Time Space Position Information (TSPI) Basics

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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 in space?
- Position What was the position?
- Information Report these in a known format

What is TSPI

- TSPI is the result of a process that describes a well defined state vector of an object at an instant in time
 - Position only (3-DOF)
 - Position and Orientation (6-DOF).
- TSPI is a part of most Test Missions
 - It is the "Truth" source
- The test community continuously needs better "truth" for PGM's and improved Threats

Some TSPI Data Observations

- 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?

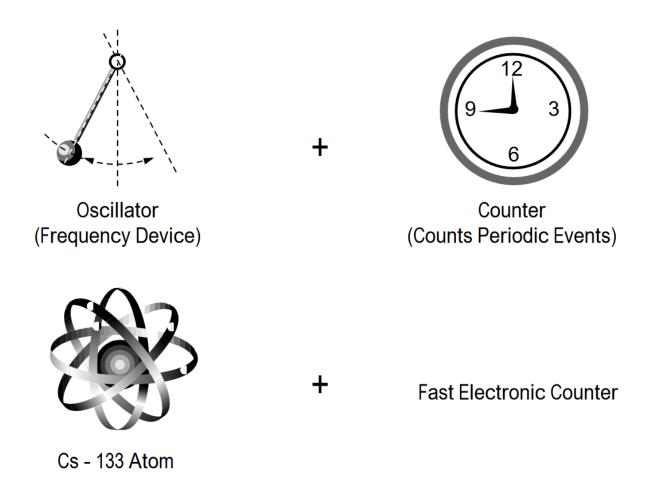
What is a Second?

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



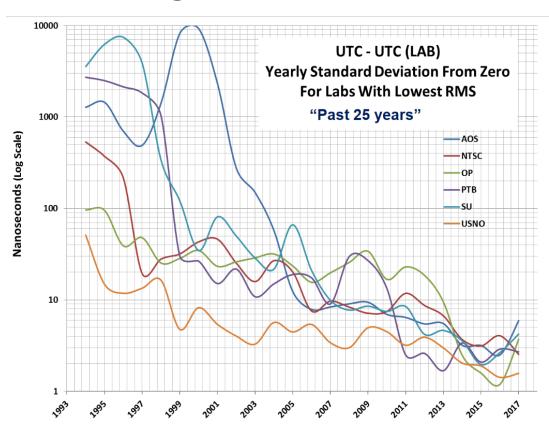
What Time Is It?

- 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

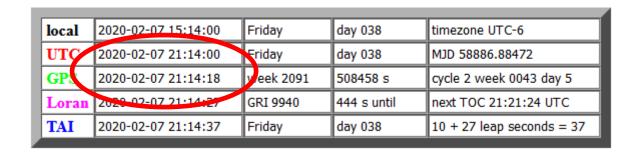
https://www.ucolick.org/~sla/leapsecs/timescales.html

UTC - Universal <u>Coordinated</u> 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?



Beware of GPS Time!

GPS Time is very close to UTC

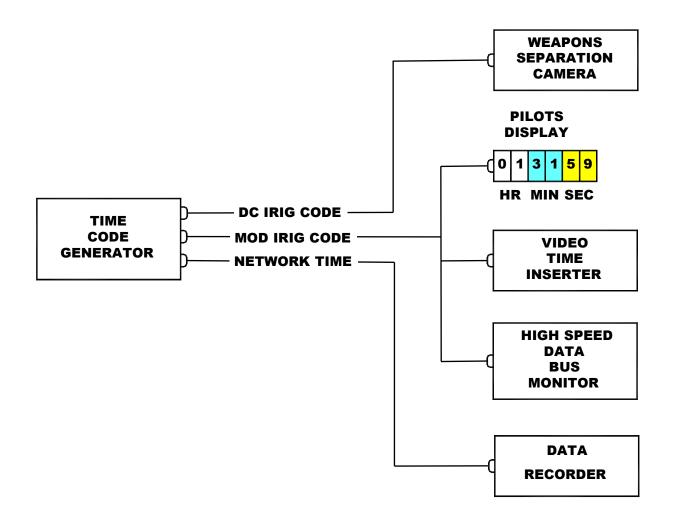
- Offset by a few seconds
- Looks very reasonable.... but probably not the time you are expecting

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 Hz
 - 1 second time data w/ 1000 microsecond (1 ms) calculated direct

