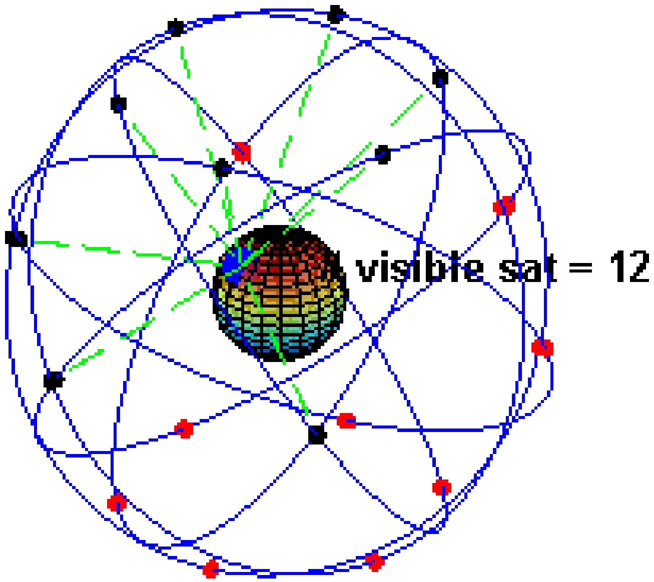
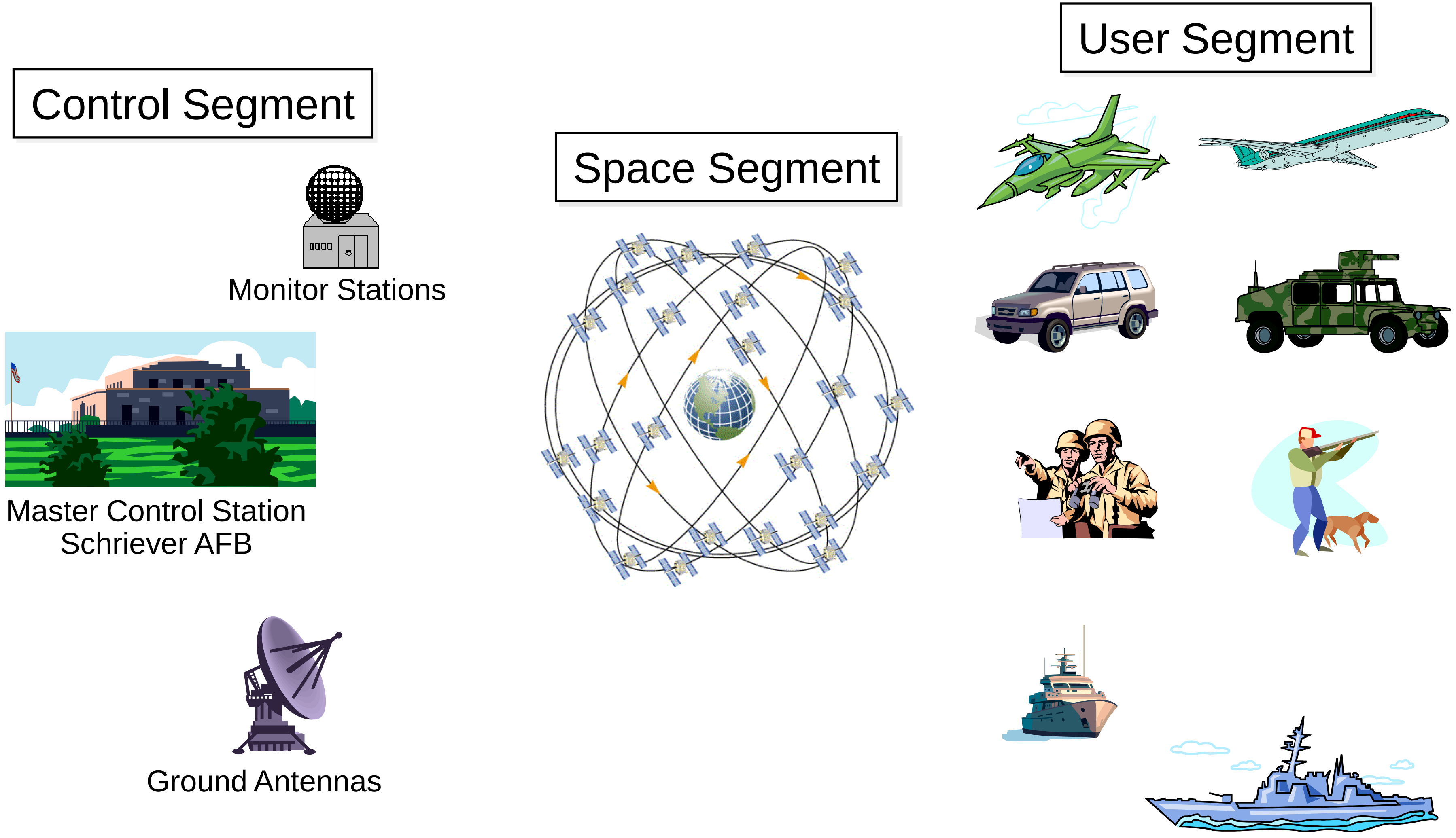
Fundamentals of GPS Operation



GPS Critical Technologies

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

GPS SYSTEM SEGMENTS



SPACE SEGMENT

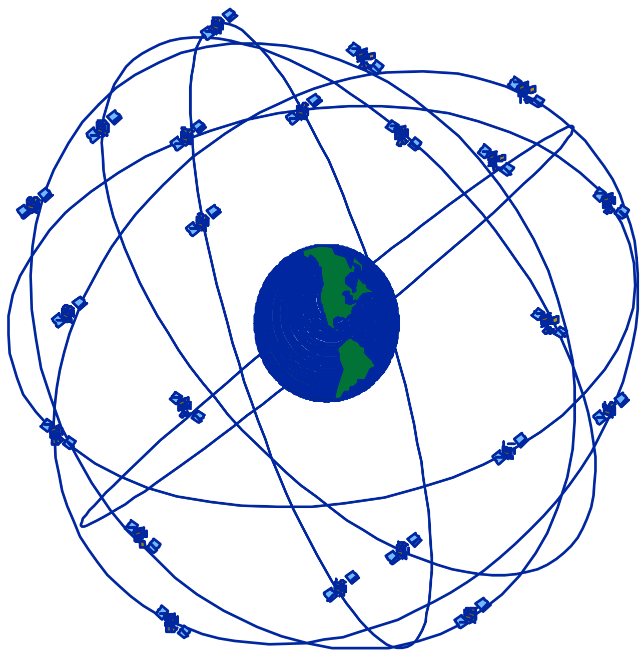
GPS Satellite Constellation

• 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)

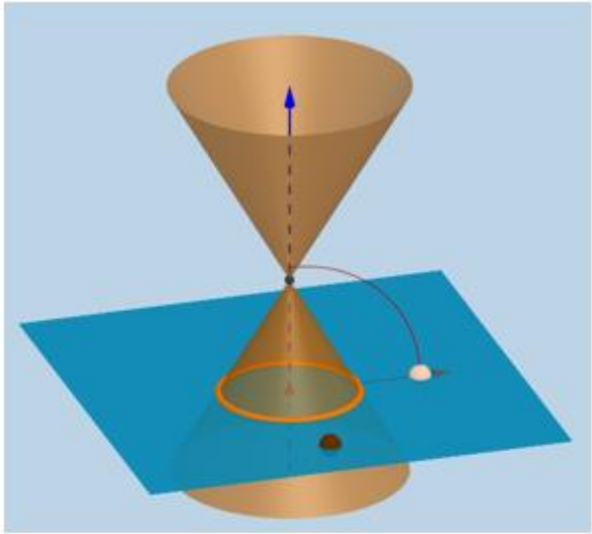
• Orbital Period: 11 hrs. 58 min.



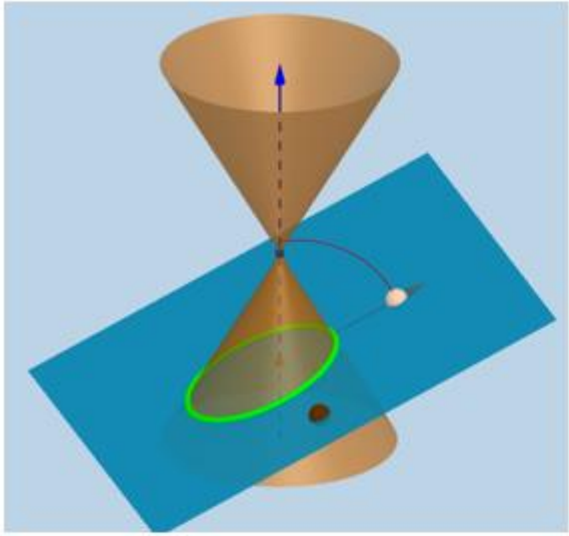
HOW DOES GPS WORK?

