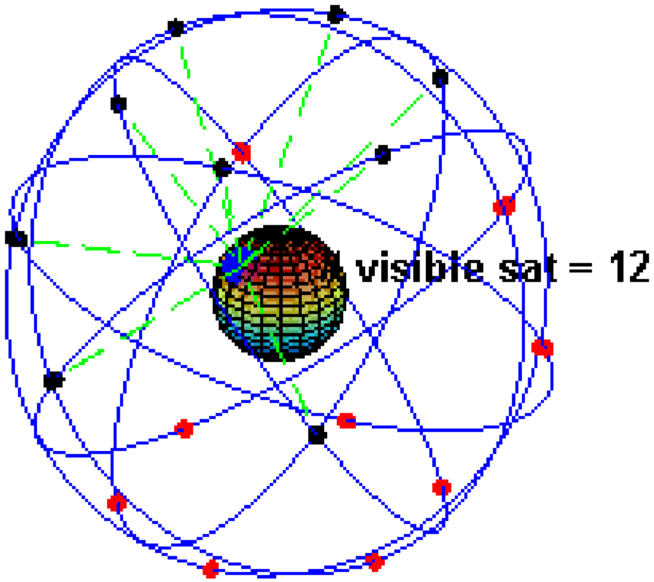
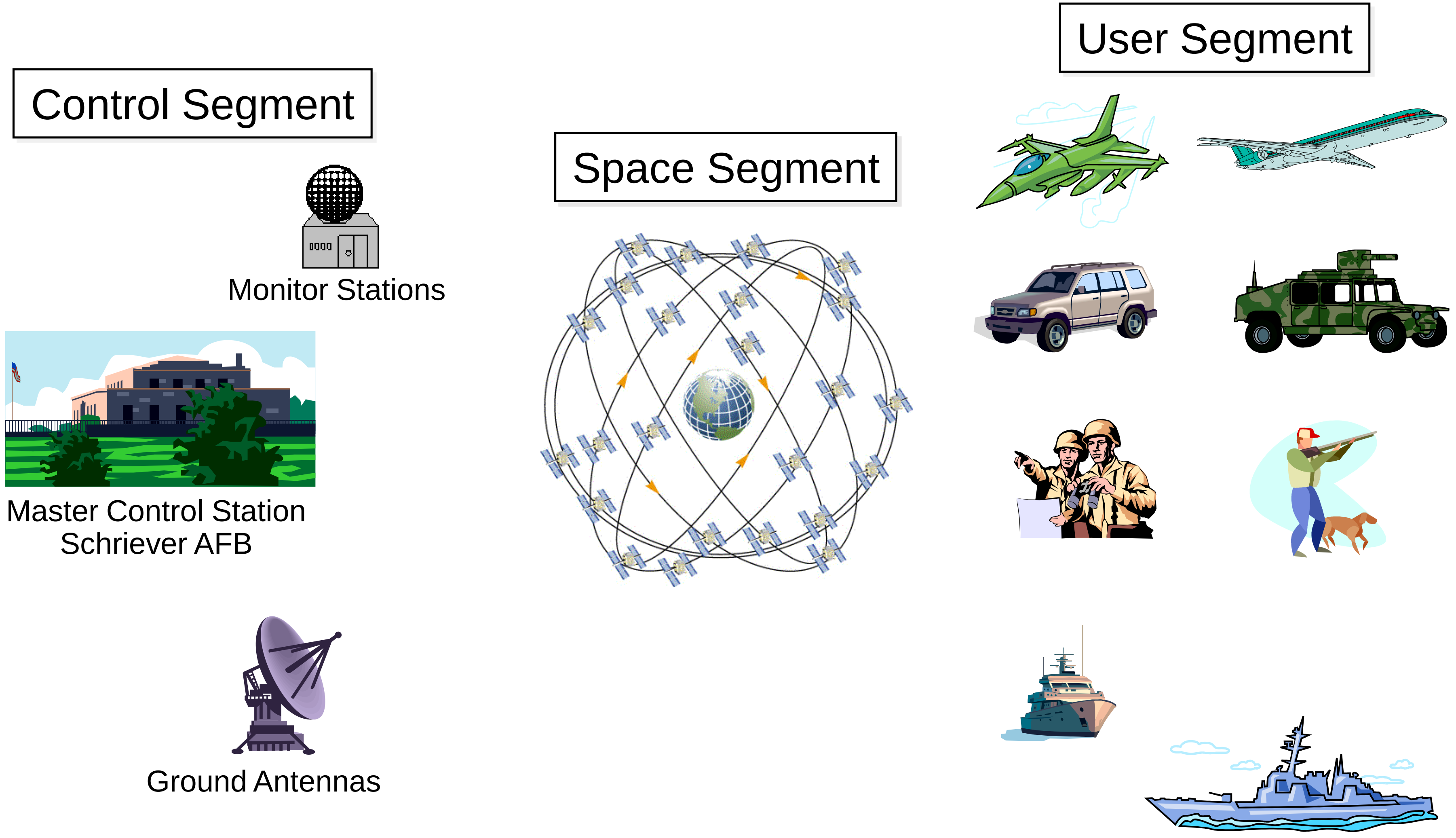
Fundamentals of GPS Operation



GPS Critical Technologies

- Time Difference of Arrival (TDoA) Multilateration
- Direct Sequence Spread Spectrum
  - Ranging
  - Interference Rejection / AntiJam / Security

GPS SYSTEM SEGMENTS



SPACE SEGMENT

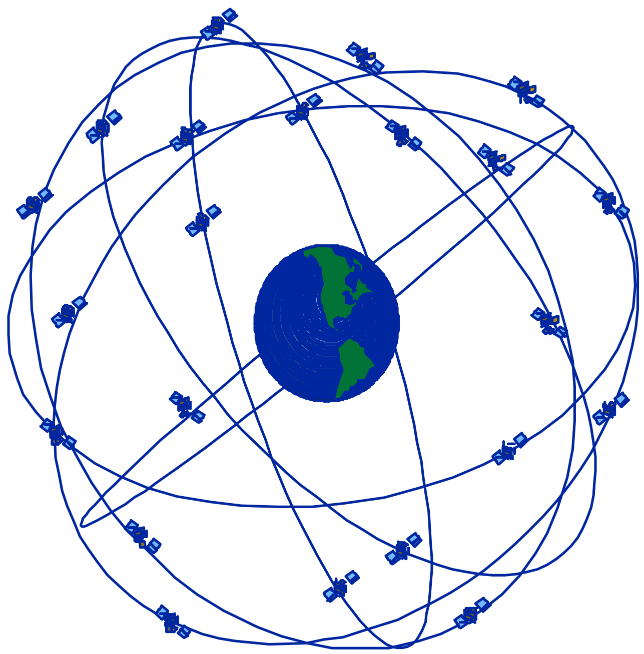
GPS Satellite Constellation

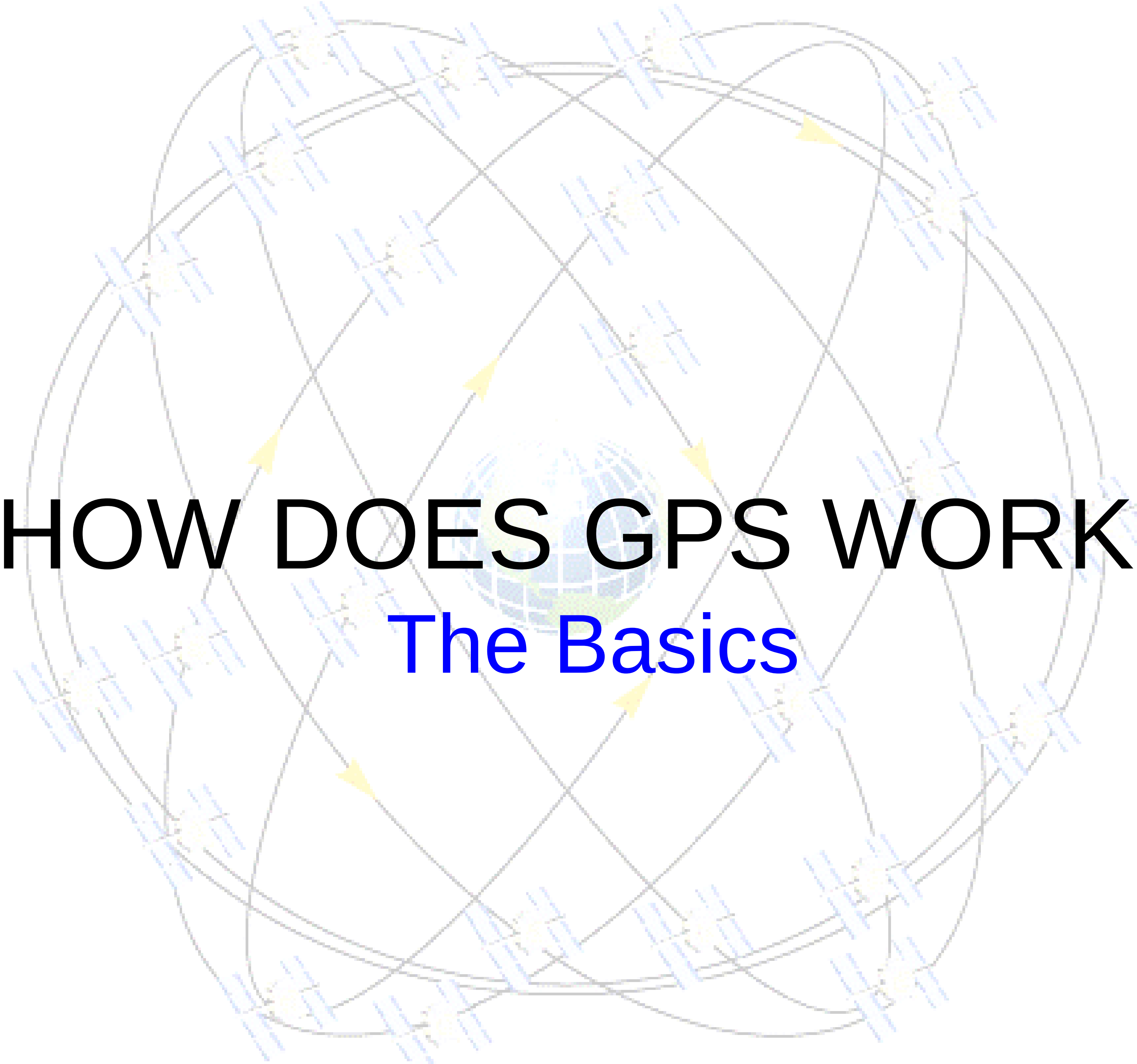
- 24 Satellites for Worldwide Coverage

- 6 Orbital Planes Inclined at 55º to Equator

- Semi-Synchronous Circular Orbits
  - Radius: 26,560 Km (14,351 Nmi)
  - Altitude: 20,183 Km (10,905 Nmi)

- Orbital Period: 11 hrs. 58 min.

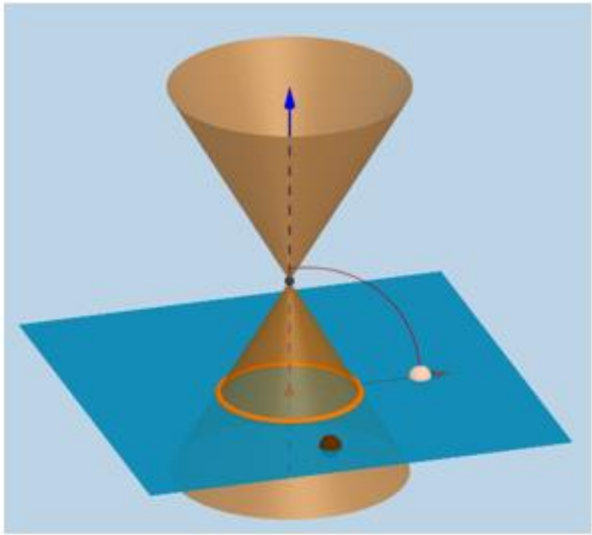


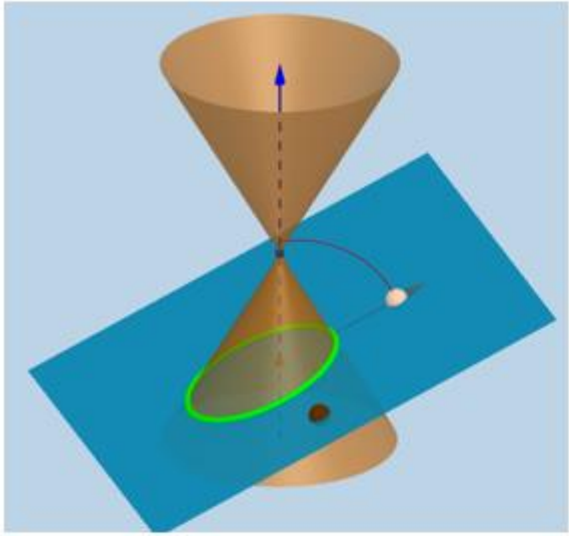


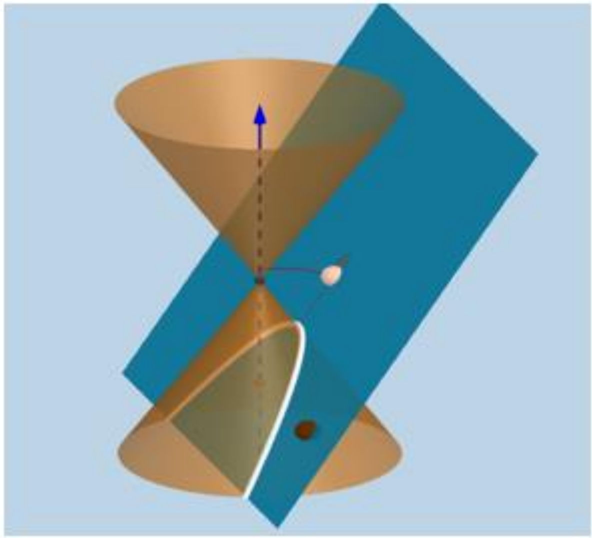
HOW DOES GPS WORK?