• IRIG A

- 10,000 Hz
 - 0.1 second time data w/ 100 microsecond (0.1 ms) calculated direct

• IRIG G

- 100,000 Hz
- 0.01 second time data w/ 10 microsecond (0.01 ms) calculated direct

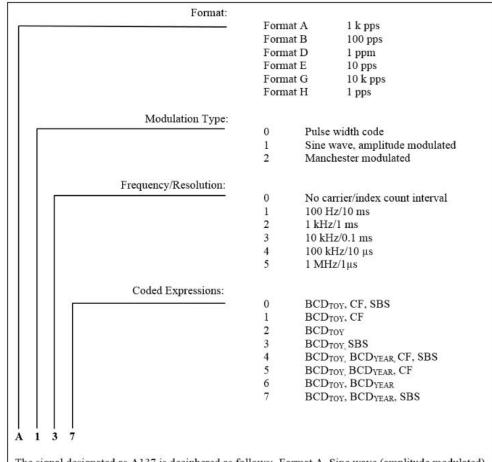
Time Code Formats

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

CF - Control Function

SBS - Straight Binary Seconds

TOY - Time of Year



The signal designated as A137 is deciphered as follows: Format A, Sine wave (amplitude modulated), 10~kHz carrier/0.1 ms resolution, and Coded expressions BCD_{TOY}, BCD_{YEAR}, and SBS.

Time Format IRIG B Examples

Common AM modulated format

```
IRIG-B122 1 = Sine wave, amplitude modulated 2 = 1 \text{ kHz/1 ms} 2 = \text{BCD}_{\text{TOY}}
```

Common baseband (unmodulated) format

```
IRIG-B002 0 = Pulse width coded (no carrier)

2 = 1 kHz/1 ms

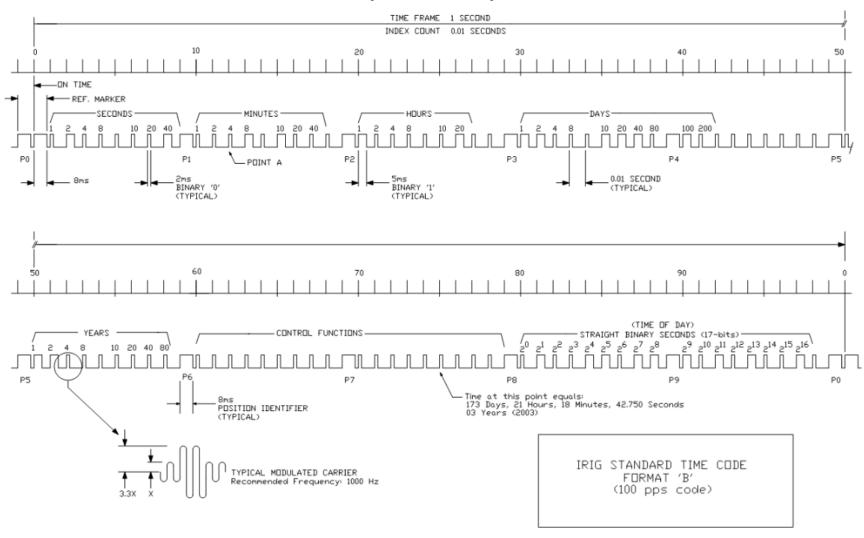
2 = BCD_{TOY}
```

AM modulated including year

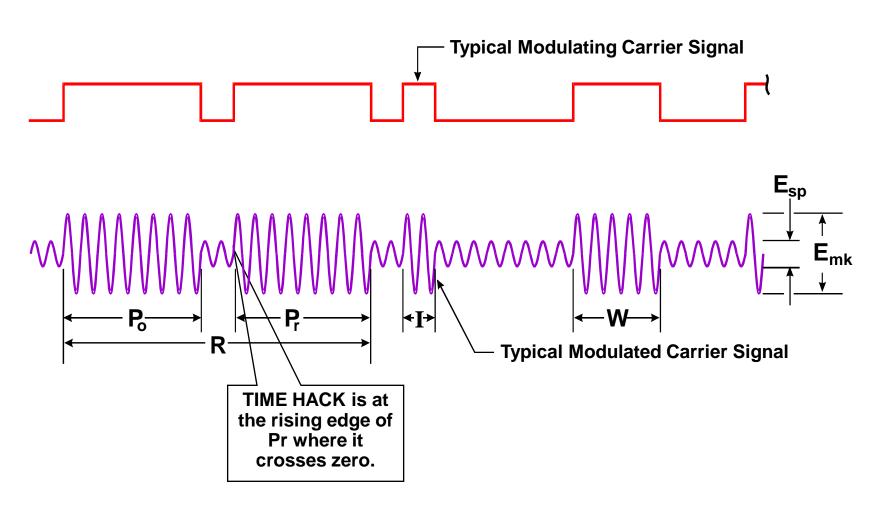
```
IRIG-B126 1 = Sine wave, amplitude modulated 2 = 1 \text{ kHz/1 ms} 6 = \text{BCD}_{\text{TOY}}, \text{BCD}_{\text{YEAR}}
```