The Basics

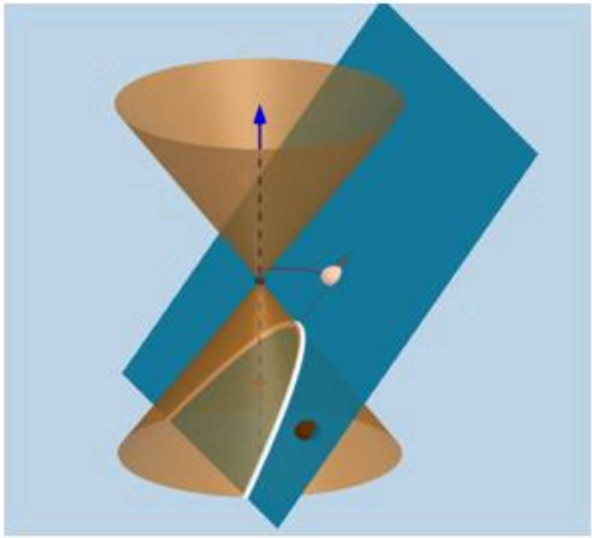
Conic Sections



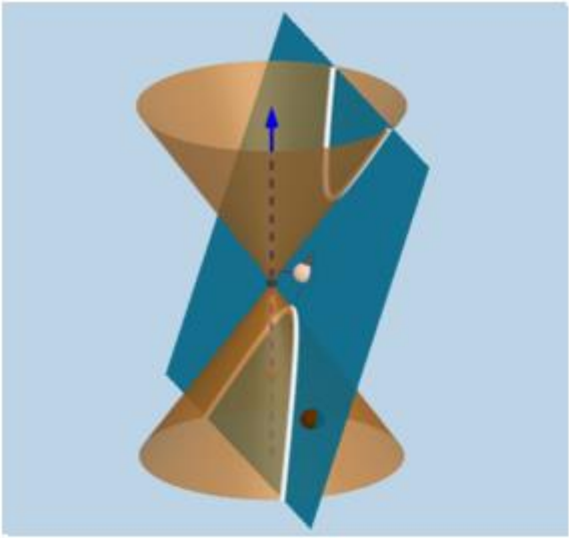
Circle



Ellipse

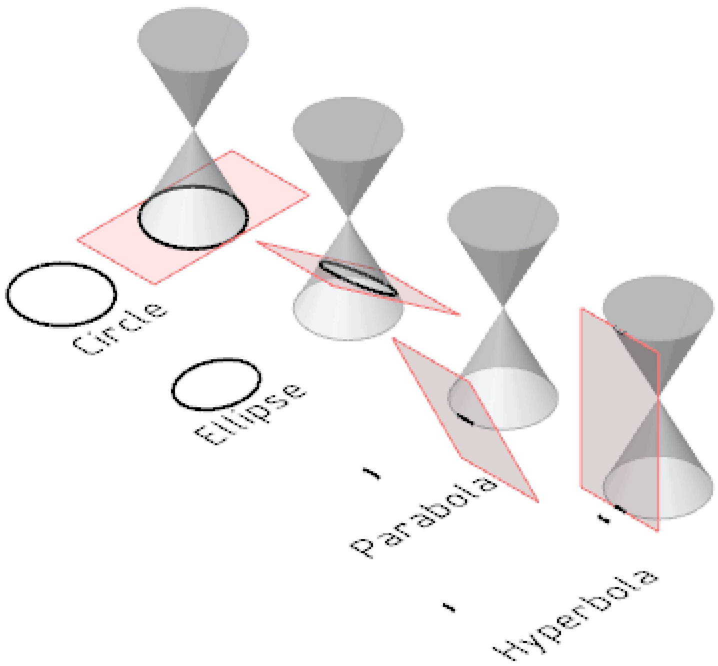


Parabola

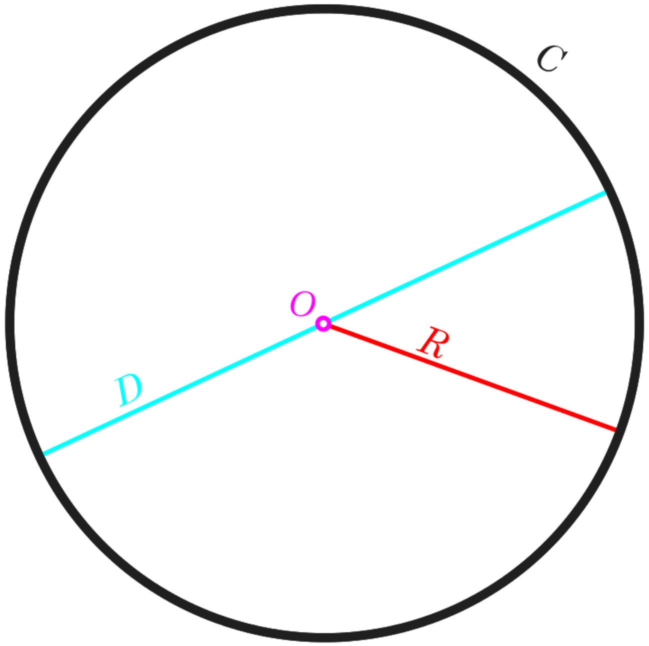


Hyperbola

Conic Sections

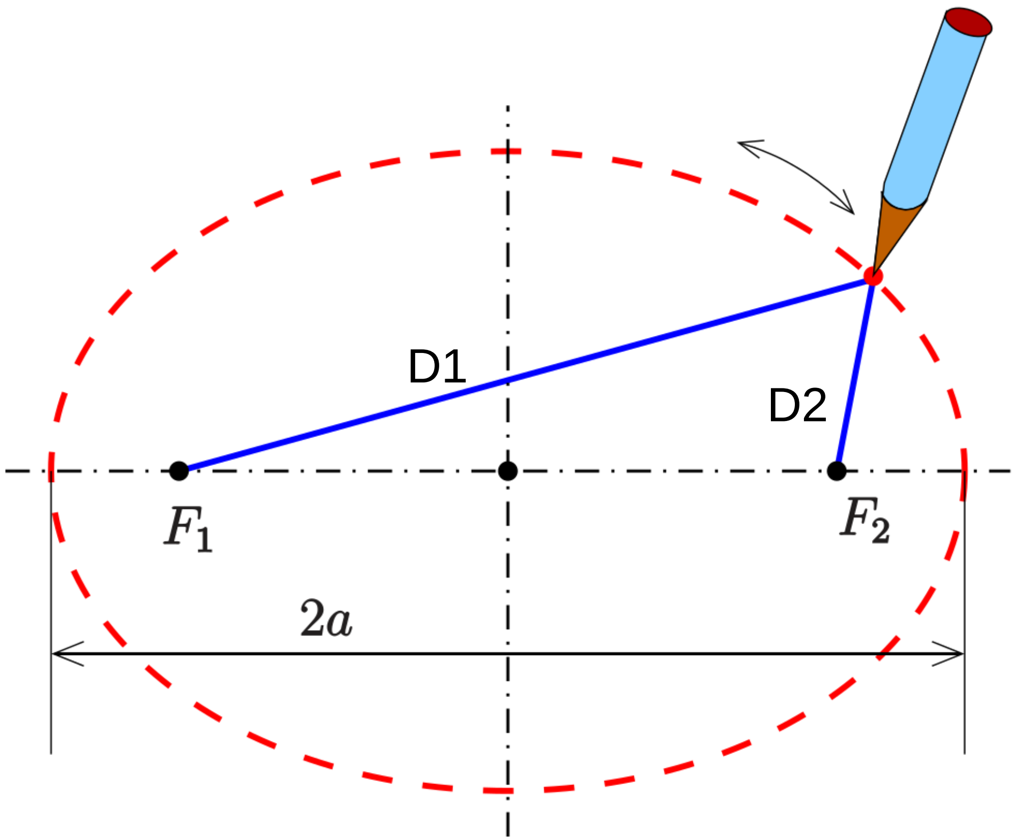


Properties of Conic Section
Circle



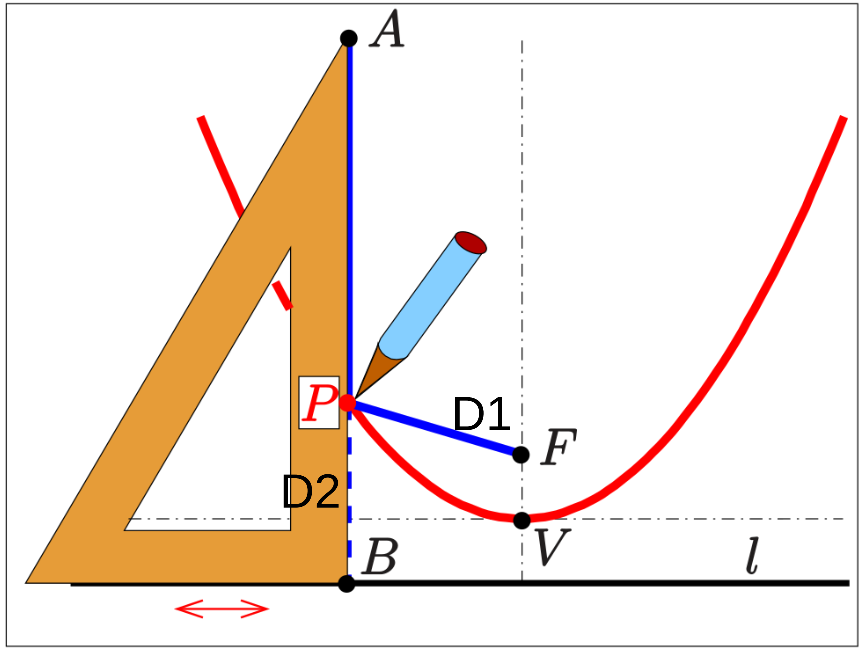
Distance R from Center (or Focus) is Constant

Properties of Conic Section
Ellipse

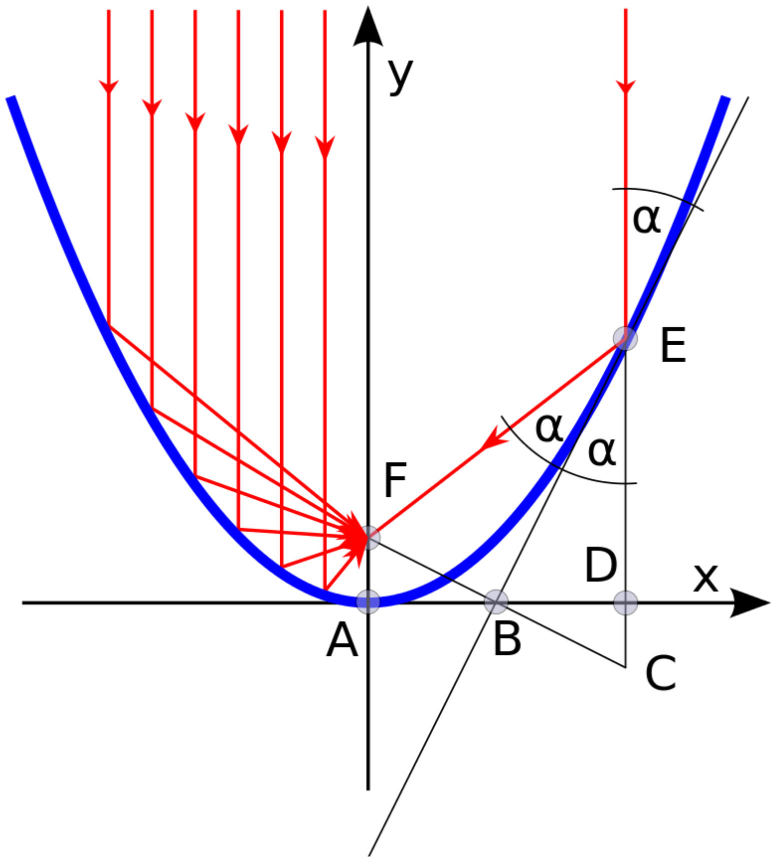


Distance D1 + D2 is a constant

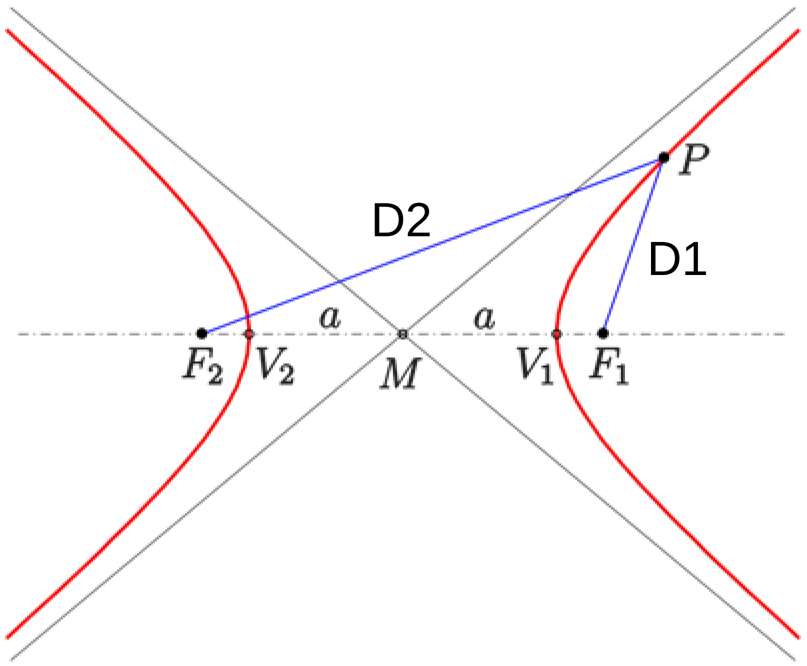
Properties of Conic Section
Parabola

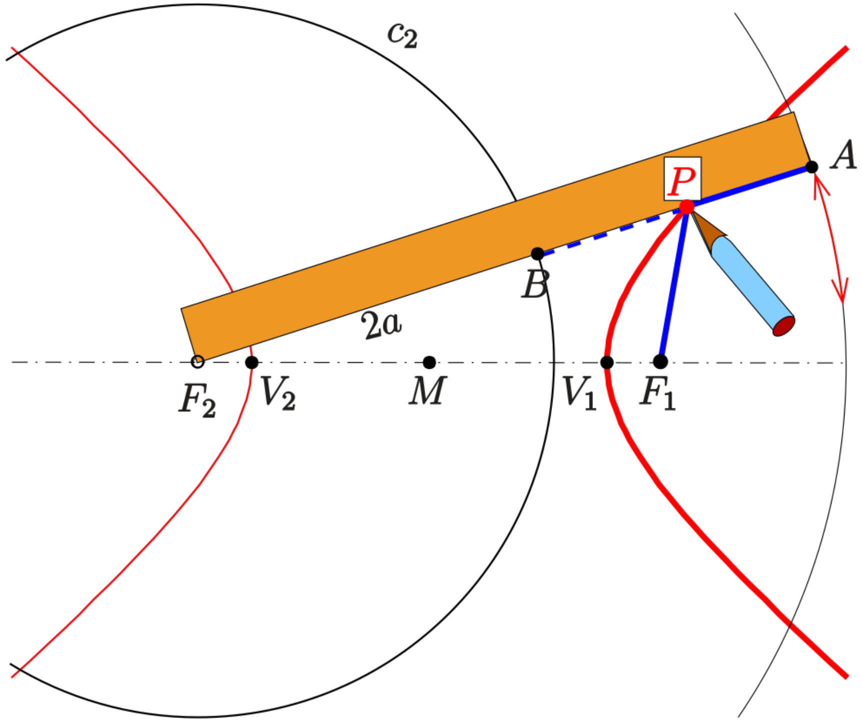


Distance D1 (FP) + D2 (PB) is a constant



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

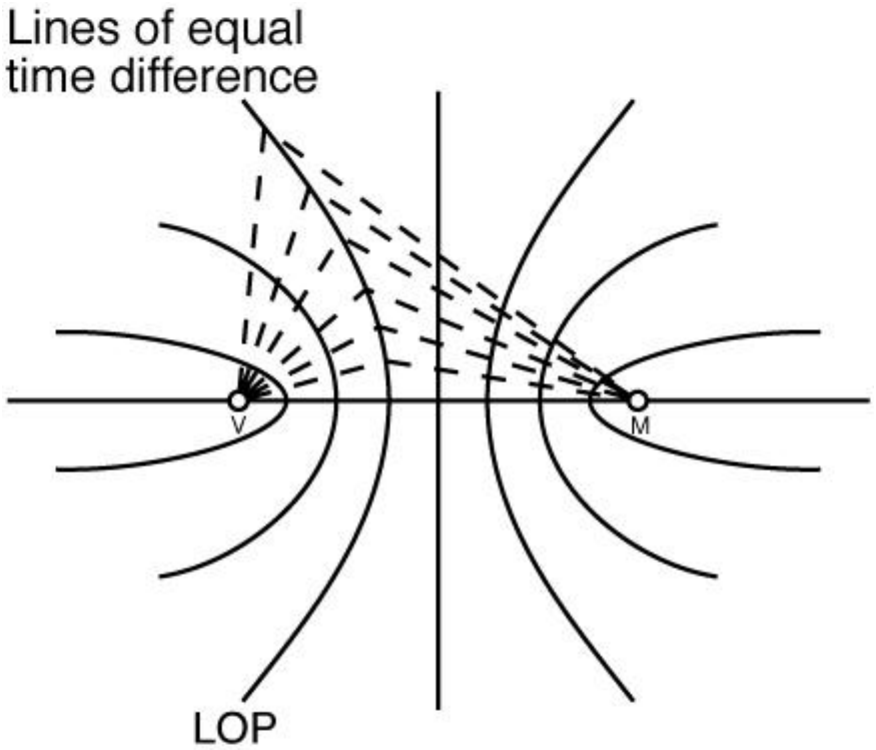
- Only Measure Time of Arrival
  - Determine Time Difference of Arrival
  - Calculate pseudo-ranges