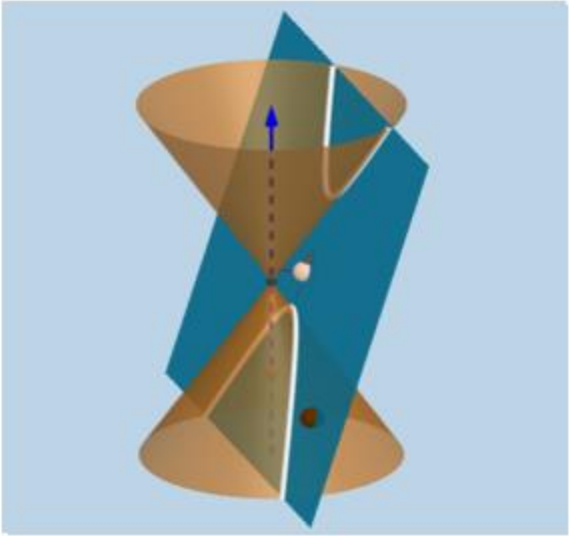
The Basics

Conic Sections

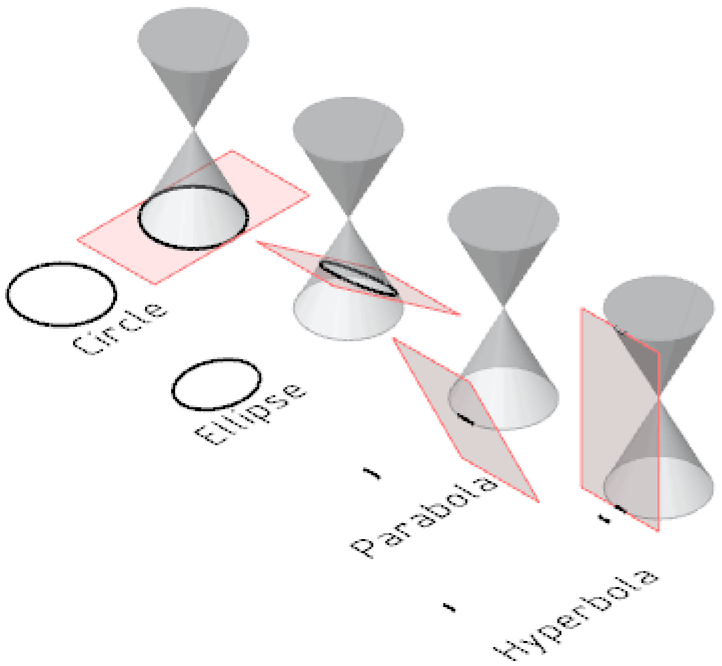

Circle


Ellipse

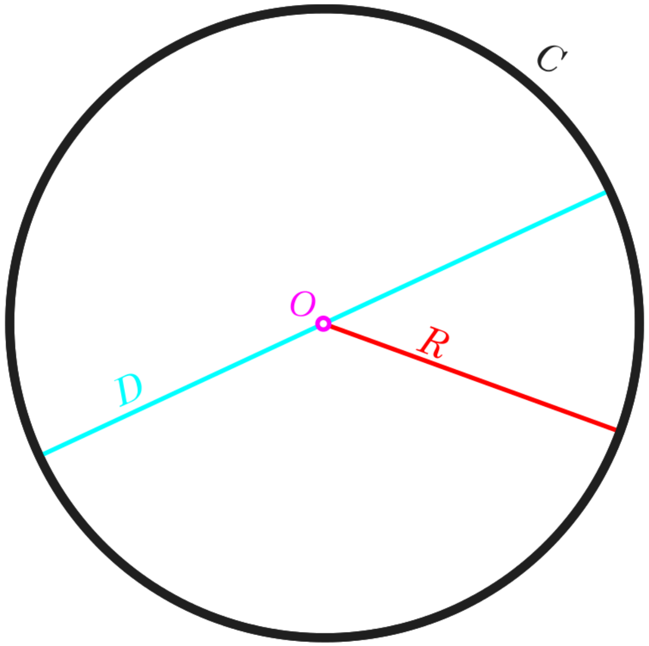

Parabola


Hyperbola

Conic Sections

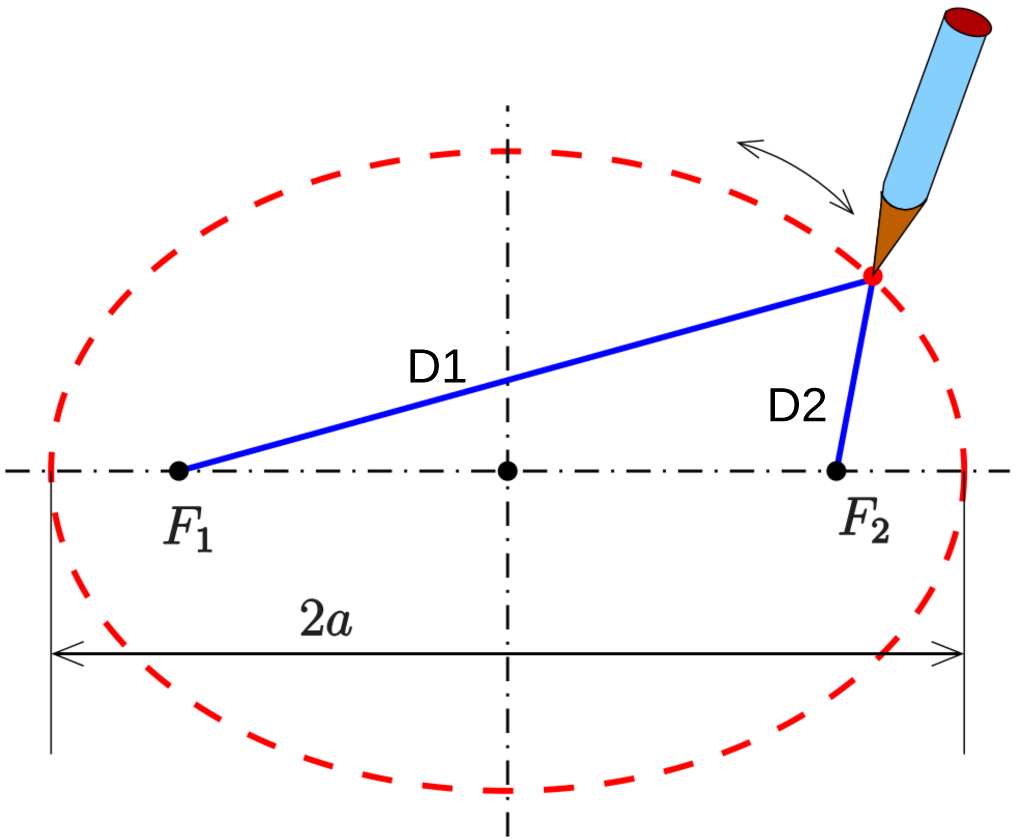


Properties of Conic Section
Circle



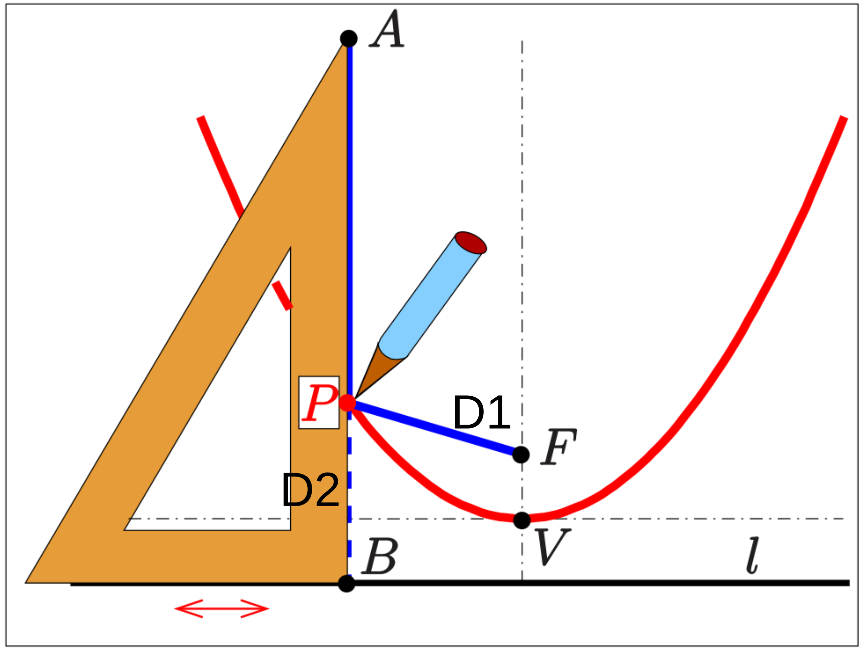
Distance R from Center (or Focus) is Constant

Properties of Conic Section
Ellipse

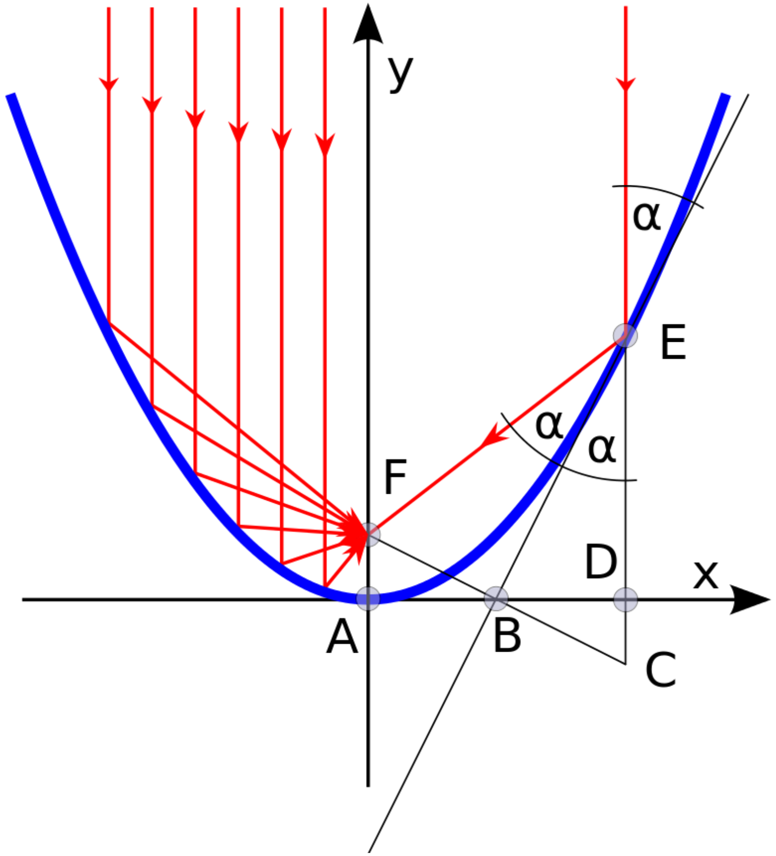


Distance D1 + D2 is a constant

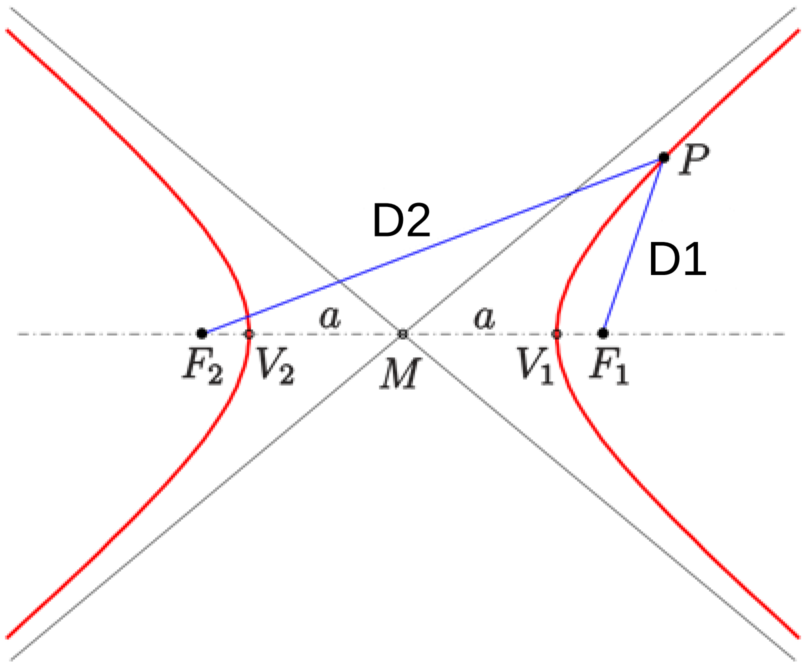
Properties of Conic Section
Parabola

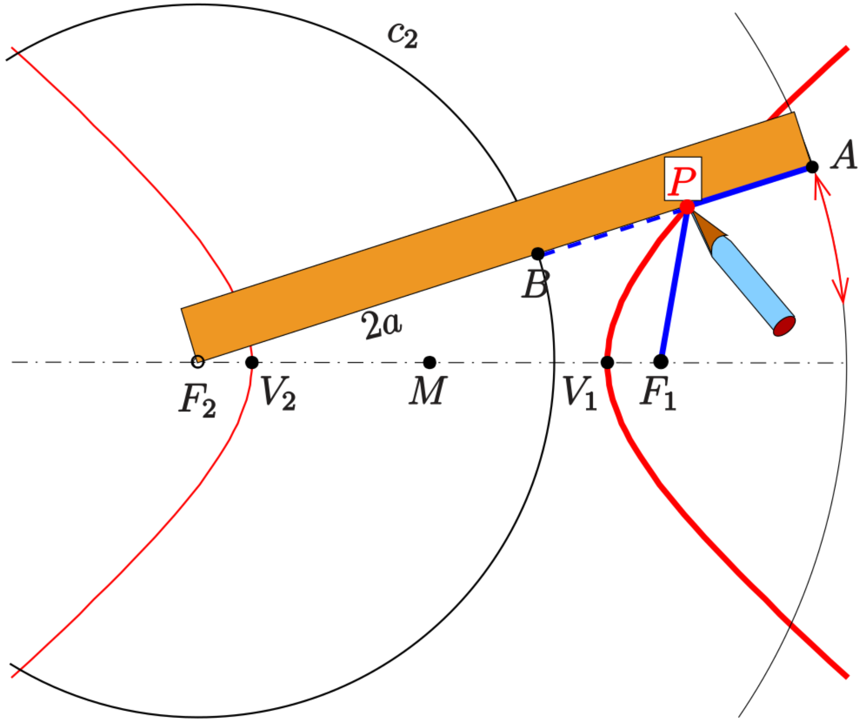


Distance D1 (FP) + D2 (PB) is a constant



Properties of Conic Section
Hyperbola





Distance D1 (F_1P) - D2 (F_2P) is a constant

Time Difference of Arrival (TDoA)

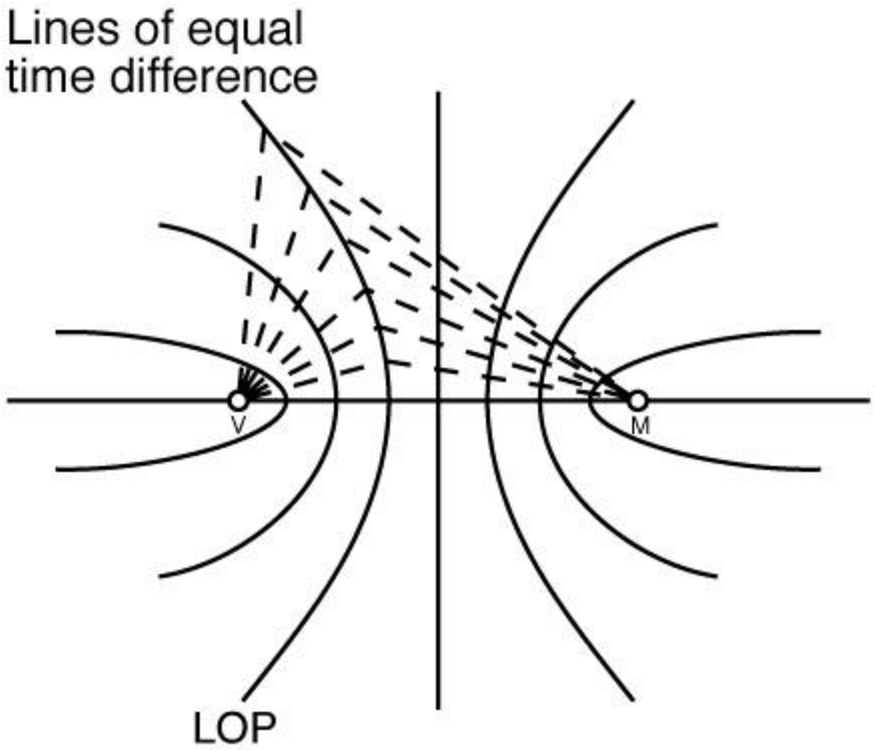
TDoA is a form of multilateration

- Only Measure Time of Arrival
  - Determine Time Difference of Arrival
  - Calculate pseudo-ranges

- Transmit clocks are synchronized to each other

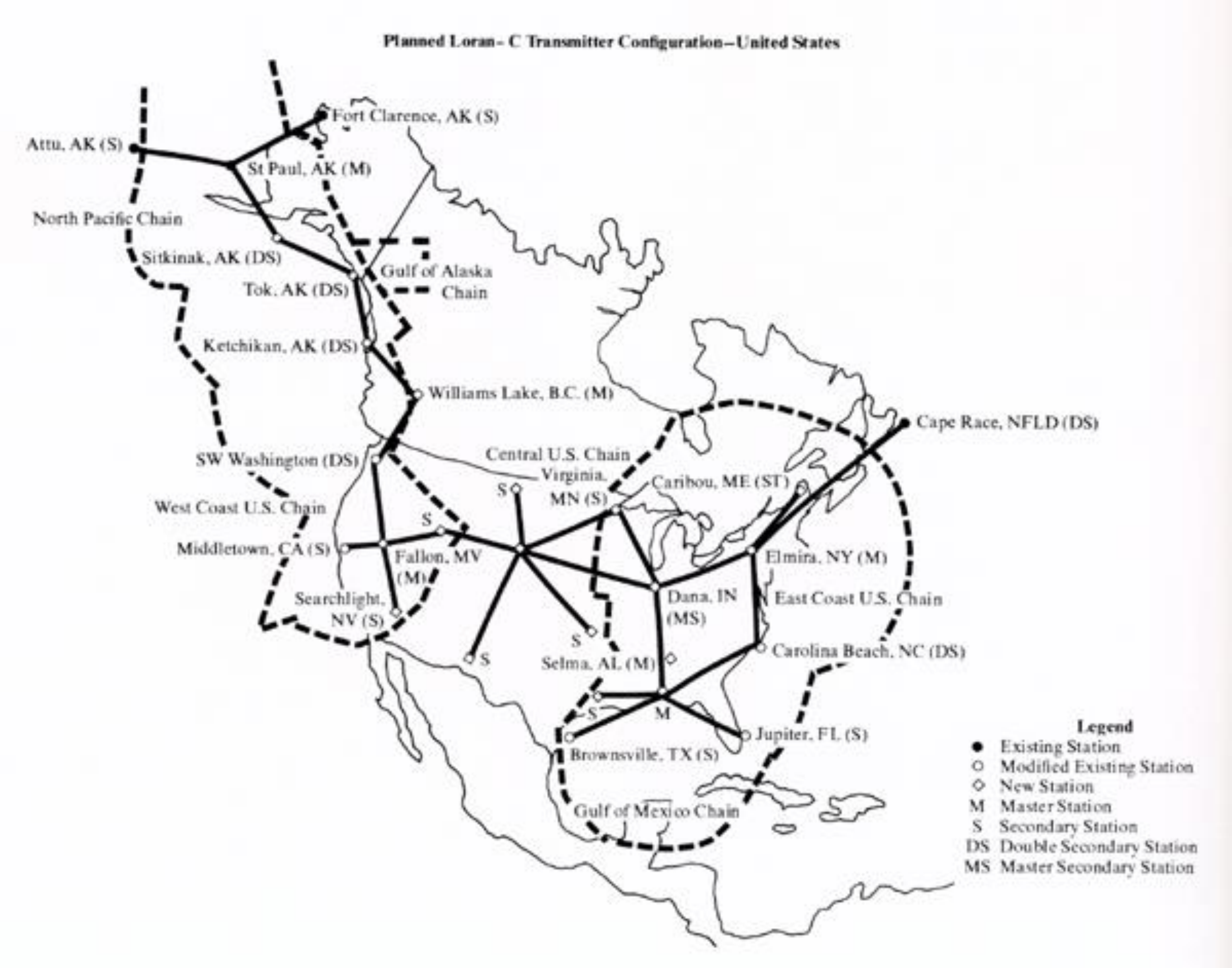
If transmit clocks are also synchronized to time then time can be also calculated