Time Format IRIG B

(Reference)



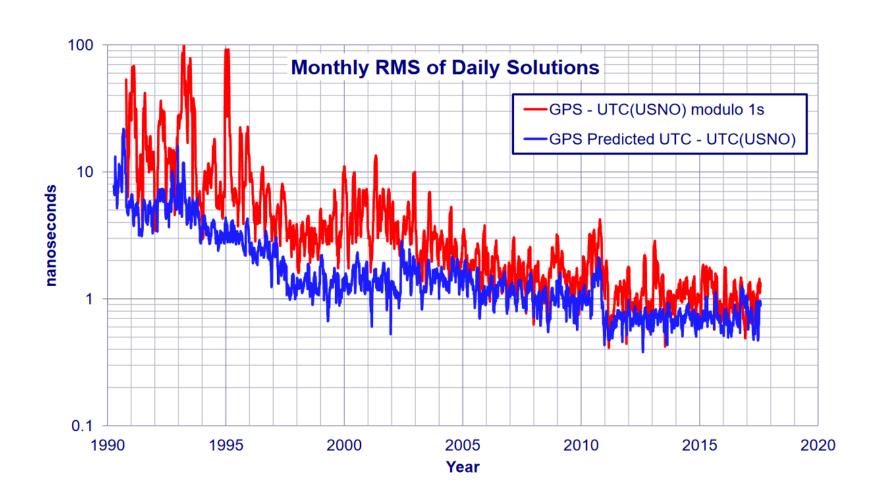
Typical IRIG Time Codes



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



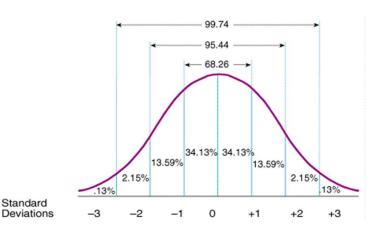
GPS as a Time Source

- 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

-50 ns 0 +50 ns

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



Time Space Position Information Basics

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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,	50 ms, TTL level, on-time leading edge
Accuracy	±60 ns of UTC	±15 ns of UTC

Meinberg



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

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

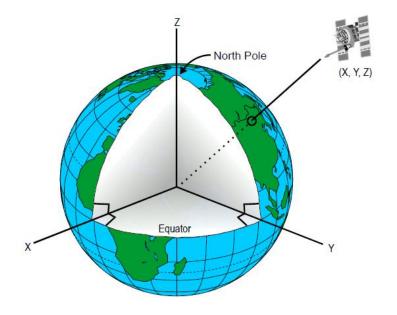
- Absolute timing means being aligned to the world
- Relative timing means being aligned to itself

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 / Range

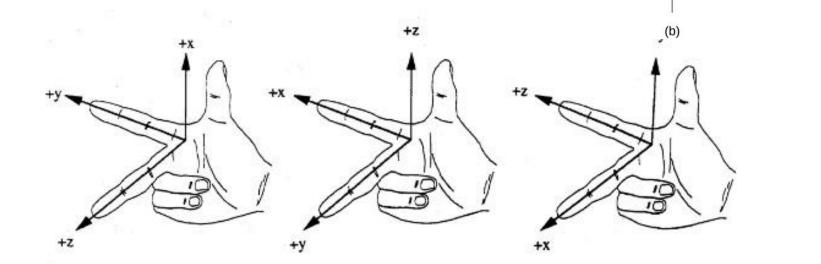
Earth Centered Earth Fixed

- 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"

