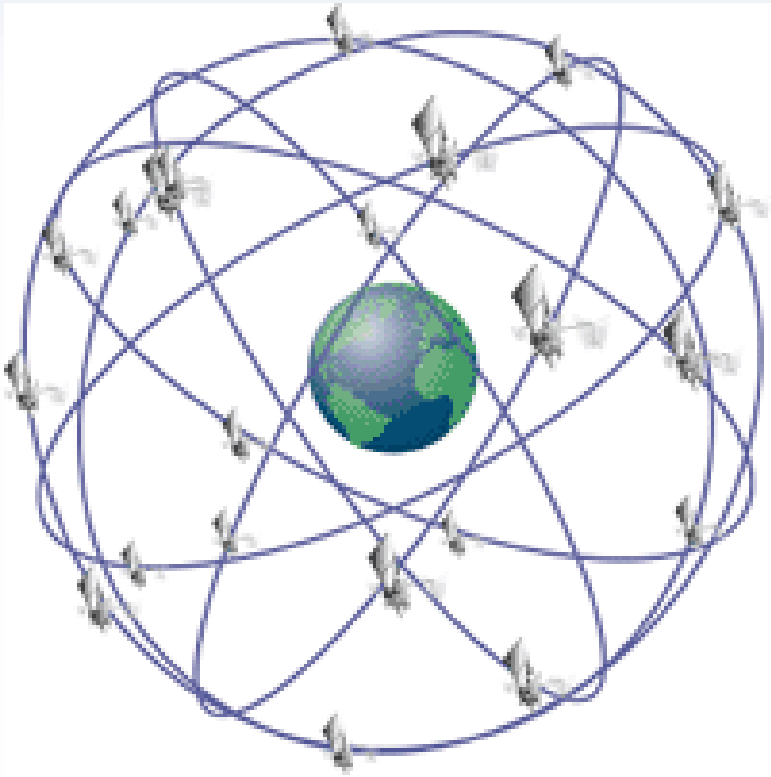
Atmospheric Corrections

Apply estimated corrections

- The signals are delayed by the ionosphere and troposphere
- Receiver makes estimated corrections for these delays



Questions



Mark L. Armstrong, PLS
NOAA/NGS Oregon State Advisor
mark.l.armstrong@noaa.gov