Time Difference of Arrival

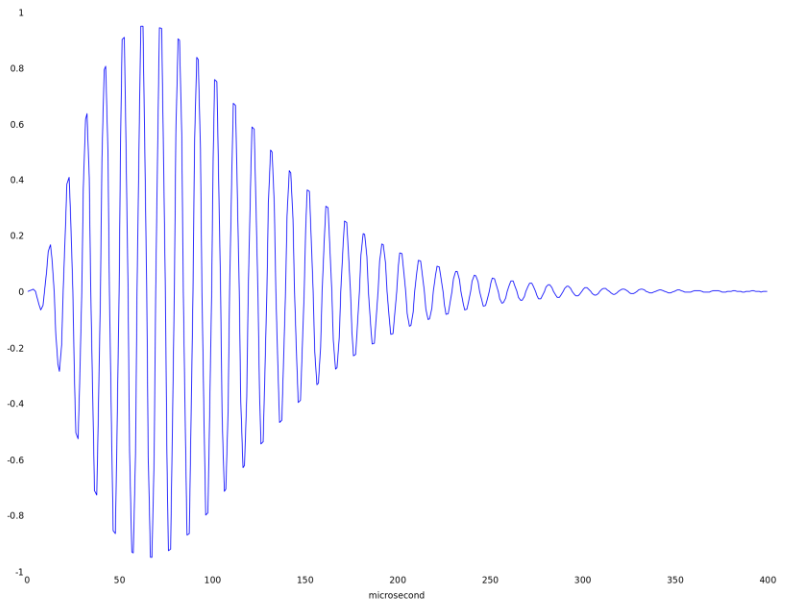


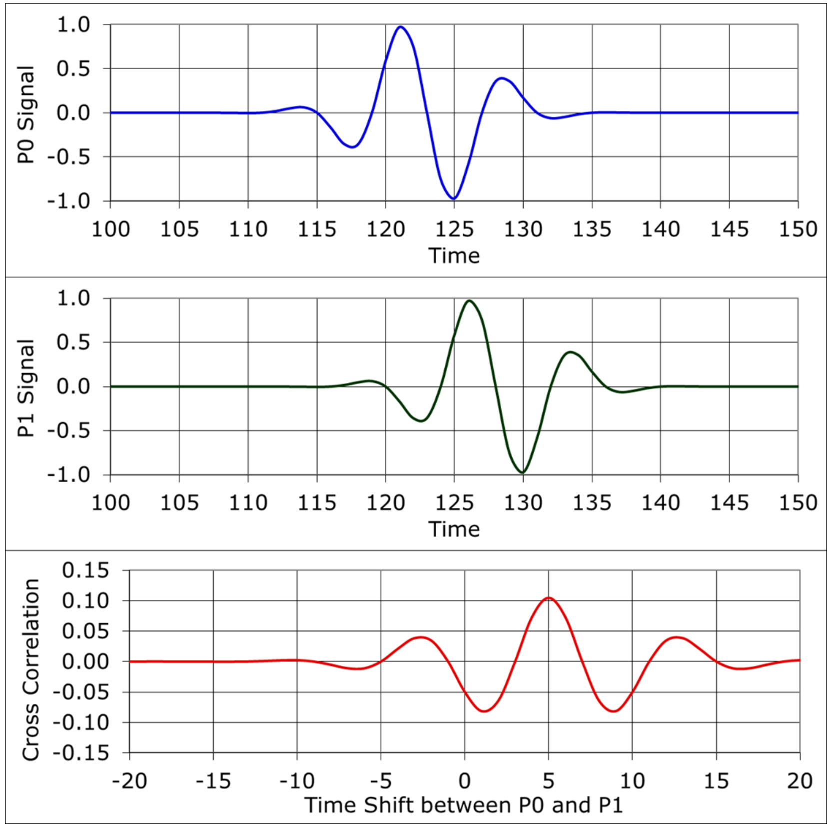
**hyperbolic
navigation system**

Time Difference of Arrival – Loran

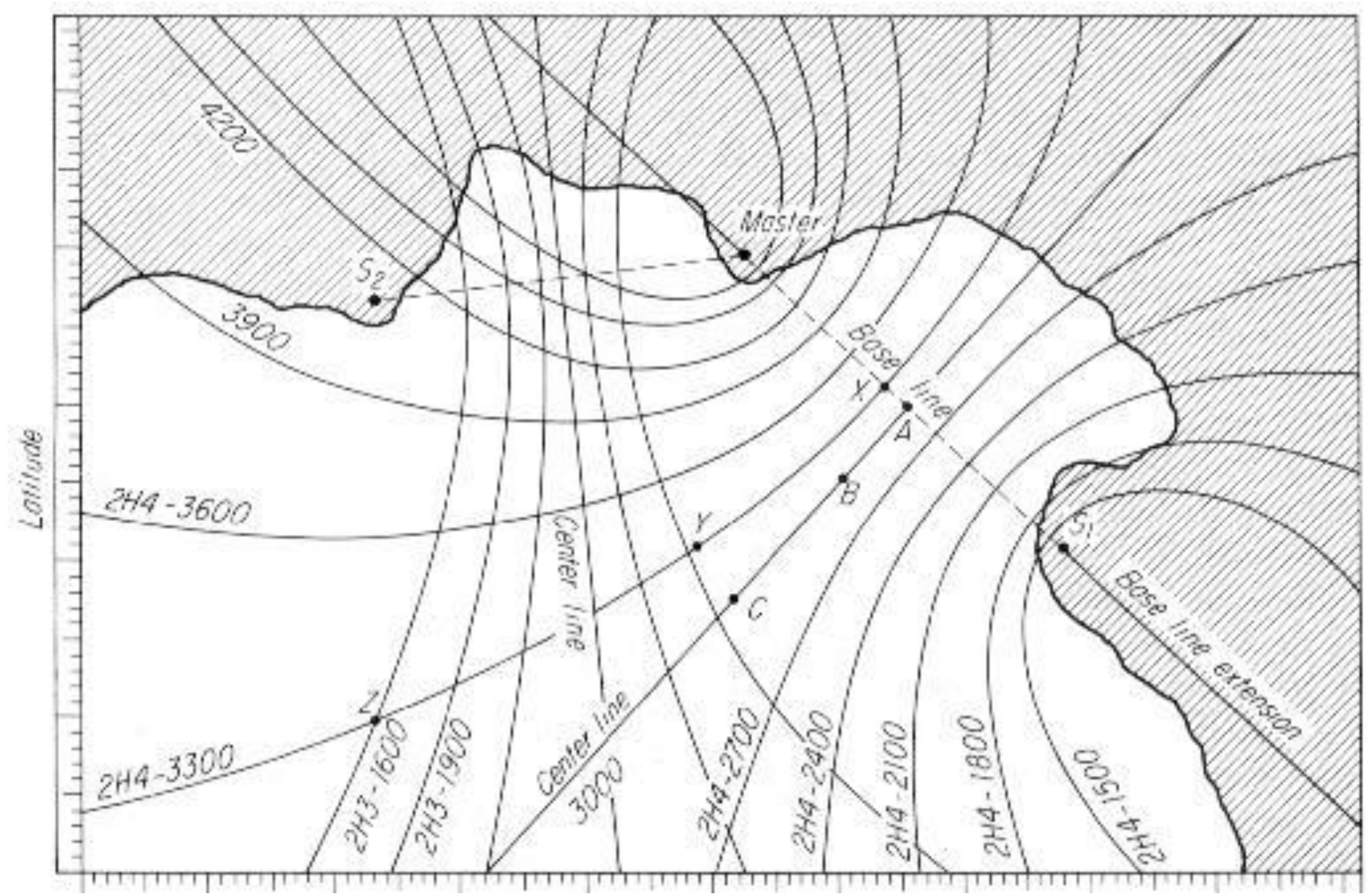


Time Difference of Arrival – Loran Pulses

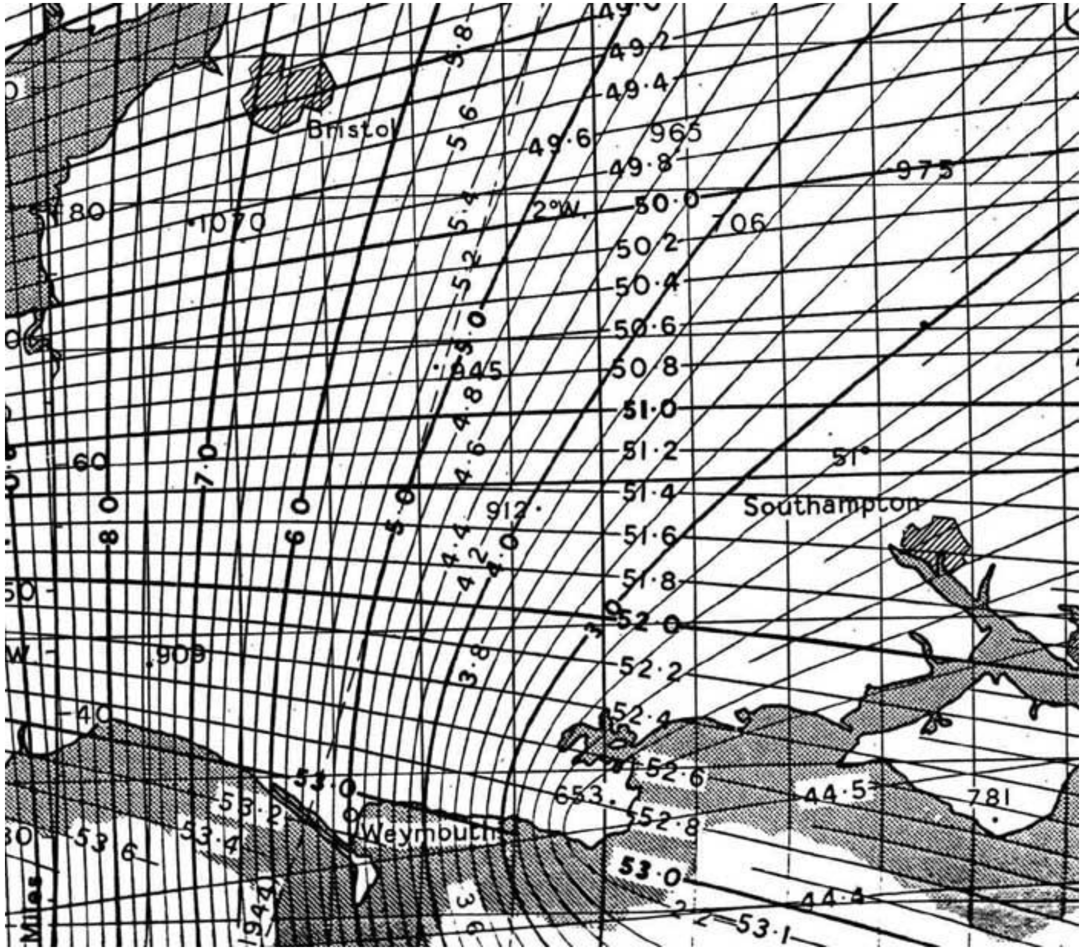


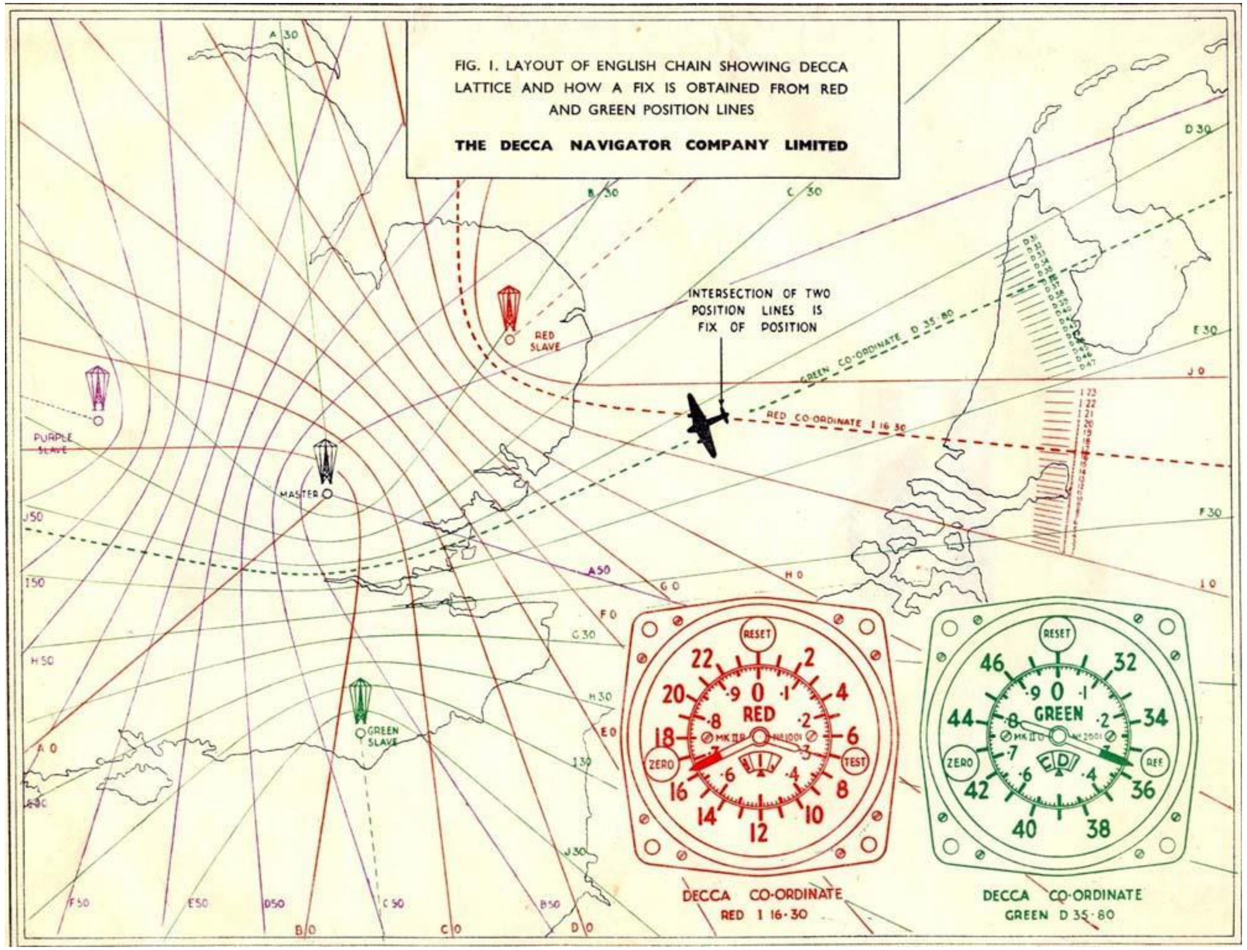


TDoA Navigation

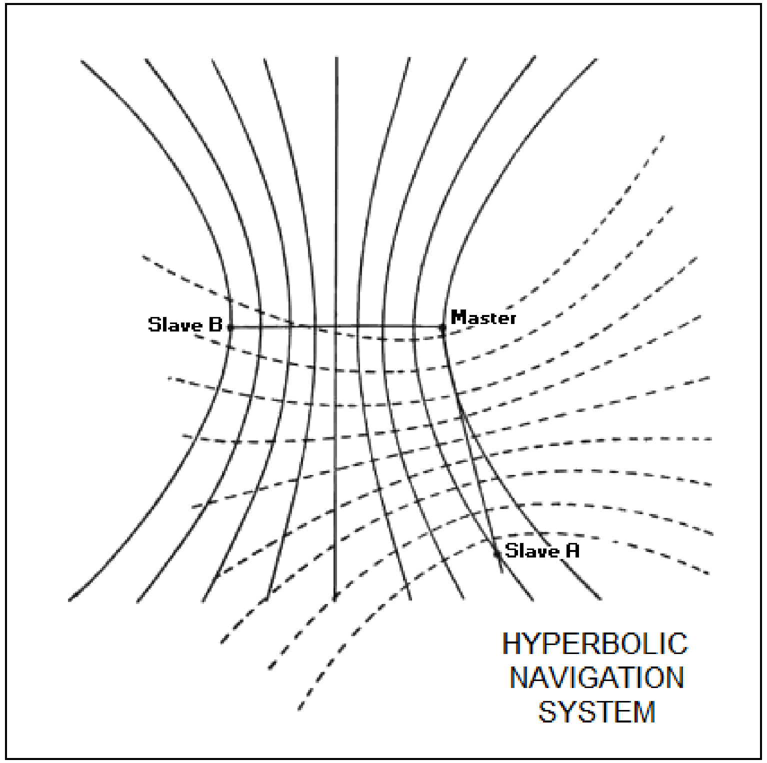


TDoA Navigation

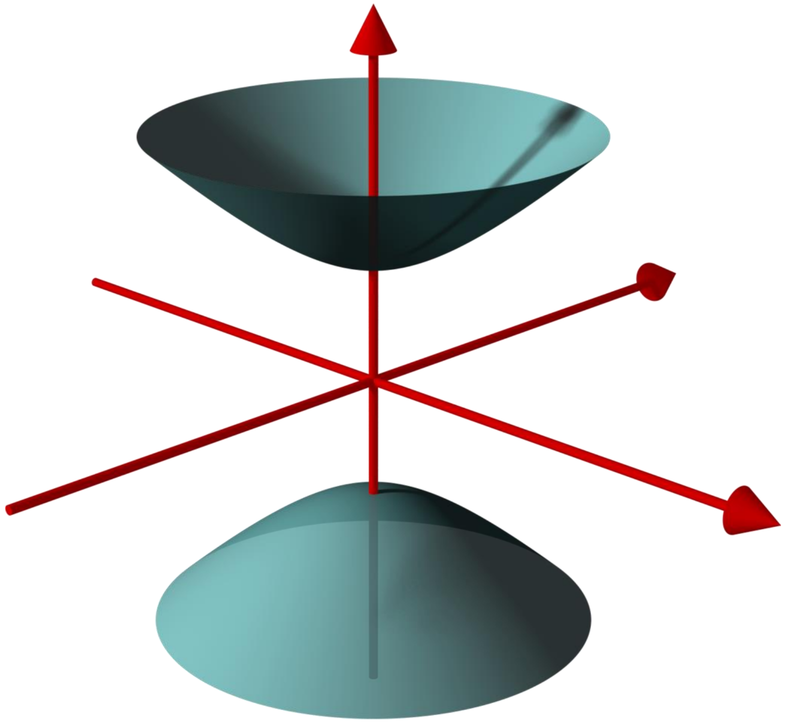




TDoA Navigation

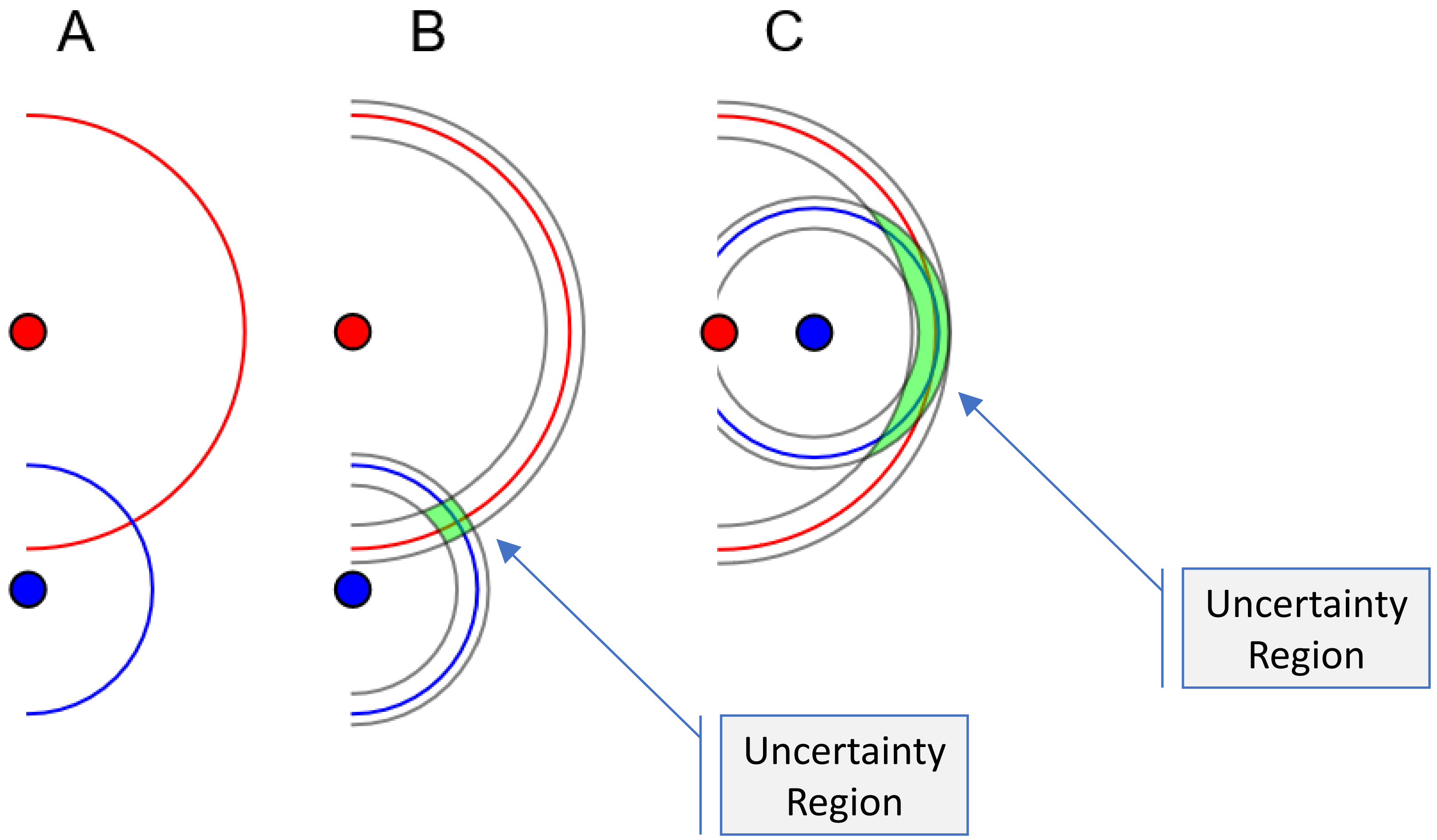


Simple 2D Earth surface case

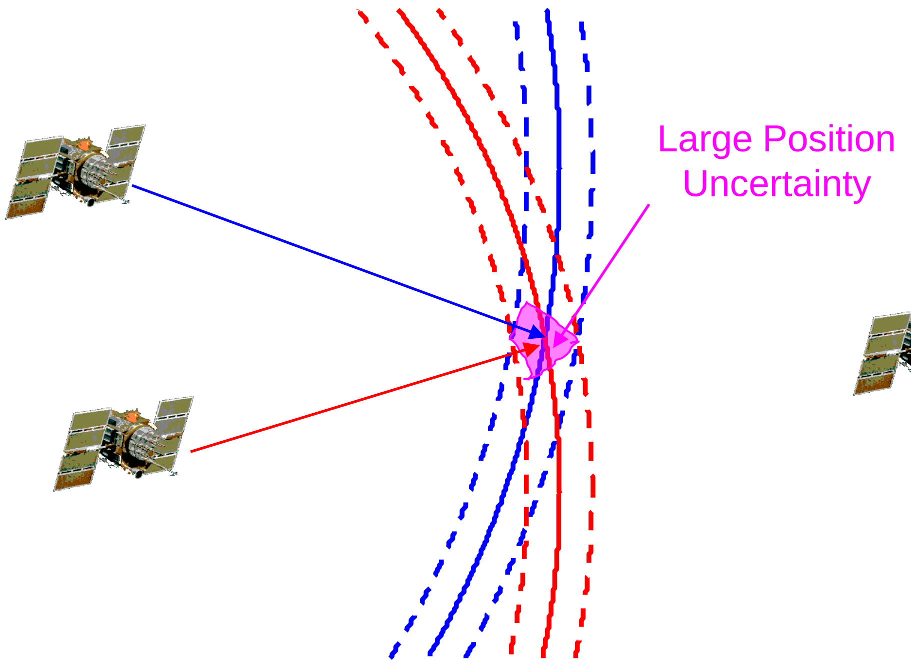


Much more complex general 3D case

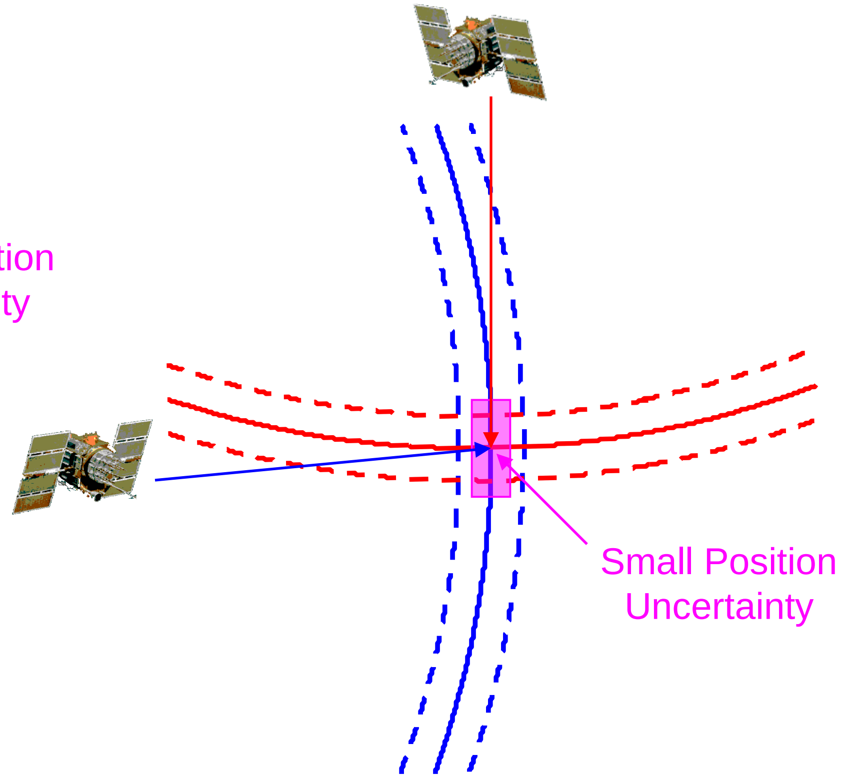
Dilution of Precision - xDOP



SATELLITE GEOMETRY



Poor Satellite Geometry
High DOP



Good Satellite Geometry
Low DOP

Dilution of Precision- DoP

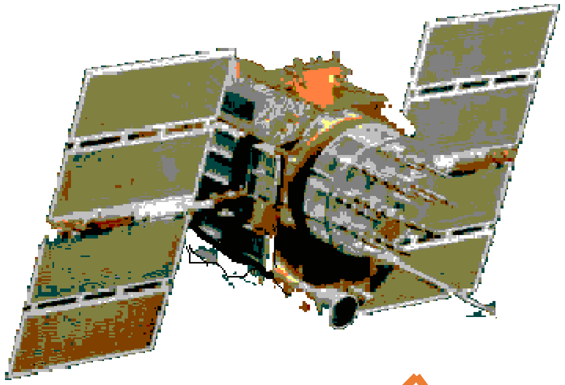
HDOP – Horizontal DOP
VDOP – Vertical DOP

Dilution of Precision is strictly a function of Satellite geometry

GPS Signal Structure

- Multiple Frequencies
- Multiple Modulations
- Direct Sequence Spread Spectrum (DSSS)
- Low Data Rate Date Transmission

GPS SIGNALS



Total Transmitted Power
~ 250-500 Watts (ERP)

L2
1227.6 MHz

L1

L1
1575.42 MHz

<u>Y-Code</u>
Precise Positioning Service (PPS)
DOD and Authorized Users
Encrypted P-Code (Anti-spoofing)

<u>C/A-Code</u>
Standard Positioning Service (SPS)
Civil Signal
Initial Acquisition for Authorized Users