- "Handedness"
 - NED vs ENU



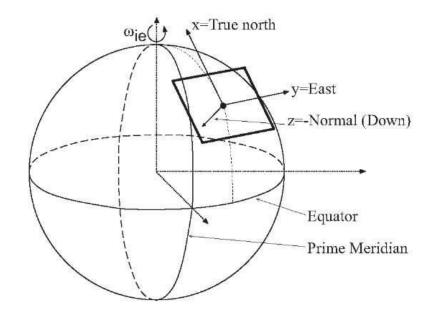
Configuration 1

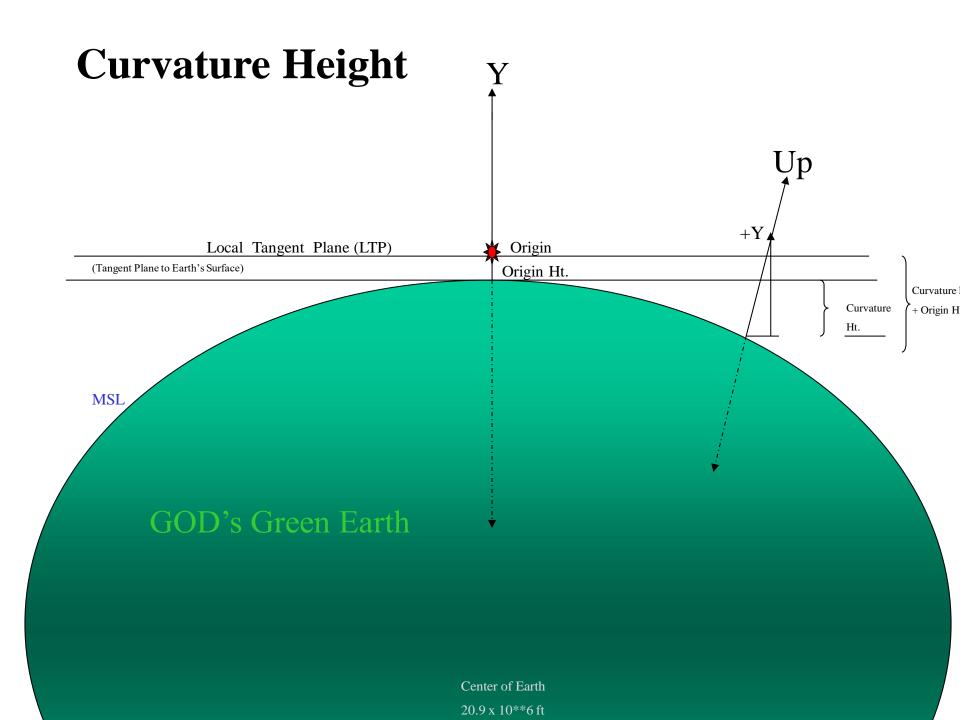
Configuration 2

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





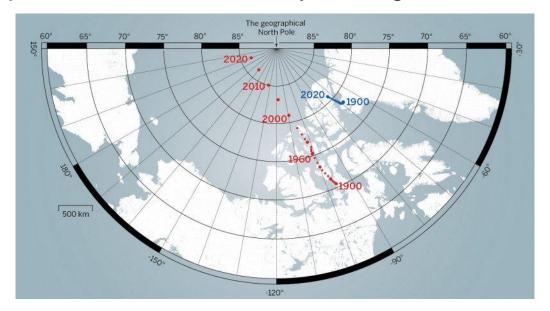
What is North?

