Time Space Position Information (TSPI)

What is TPSI

Time-Space-Position Information

- **TSPI is an observation of an entity's position and orientation in space at a specific time**

- **Time - What time did the observation take place?**
- **Space - What was the orientation?**
- **Position - What was the position?**
- **Information - Report these in a known format**

Definition

- **TSPI is the result of a process that defines a well qualified state vector of an object’s position, velocity, and acceleration at an instant in time (3-DOF).**

- **A part of most Test Missions; “Truth” source.**

- **Continuously need better “truth” for PGM’s and improved Threats.**

Uses for TSPI

- Aircraft Position (latitude, longitude, altitude)
- Aircraft Velocities
- Target Slant Range
- Target Velocities
- Target Accelerations
- Target Position [Cross range, Down range, Altitude (CDU)]
- Angles to Target (LOS, north, east, down)
- Roll Compensated Angles to Target (Elevation, Azimuth)

TSPI Time

- **Time seems like it should be easy but it is actually quite hard**
  - **How do you know what time it is?**
  - **How do you know you are right?**
  - **How should the value of time be expressed?**
  - **Are we traveling near the speed of light?**

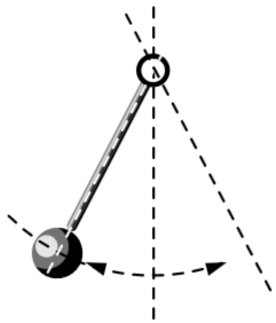
What is a Second?

13th General Conference of Weights and Measures (in 1967) CGPM [Conférence Générale des Poids et Mesures] Resolution 1…

- **"The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom."**
- **The current best accuracy for the realization of the second so defined is a value "y(t)," as defined above, of 3×10^{-15}.**
  - **This is equivalent to ±1 second in 10 million years.**

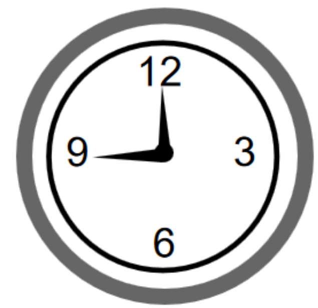
What is a Clock?

A clock is an Oscillator and a Counter

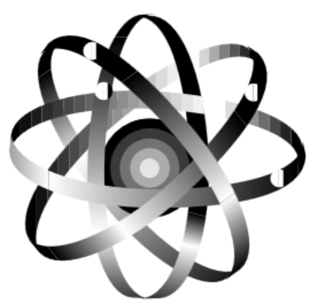


Oscillator
(Frequency Device)

+



Counter
(Counts Periodic Events)



Cs - 133 Atom

+

Fast Electronic Counter

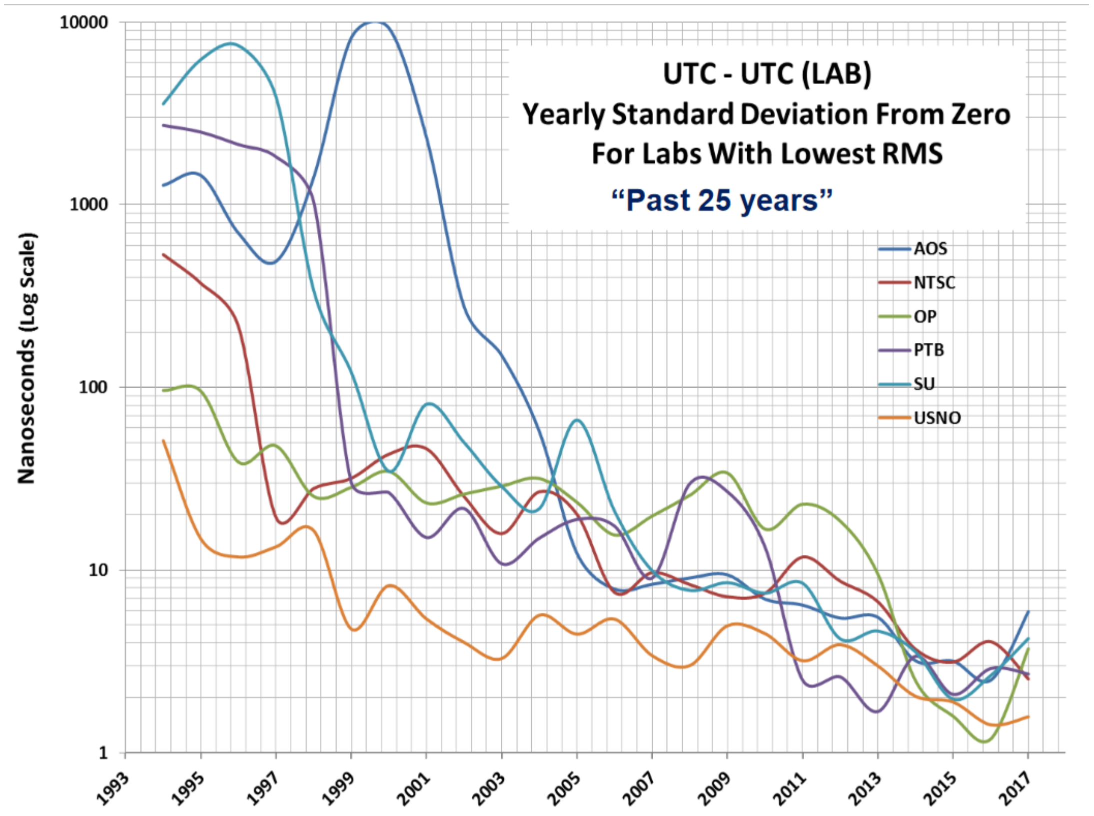
What Time Is It?

- **Sidereal Time**
  - **Determined by means of the apparent daily motion of the stars.**
- **Universal Time (UT)**
  - **Based on Sidereal Time, not SI seconds**
  - **UT0, UT1, UT1R, UT2, UT2R**
- **Universal Coordinated Time (UTC)**
  - **AKA Greenwich Mean Time (GMT)**
- **International Atomic Time (TAI) Time**
  - **International atomic time scale based on a continuous counting of the SI second.**
  - **TAI is currently ahead of UTC by 37 seconds.**
  - **TAI is always ahead of GPS by 19 seconds.**
- **GPS Time**
  - **GPS set to UTC time at 0h 6-Jan-1980**
  - **Not perturbed by leap seconds**
  - **GPS is now ahead of UTC by 18 seconds**

https://www.ucolick.org/~sla/leapsecs/timescales.html

UTC - Universal *Coordinated* Time

- **The C in UTC is "coordinated"**
- **UTC time adjustments are made after the fact from the average of world-wide clock references**



What Time Is It?

local	2020-02-07 15:14:00	Friday	day 038	timezone UTC-6
UTC	2020-02-07 21:14:00	Friday	day 038	MJD 58886.88472
GPS	2020-02-07 21:14:18	week 2091	508458 s	cycle 2 week 0043 day 5
Loran	2020-02-07 21:14:27	GRI 9940	444 s until	next TOC 21:21:24 UTC
TAI	2020-02-07 21:14:37	Friday	day 038	10 + 27 leap seconds = 37

Beware of GPS Time!

GPS Time is very close to UTC

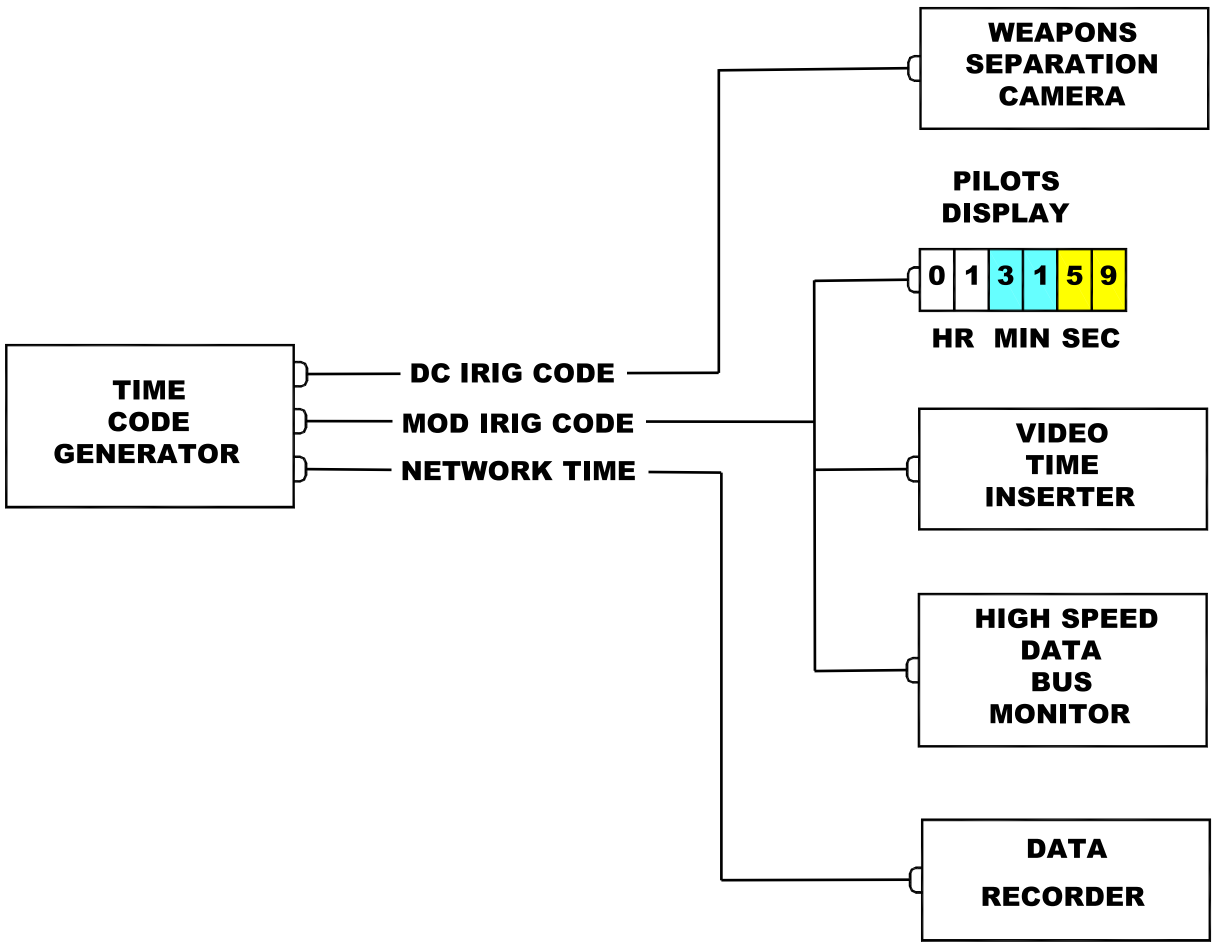
- Offset by a few seconds
- Looks very reasonable…. but probably not the time you are expecting

If someone says “GPS Time” ask if it really GPS Time or rather time supplied from a GPS (usually UTC)

Time

- Time is one of the most important test requirements for the Instrumentation engineer to correctly incorporate into the Instrumentation System due to its impact to all the data recorded.
- Data needs timing information with it so you can correlate and analyze it correctly
- Data systems can use GPS time, Range time, embedded time, or a time from an external reference source provided you understand its performance (drift and jitter) and can correlate all time sources together.
- Time is powerful but dangerous when not handled correctly

Notional Distribution of Time



Time Code Formats

- **IRIG B**
  - **1,000 hertz**
    - 1 second time data w/ 1000 microsecond (1 ms) calculated direct
- **IRIG A**
  - **10,000 hertz**
    - 0.1 second time data w/ 100 microsecond (0.1 ms) calculated direct
- **IRIG G**
  - **100,000 hertz**
  - 0.01 second time data w/ 10 microsecond (0.01 ms) calculated direct

