GPS Basics

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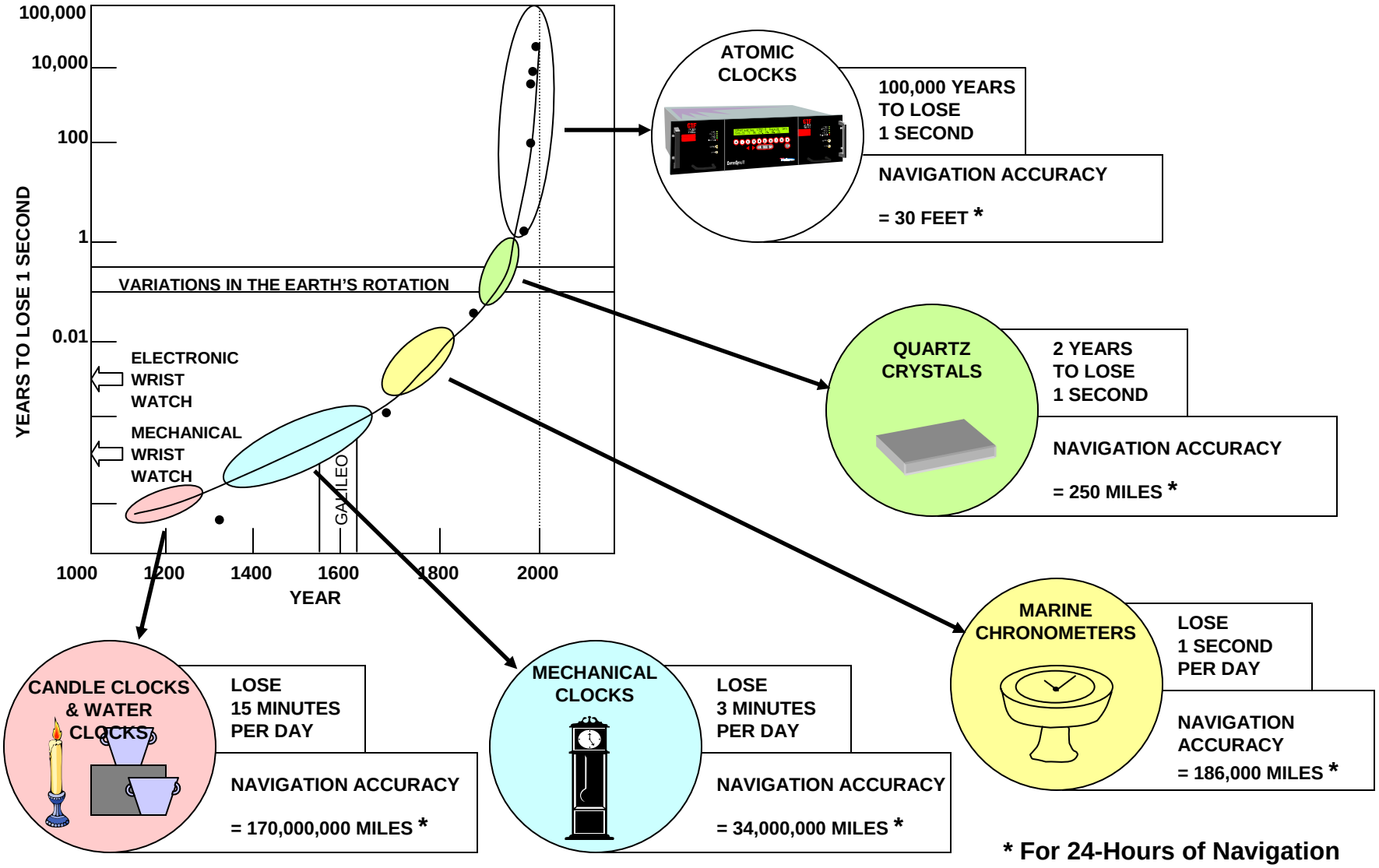
Discussion Outline

- **The Basic GPS System**
- **GPS Signal Acquisition**
- **GPS Dilution of Precision**
- **Future Signal Structure**
- **The GPS Engine**
- **What “Was” SA?**