- Transmit clocks are synchronized to each other

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

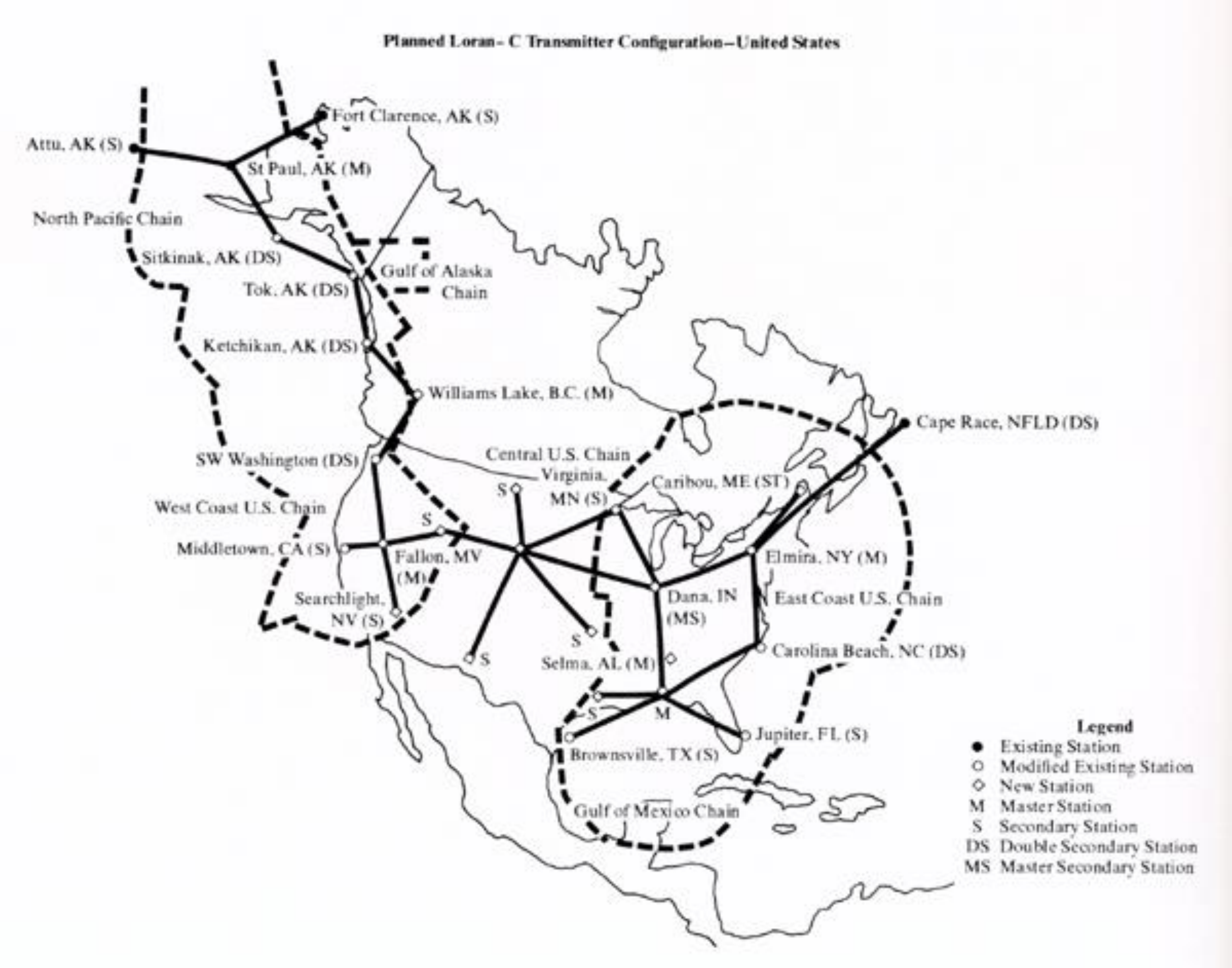
Time Difference of Arrival

Time Difference of Arrival

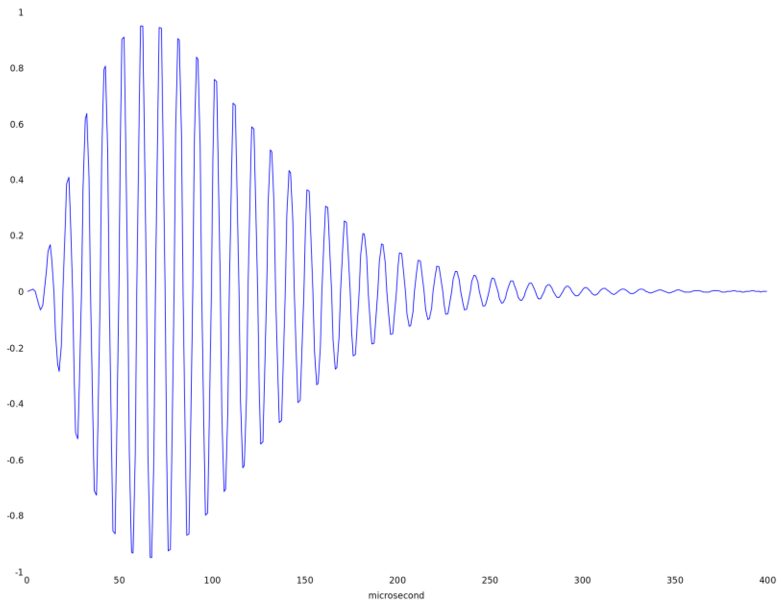


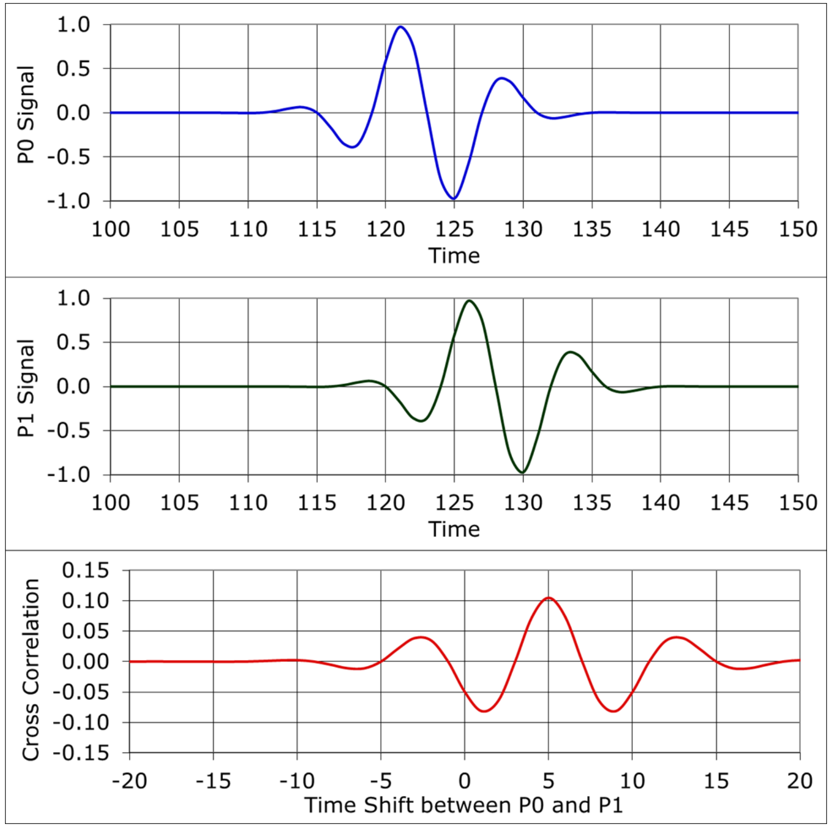
**hyperbolic
navigation system**

Time Difference of Arrival – Loran

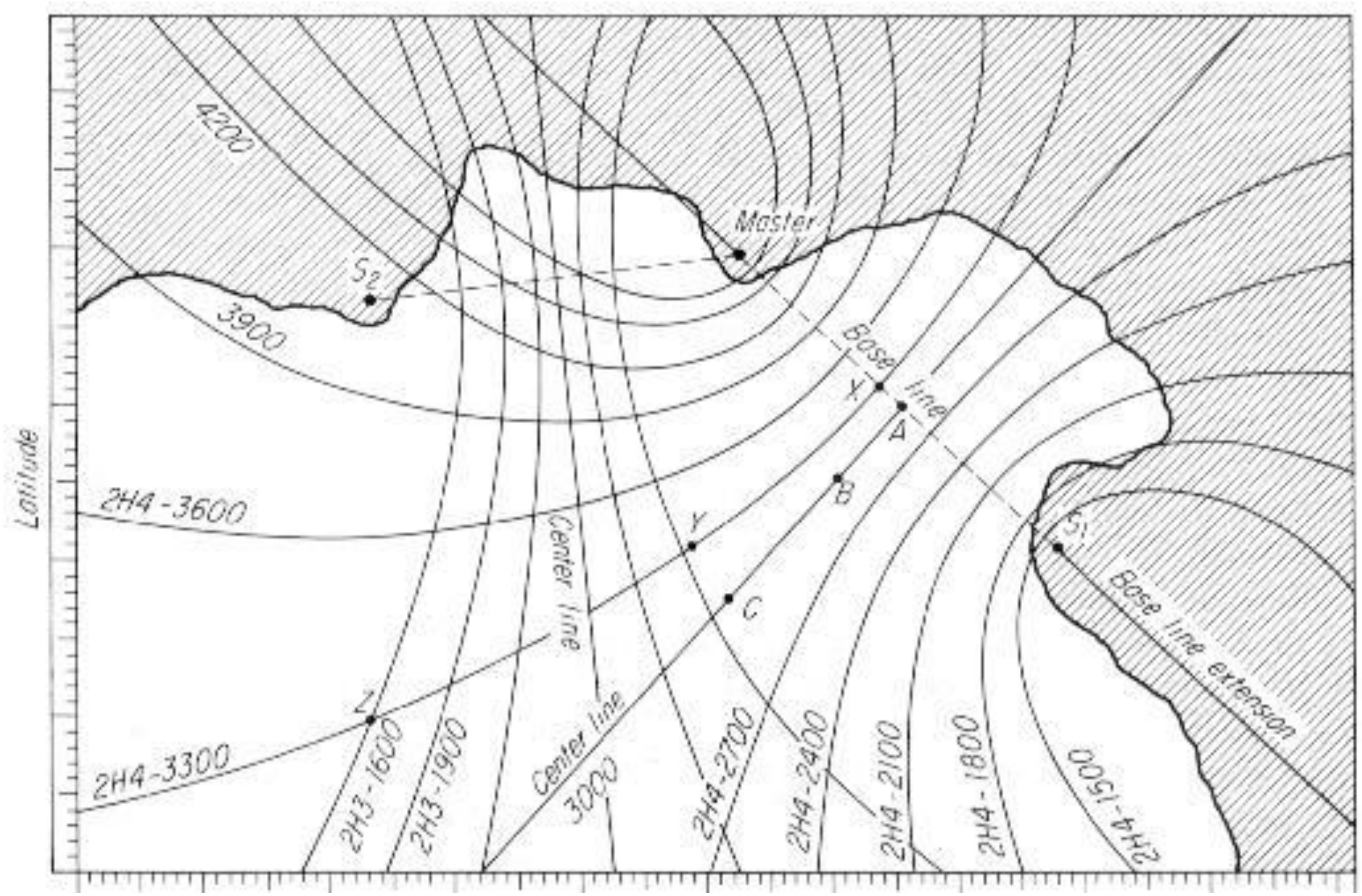


Time Difference of Arrival – Loran Pulses

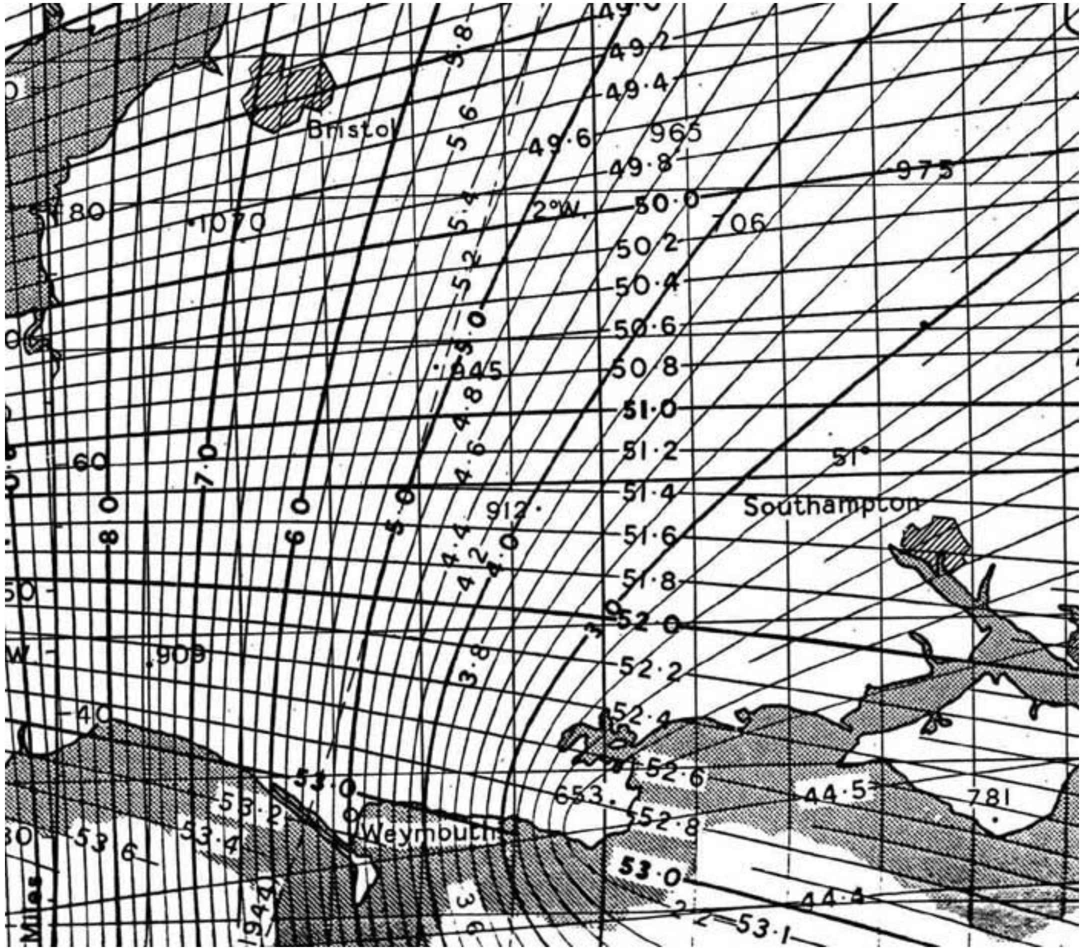


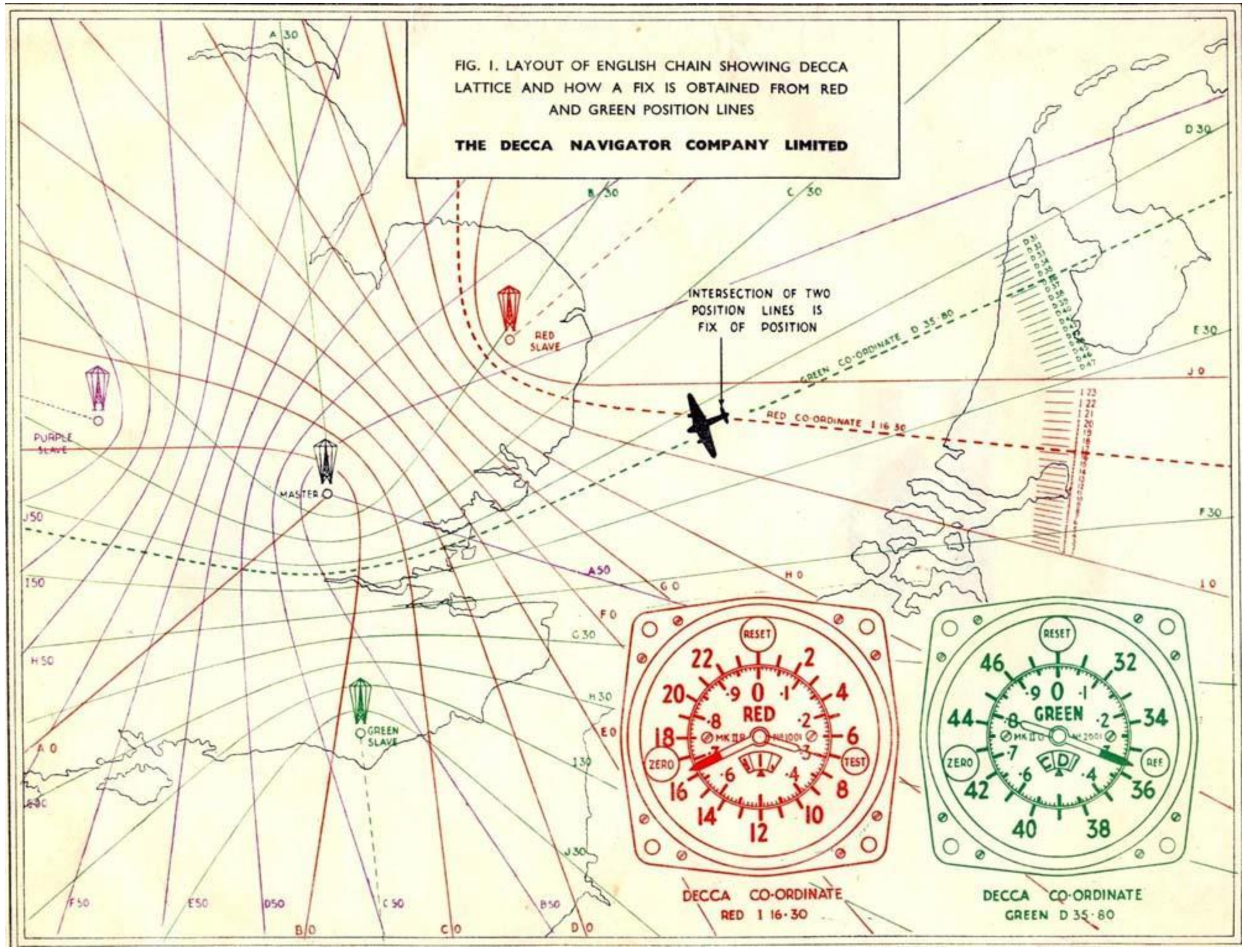


TDoA Navigation

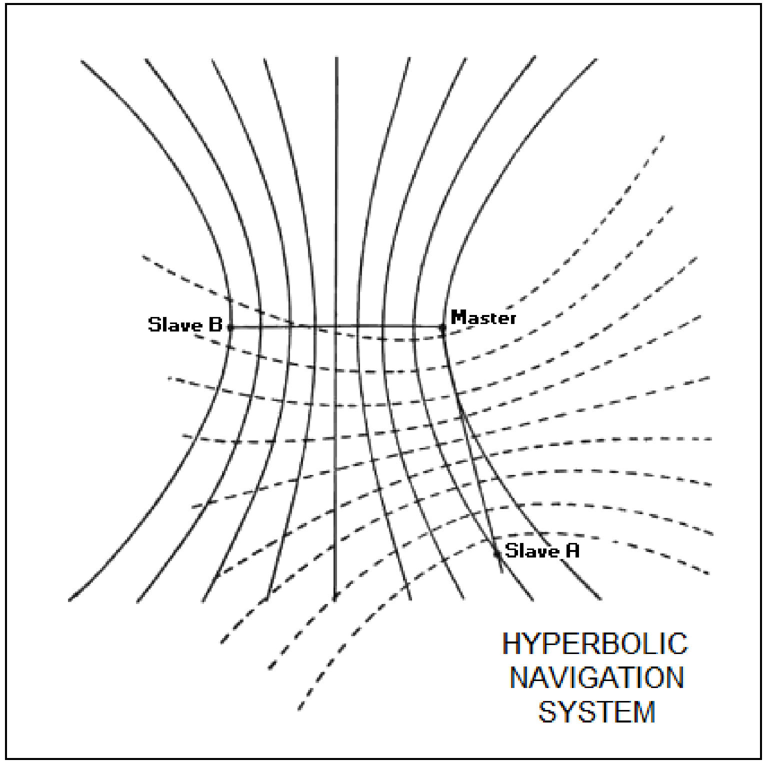


TDoA Navigation

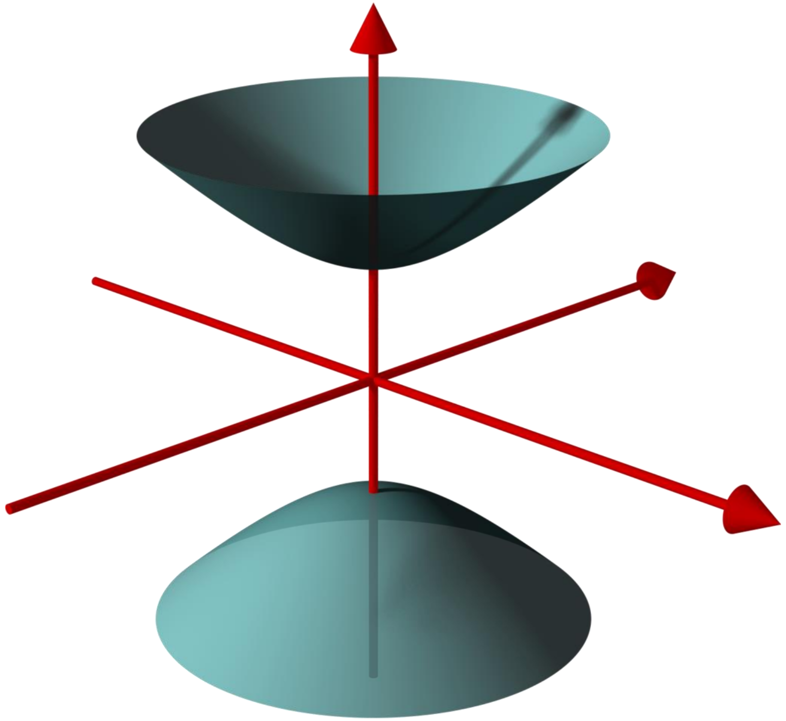




TDoA Navigation

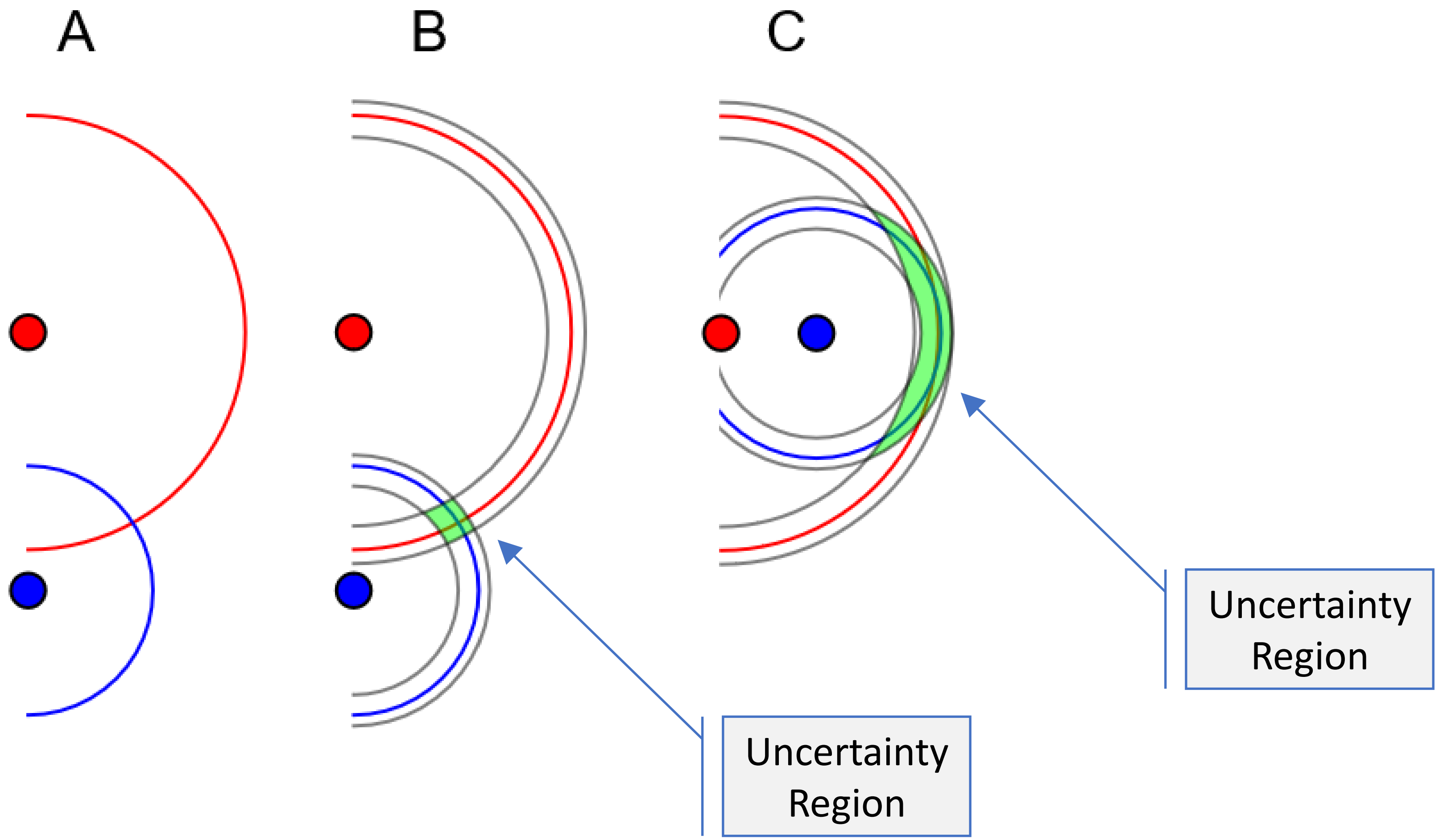


Simple 2D Earth surface case

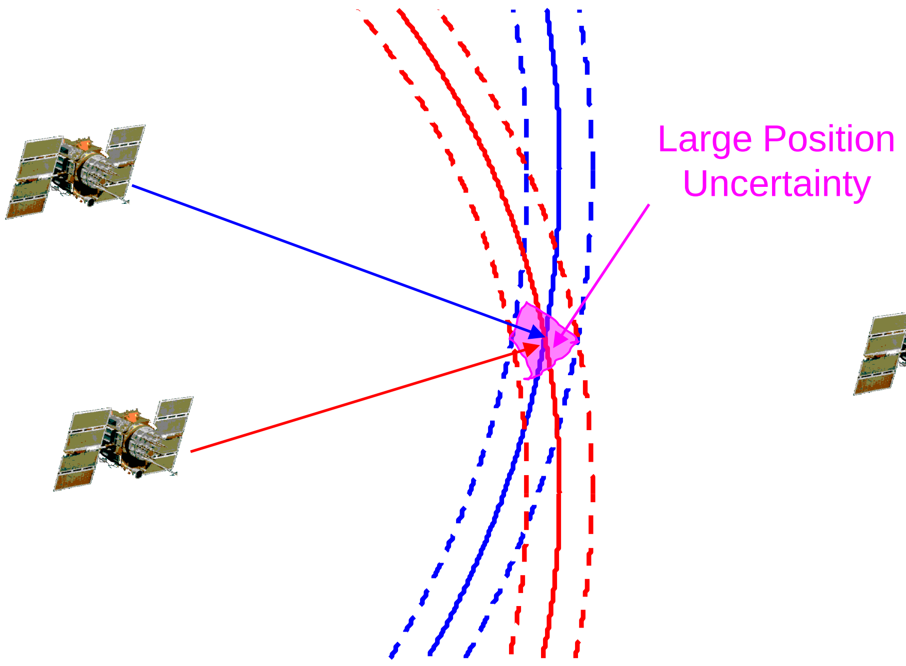