True North

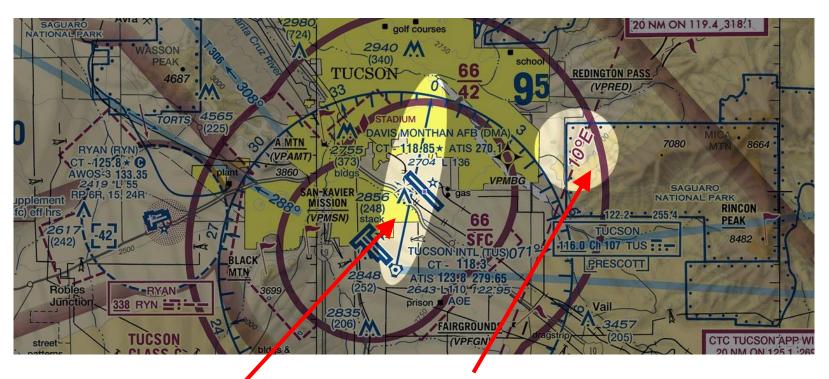
Uses North Pole navigation reference

Magnetic North

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

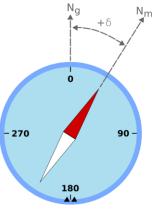


Magnetic Declination



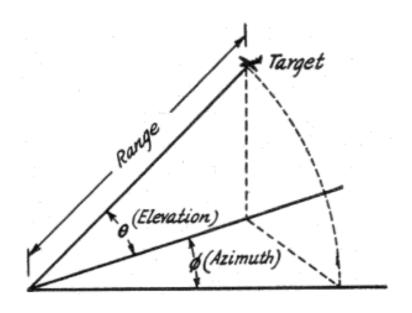
Navigation Aids Point to Magnetic North Magnetic Declination Isogonic Line near Tucson

The angle and direction from True North to Magnetic North



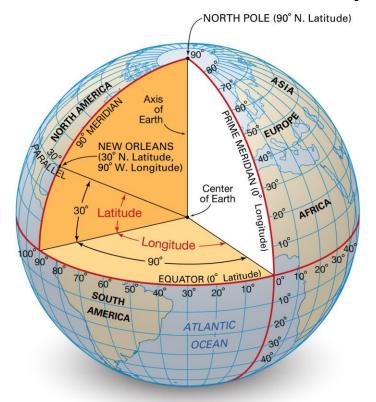
Azimuth / Elevation / Range

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

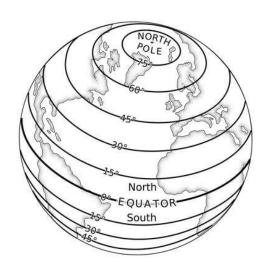


Latitude / Longitude / Altitude

- 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



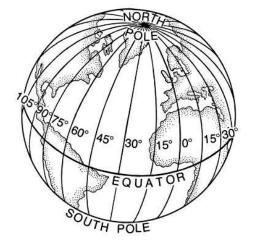
Latitude and Longitude have some fundamental differences

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

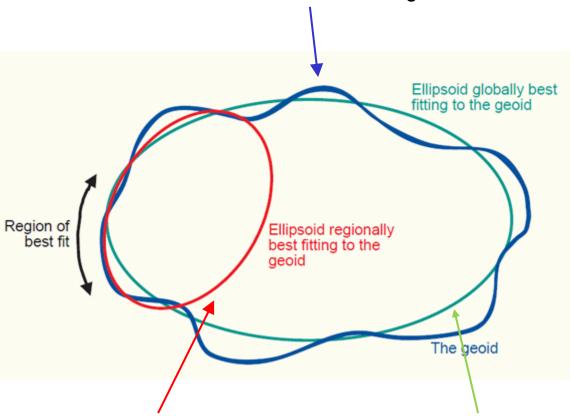
Accurate determination of longitude requires an accurate determination of rotational position (i.e. time)