~~Degraded Accuracy~~ (Selective Availability)

GPS SIGNAL SEPARATION

- All Satellites Transmit on Same Frequencies
  - L1 – 1575.42 MHz
  - L2 – 1227.60 MHz
  - L5 – 1176.45 MHz (not operational yet)

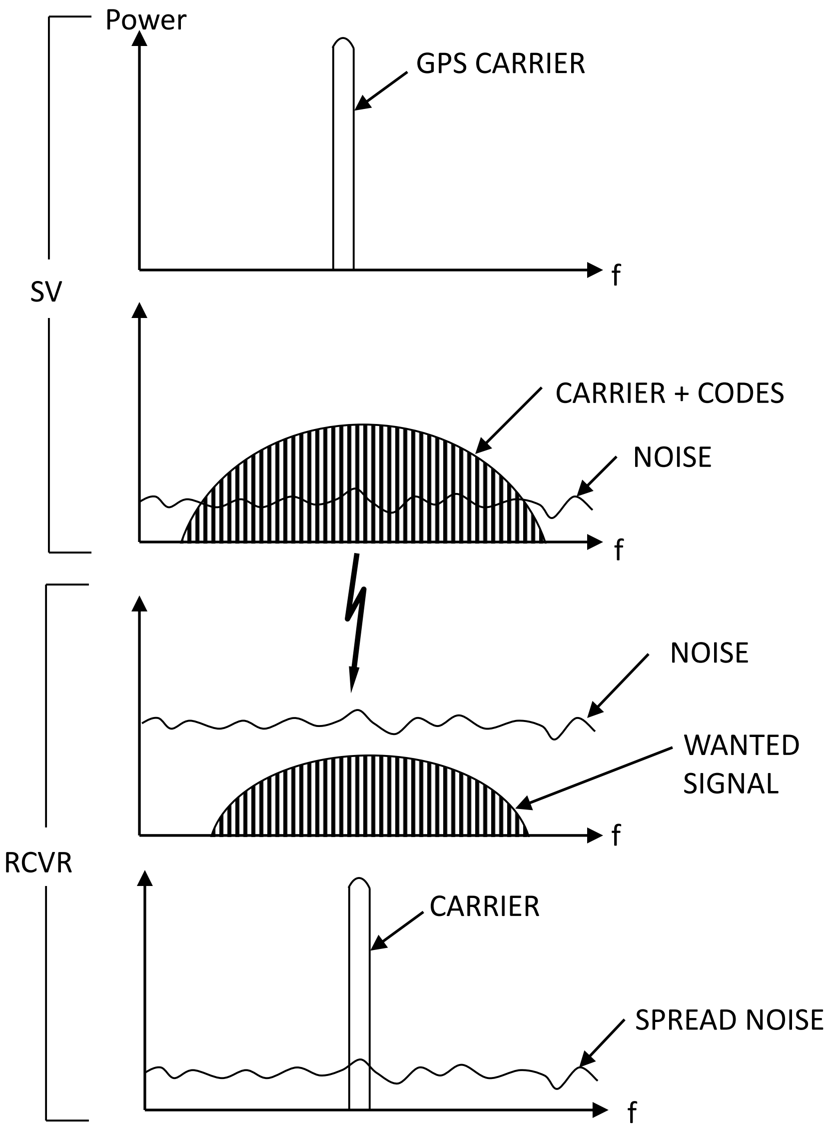
- How Do We Separate Signals From Satellite to Satellite?

- Code Division Multiple Access (CDMA)
  - Each Satellite Transmits a Unique C/A-Code - Repeats Every Millisecond
  - Each Satellite Transmits a Unique Y-Code - Encrypted P-Code That Repeats Every Week
  - Each Satellite Transmits a Navigation Message - Takes 12.5 Minutes @ 50 Bits/Second

DSSS PSEUDO-RANDOM NOISE

- Desirable Properties of C/A and Y-Codes:
  - Distinctive Signals That Are Easily Generated by Satellites and GPS Receivers
  - Codes From Different Satellites Don’t Interfere With Each Other
  - Look Random or Noise-Like to Unauthorized Users
- GPS Uses Pseudo-Random Noise (PRN) Sequences or Codes
  - Binary Sequences (0 or 1)
  - Appear to be Generated on the Basis of a Coin Toss
  - Actually Generated by Mathematical Algorithm

GPS Spread Spectrum Processing

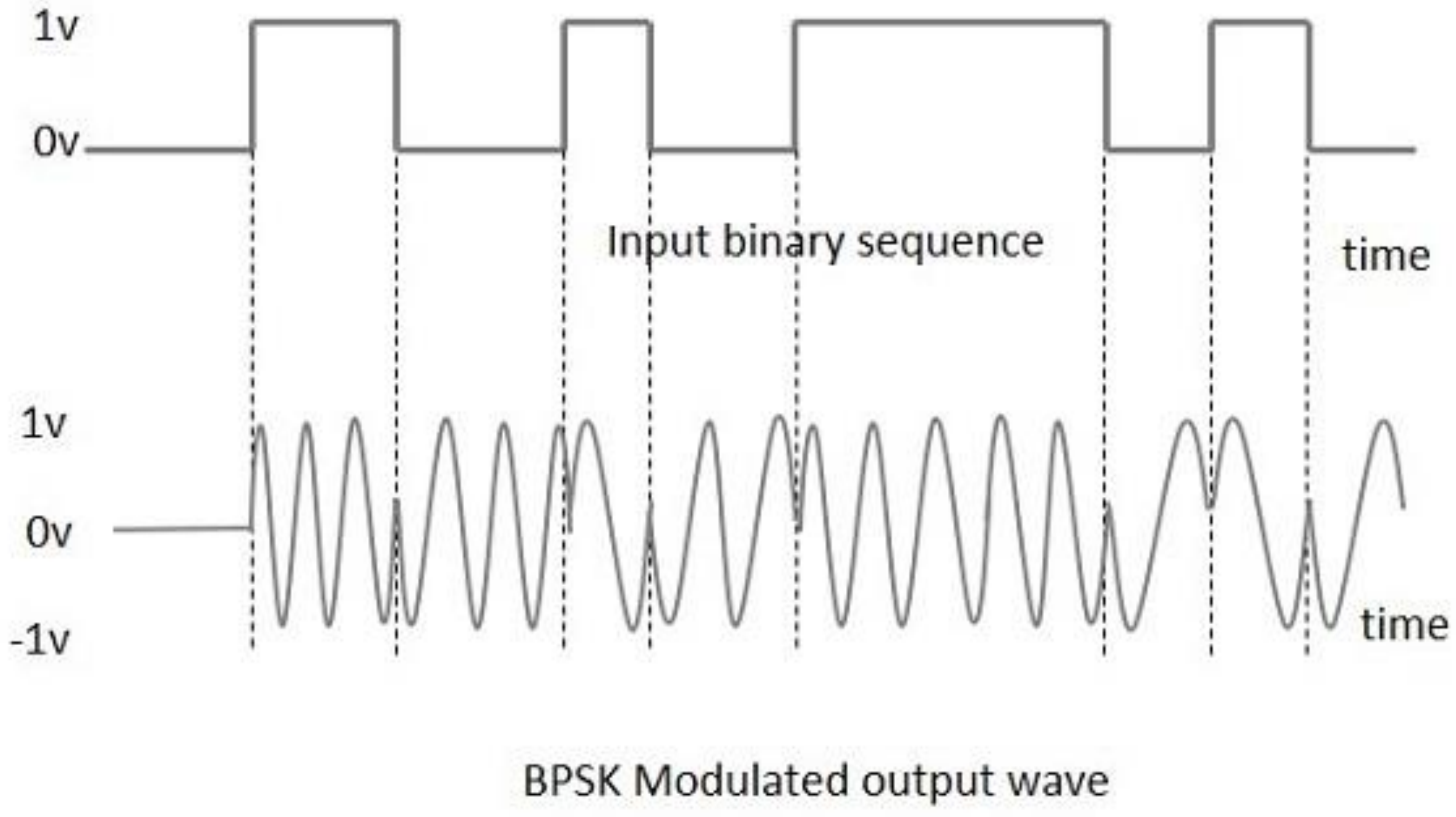


- GPS Power Output From Satellite ≈ 400 w

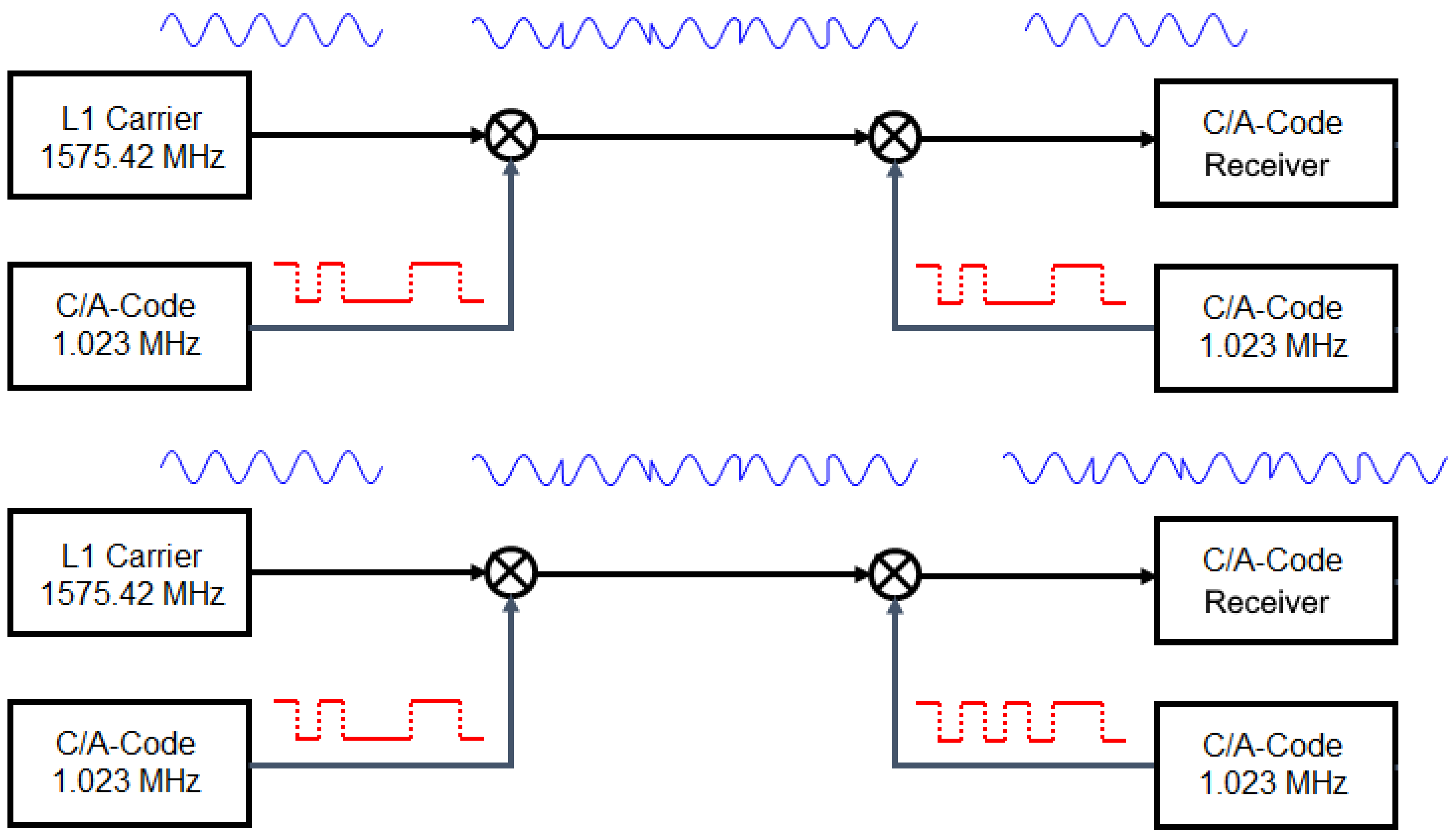
- Noise density ≅ -202 dBw/Hz
- Signal density ≅ -223 dBw/Hz
  ≅ -236 dBw/Hz (Y-code)

- GPS Signal Power Restored after Correlation in Receiver

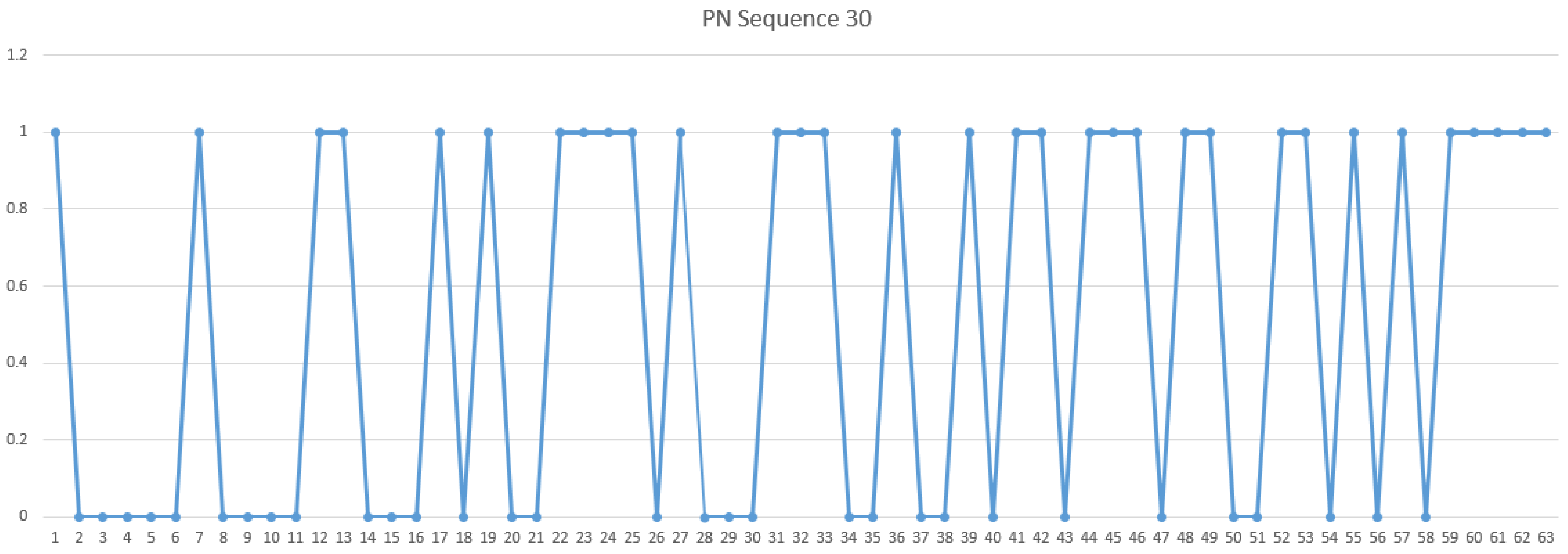
Binary Phase Shift Keying (BPSK) Modulation