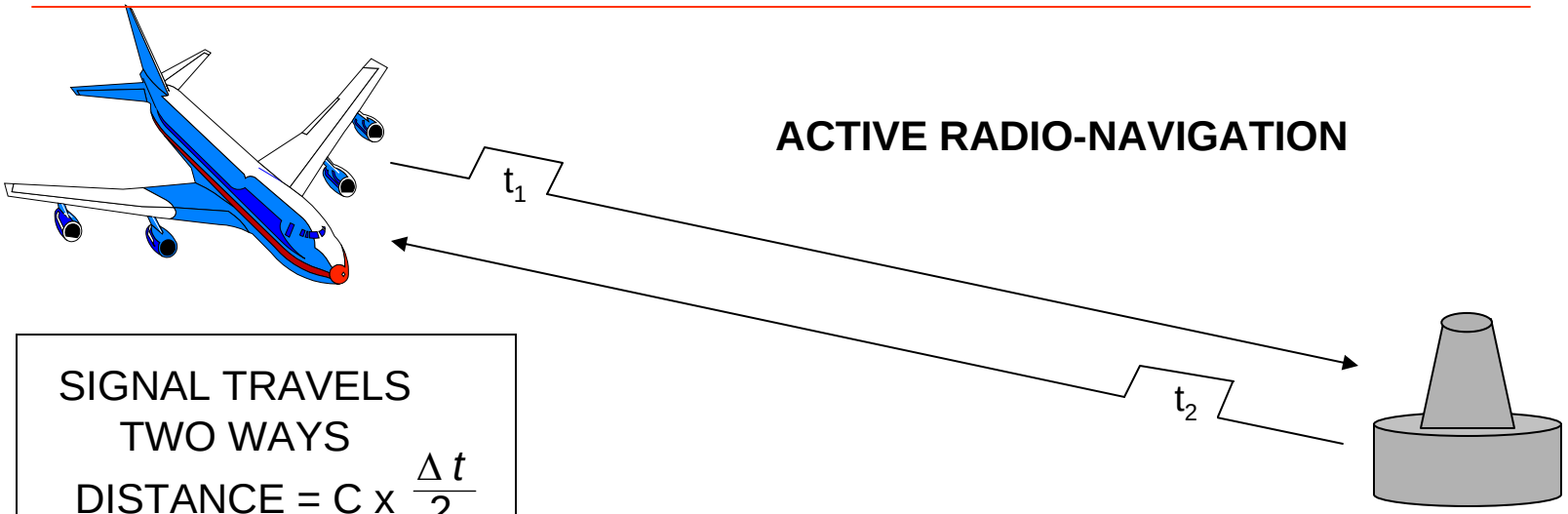
The Basic GPS System

Historical Development Of Accurate Clocks

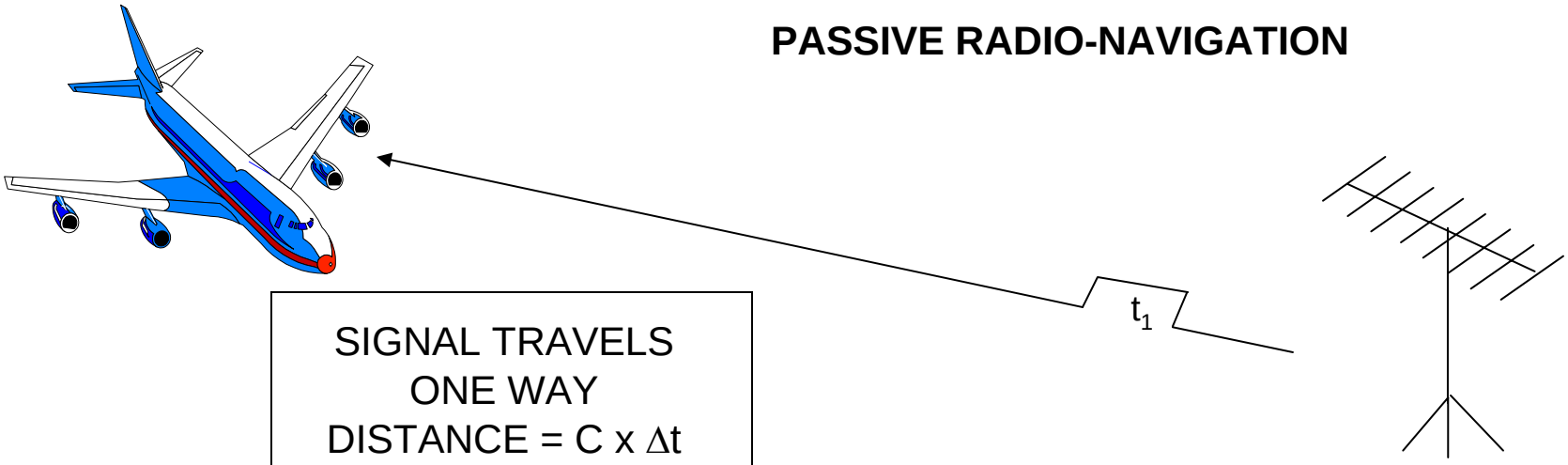


* For 24-Hours of Navigation

Active and Passive Radio-Navigation Systems

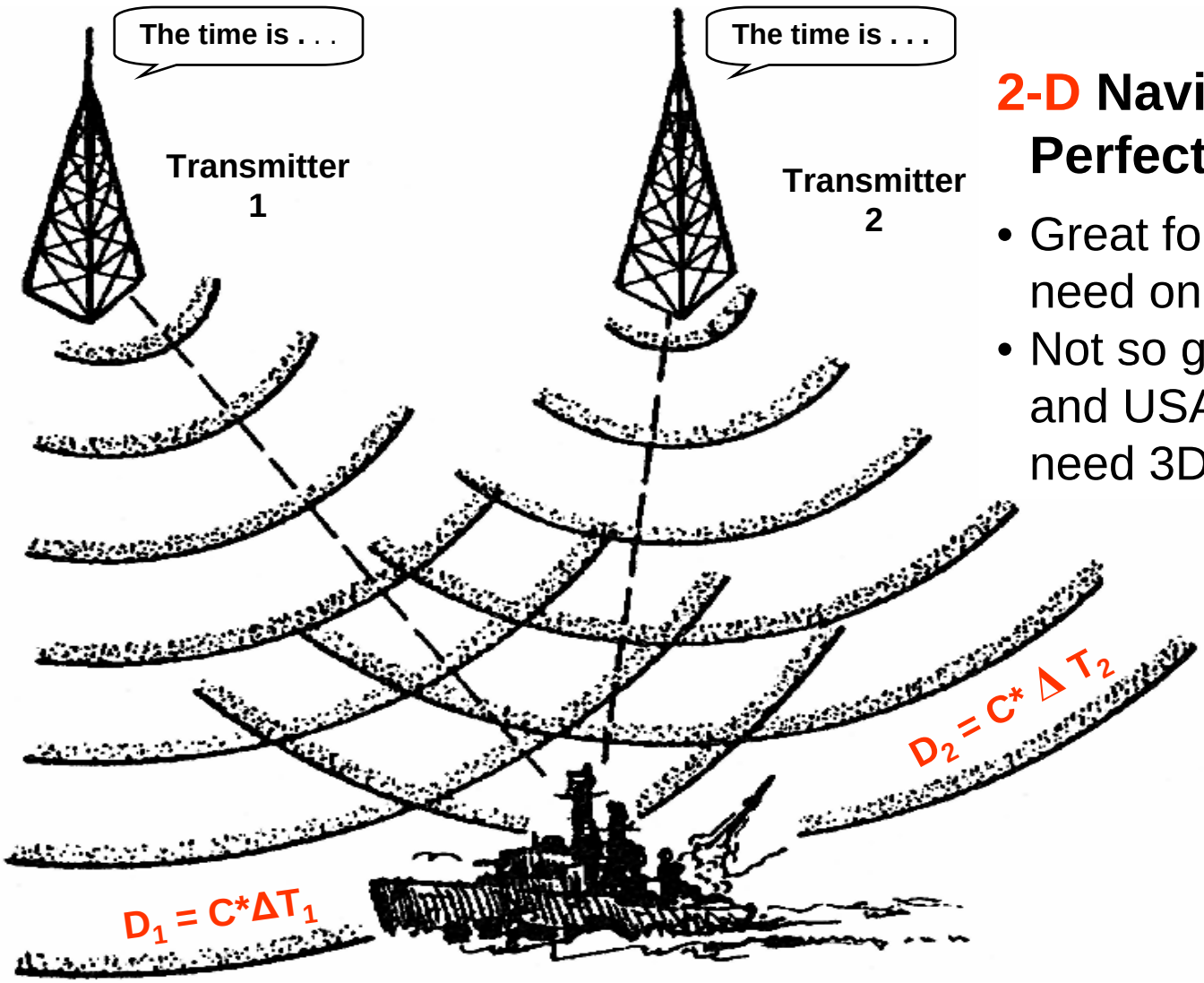


SIGNAL TRAVELS