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



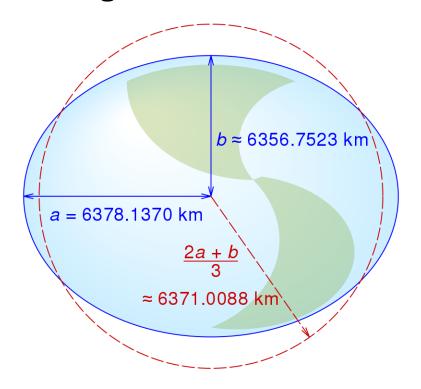


NAD-27 is optimized for North America only

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



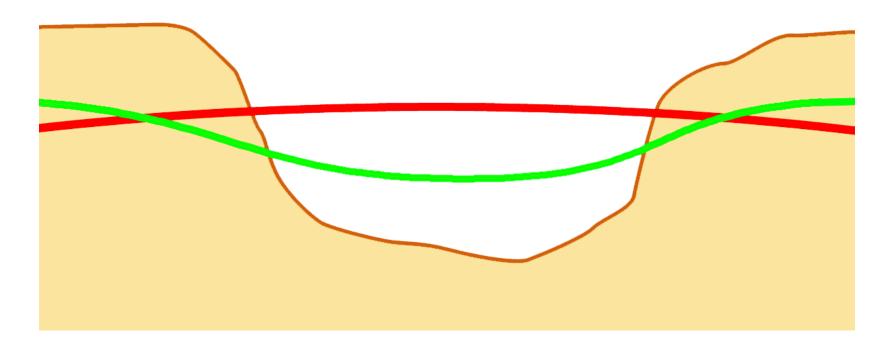
Height or Altitude

- 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

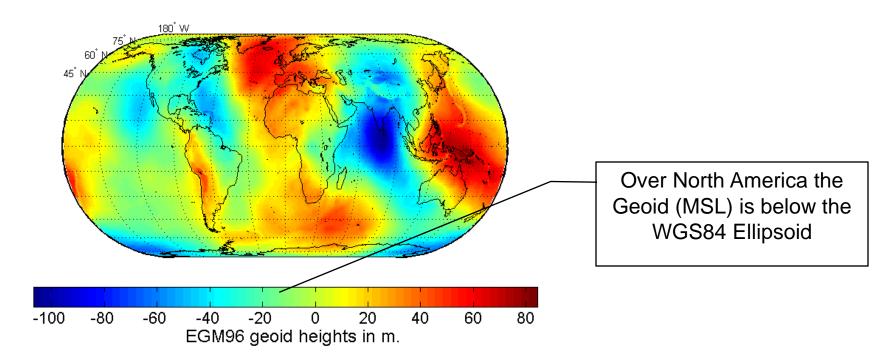
Spheroid/Ellipsoid HAEGeoid MSL

Topography AGL

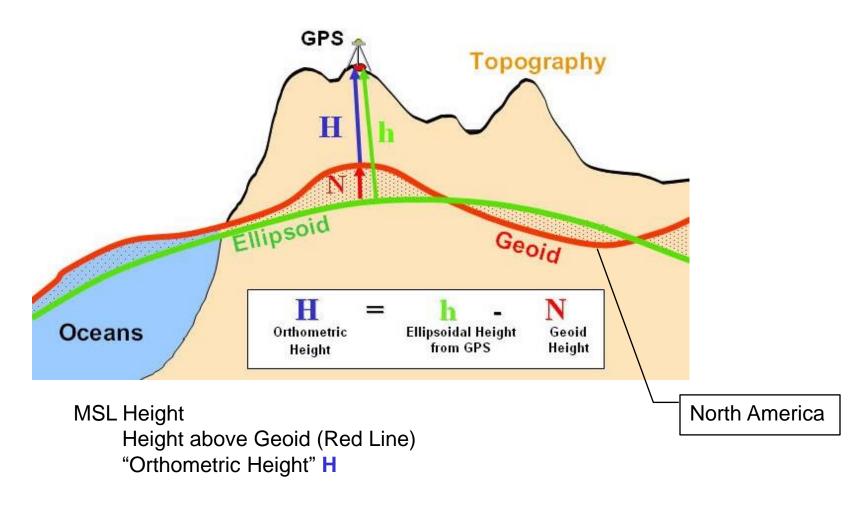


Geoid

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

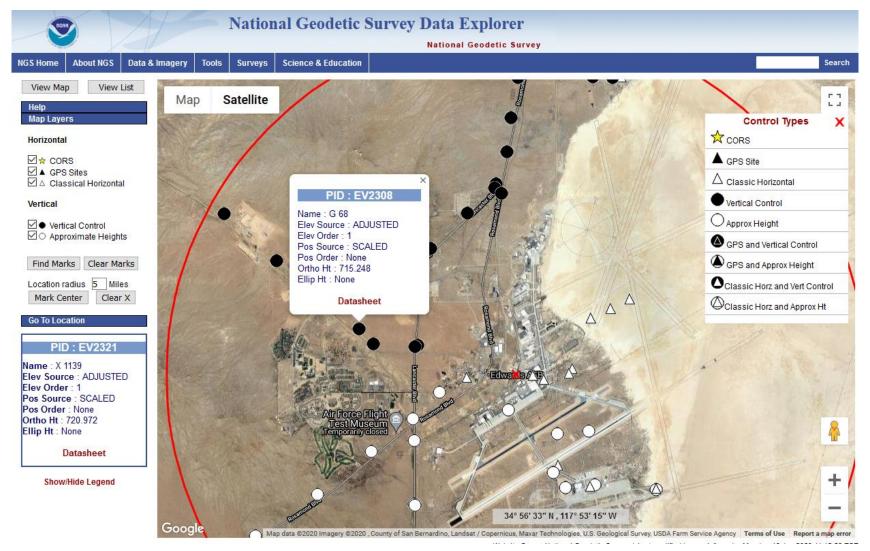


EGM96 Geoid vs WGS84 Ellipsoid



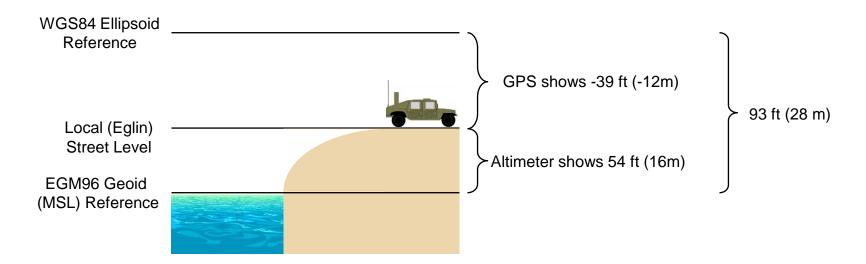
GPS Height
Height above WGS84 Ellipsoid (Green Line) h

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)

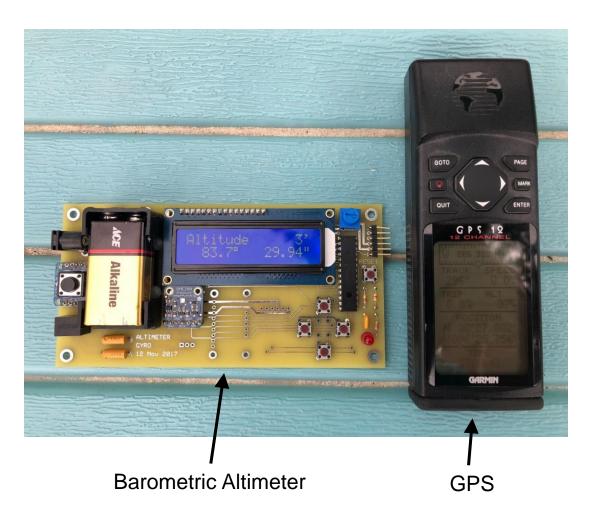