Satellite Signal Modulation

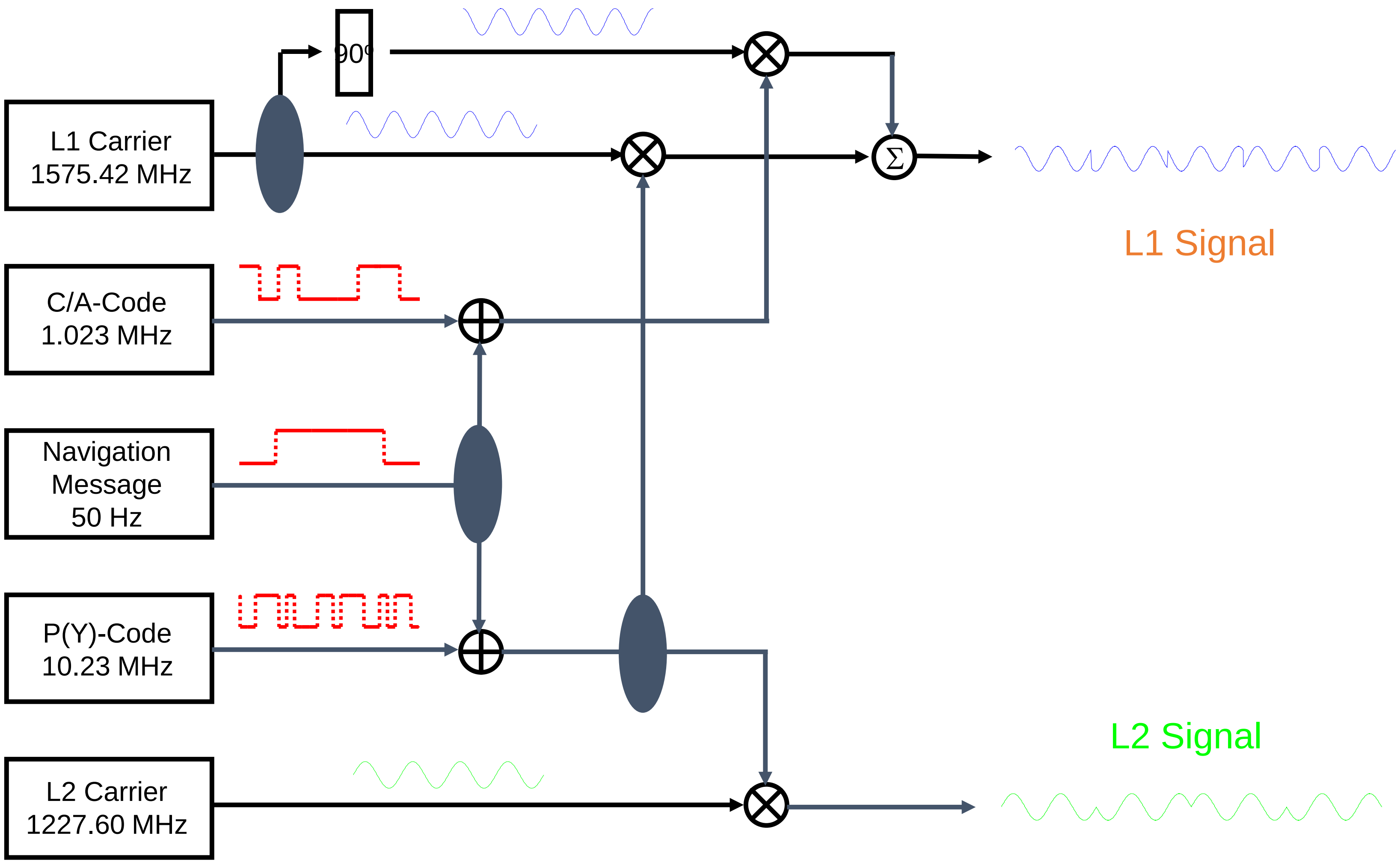


More on PRN Sequences



Satellite Signal Modulation

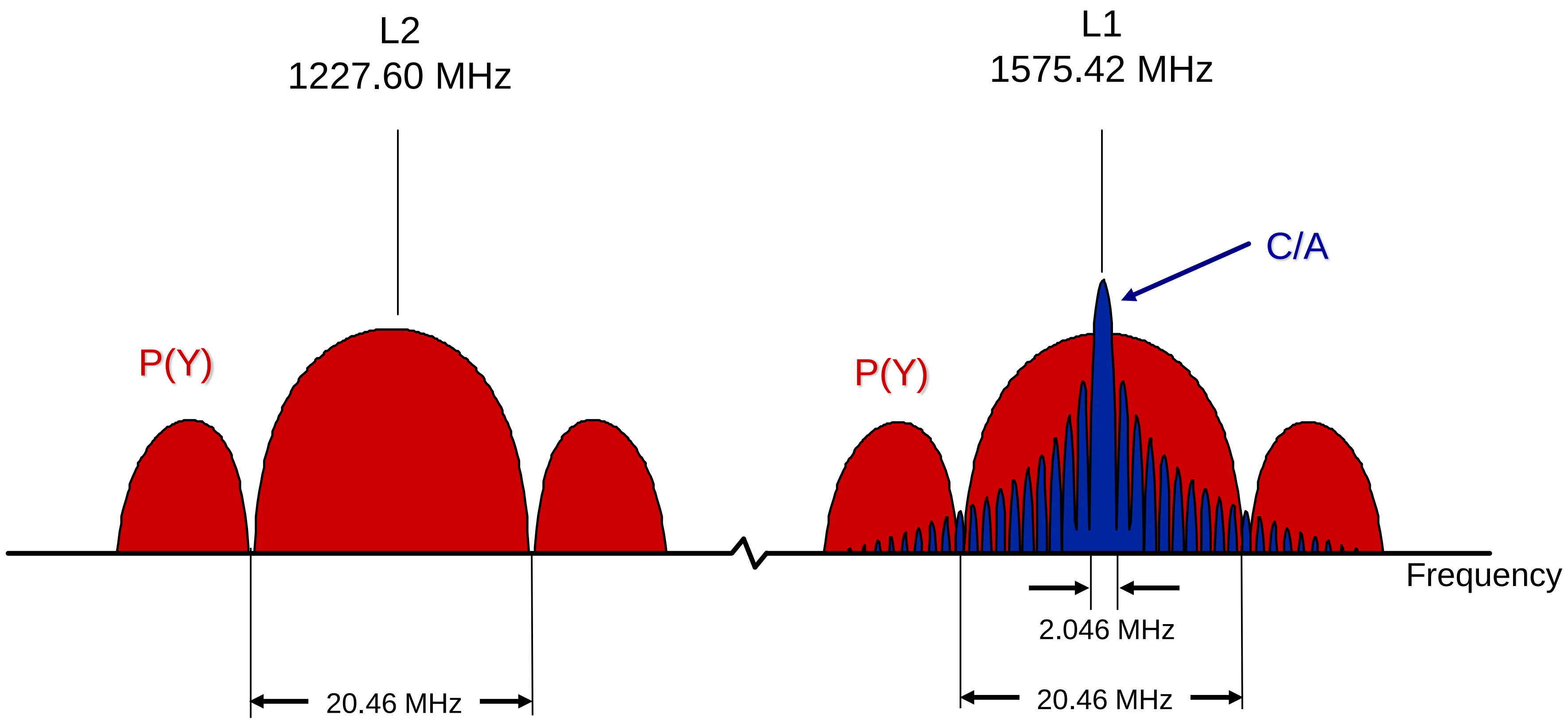
Satellite Signal Modulation – More Detail



C/A-Code vs. P(Y)-Code

Code	Frequency	Code Type	Chip Rate	Period	Features
C/A	L1	Gold	1.023 MHz	1 millisecond	• Moderate Accuracy, Civil Applications • Not Protected • Acquisition Aid for P(Y) Code
P(Y)	L1 and L2	PRN	10.23 MHz	1 Week	• High Accuracy • Encrypted (Anti-Spoof) • Military Users • 7 – 10 dB Extra AJ Compared to C/A-Code

GPS SIGNAL SPECTRUM



GPS Navigation Messages

GPS Navigation Data Format

- **Frames** (1500 bits long, 30 sec Duration) **divided into five subframes**
- **How** (hand-over-word) **contained within each subframe**
- **Precision ephemeris and clock data** (for transmitting satellite) **within each frame - changes once per 2 hour**
- **Less precise information** (almanac) **transmitted on a one-satellite-per-frame basis**

Ten 30-bit words, 6 sec/ Subframe

Subframe No.			
1	TLM	HOW	Block 1 - Clock Correction
2	TLM	HOW	Block 2 - Ephemeris
3	TLM	HOW	Block 2 - Ephemeris Continued
4	TLM	HOW	Message
5	TLM	HOW	Block 3 - Almanac - (25 frames for complete almanac)

1 Frame 30 sec 1500 bits

Contents of Navigation Data

- **Sub-Frames 1,2,3 Repeated Every Frame (Once Every Seconds)**
  - **Ephemeris and Clock Data Unique to Each Satellite**
  - **Required for Navigation Solution**
  - **Normally Requires All Satellites Be Tracked to Download (Read) Data**
  - **18 Seconds Required to Read Data for 1 SV**

- **Sub-Frame 4 Common to All Satellites**
  - **Some Pages are Reserved (Partly Used for NMCT)**
  - **Some Pages contain Data for GUV Users**
  - **Some Pages contain Almanac for SVs 25-32**
  - **One Sub-Frame for Iono Model Data for Single Frequency Users**
  - **Classified Data for SAASM Users etc**

- **Sub-Frame 5 Common to All Satellites**
  - **Each Sub-Frame 5 Contains Almanac Data for 1 Satellite (24 Frames)**
  - **Sub-Frame 5 of the 25th Frame Contains Health Data for 24 SVs**
  - **Required Only for Initial Acquisition**

12.5 Minutes to Read All Data From 25 Pages

WHERE ARE THE SATELLITES?

- Navigation Message Contains Data That Receiver Needs to Accurately Calculate Satellite Positions

- Ephemeris
  - Set of 17 Numbers That Accurately Describes Orbit
  - Calculated from Monitor Station Measurements
  - Changed Every 2 Hours
  - Valid for 4 Hours
  - Each Satellite transmits Only its Own Ephemeris

- Almanac
  - Coarse Version of Ephemeris
  - Used for Satellite Acquisition and Planning
  - Each Satellite Transmits Almanac for All Satellites
  - GPS Receivers Store Almanac for Future Use

DISTANCE MEASUREMENT SUMMARY

- **Distance is Determined Indirectly by Measuring Travel Time of GPS Signal**
- **Receiver Matches Locally Generated PRN Code Sequence to Transmitted Signal**
- **Cross-correlation Technique Used to Process Very Noisy Received Signal**

GPS – Various Other Topics

GPS Antenna Considerations

- Passive Antenna
  - No power required
  - Only works for short cable (<~10ft)
- Active Antenna
  - Built in amplifier
  - Necessary for longer cable lengths
  - Powered through the antenna cable (+3.3 or +5.0 Vdc)
    - Select based on what GPS receiver provides
  - Low (~14 dB) Medium (~28 dB) High (~40 dB) of Gain
    - Select based on anticipated cable loss

Time To First Fix

Time required to

- Acquire satellite signals
- Acquire navigation data (Ephemeris and Almanac
- Calculate a position solution

Cold – Missing position, time, and Satellite Information

Typical TTFF = ~15 minutes

Warm (or Normal) – Time estimate within 20 seconds, position within 100 km, valid almanac

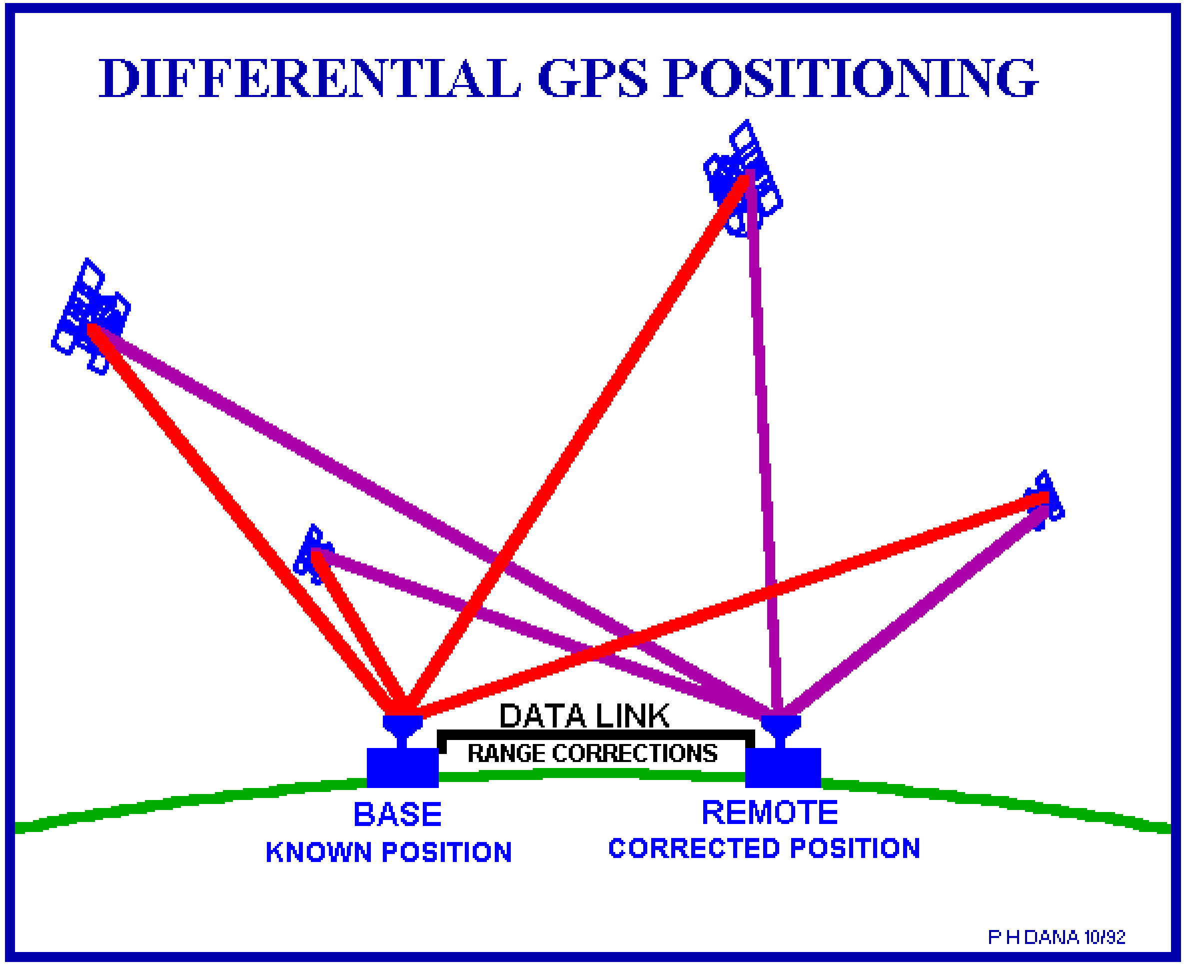
Typical TTFF = ~30 seconds

Hot (or Standby) – Valid time, position, almanac, and ephemeris

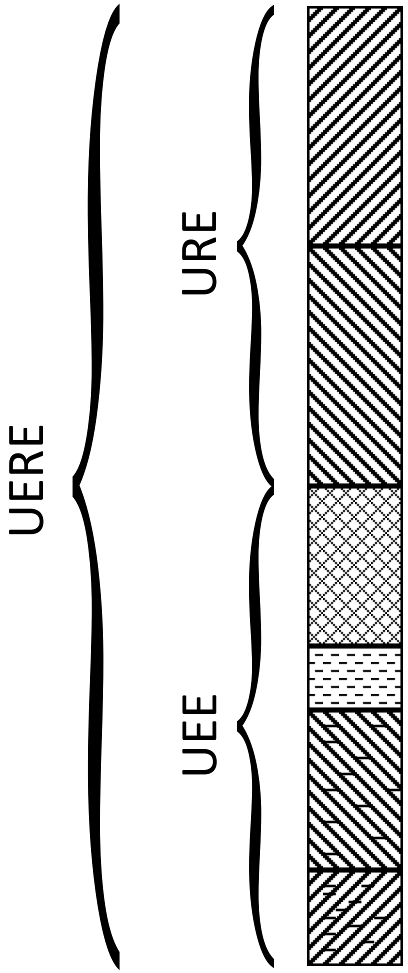
Typical TTFF = ~seconds

Note: TTFF can be sped considerably up by externally providing almanac, ephemeris, and pseudo-range data.

Differential GPS



Pseudo - Range Error Components



	GPS JPO - PPS Budget
Satellite LOS ** Ephemeris Error	4.3 m
Satellite Clock** Contribution to PR Error	3.2 m
Iono Path Delay	1.0 m
Tropo Path Delay	1.0 m
Multipath Error	1.0 m
Receiver Noise	1.0 m_
UERE =	5.7 m

** Ref: "DoD NAVSTAR GPS User Equipment Introduction – GPS JPO, Feb 1991"

Concept of Differential GPS (DGPS)

DGPS Removes Common Errors

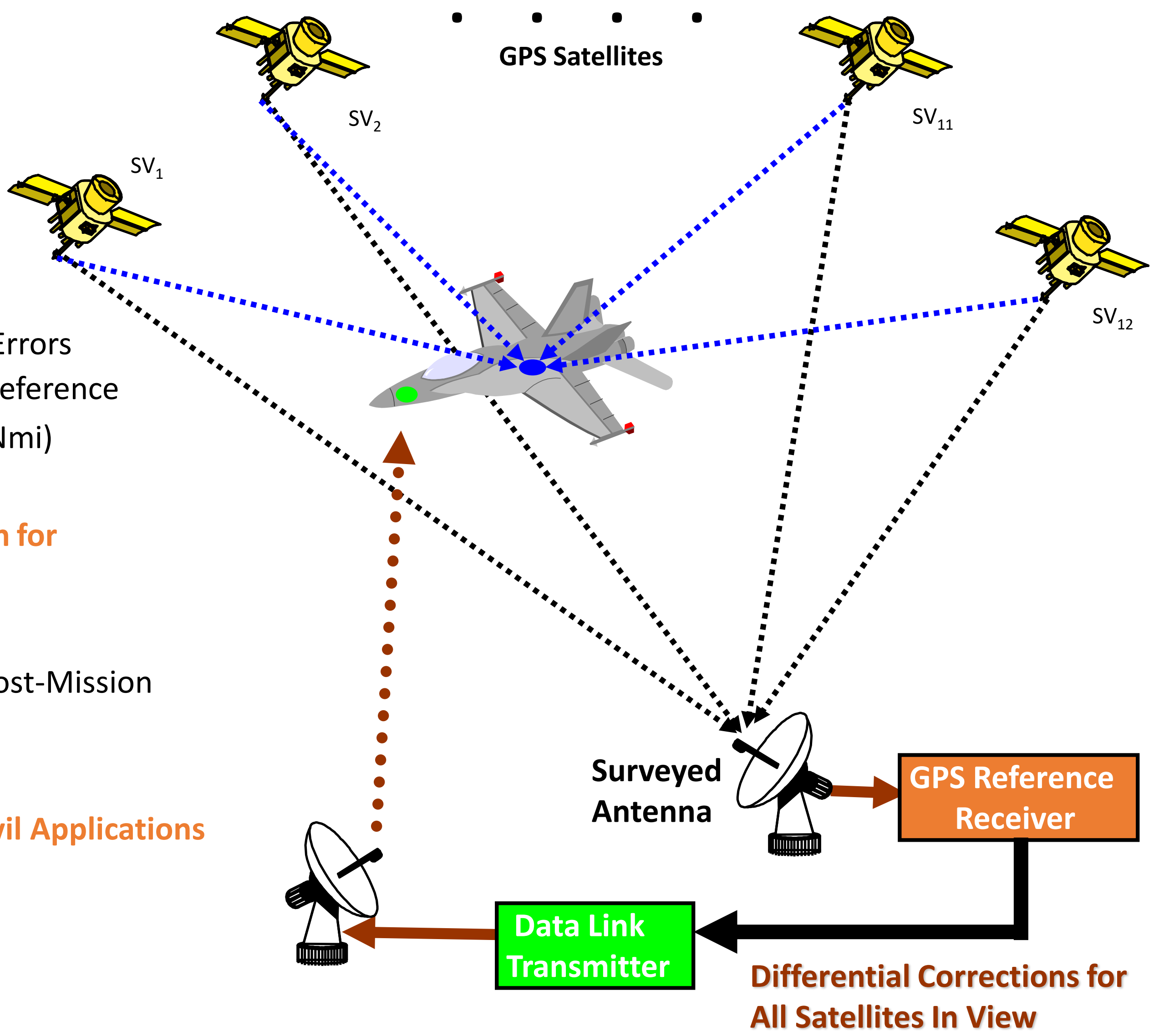
Space Segment, Tropo, Iono Errors are Common to Airborne & Reference Receivers (separation ~ 100 Nmi)