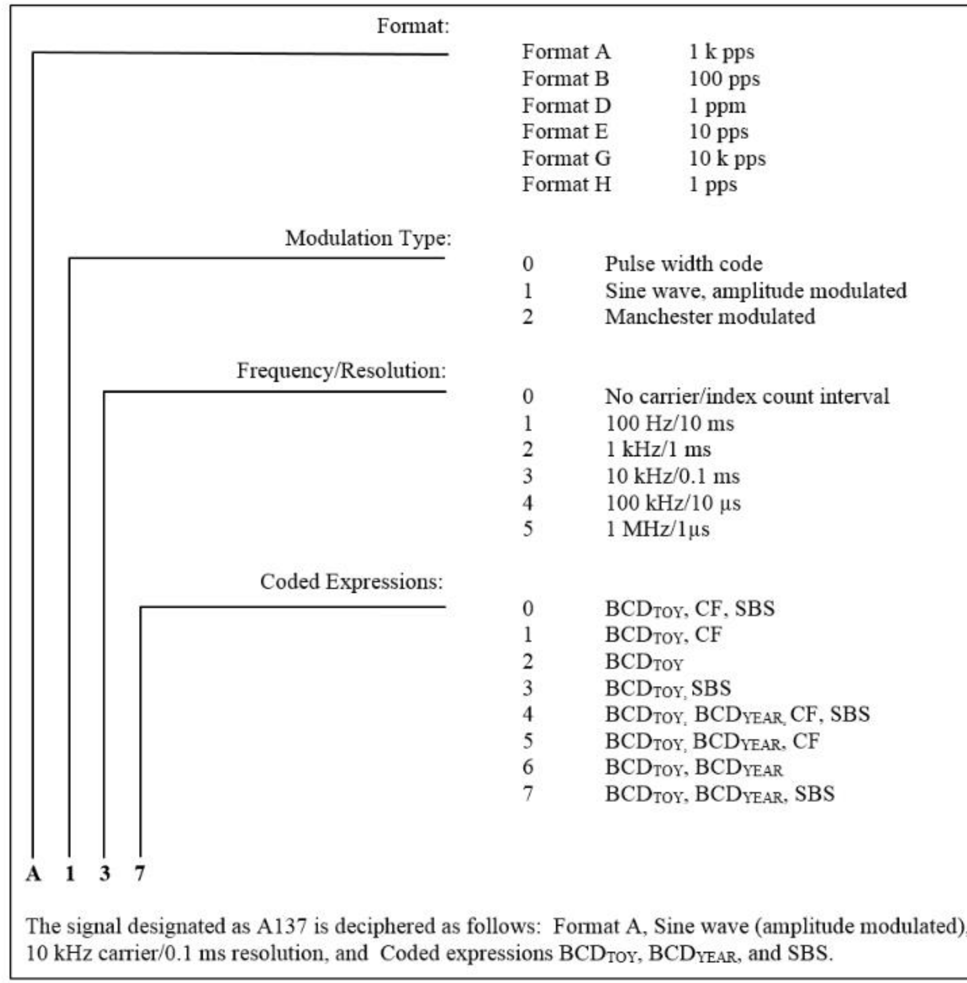
Time Code Formats

- IRIG Standard 200-16
- Must specify:
  - Signal Format
  - Modulation Type
  - Frequency
  - Data Format

CF - Control Function

SBS - Straight Binary Seconds

TOY - Time of Year



Time Format IRIG B Examples

- **Common AM modulated format**

B122 **1 = Sine wave, amplitude modulated**
2 = 1 kHz/1 ms
2 = BCD_{TOY}

- **Common baseband (unmodulated) format**

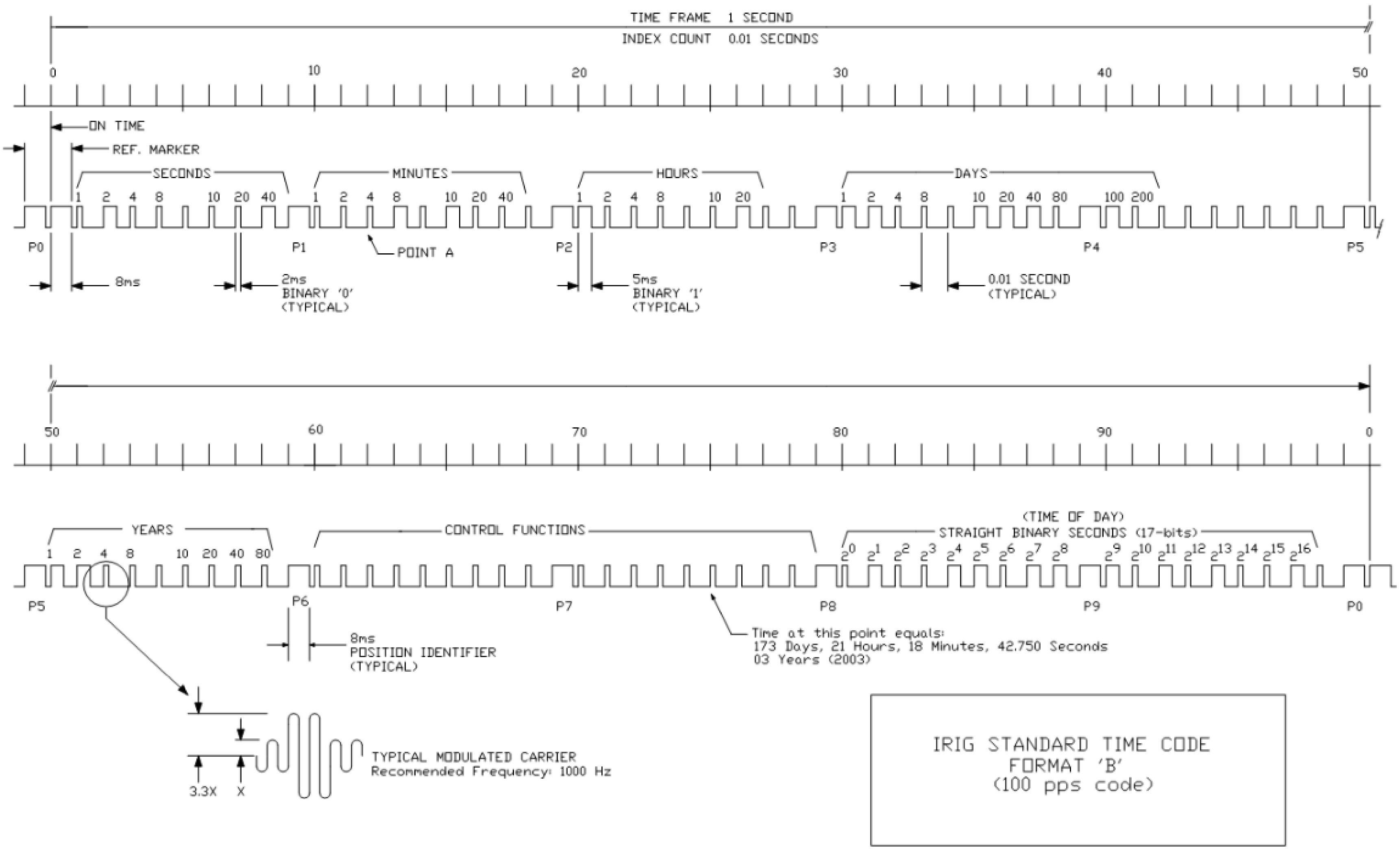
B002 **0 = Sine wave, amplitude modulated**
2 = 1 kHz/1 ms
2 = BCD_{TOY}

- **AM modulated including year**

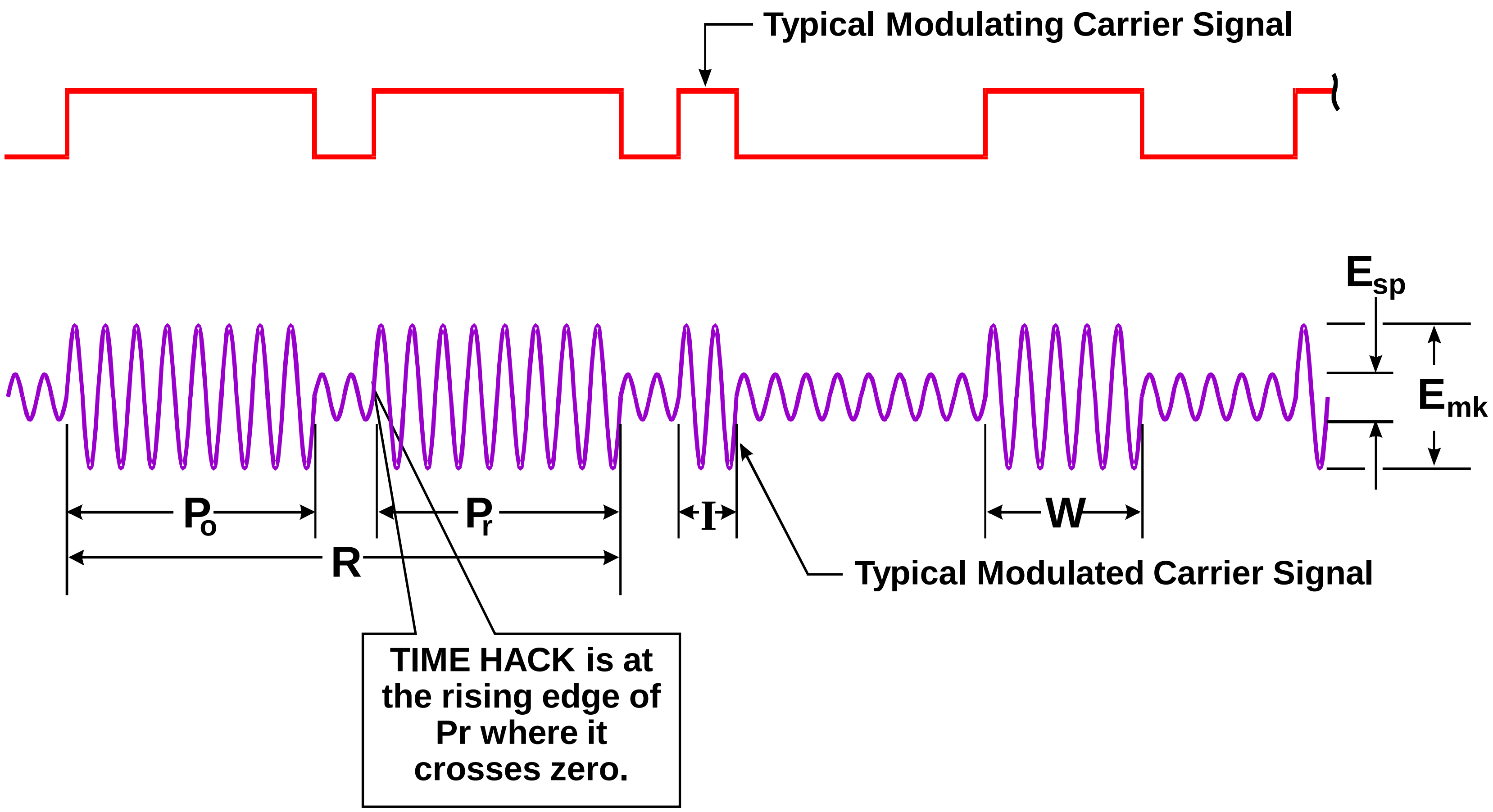
B126 **1 = Sine wave, amplitude modulated**
2 = 1 kHz/1 ms
6 = BCD_{TOY}, BCD_{YEAR}

Time Format IRIG B

(Reference)