Geoid height: -28.417 (meters)

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





EGM96 Geoid vs WGS84 Ellipsoid A Cautionary Tale

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



Barometric Altimeter reads 6 ft.
Good!

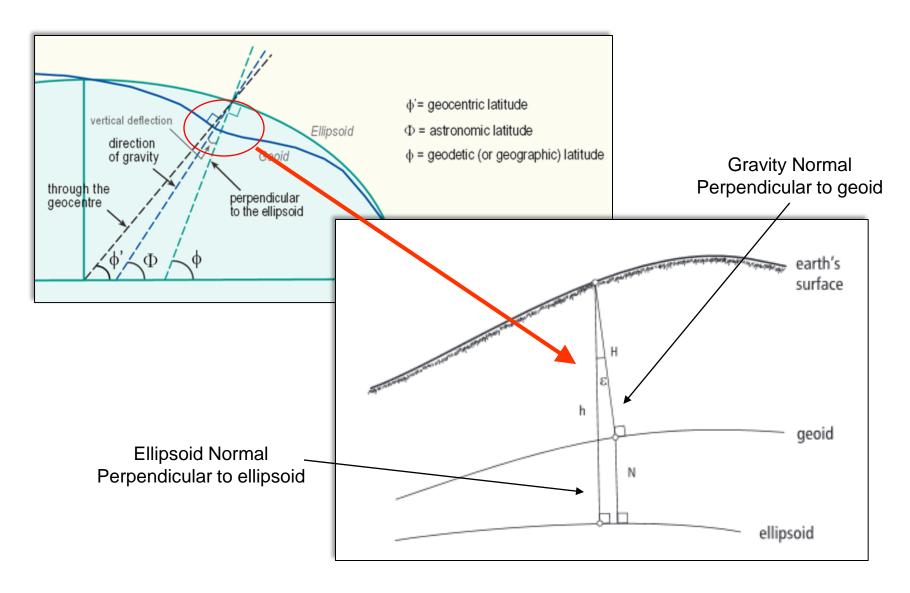
From the Garmin GPS User Manual



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

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

Other Aspects of Height

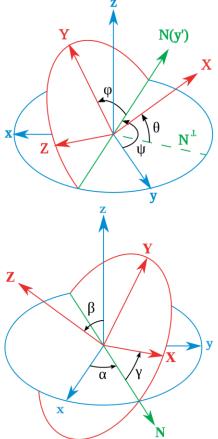


Attitude

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	\boldsymbol{k}
i	i	-1	\boldsymbol{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
- Pods with built in TSPI sensors
 - GPS's pods, built-in's
 - INS (IMU) Inertial systems
 - Altimeter
- Weather (meteorological) Data refraction, etc.