Data Link Security Consideration for DoD Applications

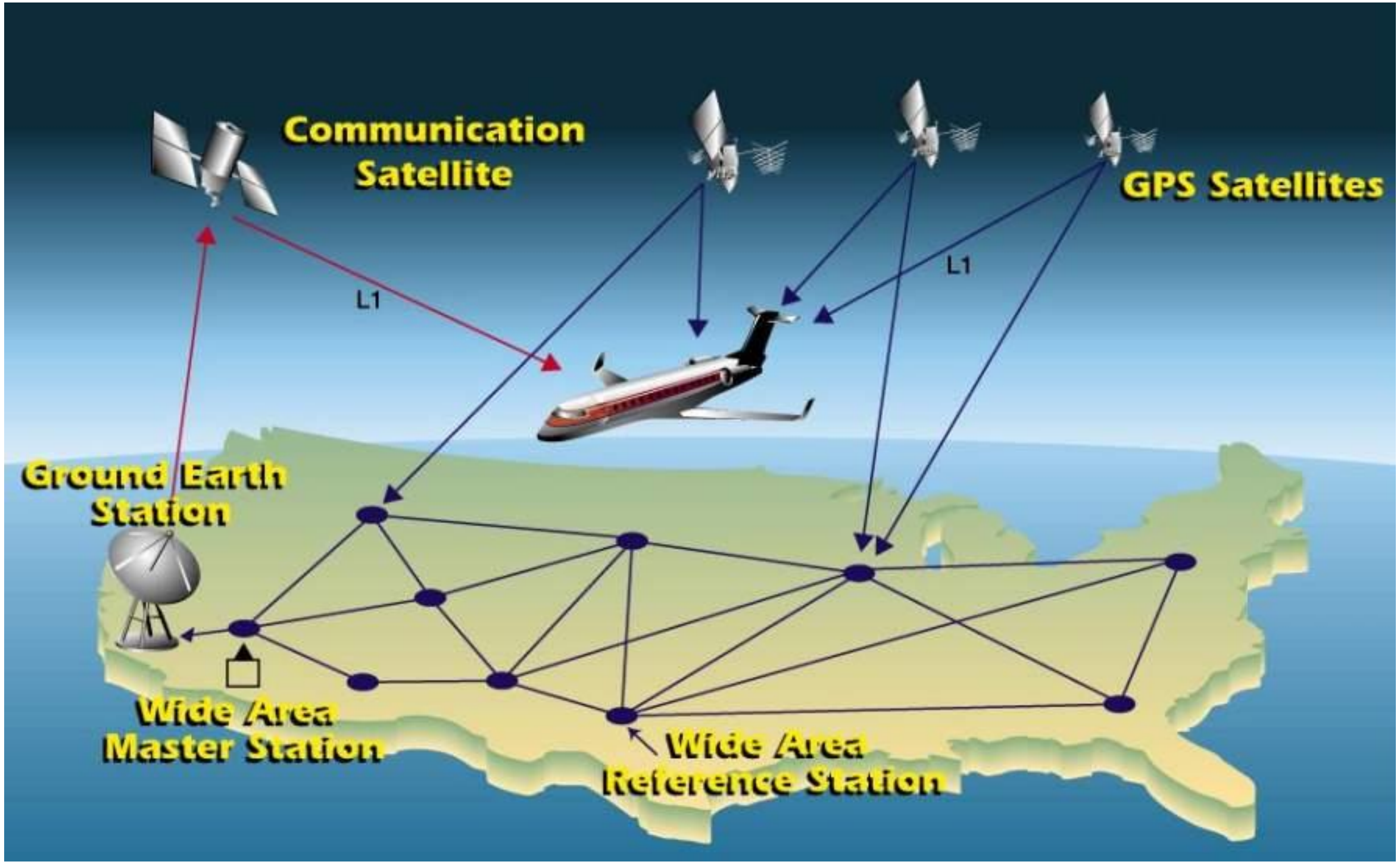
Data Link not Required for Post-Mission Applications

Faster Rate of Corrections for Civil Applications

(If SA Effects on)



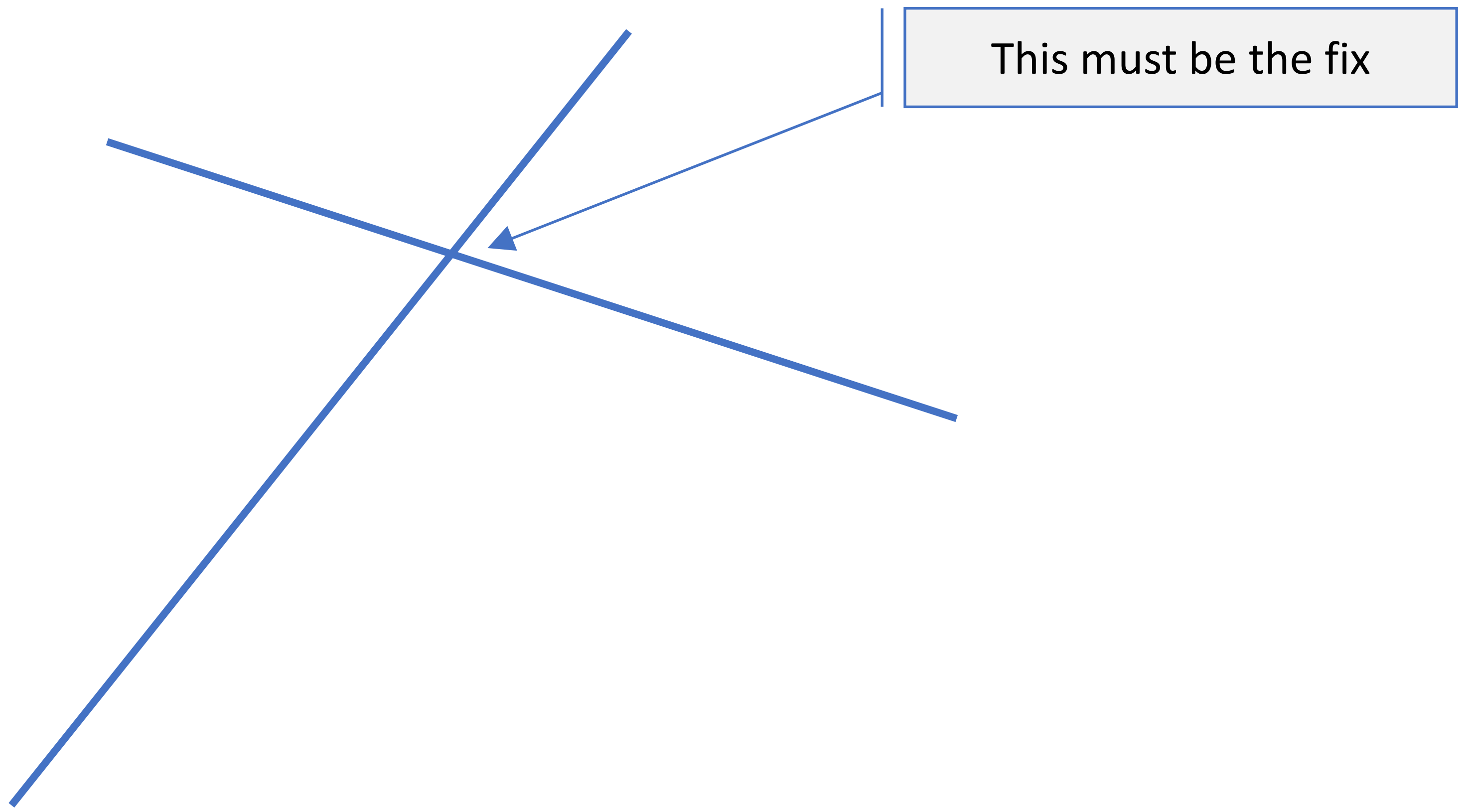
FAA’s Wide Area Augmentation System (WAAS)



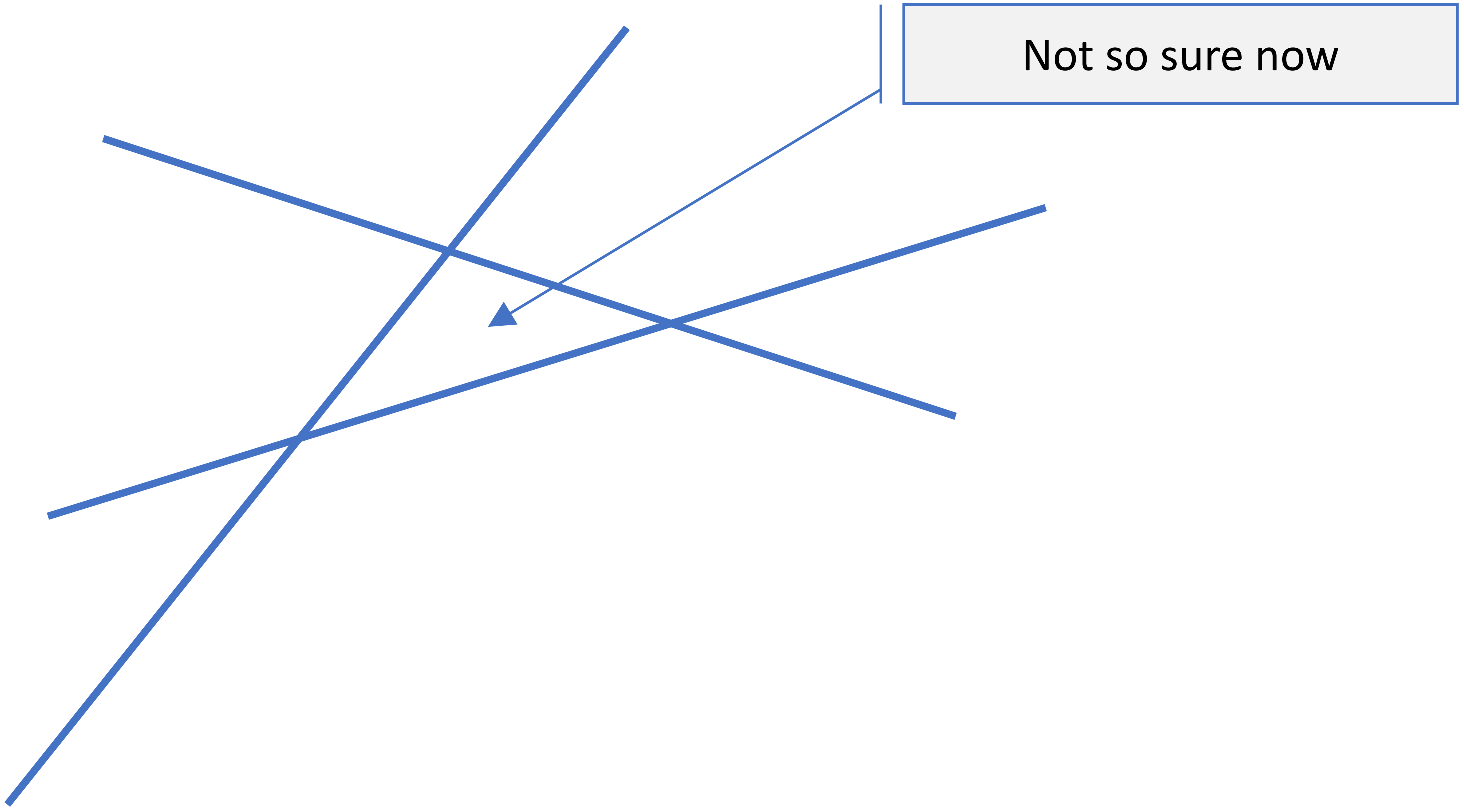
- Provides Differential Correction Data for Single Frequency Receivers
- Provides Integrity Data for All Satellites

RAIM - Receiver Autonomous Integrity Monitoring

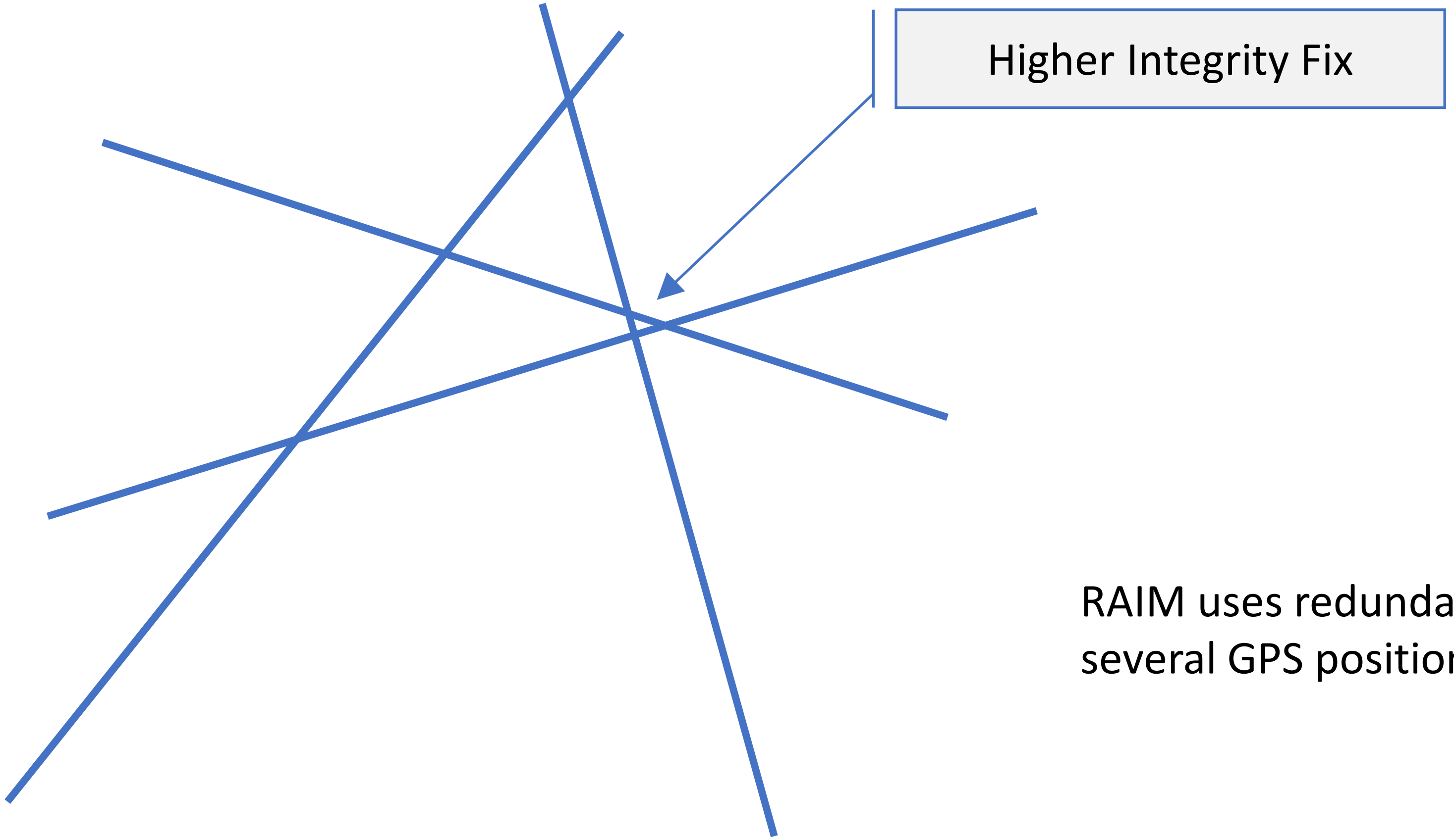
RAIM - Receiver Autonomous Integrity Monitoring



RAIM - Receiver Autonomous Integrity Monitoring



RAIM - Receiver Autonomous Integrity Monitoring



RAIM uses redundant signals to produce several GPS position fixes and compare them

Accuracy

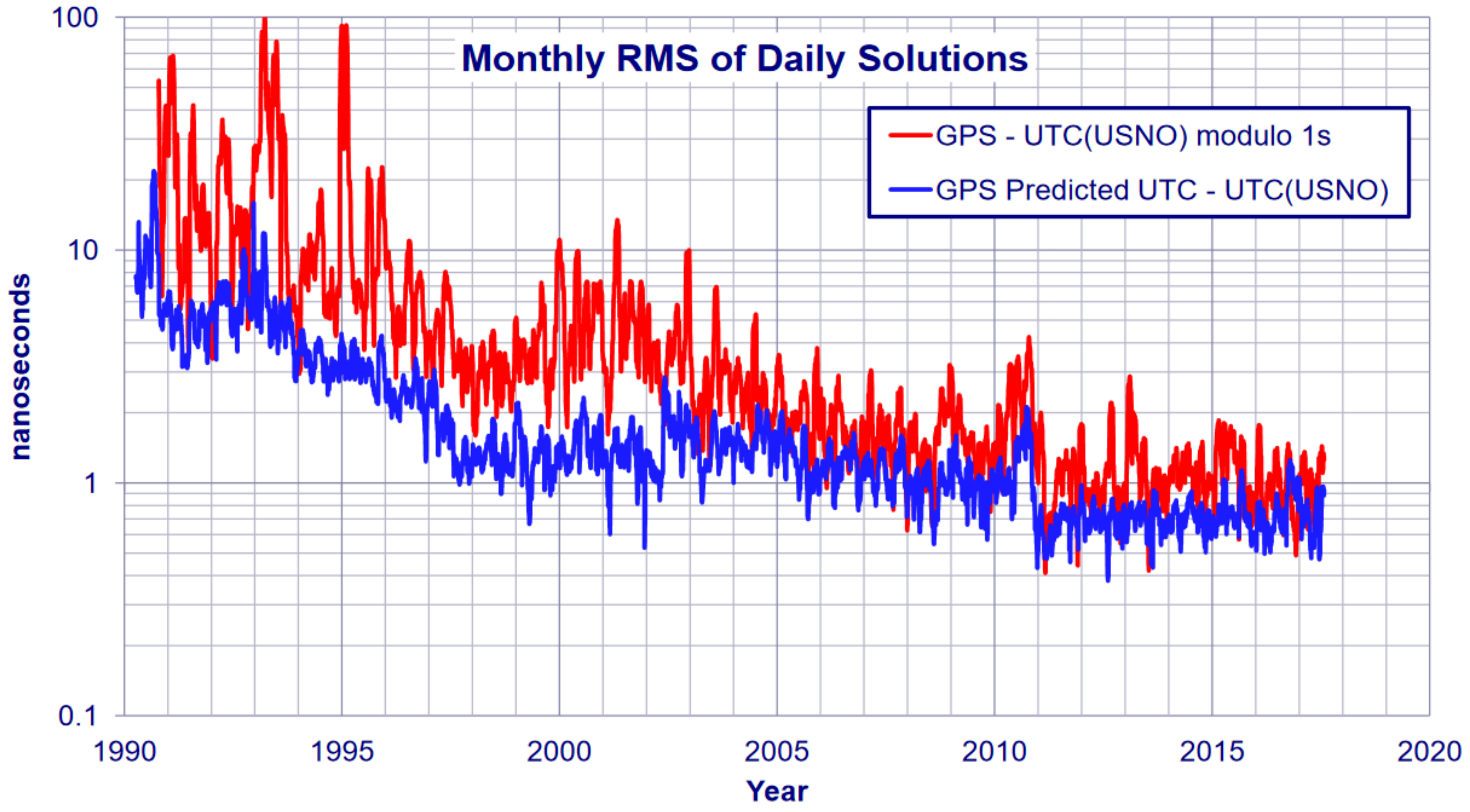
Very Important!