Much more complex general 3D case

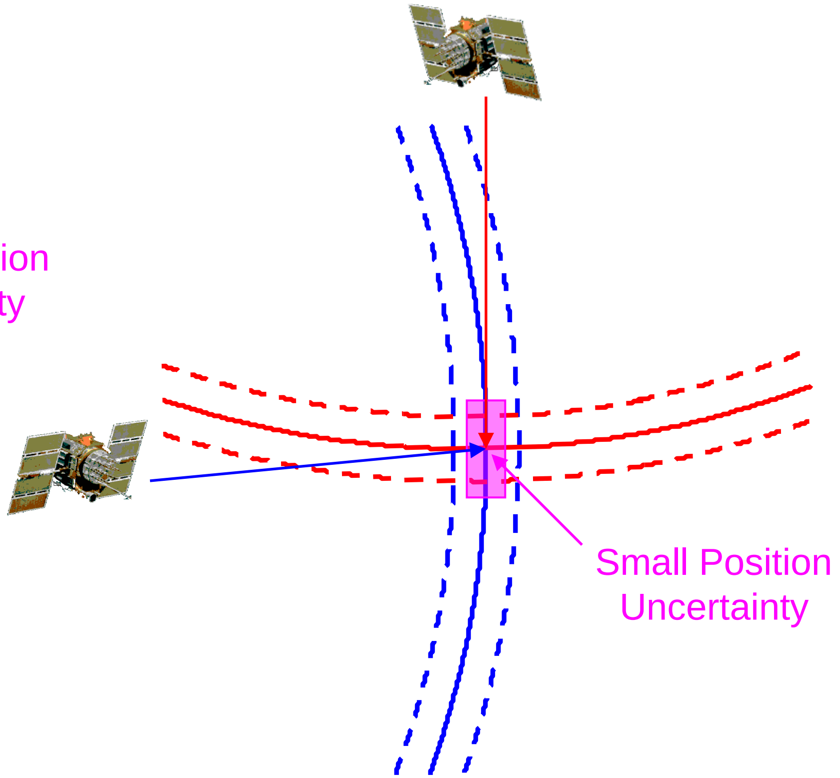
Dilution of Precision - xDOP



SATELLITE GEOMETRY



Poor Satellite Geometry
High DOP



Good Satellite Geometry
Low DOP

Dilution of Precision- DoP

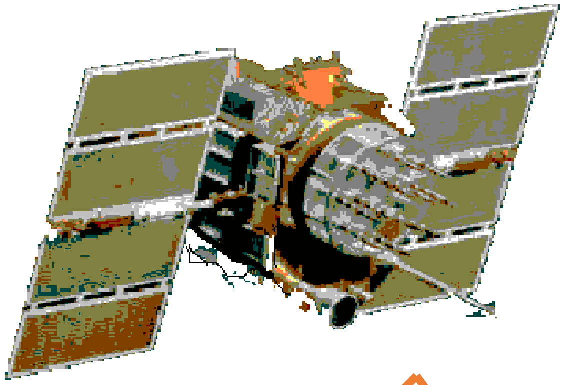
HDOP – Horizontal DOP
VDOP – Vertical DOP

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

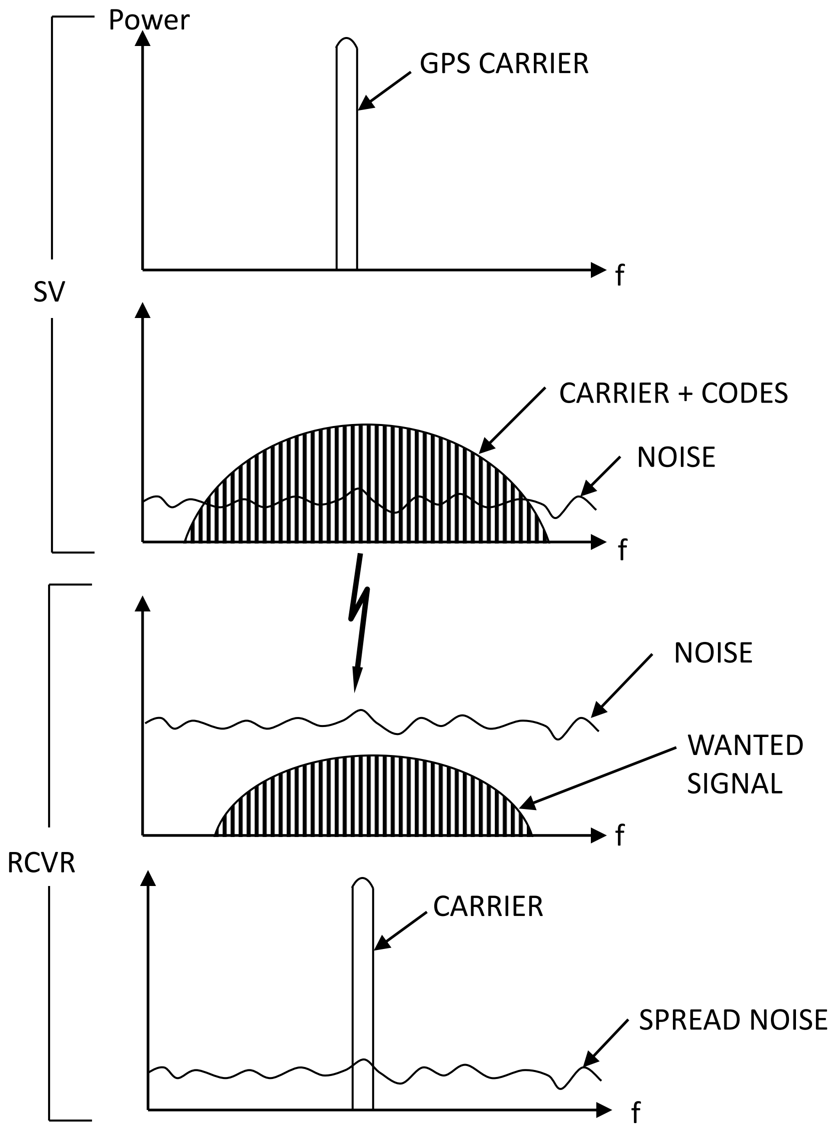
- **All Satellites Transmit on Same Frequencies (L1 & L2)**
- **How Do We Separate Signals From Satellite to Satellite?**
- **Code Division Multiple Access (CDMA)**
  - **Each Satellite Transmits a Unique C/A-Code - Repeats Every Millisecond**
  - **Each Satellite Transmits a Unique Y-Code - Encrypted 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