Typical Time Codes

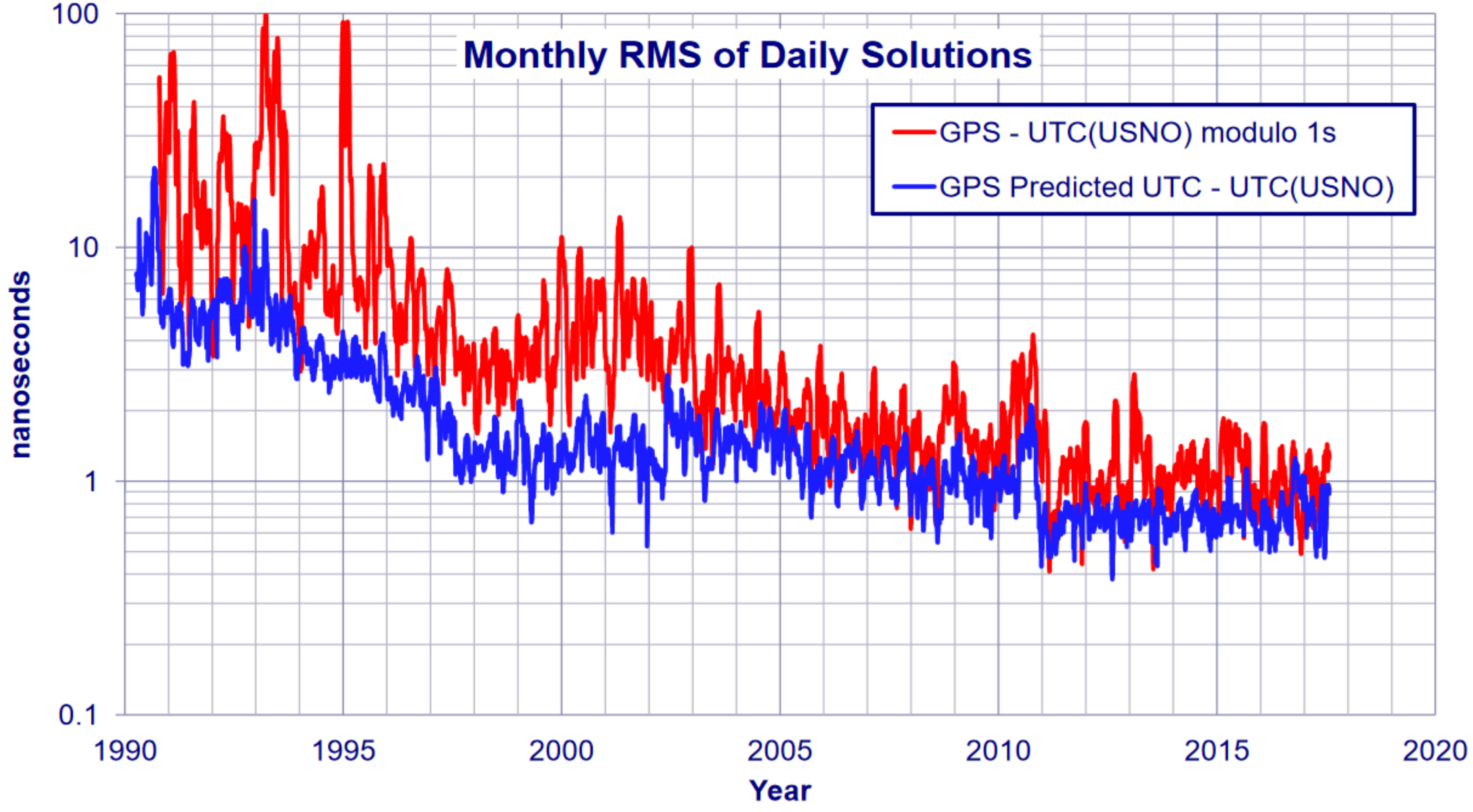


GPS as a Time Source

- **GPS Time is slowly adjusted to maintain alignment with UTC**
  - **No leap seconds though**

- **GPS time accuracy is related to GPS position accuracy**
  - **GPS calculates 4 unknowns… X, Y, Z, and time**
  - **GPS signals travel at the speed of light**
    - 1 foot per nanosecond
  - **If GPS position error is 100 feet then time error may be on the order of 100 nanoseconds**

GPS Time Stability

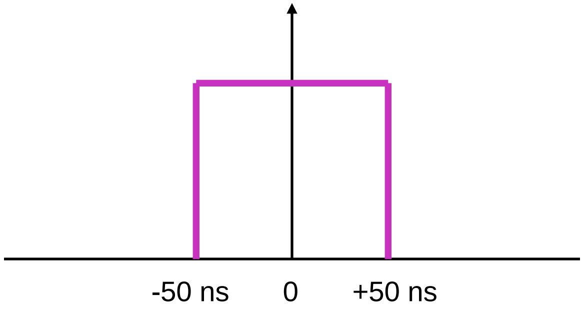


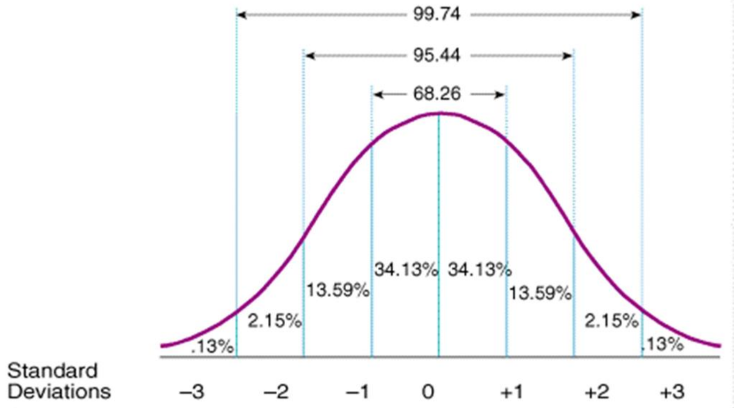
GPS as a Time Source

- **How accurate is GPS time from a GPS receiver?**
- **Just about every quoted accuracy figure is WRONG!**
- **GPS receiver time error, like GPS position error, is not bounded**
  - **Error is probabilistic and needs to be quoted as such**

WRONG
GPS Time Error < 50 nSec

RIGHT
GPS Time Error < 50 nSec 95% of the time





GPS Accuracy Specs

Masterclock

RECEIVER OPTIONS

	GPS Option	GPS+GNSS Option
Satellites	12-channel, up to 12 satellites simultaneously, parallel	32-channel, up to 24 satellites simultaneously, parallel
Frequency	L1, 1575 MHz	L1, 1575 MHz and 1598-1606 MHz
Antenna Connector	SMA female	SMA female
RF Bias to Antenna	5 V DC, center pin	5 V DC, center pin
PPS	50 ms, TTL level, on-time leading edge	50 ms, TTL level, on-time leading edge
Accuracy	±60 ns of UTC	±15 ns of UTC

Brandywine Communications

- IEEE 1588-2008 (v2) Time protocol
- Distributes frequency, phase and time-of-day to ren
- Advanced hardware-generated timestamps
- GPS input source
- ±100 ns timing accuracy when locked to GPS
- Highly stable internal oscillator maintain accurate sy
- Auxiliary outputs include 1PPS, 10MHz, 2.048 MHz,
- 19 inch 1U high rack mountable chassis

Meinberg

Pulse outputs	Pulse Per Second (PPS) via BNC connector (TT
Accuracy of pulse outputs	< ±100ns (OCXO HQ, OCXO DHQ, Rubidium)
Interface	Two independent serial RS232-interfaces, me

The Science of Timekeeping
HP Application Note 1289

Currently, GPS can be used to obtain an estimate of the UTC(USNO MC) clock. If the time output of a good multi-channel Clear Access (C/A) code GPS receiver is averaged for one day against a sufficiently stable local clock, such as a cesium standard, the resulting estimate of UTC(USNO MC) will be within 20 ns 95 percent of the time. Since UTC(USNO MC) is steered to be within 20 ns of UTC at least 95 percent of the time, we can expect that the GPS broadcast correction will be within 30 ns of UTC 95 percent of the time. The frequency

Is Accuracy Important?

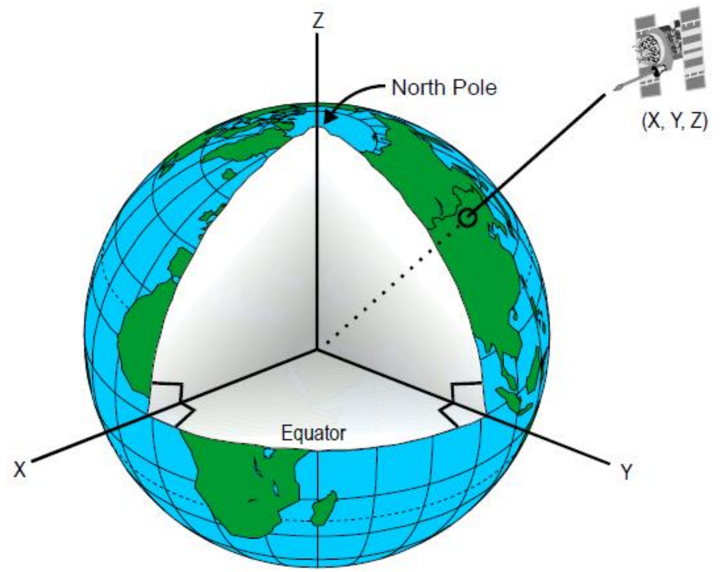
- **Maybe!**
  - If you have data recorded at two different locations and you want to “glue” the data sets together to make one complete and total mission, timing accuracy may be important.
- **Maybe Not!**
  - If you are interested in a sequence of events and the timing relationship between those events, then timing accuracy may not be important.
- **Absolute versus Relative Timing**
  - Absolute timing means being aligned to the world
  - Relative timing means being aligned to itself

TSPI Position
Coordinate Systems

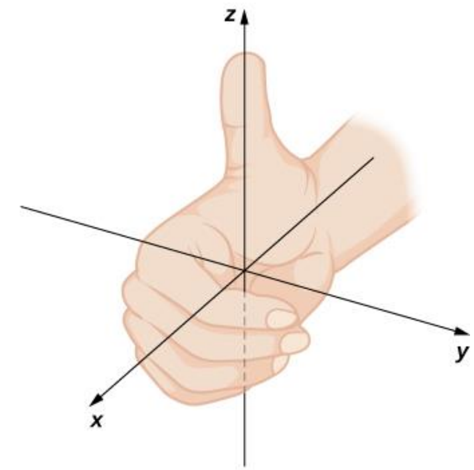
	Earth Reference	Local Reference
Cartesian XYZ	ECEF (Earth Centered Earth Fixed)	NED (North / East / Down)
Spherical RAE	Lat / Lon / Alt	Az / El / Alt

Earth Centered Earth Fixed

- **Cartesian Coordinates / Earth Referenced**
  - **Center of Earth is 0,0,0 origin**
  - **X axis passes through Prime Meridian at Equator**
  - **Z axis passes through True North**
  - **Right hand coordinate system**
- Can be more convenient for calculations

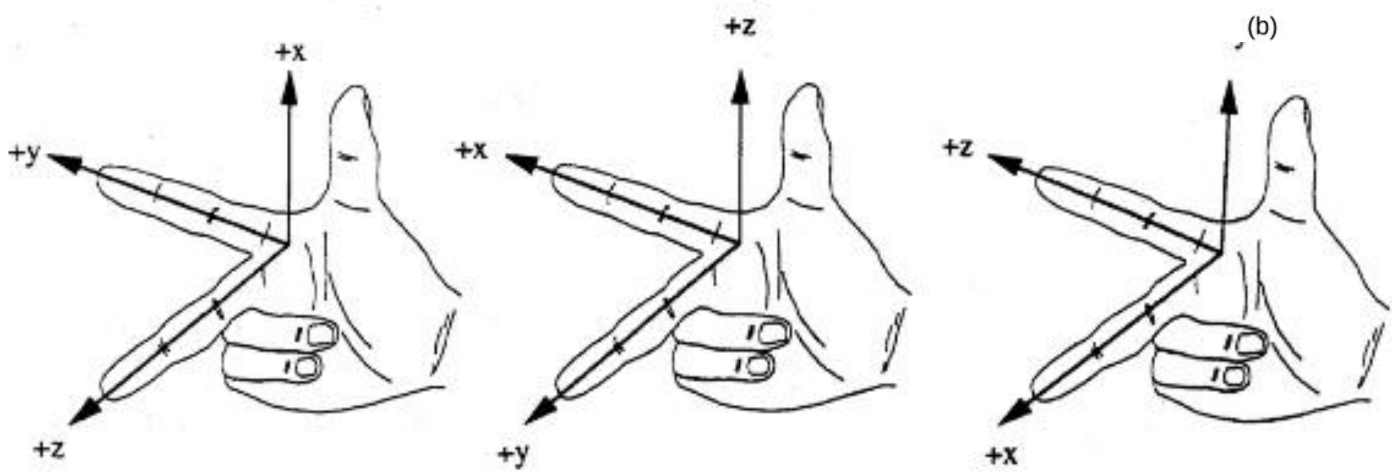


TSPI Position
“Handedness”



(b)