System	95% Accuracy (Lateral / Vertical)	Details
LORAN-C Specification	460 m / 460 m	The specified absolute accuracy of the LORAN-C system.
Distance Measuring Equipment (DME) Specification	185 m (Linear)	DME is a radionavigation aid that can calculate the linear distance from an aircraft to ground equipment.
GPS Specification	100 m / 150 m	The specified accuracy of the GPS system with the Selective Availability (SA) option turned on. SA was employed by the U.S. Government until May 1, 2000.
LORAN-C Measured Repeatability	50 m / 50 m	The U.S. Coast Guard reports "return to position" accuracies of 50 meters in time difference mode.
Differential GPS (DGPS)	10 m / 10 m	This is the Differential GPS (DGPS) worst-case accuracy. According to the 2001 Federal Radionavigation Systems (FRS) report published jointly by the U.S. DOT and Department of Defense (DoD), accuracy degrades with distance from the facility; it can be < 1 m but will normally be < 10 m.
Wide Area Augmentation System (WAAS) Specification	7.6 m / 7.6 m	The worst-case accuracy that the WAAS must provide to be used in precision approaches.
GPS Measured	2.5 m / 4.7 m	The actual measured accuracy of the system (excluding receiver errors), with SA turned off, based on the findings of the FAA's National Satellite Test Bed, or NSTB.
WAAS Measured	0.9 m / 1.3 m	The actual measured accuracy of the system (excluding receiver errors), based on the NSTB's findings.

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

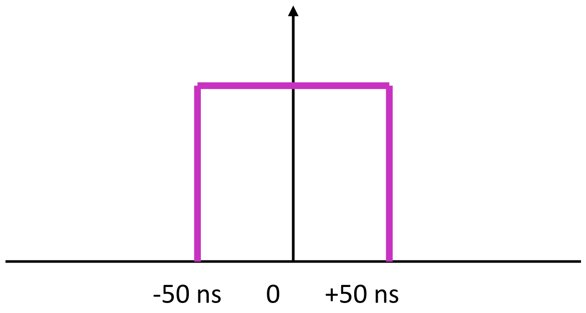
GPS Time Stability



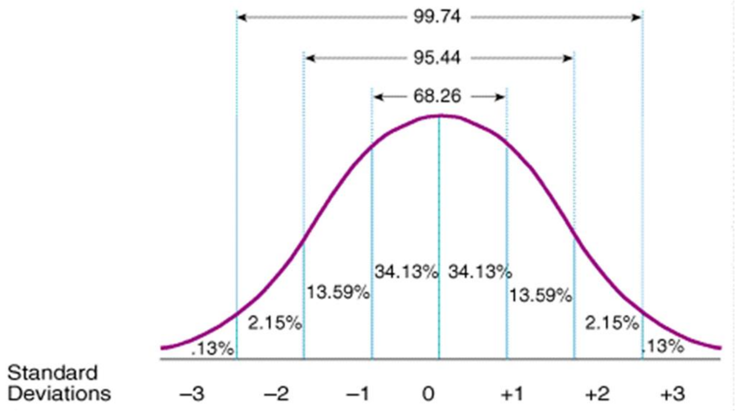
GPS as a Time Source

- 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

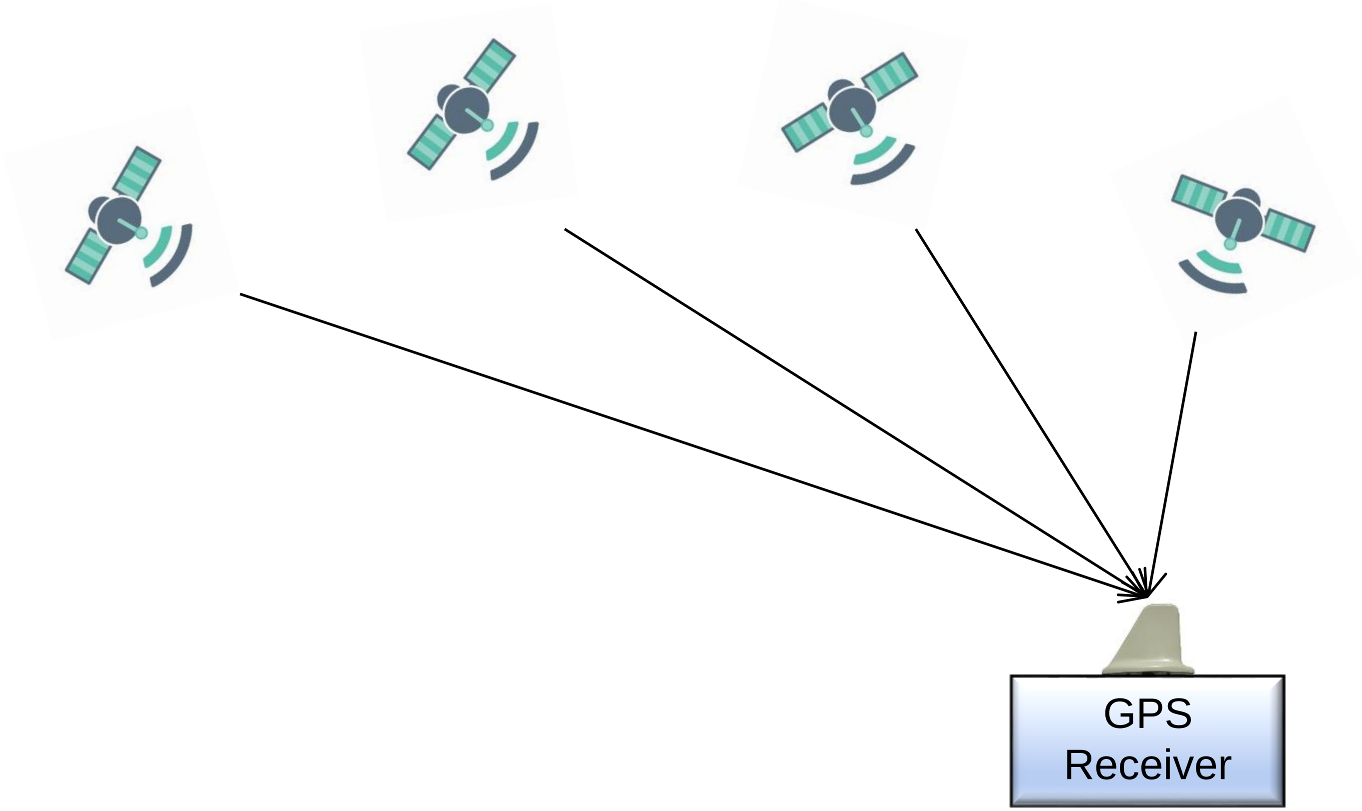
Meinberg

Pulse outputs	Pulse Per Second (PPS) via BNC connector (T
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

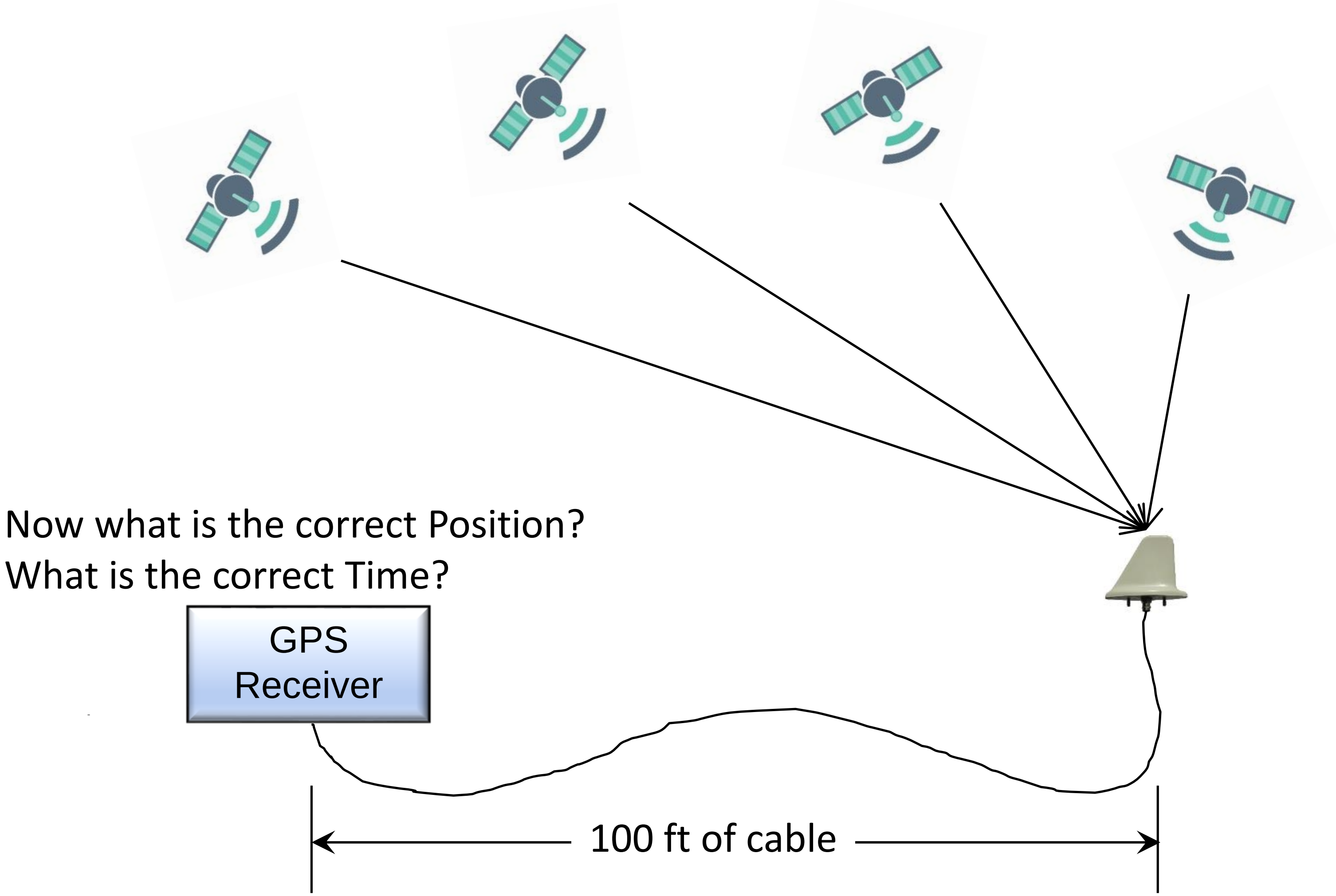
Currently, GPS can be used to obtain an estimate of the UTC(USNO MC) clock. If the time output of a good multi-channel Clear Access (C/A) code GPS receiver is averaged for one day against a sufficiently stable local clock, such as a cesium standard, the resulting estimate of UTC(USNO MC) will be within 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

The GPS Antenna Cable Problem



Accurate Position and Time

The GPS Antenna Cable Problem



ADS-B

ADS-B - Automatic Dependent Surveillance-Broadcast
Replaces FAA primary radar
Required after 1 Jan 2020

ADS-B requirements spelled out in FAA AC 20-165A
Permits TSO C129, C196, C145, and C146 based GPS receivers

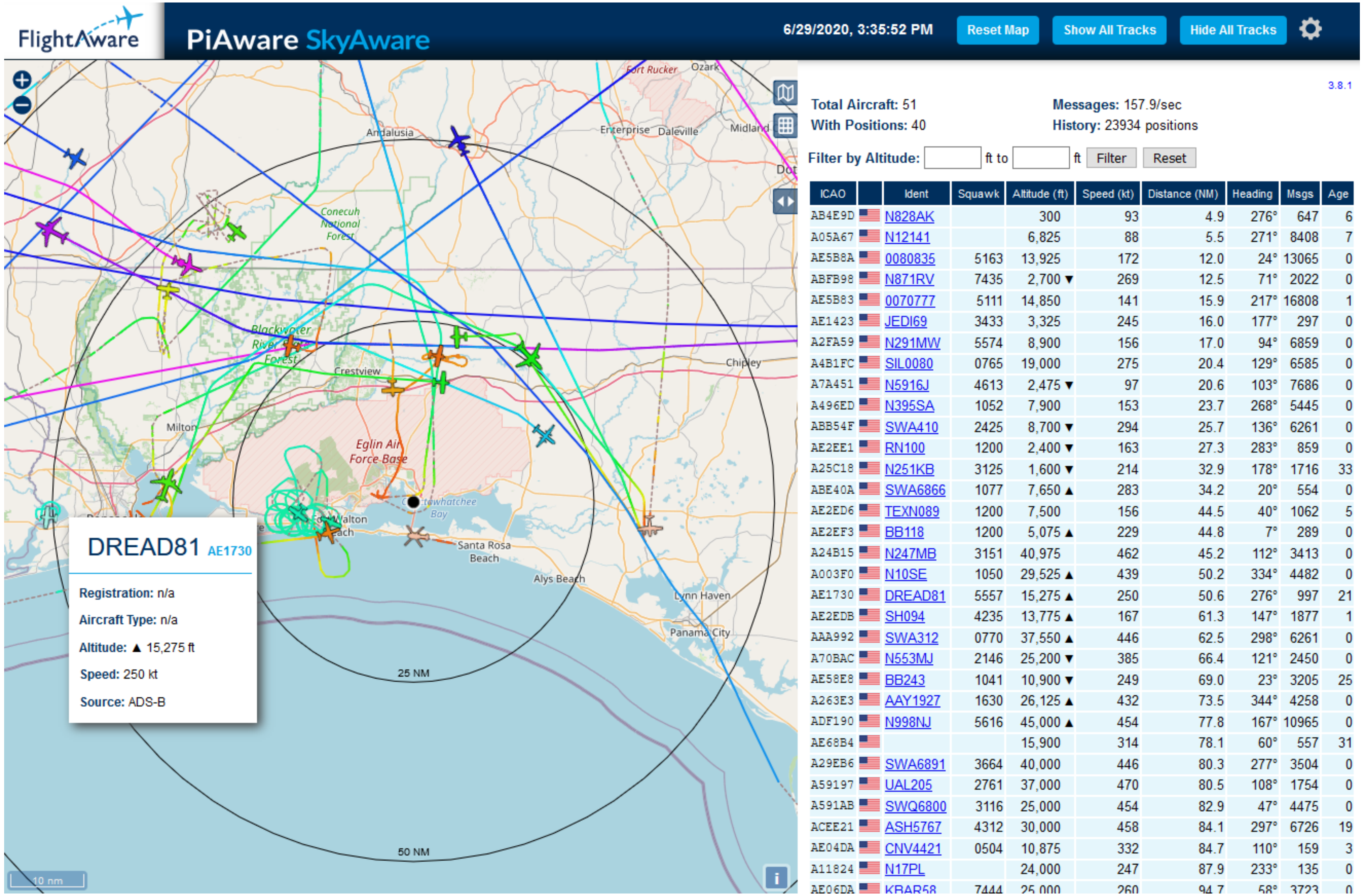
WAAS is not a technical requirement, but as a practical matter, the position source requirements are stringent enough that most non WAAS position sources are not adequate to meet the FAA requirements.

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



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

GPS NMEA Data Formats

- NMEA - National Marine Electronics Association
- Standard for serial data format for maritime applications
- De Facto standard for serial data format for airborne applications
- NMEA defines “sentences”
  - Identified by leading 5 character tag
  - Each has different data fields

Example

$GPGGA,181908.00,3404.7041778,N,07044.3966270,W,4,13,1.00,495.144,M,29.200,M,0.10,0000*40

All NMEA messages start with the $ character, and each data field is separated by a comma
GP represent that it is a GPS position (GL would denote GLONASS)
181908.00 is the time stamp: UTC time in hours, minutes and seconds
3404.7041778 is the latitude in the DDMM.MMMMM format
N denotes north latitude
07044.3966270 is the longitude in the DDDMM.MMMMM format
W denotes west longitude
4 denotes the Quality Indicator
13 denotes number of satellites used in the coordinate
1.0 denotes the HDOP (horizontal dilution of precision)
495.144 denotes altitude of the antenna
M denotes units of altitude (eg. Meters or Feet)
29.200 denotes the geoidal separation (to calculate Height Above Ellipsoid)
M denotes the units used by the geoidal separation.
1.0 denotes the age of the correction (if any)
0000 denotes the correction station ID (if any)
***40** denotes the checksum

GPS NMEA Data Formats

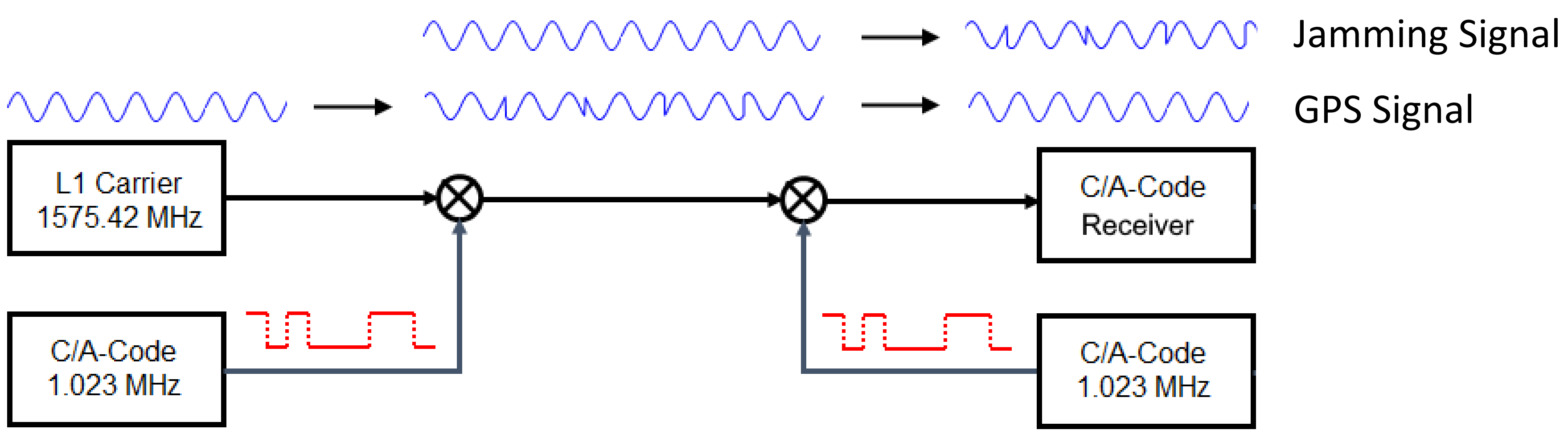
- NMEA "sentences"
  - $GPGGA – Latitude / Longitude / Altitude
  - $GPGLL – Latitude / Longitude (Higher Precision)
  - $GPRMC – Navigation (Track / Speed)
  - $GPGSA – Detailed GPS DOP and detailed satellite tracking information
  - $GPGSV – Detailed GPS satellite information such as azimuth and elevation of each satellite being tracked
  - $GPVTG – Speed over ground and tracking offset
  - $GPGST – Estimated horizontal and vertical precision
- Often multiple sentences required for a complete set of data