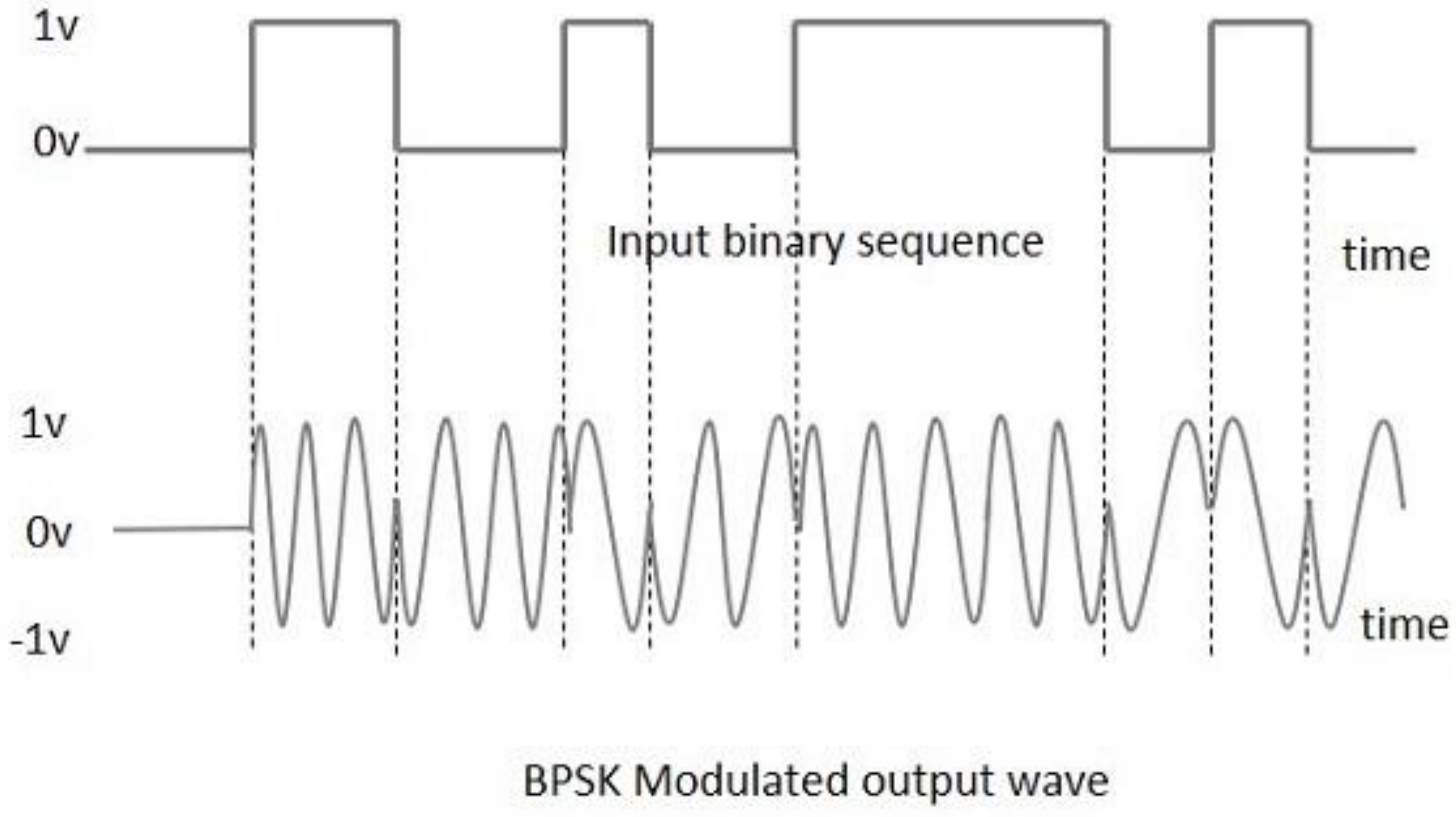


- GPS Power Output From Satellite ≈ 400 w

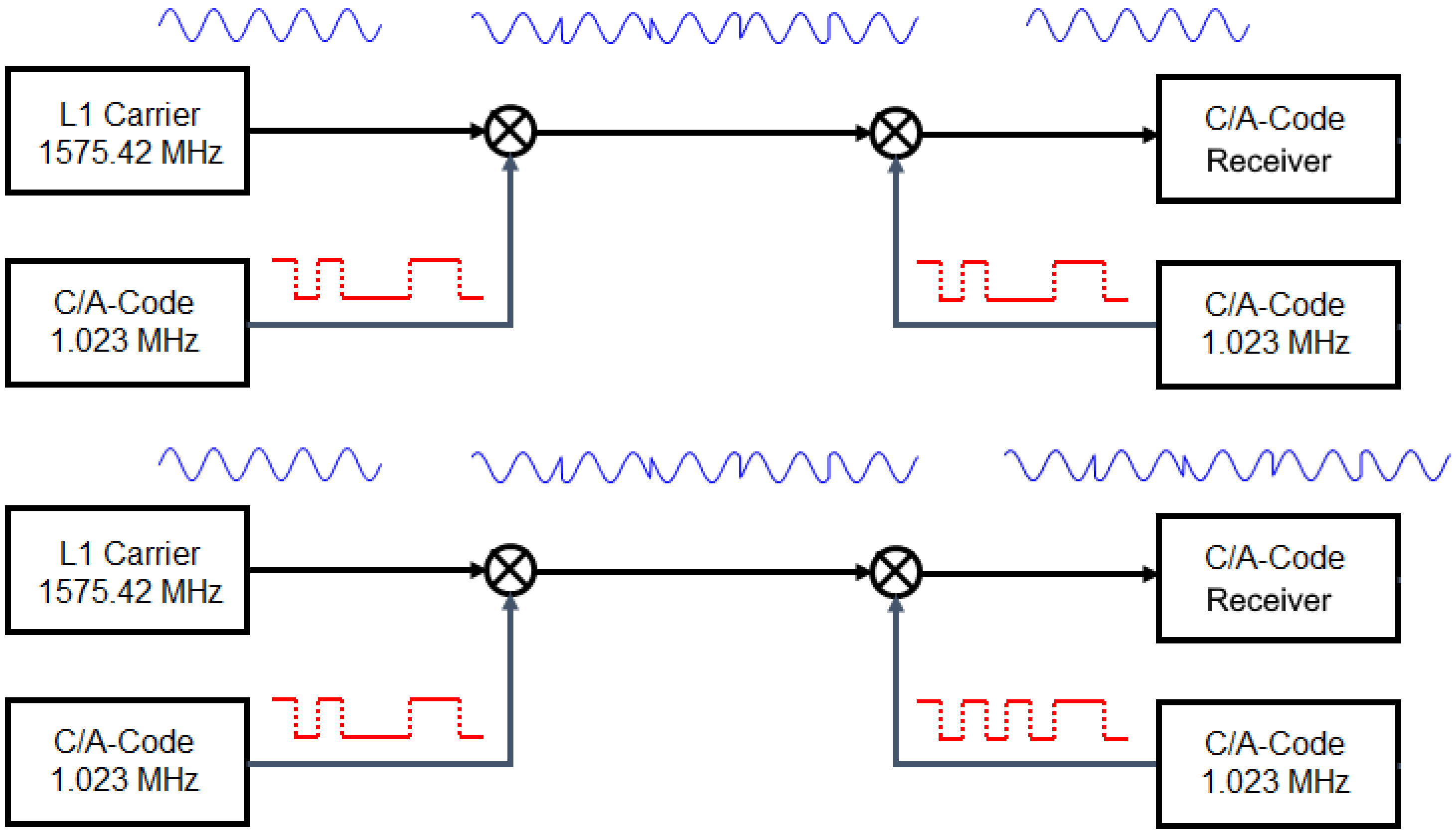
- Noise density ≅ -202 dBw/Hz
- Signal density ≅ -223 dBw/Hz
  ≅ -236 dBw/Hz (Y-code)

- GPS Signal Power Restored after Correlation in Receiver

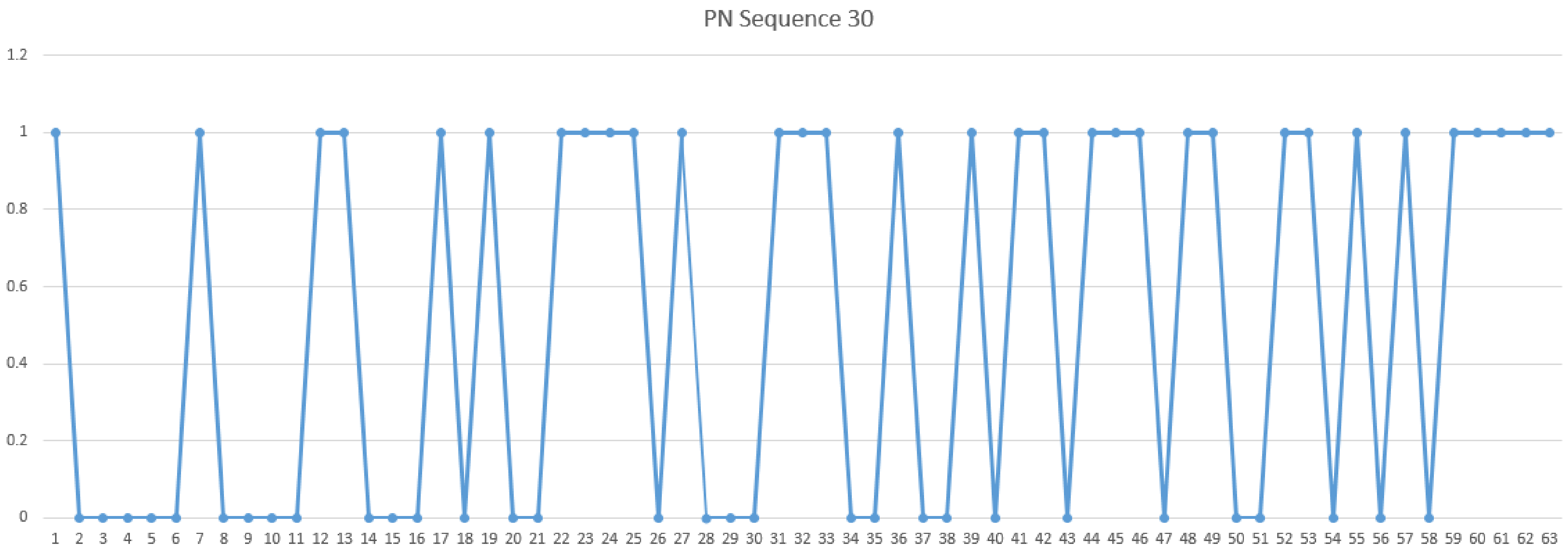
Binary Phase Shift Keying (BPSK) Modulation



Satellite Signal Modulation



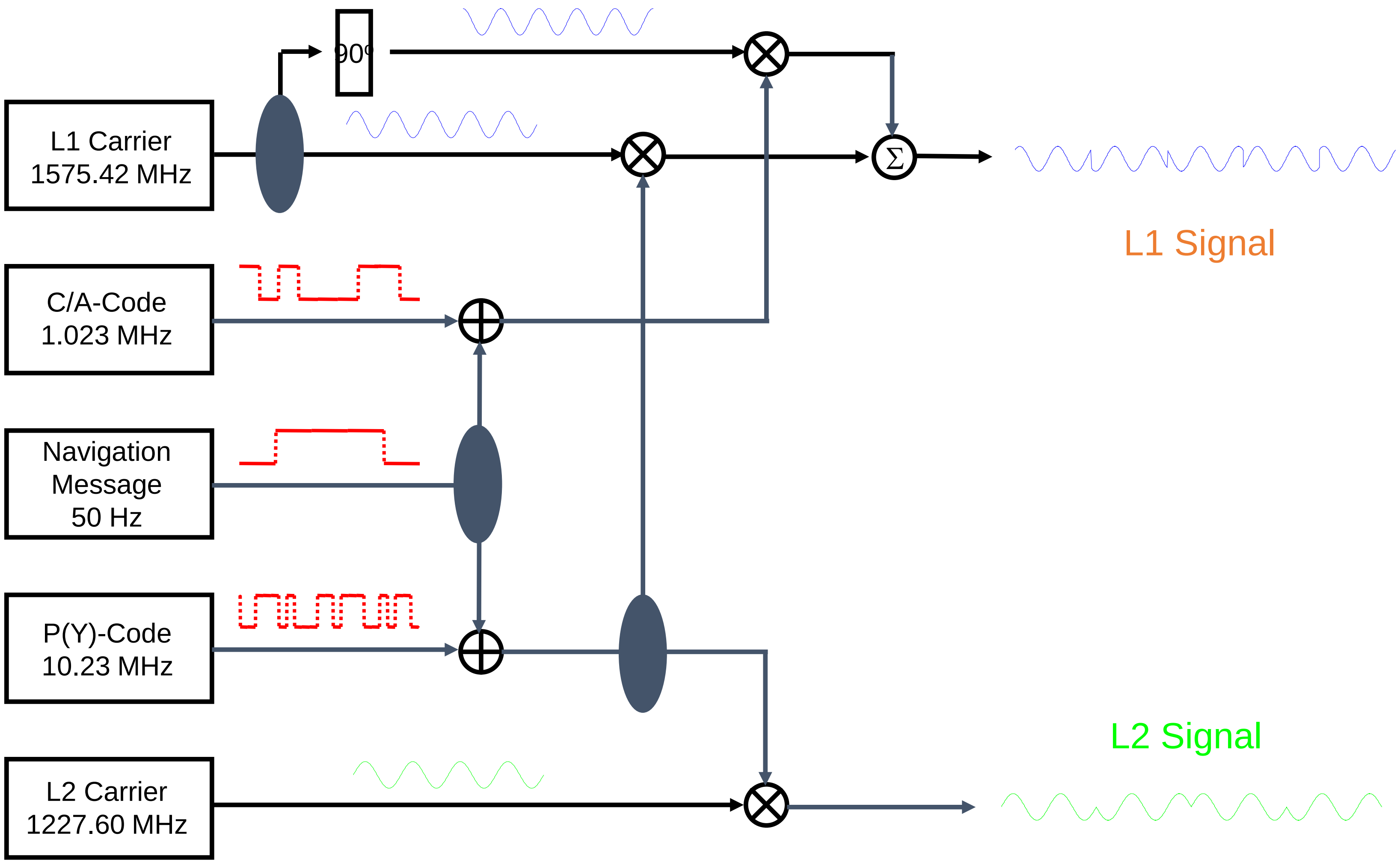
More on PRN Sequences



Satellite Signal Modulation

Spectrum

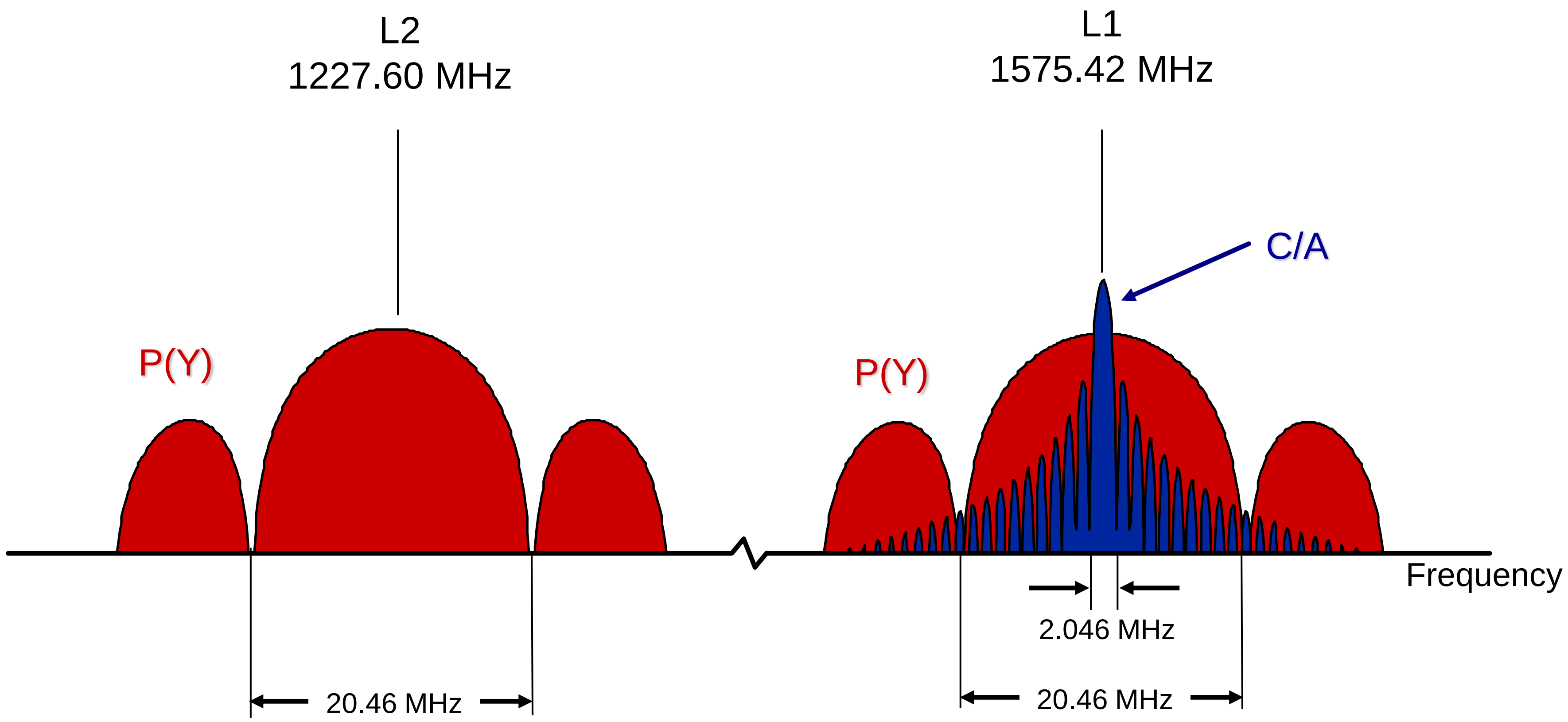
Satellite Signal Modulation – More Detail