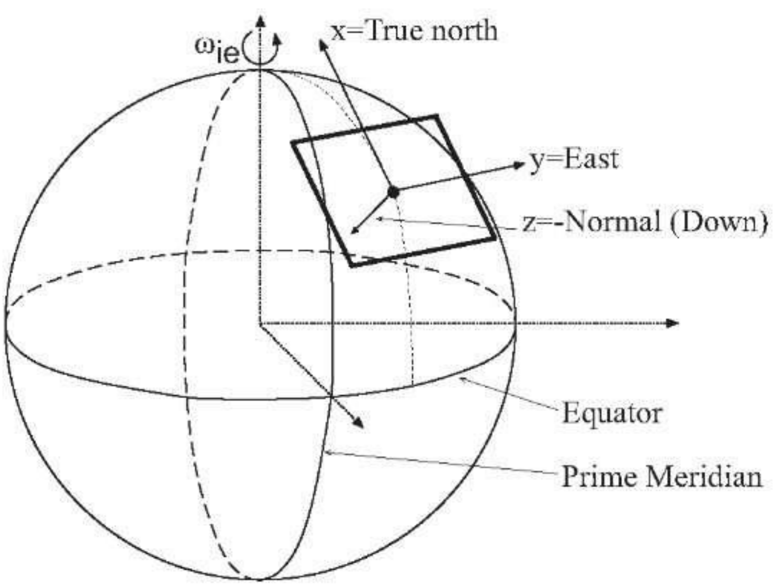
- **“Handedness”**
  - **NED vs ENU**



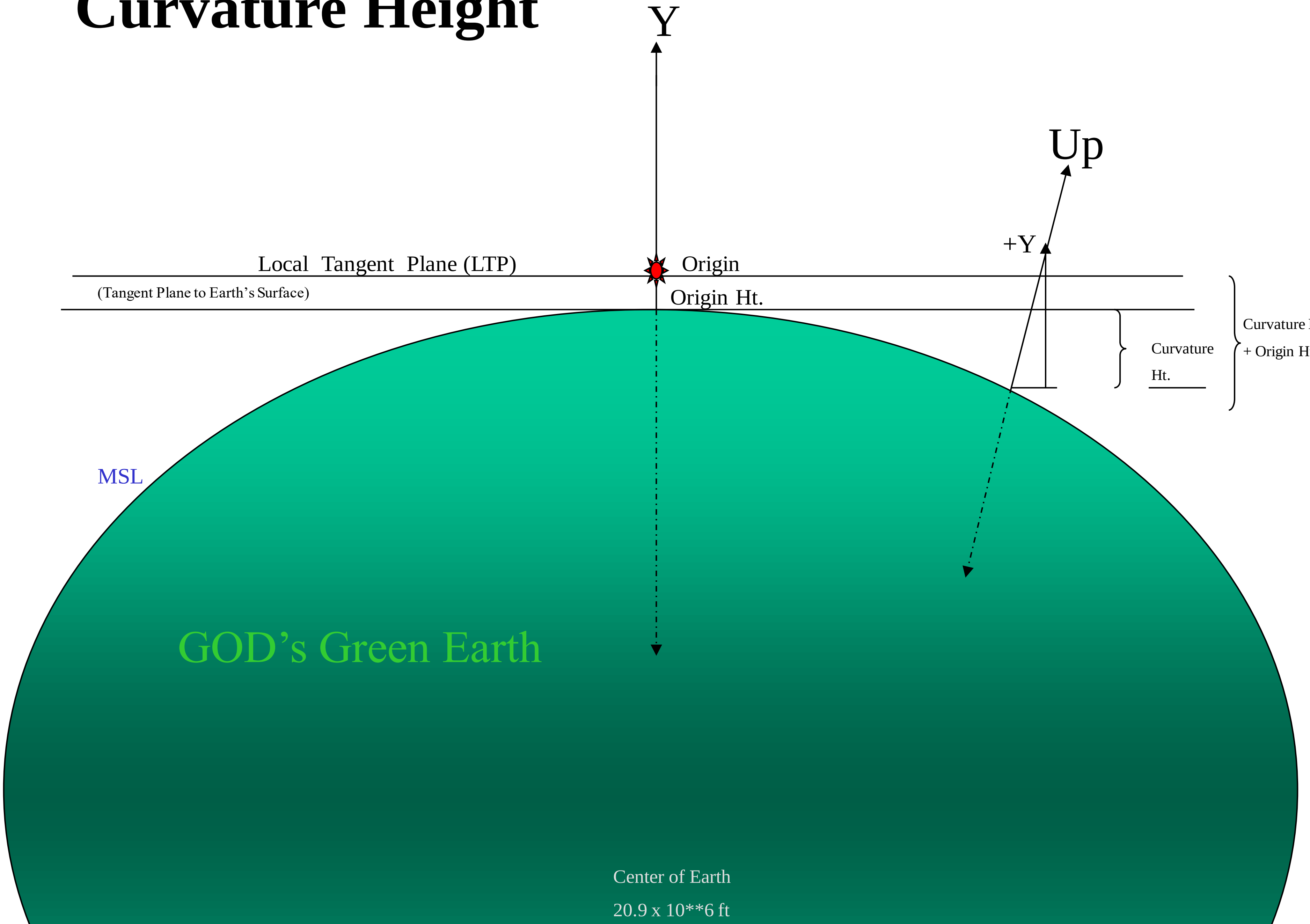
Configuration 1 Configuration 2 Configuration 3

North / East / Down

- **Cartesian Coordinates / Local Reference Plane**
  - North is usually True North
  - Why down and not up?
  - Right hand coordinate system!
- **Can be more convenient for calculations**

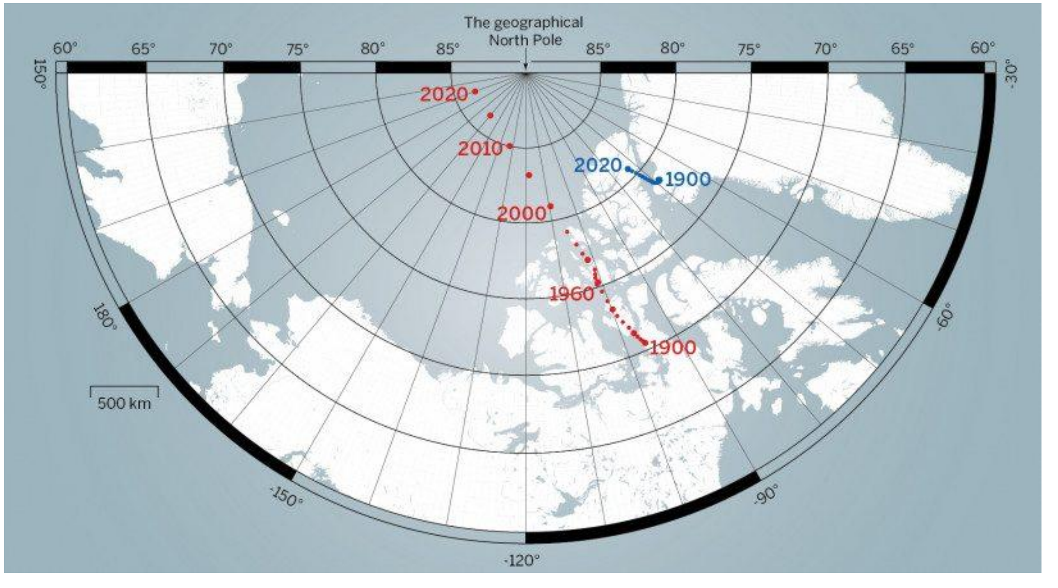


Curvature Height

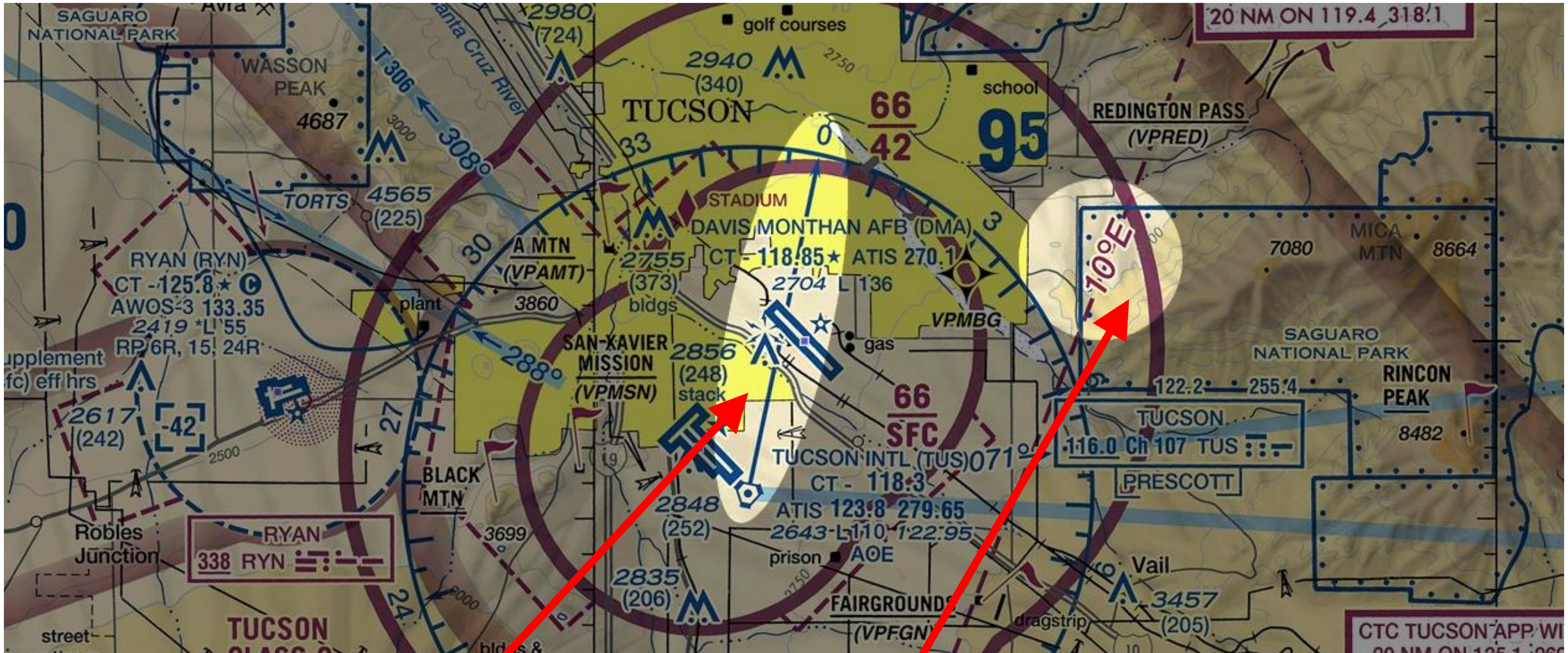


What is North?

- **True North**
  - Uses North Pole navigation reference
- **Magnetic North**
  - Uses Magnetic Pole as navigation reference
  - Magnetic North is easily measured in an aircraft
  - The pole location is constantly moving

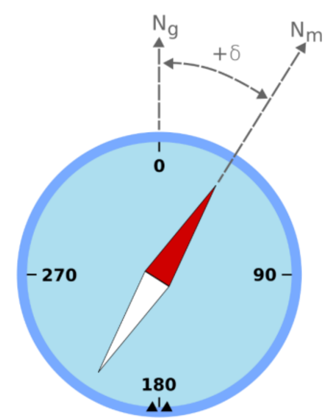


Magnetic Declination



Navigation Aids Point to Magnetic North

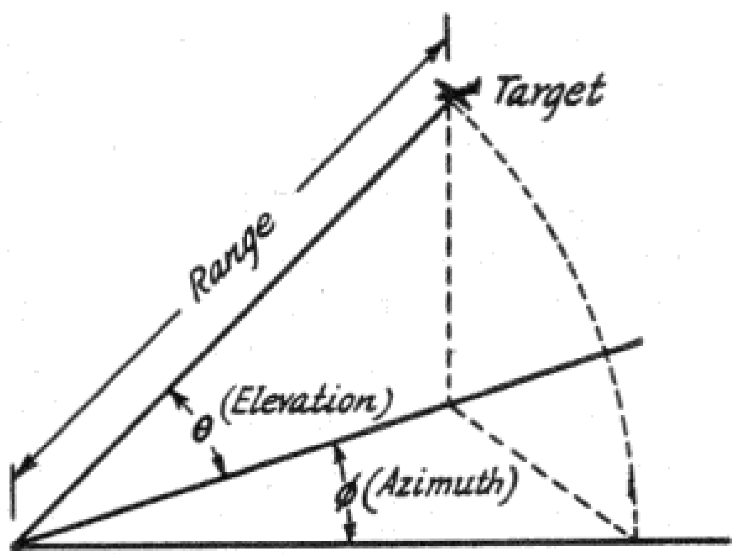
Magnetic Declination Isogonic Line near Tucson