Jamming

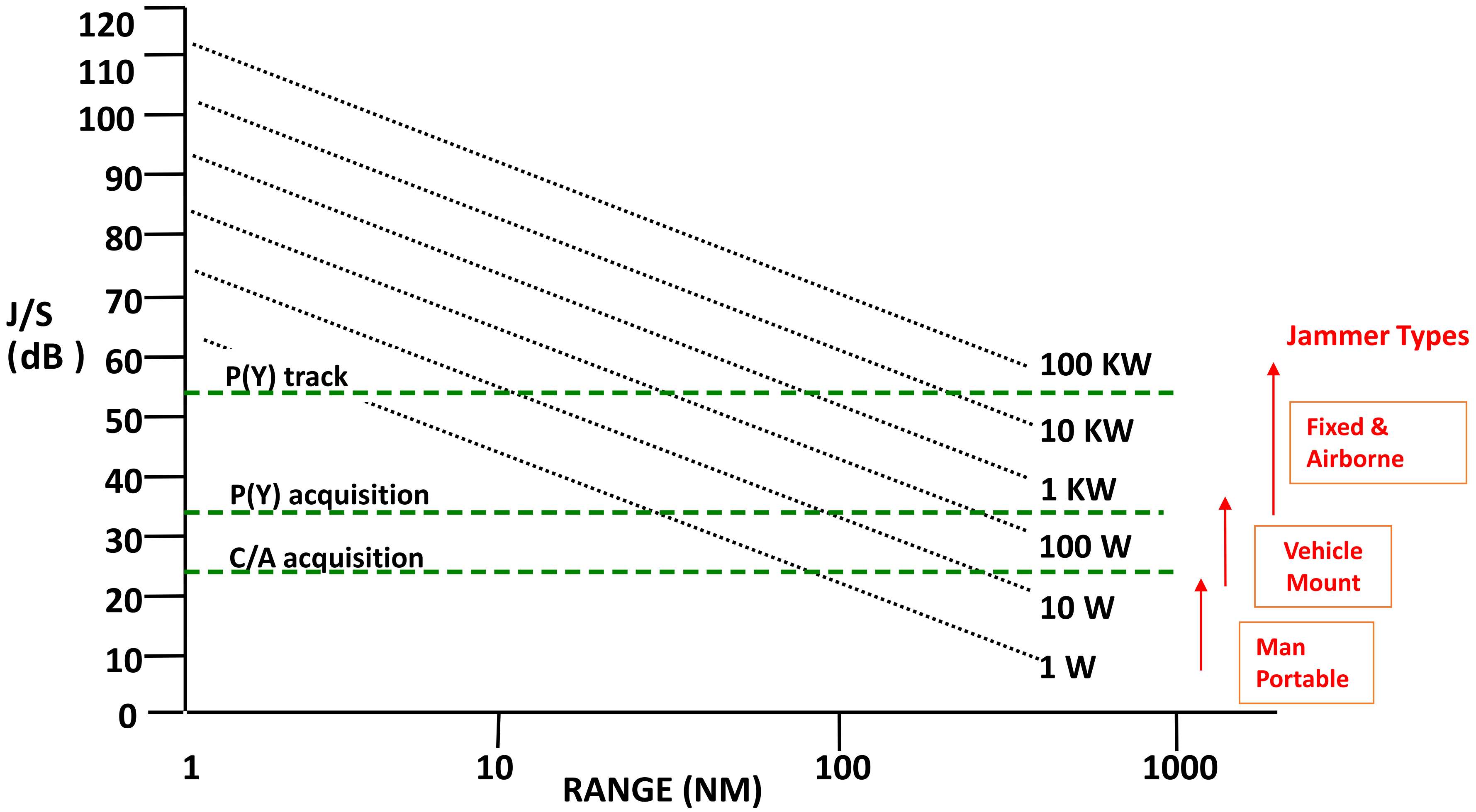
- GPS benefits greatly from DSSS against interfering sources
  - Narrow band jamming
  - Unintentional sources
  - Multipath
- But GPS is a low power signal
  - Little power margin

- Cryptographically secure Y-Code protects against spoofing

Satellite Signal Modulation with Jamming

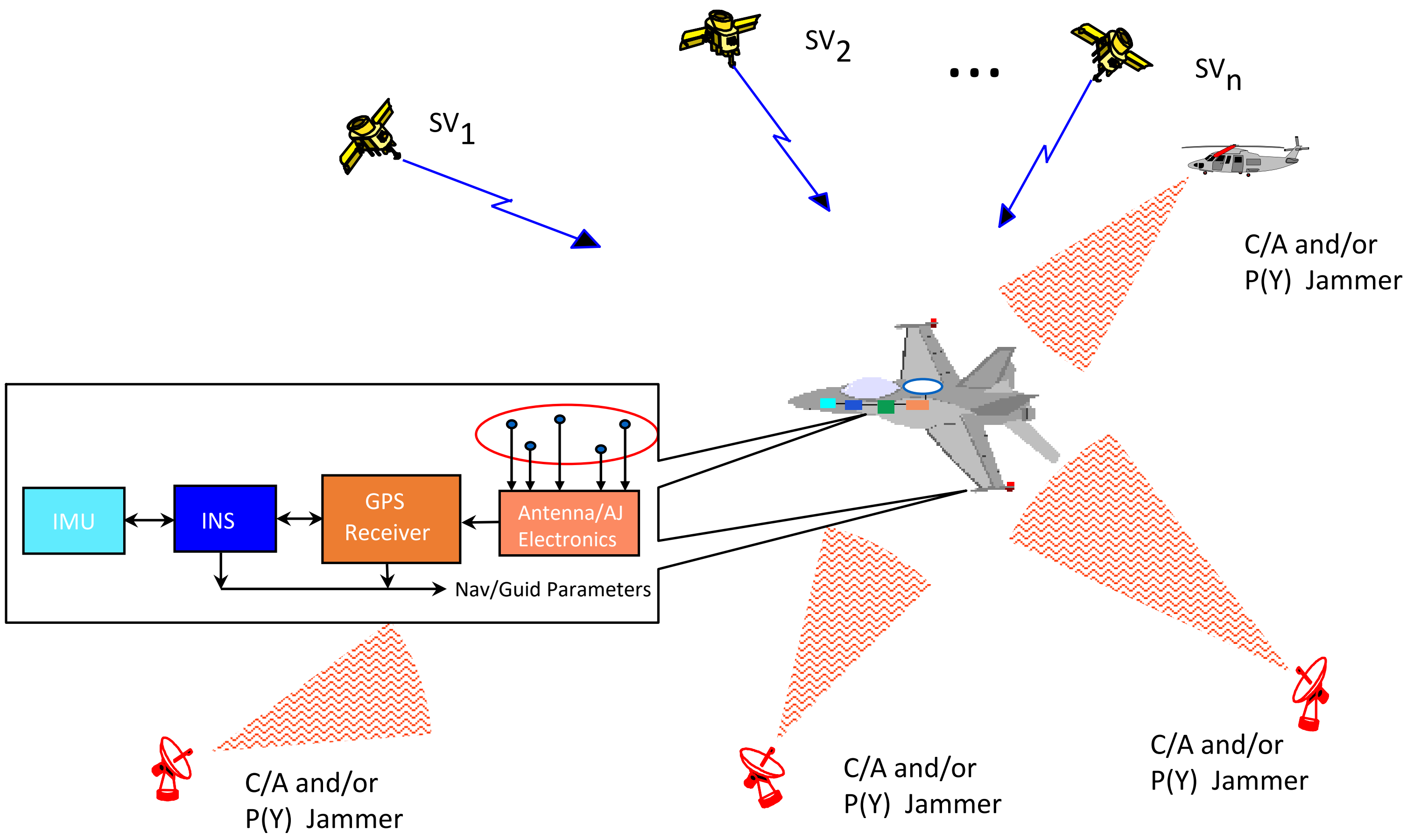


The GPS Jamming Problem



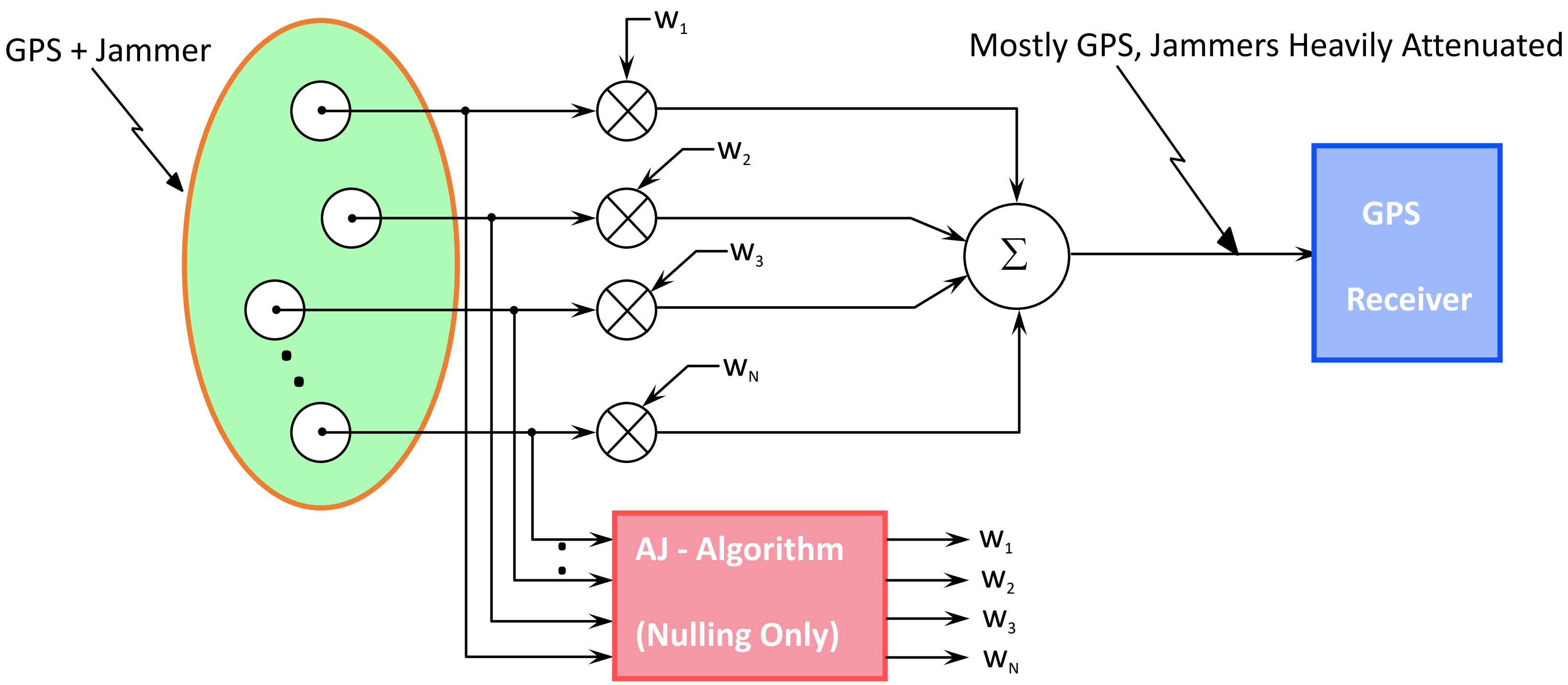
Even the Lowest Power Jammers Deny GPS Acquisition & Track

Aircraft/Weapon in a Conceptual Jamming Scenario



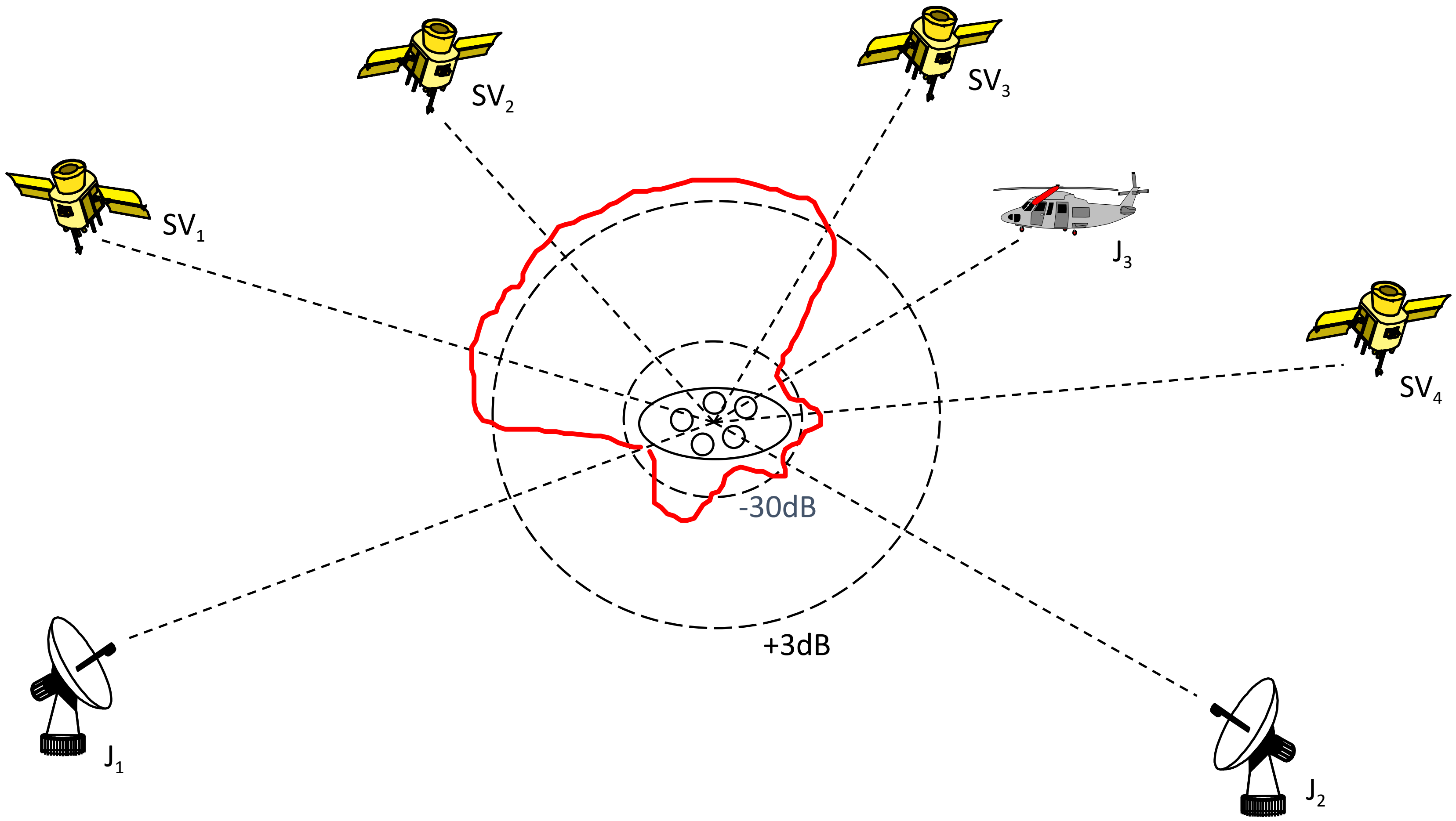
- **C/A - Spoofing/Jamming $\Rightarrow$ Direct-Y Requirement for Weapon**
- **Aircraft and Weapon Anti-Jam Level Depends on Scenario, Mission, etc.**

“Nulling” Algorithm Concept



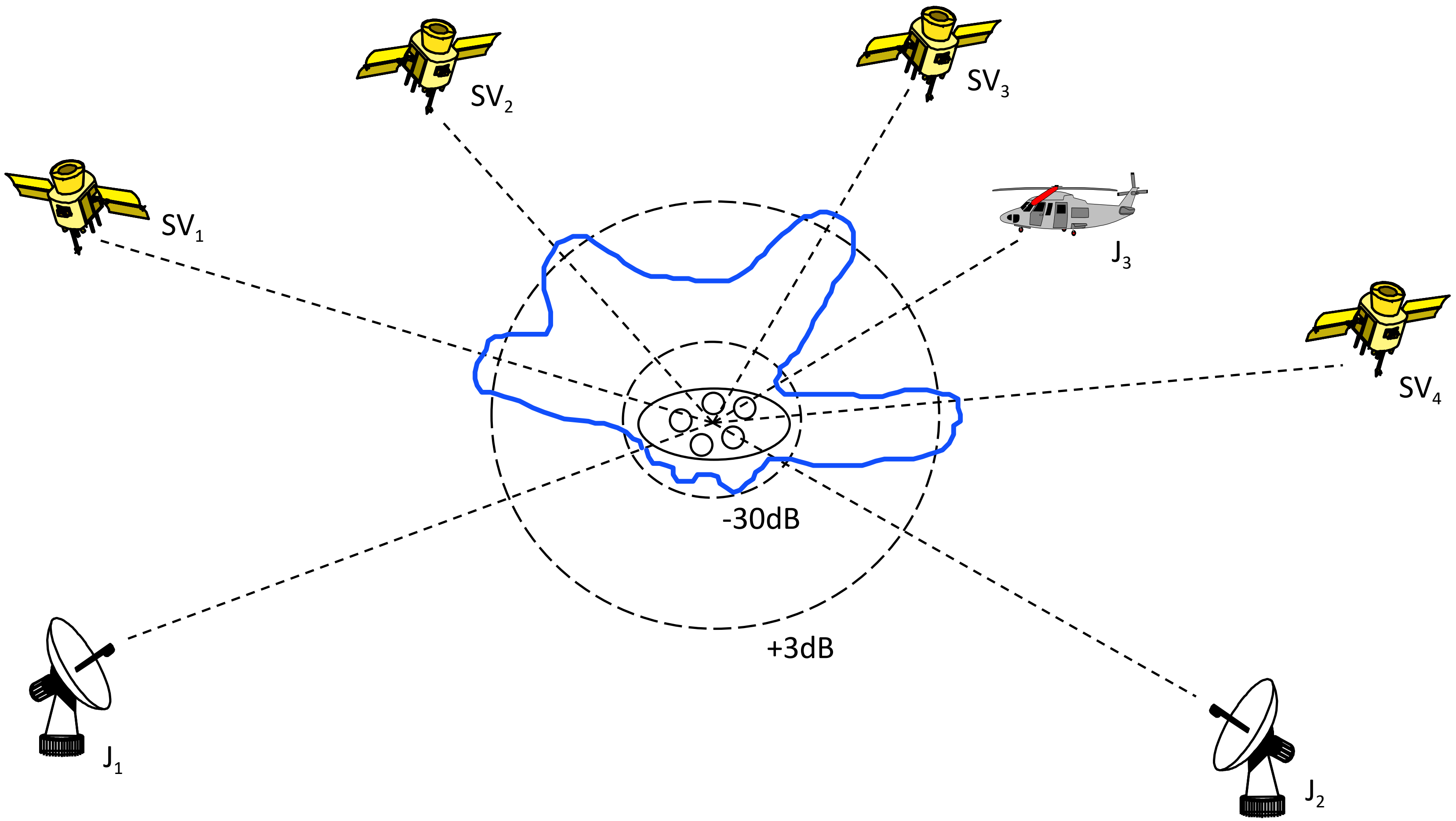
- Only one set of Antenna Weights w_1, w_2, w_3, • • w_N is Adaptively Determined that Minimizes Jammer Power by Minimizing Gains in the Direction of Jammers
- The “Nulling - Only” Algorithm may cause inadvertent Nulling of some Satellite Signals (All-In-View Receivers can Mitigate this Effect)

“Nulling - Only” Antenna Pattern Concept



- All Jammers are Effectively Nulled due to Low Gain in their Directions
- SV_4 is Inadvertently Nulled

"Nulling and Beam - Forming" Antenna Pattern Concept



- All Jammers are Effectively Nulled due to Low Gain in their Directions
- Gain in Direction of all Satellites Maximized (Beams)