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
  - 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**

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

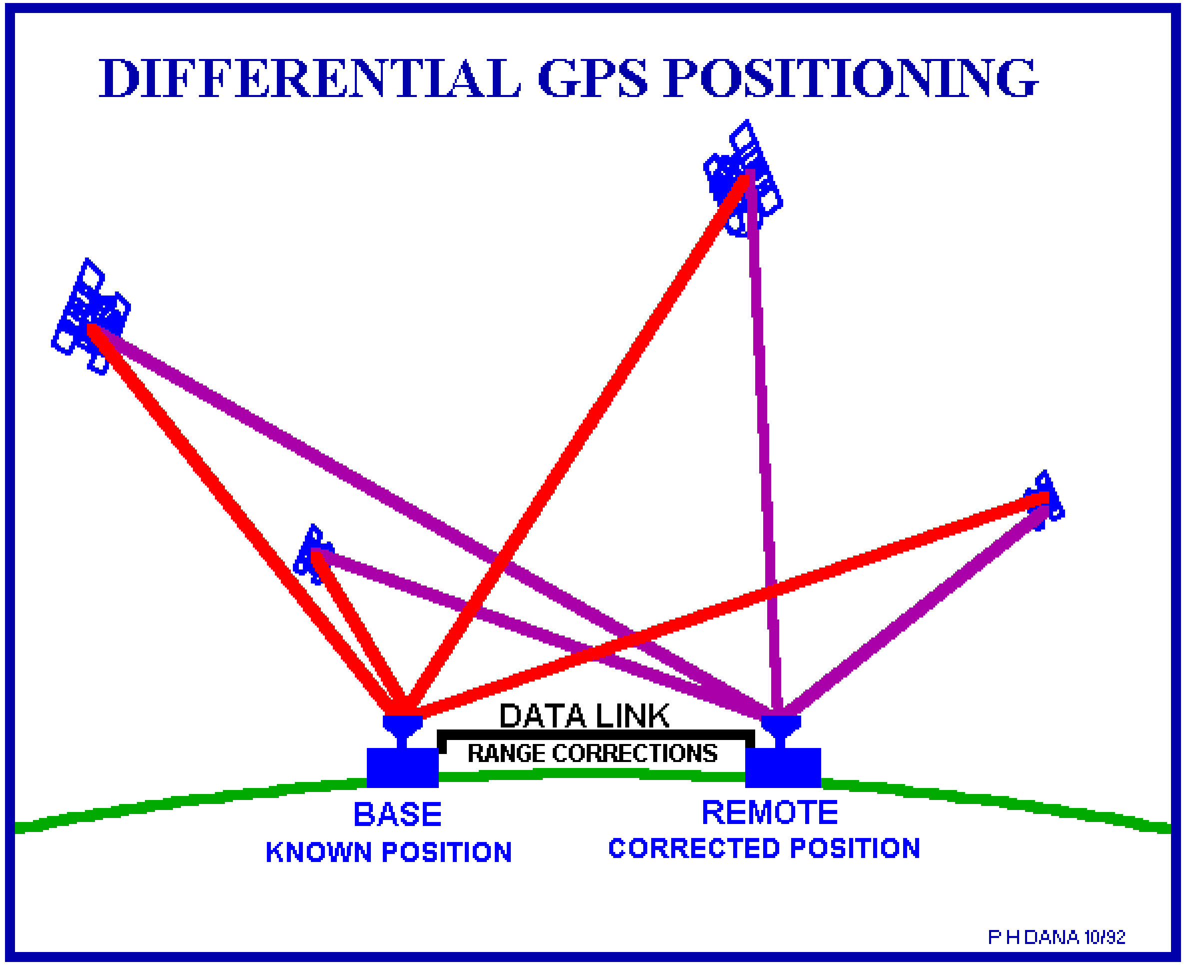
Typical TTFF = ~30 seconds

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

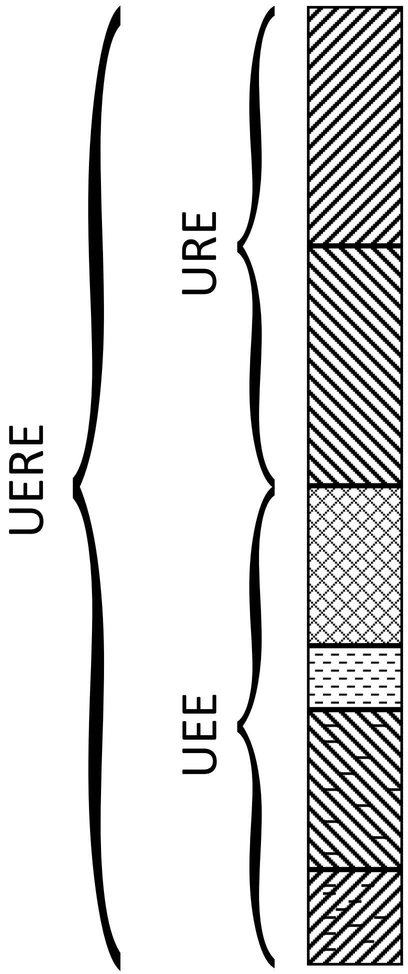
Typical TTFF = ~seconds

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

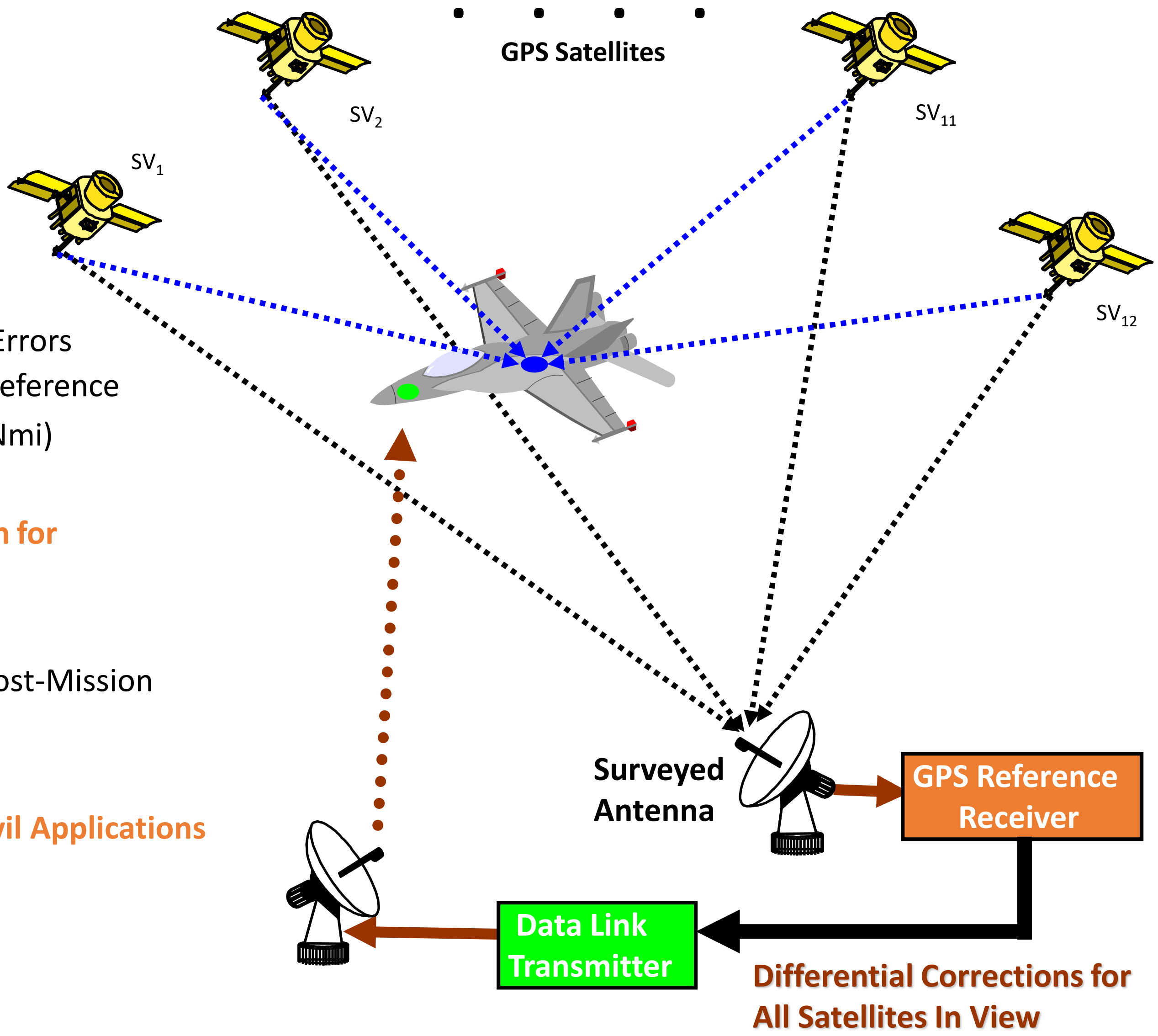
Space Segment, Tropo, Iono Errors are Common to Airborne & Reference Receivers (separation ~ 100 Nmi)

Data Link Security Consideration for DoD Applications

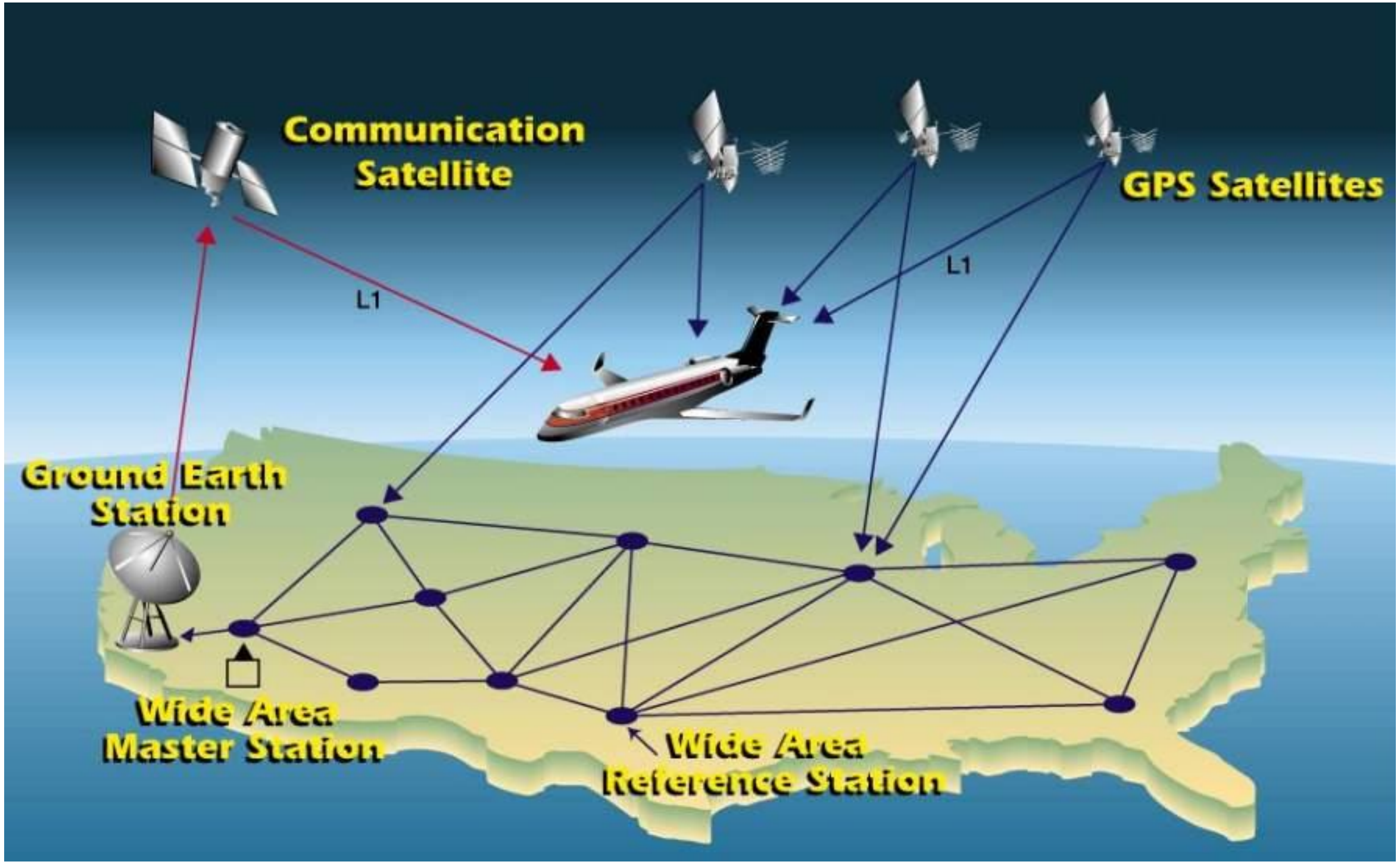
Data Link not Required for Post-Mission Applications

Faster Rate of Corrections for Civil Applications

(If SA Effects on)



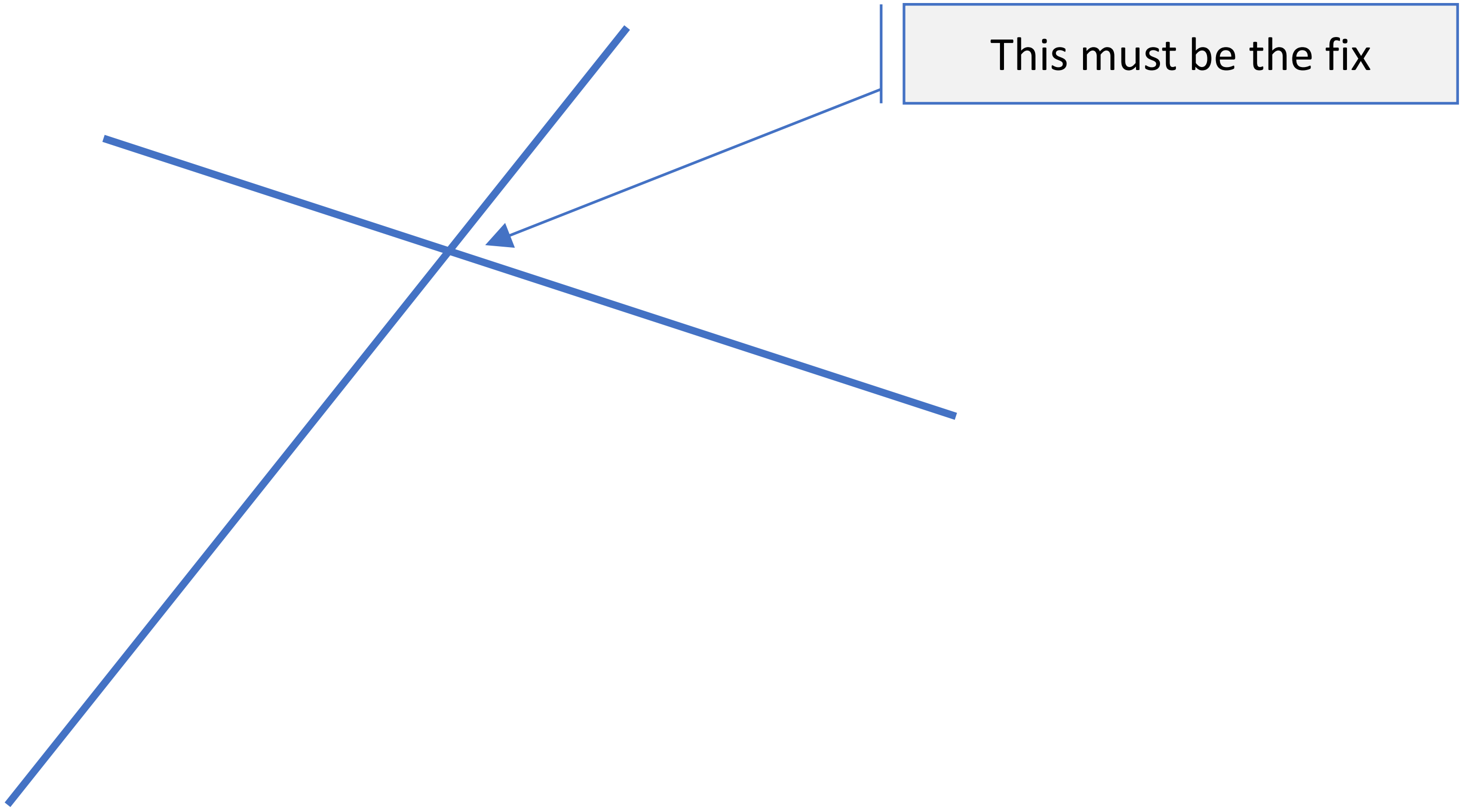
FAA's Wide Area Augmentation System (WAAS)