The angle and direction **from** True North **to** Magnetic North

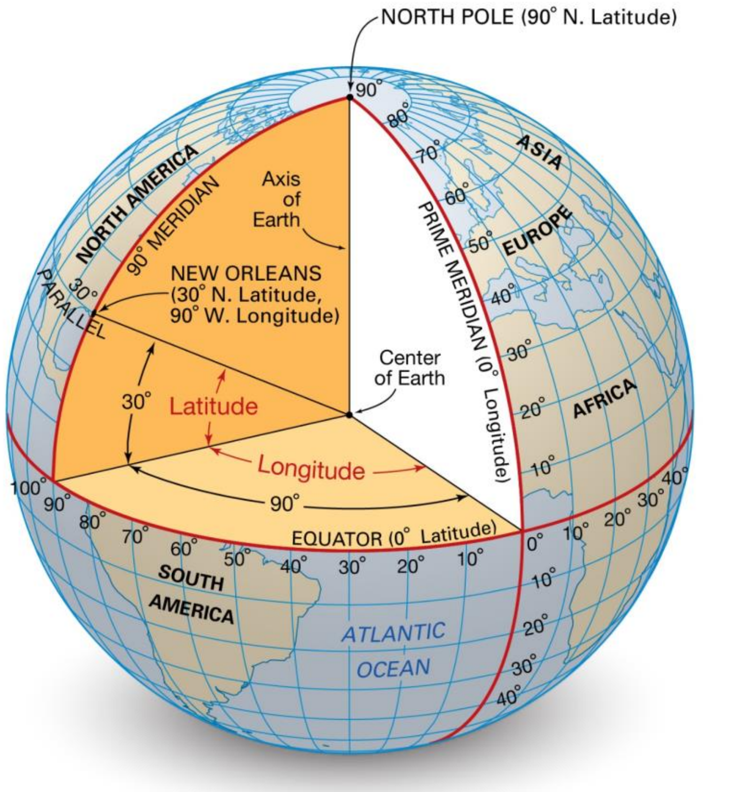
Azimuth / Elevation / Range

- **Spherical Coordinates / Local Reference Plane**
  - **Azimuth usually from True North**
  - **Elevation from local horizontal**
- **Typically from a tracking radar**

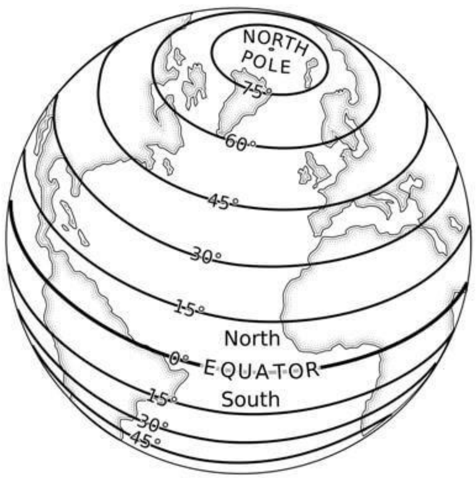


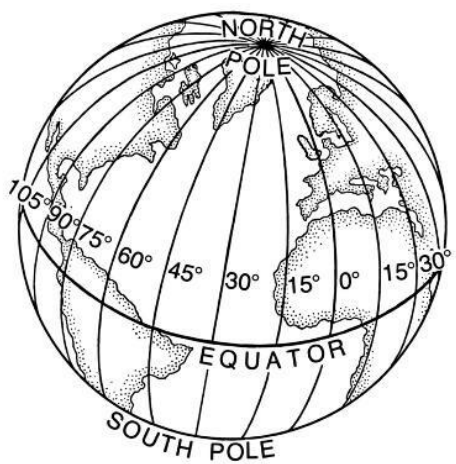
Latitude / Longitude / Altitude

- **Spherical Coordinates / Earth Reference**
  - **Latitude is vertical angle from Equator**
  - **Longitude is horizontal angle from Prime Meridian**
  - **Altitude is measured from a reference plane**



Latitude vs Longitude





<u>Latitude and Longitude have some fundamental differences</u>

Latitude is defined by the geometry of a rotating sphere

0 is the equator
90 is at the poles

Latitude is fixed in inertial space

Any sailor worth his salt can easily determine latitude with a simple sextant

Longitude is defined by politics

We must all agree on the “0” or “Prime” meridian

Longitude is constantly rotating in inertial space

Accurate determination of longitude requires an accurate determination of rotational position (i.e. time)

Coordinate Systems

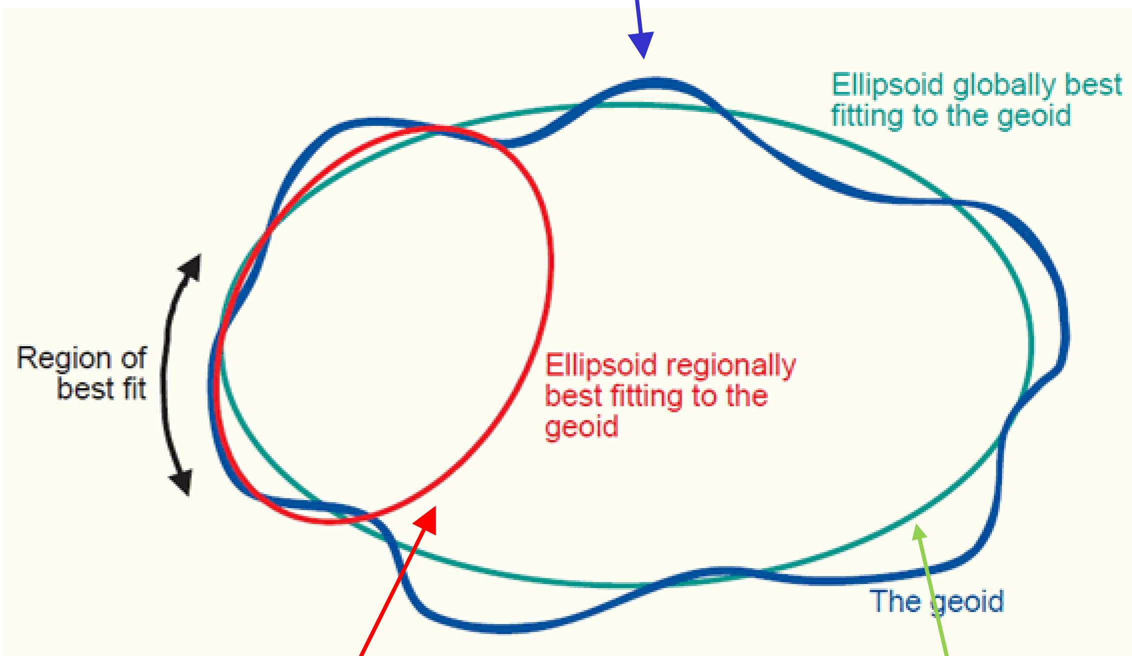
- **Lat / Lon / Alt are expressed in reference to a specific “Datum”**

- **Datum - A formal description of the shape of the Earth along with an "anchor" point for the coordinate system.**

- **TSPI files usually one of the usual “Big Three” Datums**
  - **NAD-27 North American Datum 1927**
  - **WGS-72 World Geodetic System 1972**
  - **WGS-84 World Geodetic System 1984**

Coordinate Datums

The Earth's surface is irregular

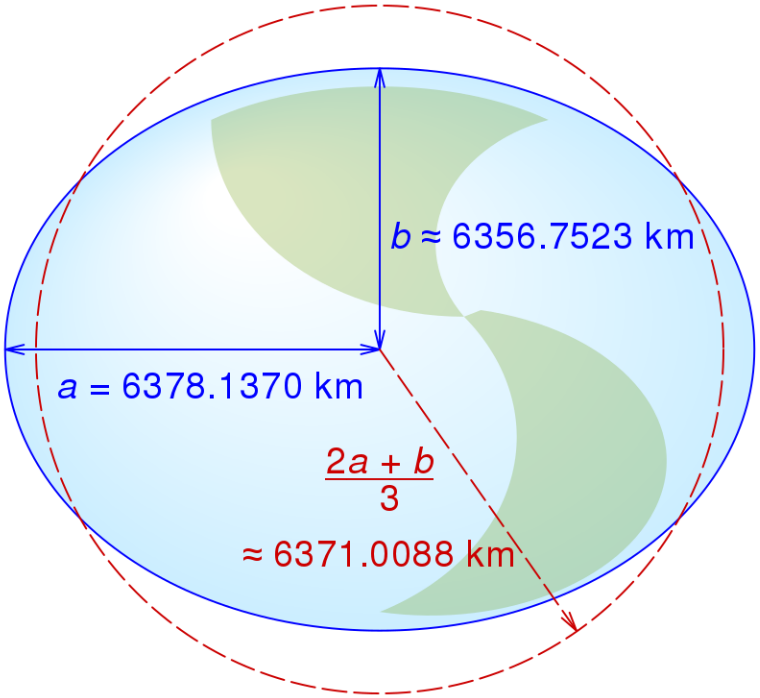


NAD-27 is optimized
for North America only

WGS-84 is optimized
for the entire globe

WGS-84 Ellipsoid

- Reference surface is an oblate ellipsoid
- About 43 meter difference between height and width
- Latitude and Longitude are overlaid on ellipsoid

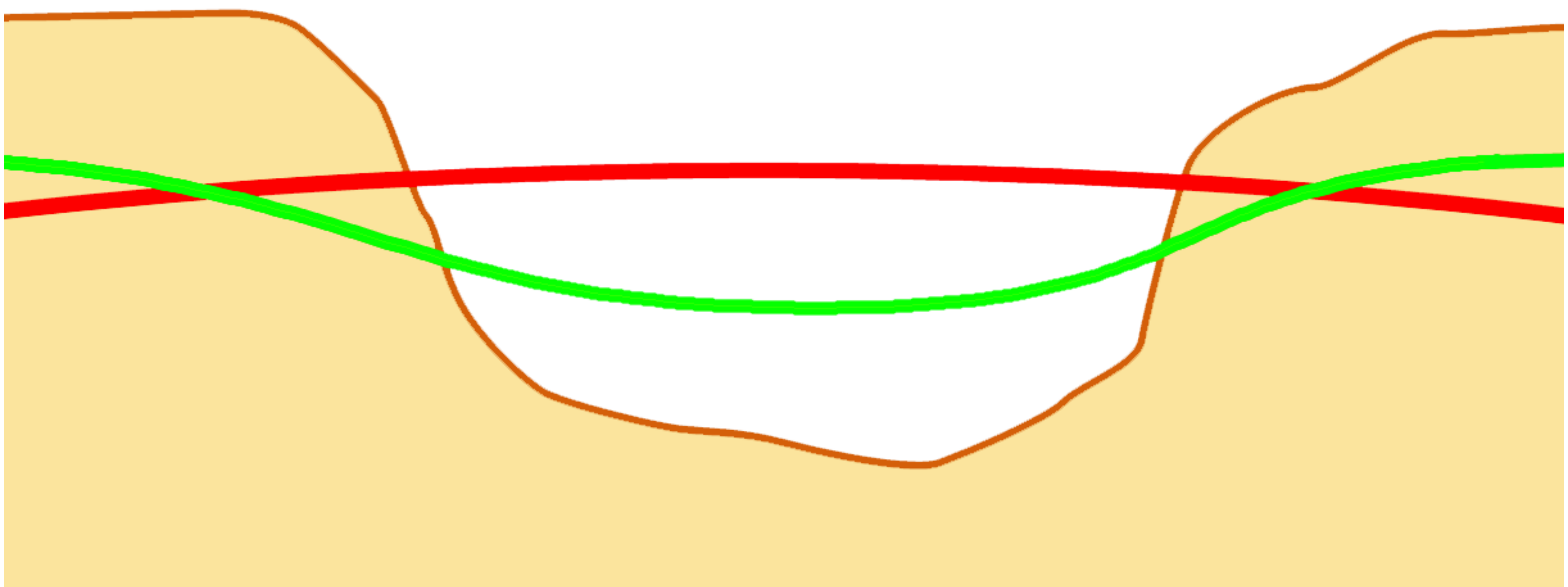


Height or Altitude

- **MSL – Mean Sea Level**
  - **Height above constant gravity geoid (usually EGM96)**
  - **This is the altitude used by aircraft to navigate**
  - **Easily measured with barometric altimeter**
    - Requires calibration to current barometric pressure
- **AGL – Above Ground Level**
  - **Rather difficult to determine**
  - **AGL is always changing even in level flight**
  - **Generally isn't very useful**
- **HAE – Height Above Ellipsoid**
  - **HAE is the most consistent way to express altitude**
  - **GPS altitude is HAE (usually the WGS84 ellipsoid)**