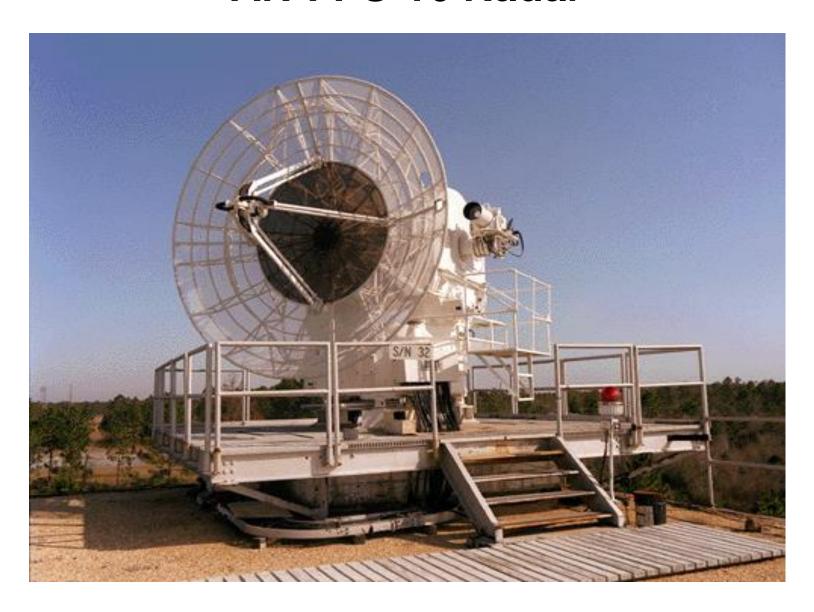
Tracking Radar

- 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 $\frac{1}{Range^2}$

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

- Real time 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 / horizon)
- 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 Real time 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

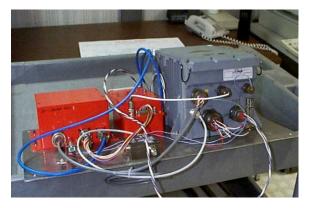
Common TSPI Solutions



ARDS FRP Plate
(GNP Plate 2 Enclosures)



G-12 (OEM Only)



GAINR I/II
(Engineering Unit)



GAINR Lite (Self Contained)



OEM4



Z-12

Pod GPS

Pros

- Real time 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)

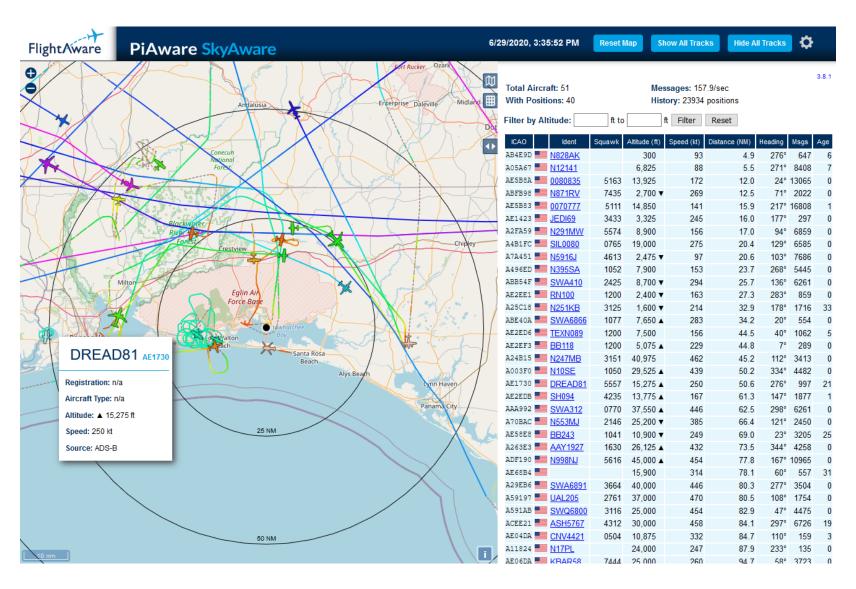
Dependent Broadcast

- 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



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.)

Reference and Read Ahead

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

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