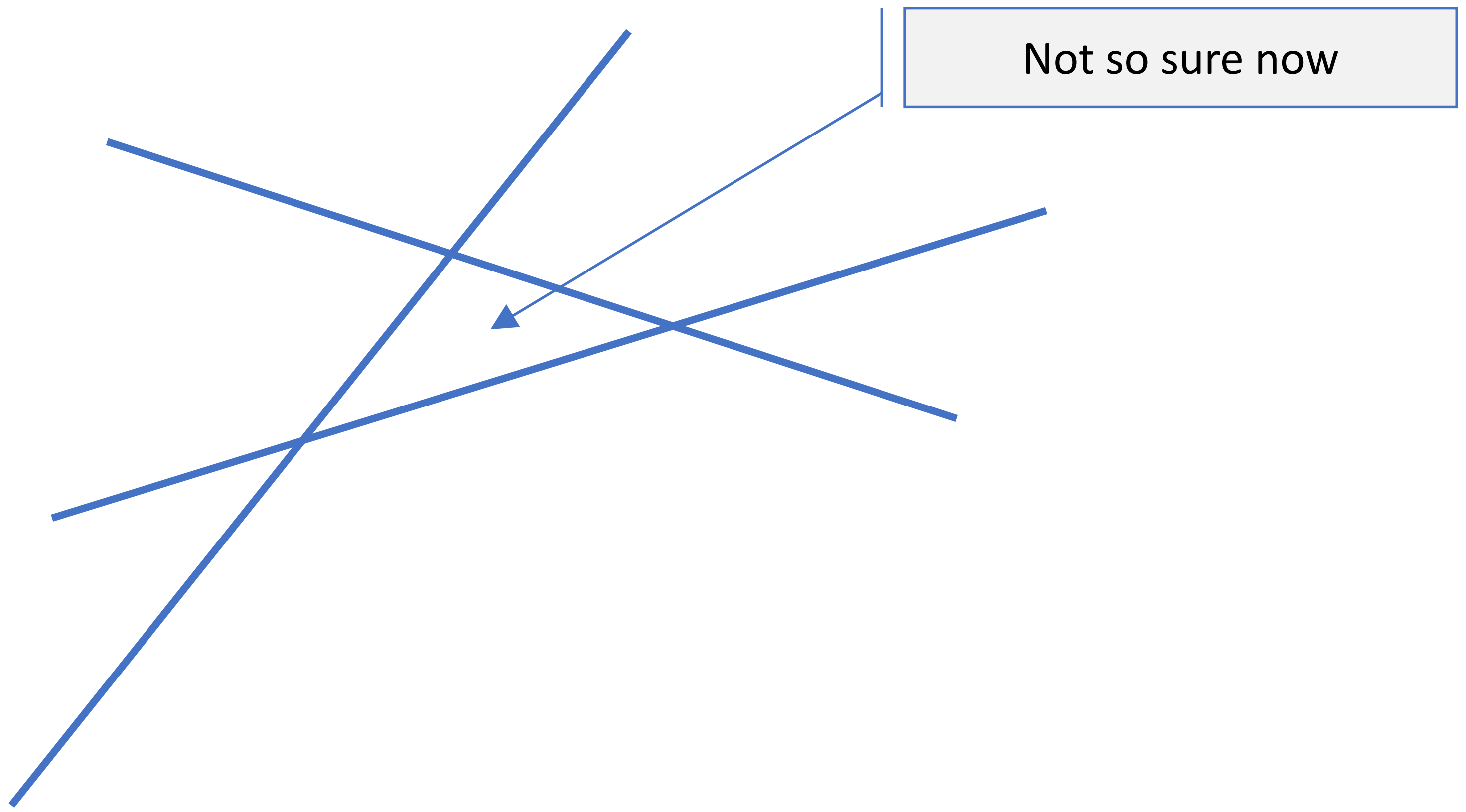
- Provides Differential Correction Data for Single Frequency Receivers
- Provides Integrity Data for All Satellites

RAIM - Receiver Autonomous Integrity Monitoring

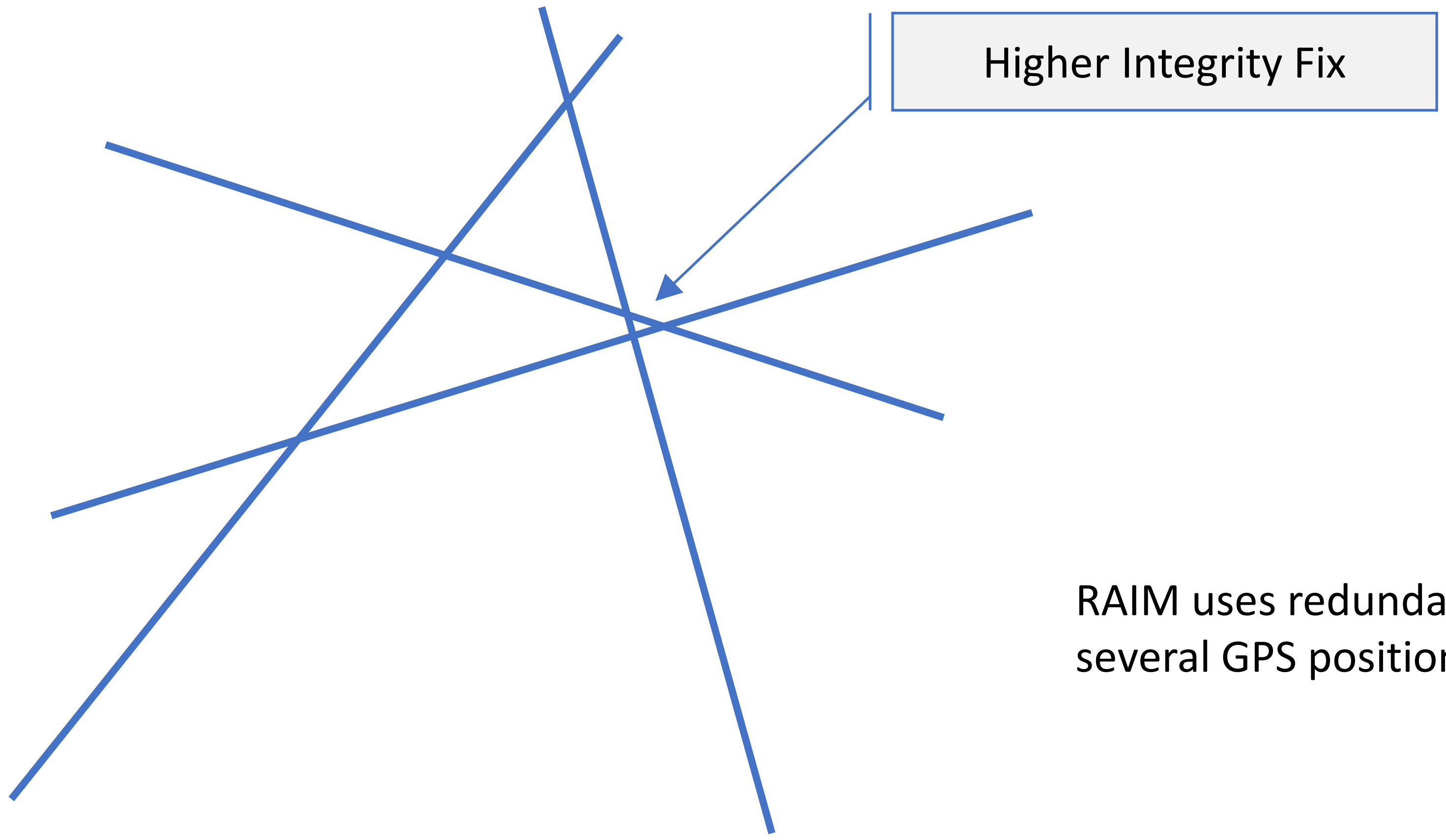
RAIM - Receiver Autonomous Integrity Monitoring



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.

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

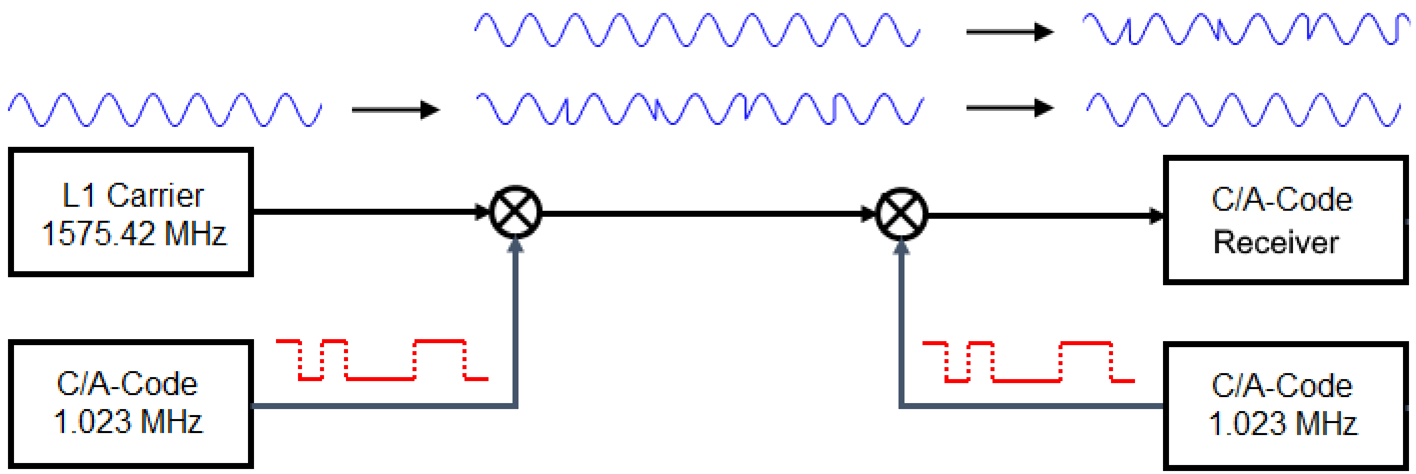
WAAS is not a technical requirement, but as a practical matter, the position source requirements are stringent enough that most non WAAS position sources are not adequate to meet the FAA requirements.

Jamming

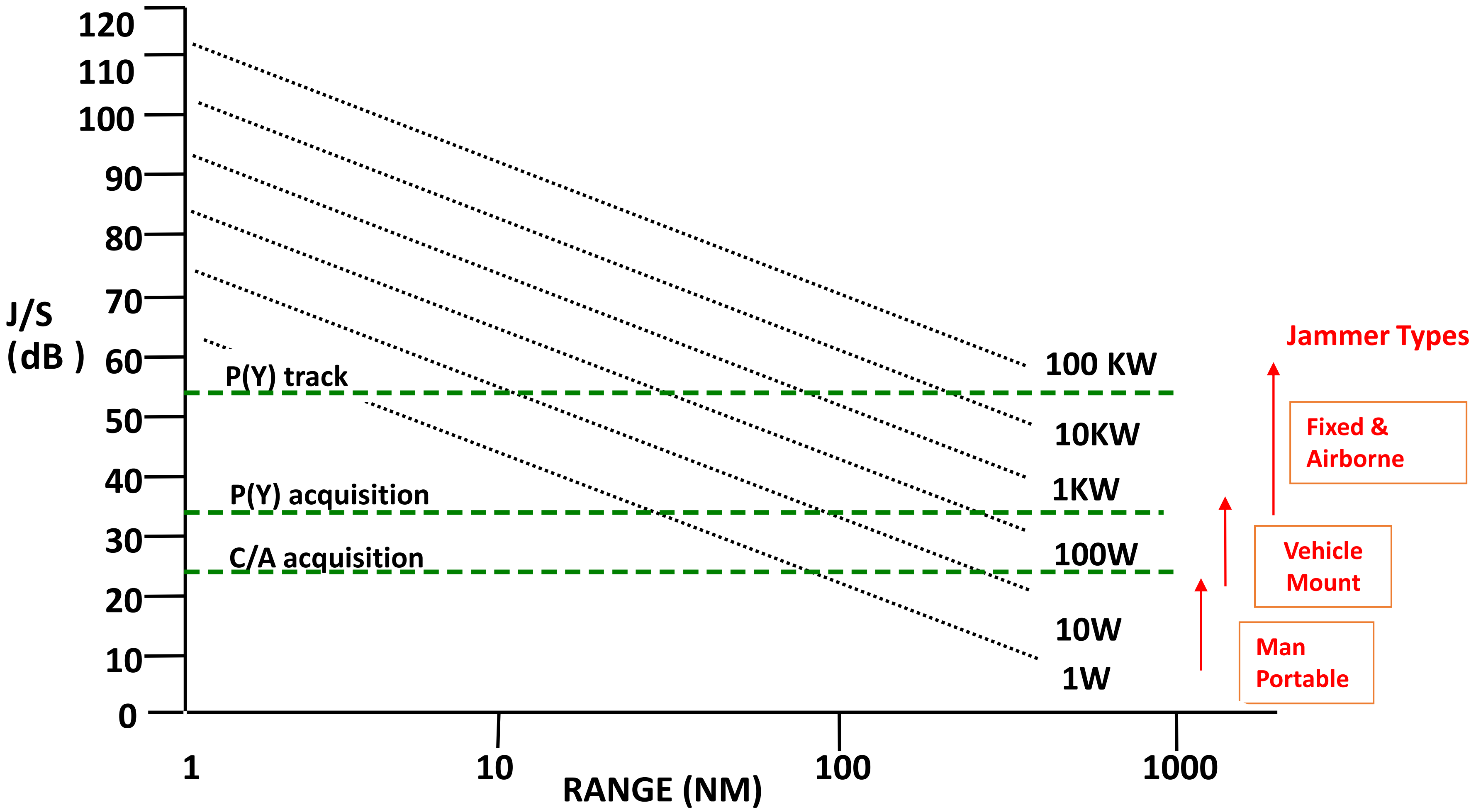
- GPS benefits greatly from DSSS against interfering sources
  - Narrow band jamming
  - Unintentional sources
  - Multipath
- But GPS is a low power signal
  - Little power margin