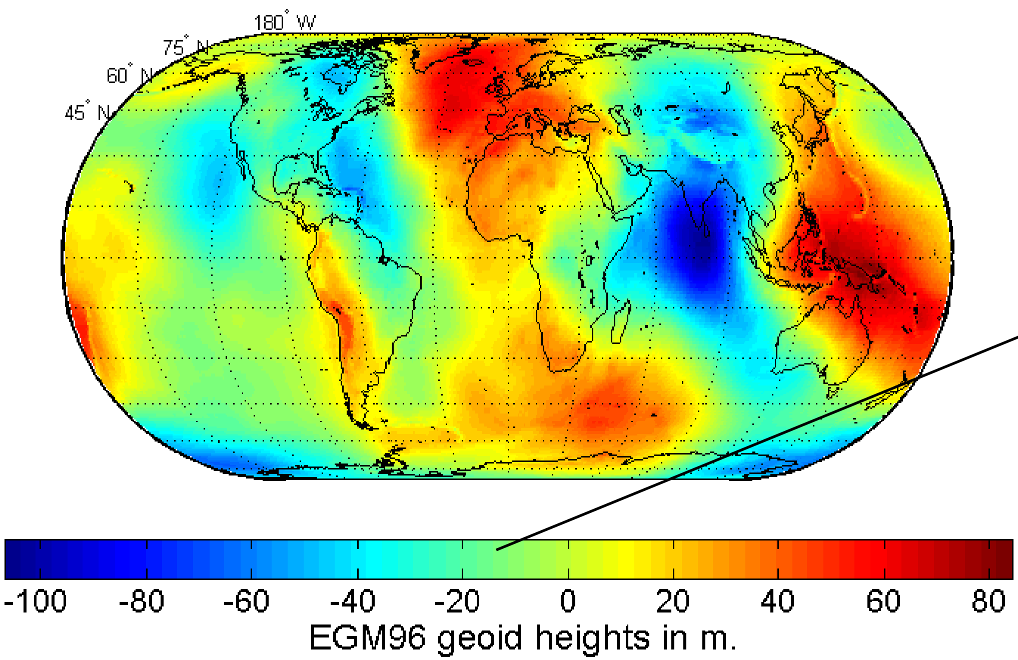
Types of Reference Heights

Spheroid/Ellipsoid	HAE
Geoid	MSL
Topography	AGL



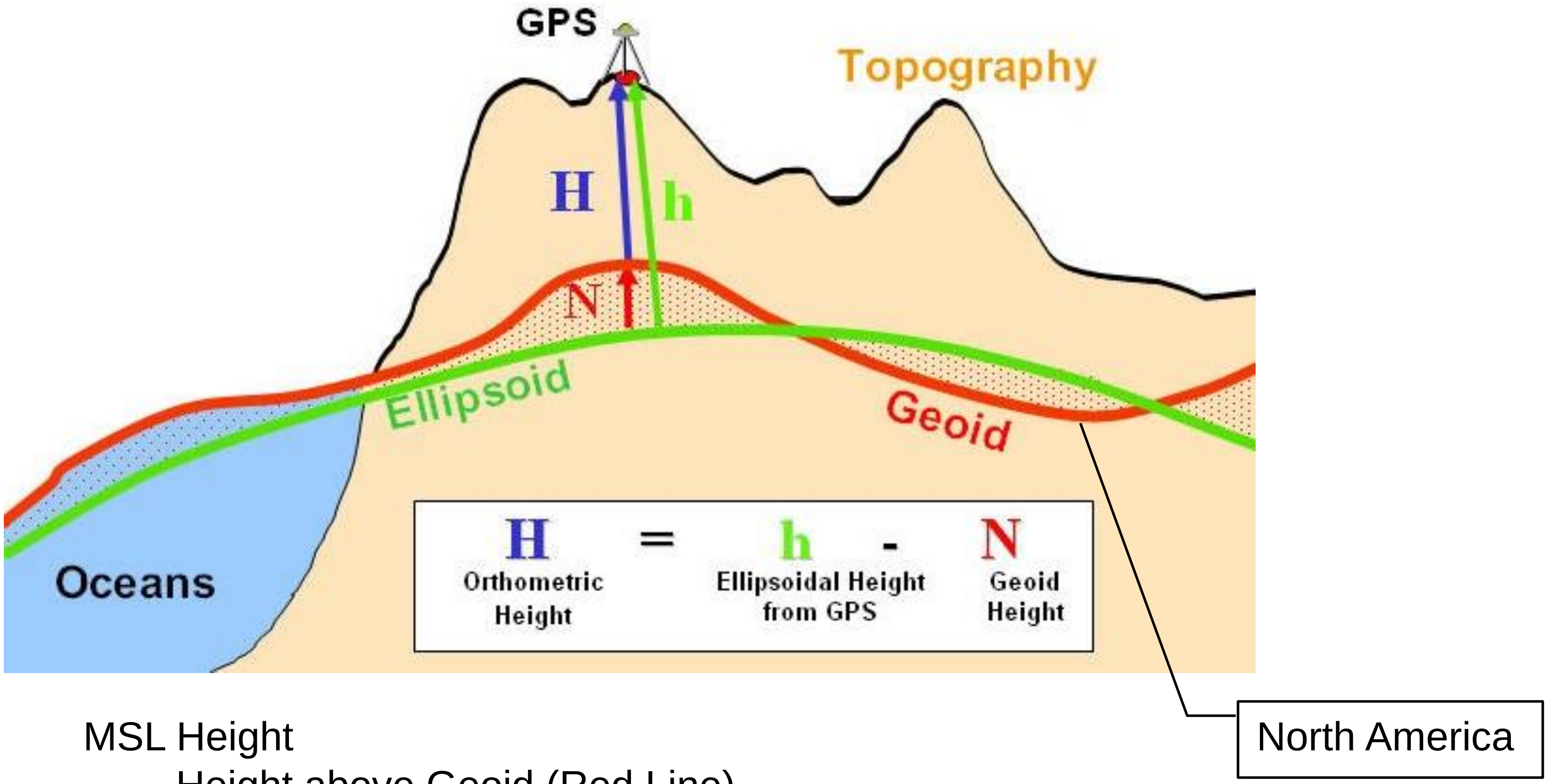
Geoid

- A gravitationally equi-potential **surface** which approximates the **Mean Sea Level**.
- Differs from the ellipsoid due to gravitational variances at different latitudes, and longitudes.



Over North America the Geoid (MSL) is below the WGS84 Ellipsoid

EGM96 Geoid vs WGS84 Ellipsoid



MSL Height

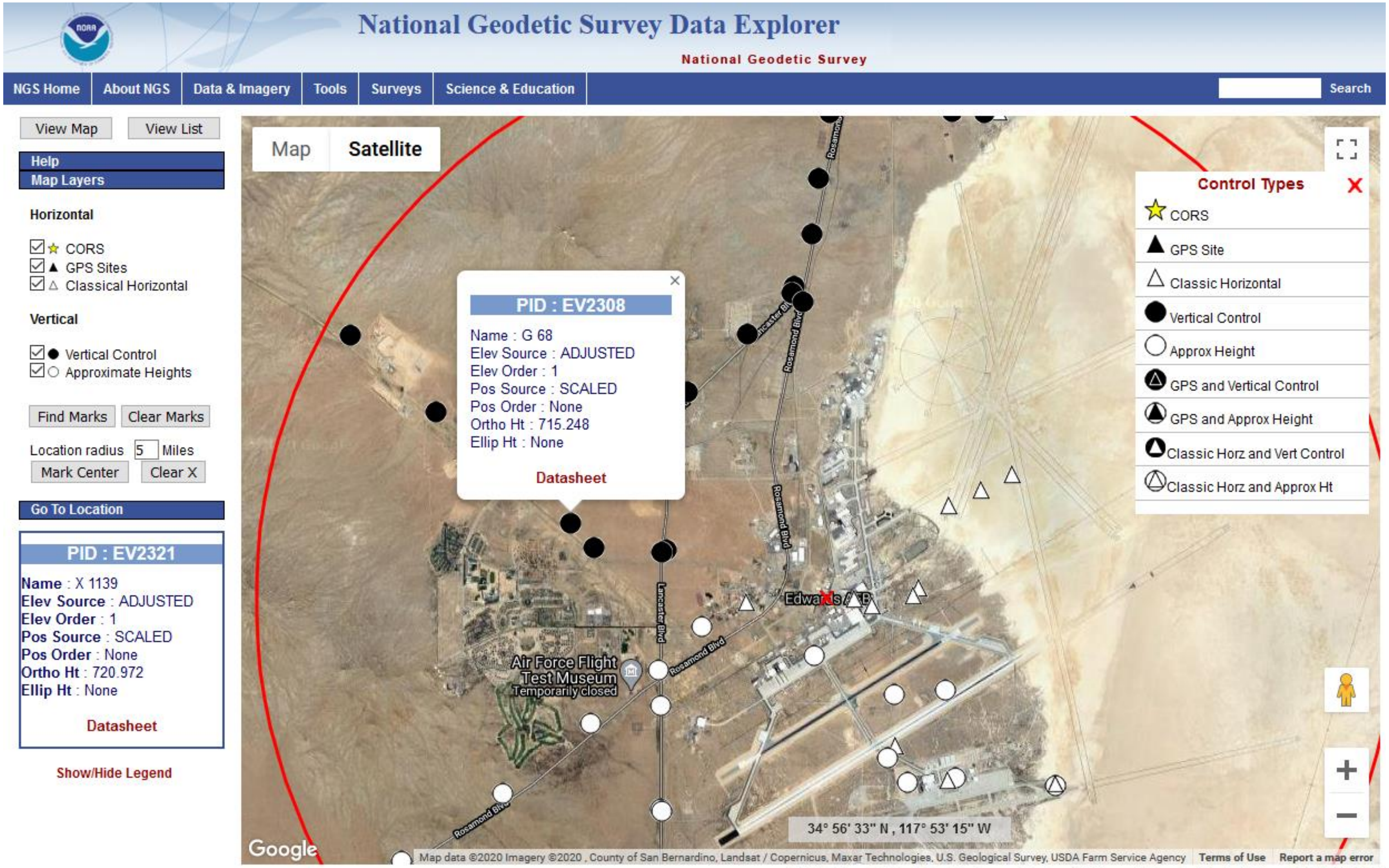
Height above Geoid (Red Line)

"Orthometric Height" H

GPS Height

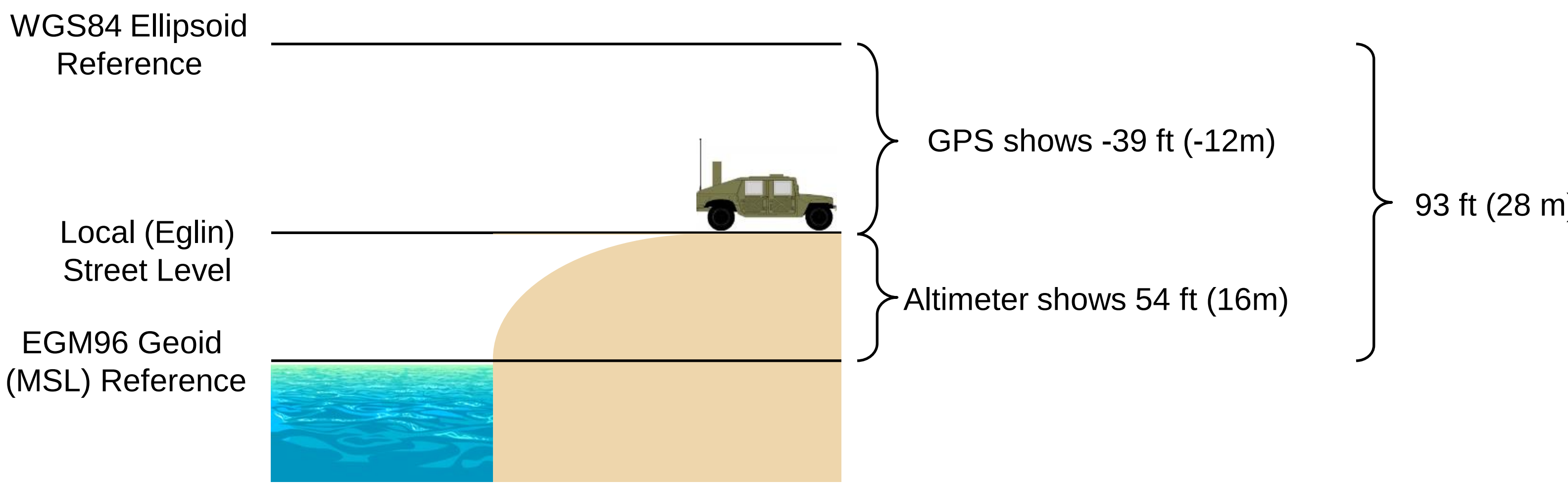
Height above WGS84 Ellipsoid (Green Line) h