- Cryptographically secure Y-Code protects against spoofing

Satellite Signal Modulation with Jamming

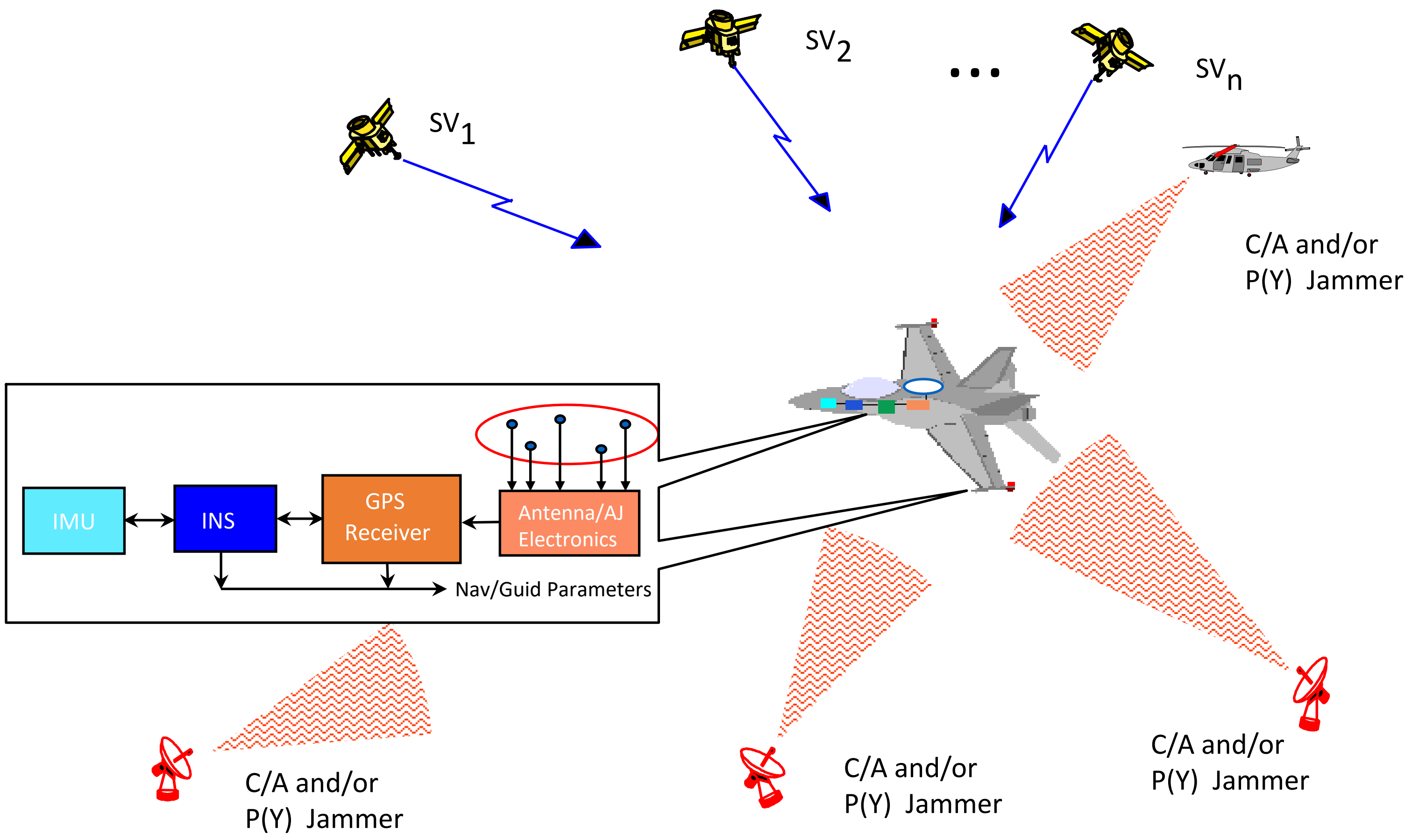


The GPS Jamming Problem



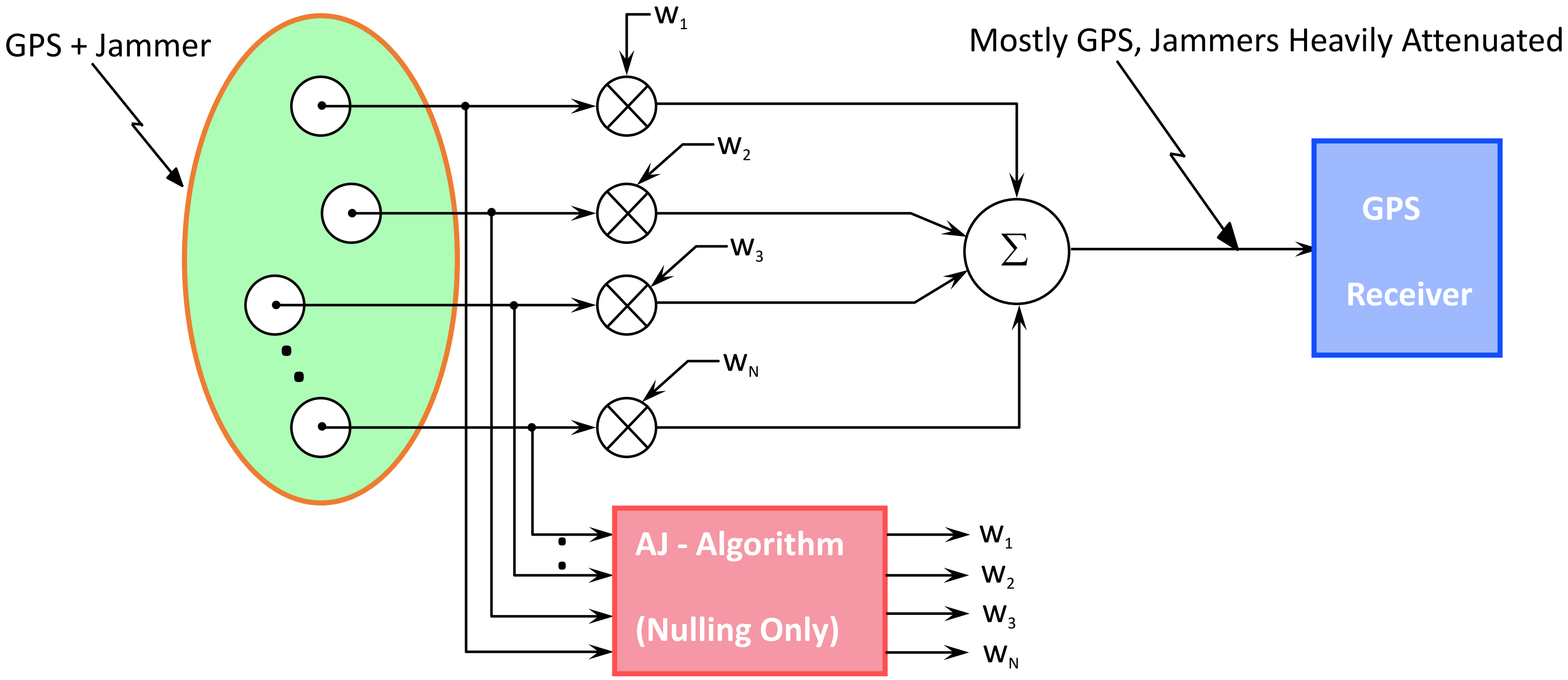
Even the Lowest Power Jammers Deny GPS Acquisition & Track

Aircraft/Weapon in a Conceptual Jamming Scenario



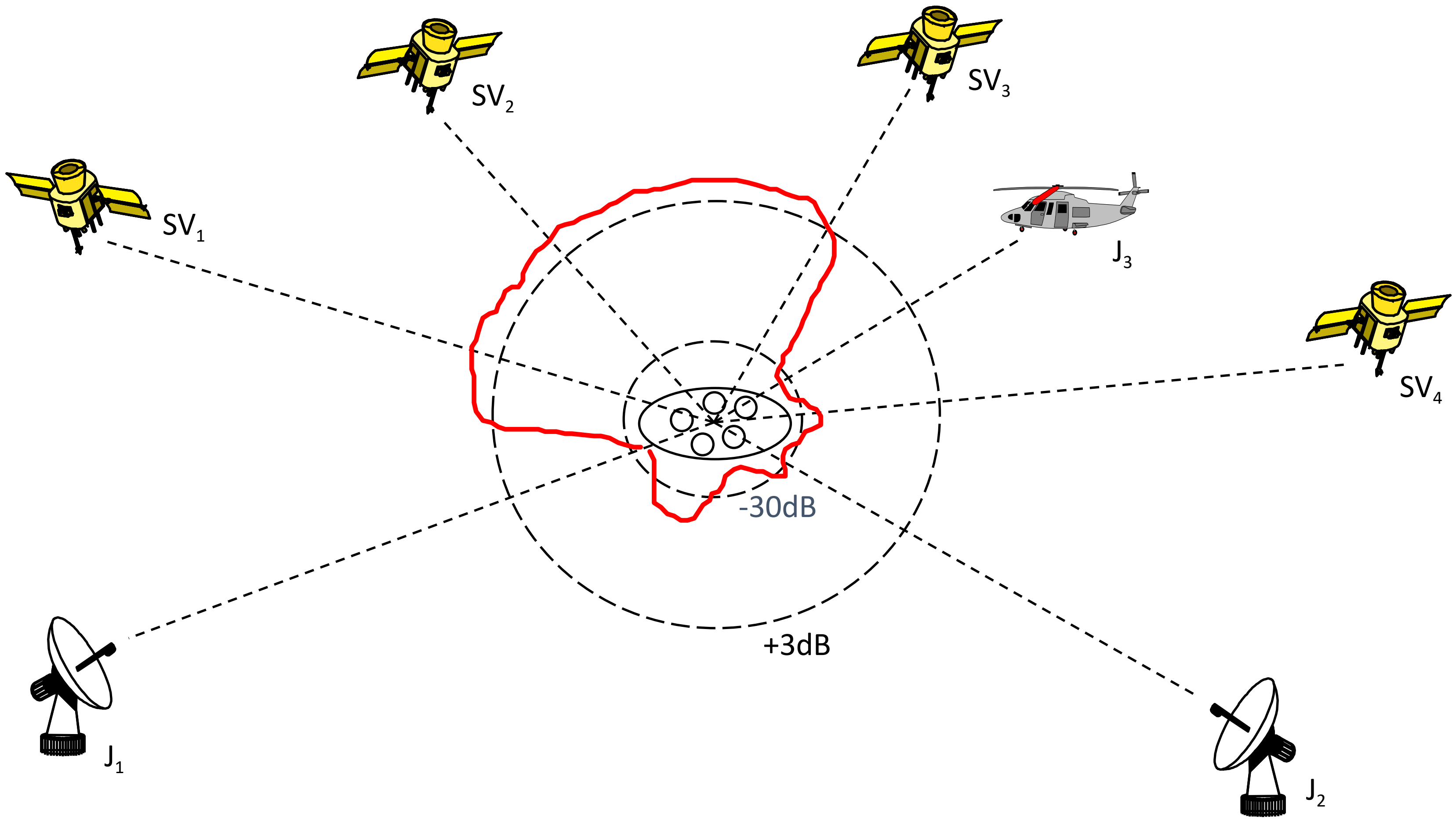
- C/A - Spoofing/Jamming $\Rightarrow$ Direct-Y Requirement for Weapon
- Aircraft and Weapon Anti-Jam Level Depends on Scenario, Mission, etc.

“Nulling” Algorithm Concept



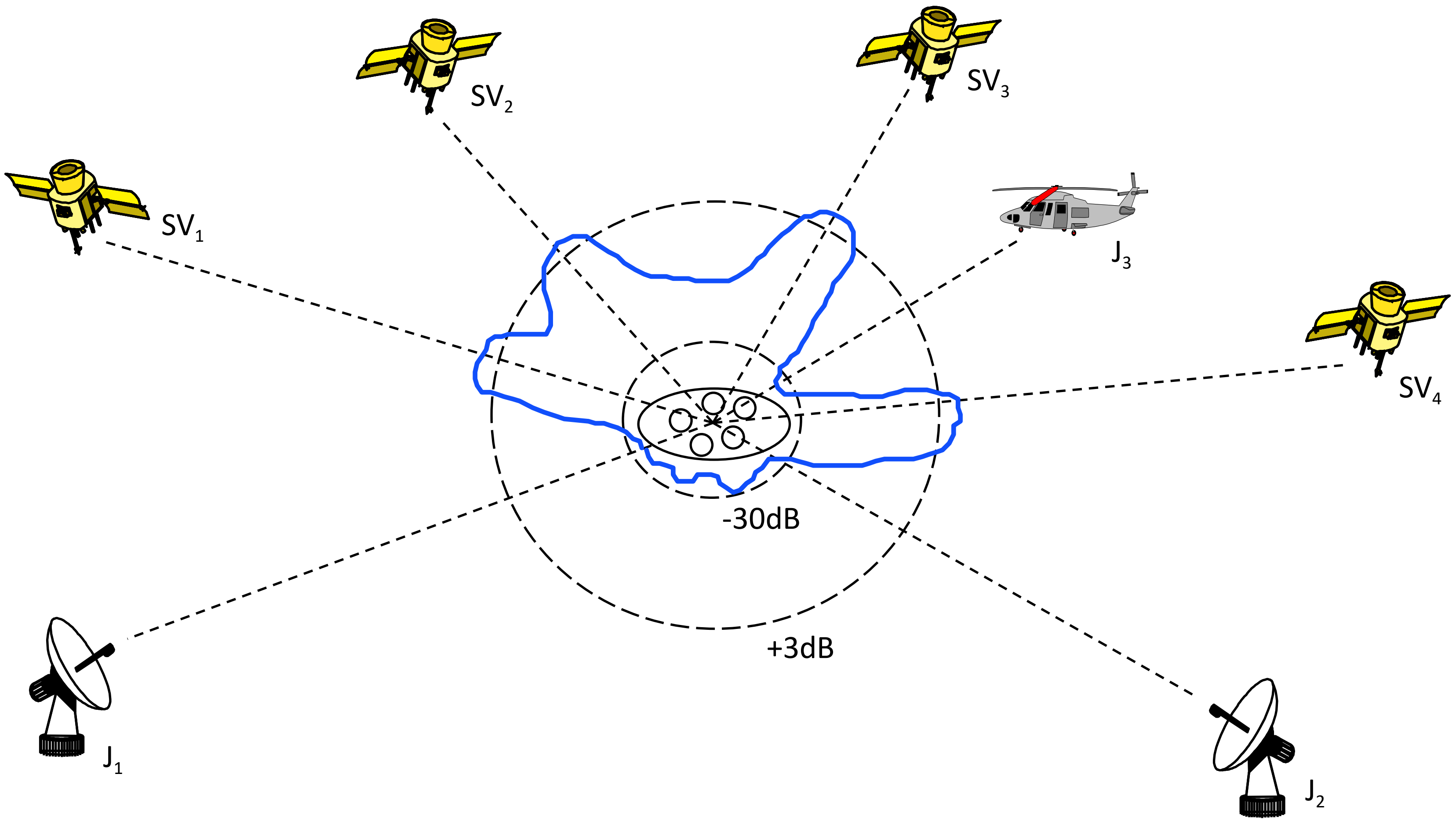
- Only one set of Antenna Weights w_1, w_2, w_3, • • w_N is Adaptively Determined that Minimizes Jammer Power by Minimizing Gains in the Direction of Jammers
- The “Nulling - Only” Algorithm may cause inadvertent Nulling of some Satellite Signals (All-In-View Receivers can Mitigate this Effect)

"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)