Surveyed Heights at Edwards AFB



https://www.ngs.noaa.gov/NGSDataExplorer/

EGM96 Geoid vs WGS84 Ellipsoid



Your Input Coordinates and GPS Height:

Latitude: 30.48° N = 30° 28' 48" N

Longitude: 86.41° W = 86° 24' 36" W

GPS ellipsoidal height: -12 (meters)

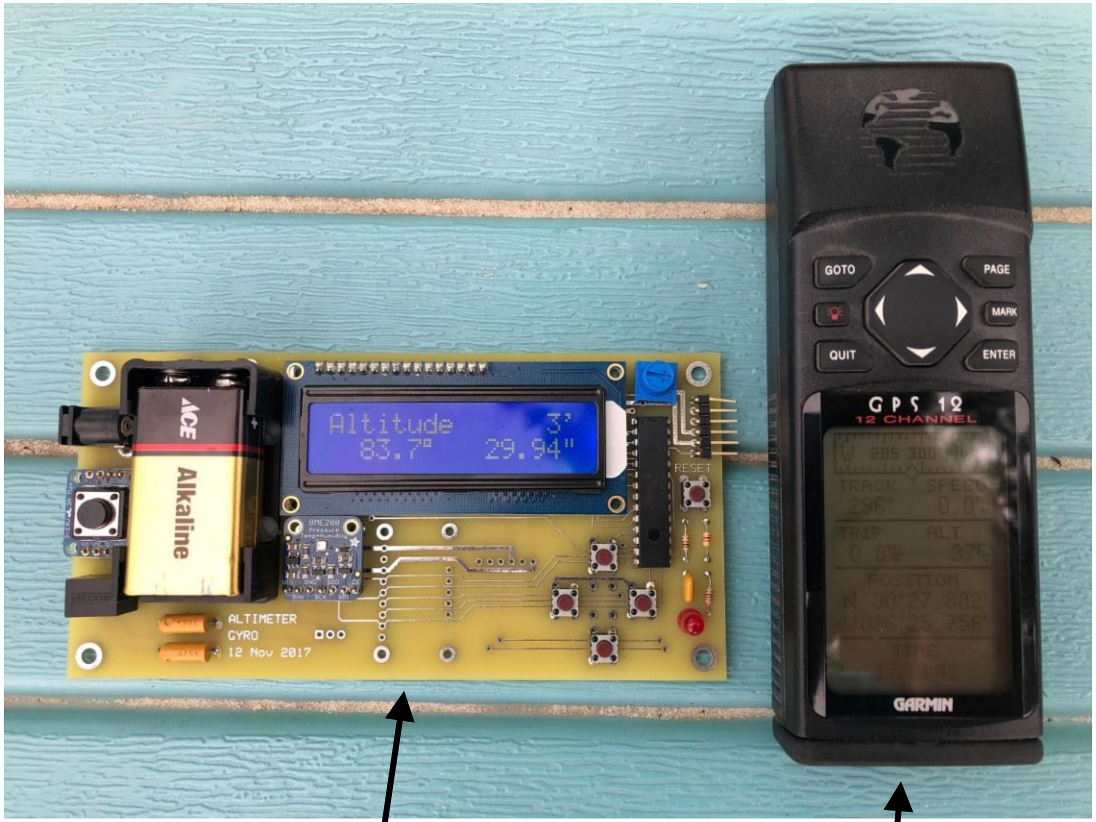
Geoid height: -28.417 (meters)

Orthometric height (height above EGM96 geoid which approximates mean sea level)**:** 16.417 (meters)

(Note: orthometric height = GPS ellipsoidal height - geoid height)

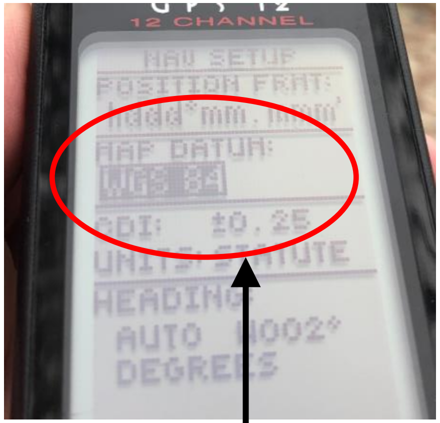
https://www.unavco.org/software/geodetic-utilities/geoid-height-calculator/geoid-height

EGM96 Geoid vs WGS84 Ellipsoid
A Cautionary Tale



Barometric Altimeter

GPS

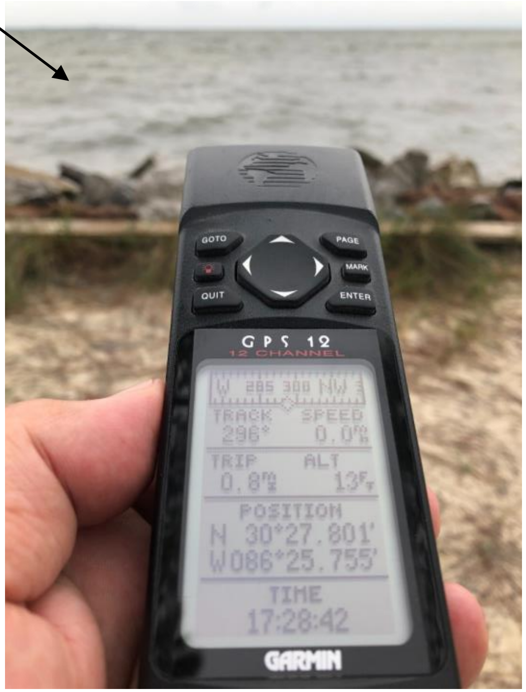


GPS uses
WGS 84

EGM96 Geoid vs WGS84 Ellipsoid
A Cautionary Tale

Near Sea Level
(i.e. the MSL Geoid)

Barometric Altimeter
reads 6 ft.
Good!

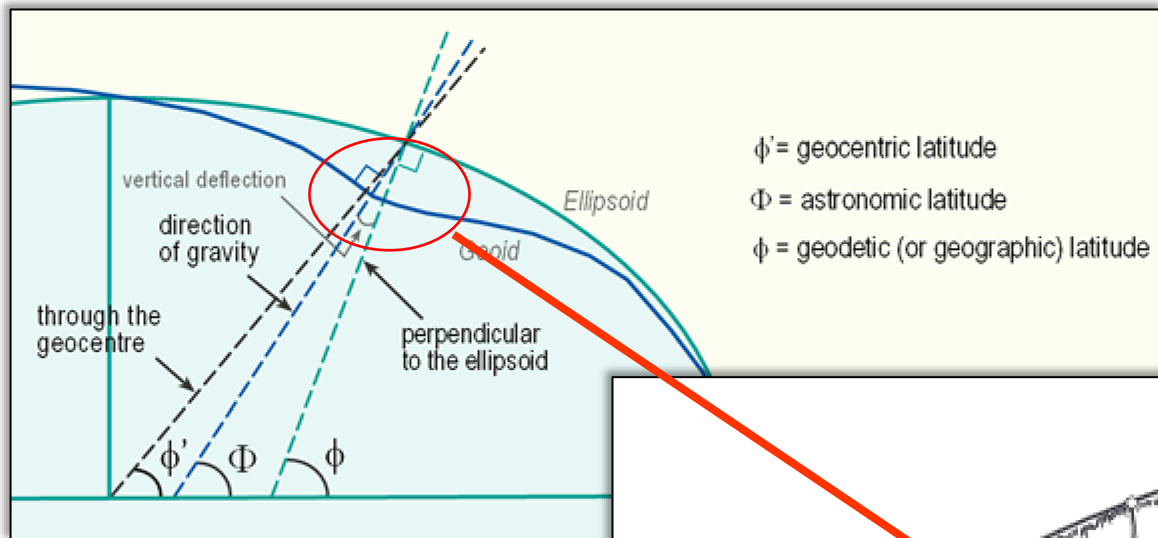


GPS reads
13 to 35 ft.
Why not -87 ft?

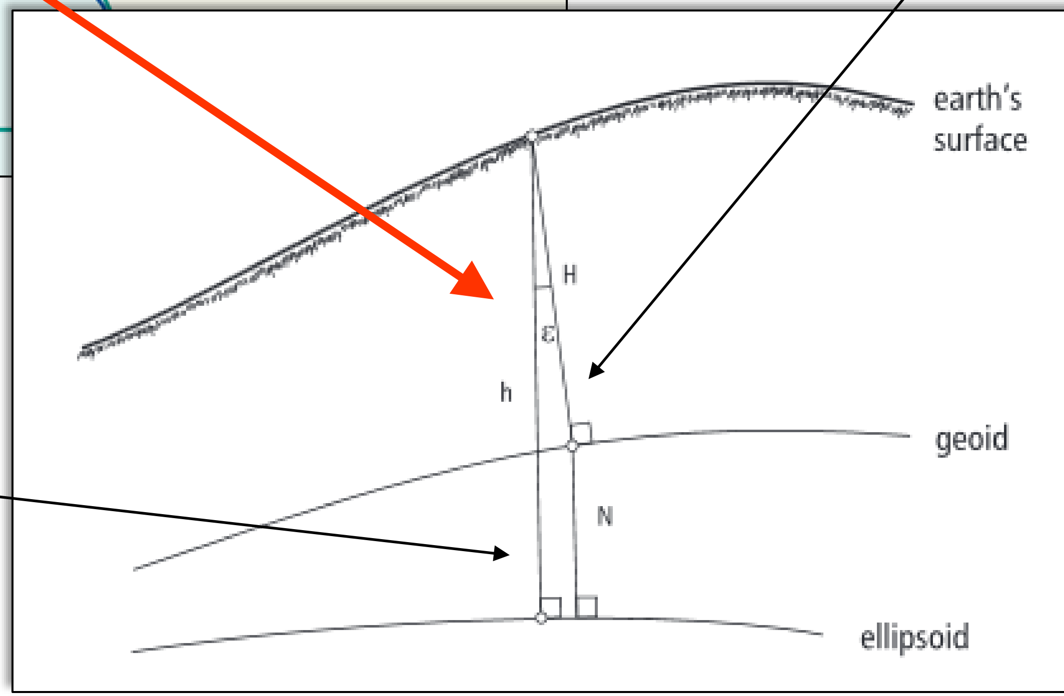
From the
Garmin GPS
User Manual

Altitude (ALT)— vertical distance above mean sea level.

Other Aspects of Height



Gravity Normal
Perpendicular to geoid

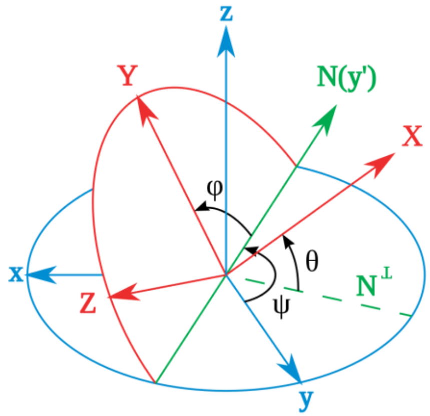


Ellipsoid Normal
Perpendicular to ellipsoid

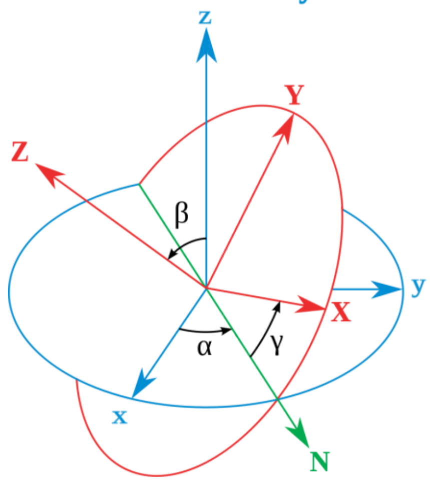
Attitude

Attitude is the orientation of a body with respect to a fixed coordinate system

- **Tait–Bryan or Cardan angles**
  - **Successive extrinsic rotations**
  - **Heading or Yaw**
  - **Pitch or Elevation**
  - **Roll or Bank**



- **Proper Euler Angles**
  - **Successive intrinsic rotations**



- **The order of rotation is important!**

Attitude

Quaternions

- Similar to imaginary numbers but 4 dimensional

$$a + bi + cj + dk$$

- ***a,b,c,d*** are real numbers
- ***i,j,k*** are unit vectors of three spatial axes
- Rotations by quaternions are more compact and quicker to compute
- No “Gimbal Lock”

Quaternion multiplication

×	1	i	j	k
1	1	i	j	k
i	i	-1	k	$-j$
j	j	$-k$	-1	i
k	k	j	$-i$	-1

TSPI Sources

- **Radar – Radio Direction And Ranging**
- **Cine/Video (KTM) – tracking, optical, images**
- **Fixed Camera – hi-speed, staring, optical, images**
- **GPS's – pods, built-in's**
- **GRDCS (DME) – Gulf Range Drone Control Sys**
- **INS (IMU) – Inertial systems**
- **Altimeter**
- **Weather (meteorological) Data – refraction, etc.**

Tracking Radar

- Good for high dynamic target
  - 20 or more samples per second
- Good for non-cooperating targets
- Measures absolute position
  - Az / El / Range
  - Doppler radar also measures velocity
- Radar signal power fades with range
  - Proportional to $^{1}/_{Range^4}$
- Radar Transponder greatly increase range
  - Proportional to $^{1}/_{Range^2}$

Surveillance Radar

- **FAA**
  - **Air Route Surveillance Radar (ARSR)**
    - ARSR-1 / -2 / -3 / -4
  - **Airport Surveillance Radar (ASR)**
    - ASR-9

AN-FPS-16 Radar

Radar

- **Pros**
  - **Realtime capable**
  - **All weather**
  - **Good target acquisition**
  - **Support non-cooperative target**
  - **Good for targets that are too small, cheap, can’t be altered,**
  - **Good for radar cross section measurements, debris pattern, damage assessment**
- **Cons**
  - **Fixed location**
  - **Limited by line-of-sight (obstructions)**
  - **Multipath at low elevations**

Optical Tracker

- **Cine-theodolite**
  - Nicknamed Cine-T
  - Cine = timed sequence of photographs
  - Theodolite = Az & El measurement instrument (Surveyor’s tool)
- Records image, Time, Az, El (edge code, raster encoding)
- Synchronization (coincident measurements)
- Multiple stations (3+) combine to produce a refined data point with minimized errors

Cine-Theodolite

KINETO Tracking Mount (KTM)

Laser Tracker

This isn’t a laser tracker, just a cool picture

Laser Tracker

Cine-Theodolite

- **Pros**
  - **High accuracy**
  - **Provides documentary record (events)**
- **Cons**
  - **Multiple instruments required (3+)**
  - **Limited Realtime capabilities**
  - **Constrained Geometrically & Visually**
  - **Not weather tolerant**
  - **Reasonably short range (may require many instruments for desired coverage)**

Internal and Pod TSPI Sources

- **ARDS**
- **CRIIS**
- **GAINR - GPS Aided Inertial Navigation Reference**
  - **GAINR II (GPS/INS)**
  - **GAINR III (GPS/INS)**
  - **GLITE C1 (GPS only)**
  - **GLITE C2B (GPS/INS)**
  - **GLITE C2R (GPS/INS)**
- **GRITS - Gulf Range Instrument TSPI System**

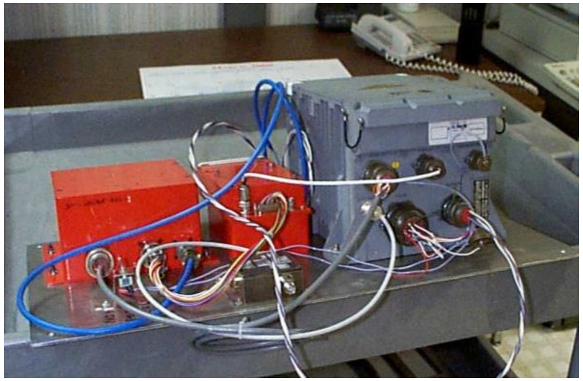
Common TSPI Solutions

ARDS FRP Plate

(GNP Plate 2 Enclosures)

G-12

(OEM Only)



GAINR I/II

(Engineering Unit)

GAINR Lite (Self Contained)

OEM4

Z-12

Expected GPS Accuracies

- **Before SA eliminated: C/A => 250’**
- **With SA removed:**
  - **no diff corr, no INS => 100’**
  - **no diff corr, w/INS => 20’**
- **Differentially Corrected, INS Aided (normal) => 10’**

per Principles of GPS & RAJPO TSPI Equipment
and 46TW GPS-SS Pod Test Tech Report 94-07

Pod GPS

- **Pros**
  - **Realtime capable**
  - **Good, consistent accuracy**
  - **Universally available at all altitudes up to 100+ nm from Reference Receiver**
  - **All weather**
- **Cons**
  - **Must reside with cooperating participant**
  - **May require reference station within 100+ nm**
  - **“Shadowing” (of satellites) and “Shielding” (of data link)**

Dependent Broadcast

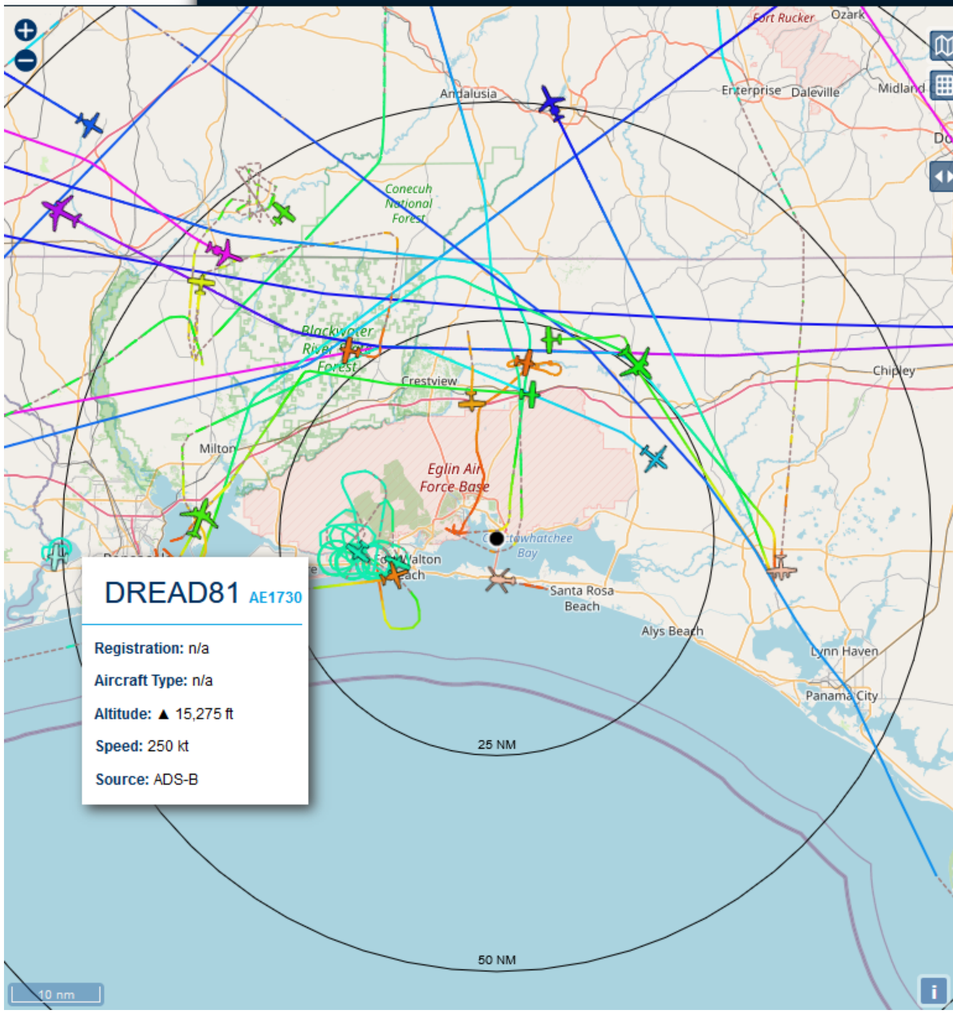
- **ADS-B – Automatic Dependent Surveillance– Broadcast**
- **Required for most (but not all!) aircraft starting in 2020**
- **Participating aircraft broadcast their GPS position and other information**
- **Inexpensive receivers available**

$75 receiver kit + Raspberry Pi

Dependent Broadcast

FlightAware PiAware SkyAware

6/29/2020, 3:35:52 PM Reset Map Show All Tracks Hide All Tracks



3.8.1

Total Aircraft: 51
With Positions: 40
Messages: 157.9/sec
History: 23934 positions

Filter by Altitude: ft to ft Filter Reset

ICAO		Ident	Squawk	Altitude (ft)	Speed (kt)	Distance (NM)	Heading	Msgs	Age
AB4E9D		N828AK		300	93	4.9	276°	647	6
A05A67		N12141		6,825	88	5.5	271°	8408	7
AE5B8A		0080835	5163	13,925	172	12.0	24°	13065	0
ABFB98		N871RV	7435	2,700 ▼	269	12.5	71°	2022	0
AE5B83		0070777	5111	14,850	141	15.9	217°	16808	1
AE1423		JEDI69	3433	3,325	245	16.0	177°	297	0
A2FA59		N291MW	5574	8,900	156	17.0	94°	6859	0
A4B1FC		SIL0080	0765	19,000	275	20.4	129°	6585	0
A7A451		N5916J	4613	2,475 ▼	97	20.6	103°	7686	0
A496ED		N395SA	1052	7,900	153	23.7	268°	5445	0
ABB54F		SWA410	2425	8,700 ▼	294	25.7	136°	6261	0
AE2EE1		RN100	1200	2,400 ▼	163	27.3	283°	859	0
A25C18		N251KB	3125	1,600 ▼	214	32.9	178°	1716	33
ABE40A		SWA6866	1077	7,650 ▲	283	34.2	20°	554	0
AE2ED6		TEXN089	1200	7,500	156	44.5	40°	1062	5
AE2EF3		BB118	1200	5,075 ▲	229	44.8	7°	289	0
A24B15		N247MB	3151	40,975	462	45.2	112°	3413	0
A003F0		N10SE	1050	29,525 ▲	439	50.2	334°	4482	0
AE1730		DREAD81	5557	15,275 ▲	250	50.6	276°	997	21
AE2EDB		SH094	4235	13,775 ▲	167	61.3	147°	1877	1
AAA992		SWA312	0770	37,550 ▲	446	62.5	298°	6261	0
A70BAC		N553MJ	2146	25,200 ▼	385	66.4	121°	2450	0
AE58E8		BB243	1041	10,900 ▼	249	69.0	23°	3205	25
A263E3		AAY1927	1630	26,125 ▲	432	73.5	344°	4258	0
ADF190		N998NJ	5616	45,000 ▲	454	77.8	167°	10965	0
AE68B4				15,900	314	78.1	60°	557	31
A29EB6		SWA6891	3664	40,000	446	80.3	277°	3504	0
A59197		UAL205	2761	37,000	470	80.5	108°	1754	0
A591AB		SWQ6800	3116	25,000	454	82.9	47°	4475	0
ACEE21		ASH5767	4312	30,000	458	84.1	297°	6726	19
AE04DA		CNV4421	0504	10,875	332	84.7	110°	159	3
A11824		N17PL		24,000	247	87.9	233°	135	0
AE06DA		KBAR58	7444	25,000	260	94.7	58°	3723	0

Scoring Systems

- **DRQ-4 Cooperative Doppler Miss-Distance Measurement System**
- **DSQ-37 Radar Miss-Distance Measurement System**
- **Non-Cooperative Airborne Vector Scoring System**
- **Photon Miss-Distance Indicator System**

Some Expected Accuracies

- Single Radar => 30-50 ft. (as traditional)
- Dual Radar => 10 - 30 ft.
- Dual Radar + INS => 5 - 10 ft.
- Cine + Radar + INS => 1 - 3 ft.
- (Traditional Cine-only => 2-3 ft.)
- Cine + Radar + INS + GPS => 1-3 ft.
- (DGPS & INS => 6-12 ft.)

Other Related Documents

- **WORLD COORDINATE SYSTEMS**

- **Mathematical Description of TSPI Derived Parameters** (99 answers!)

- **Advanced Test Data Optimal Processor (ATDOP)**
  - Capabilities

Read Ahead

- https://eos-gnss.com/elevation-for-beginners
- https://kartoweb.itc.nl/geometrics/Reference%20surfaces/refsurf.html
- https://www.ngs.noaa.gov/NGSDataExplorer/