TWO WAYS
DISTANCE = C x $\frac{\Delta t}{2}$



SIGNAL TRAVELS
ONE WAY
DISTANCE = C x Δt

1-Way 2D Electronic Ranging System



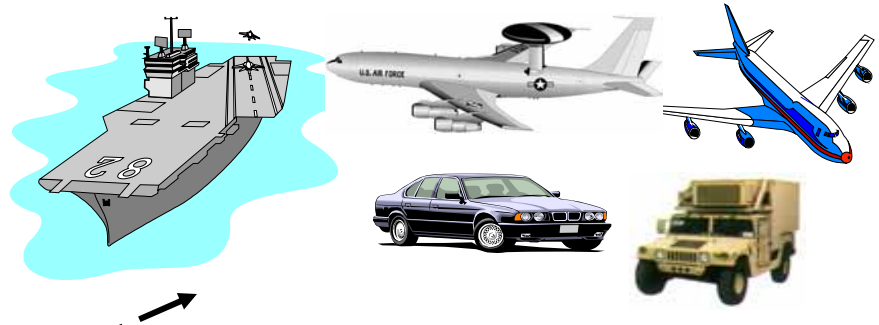
2-D Navigation: Perfect Clocks

- Great for Navy Ships; need only – 2D
- Not so great for Navy and USAF flyers – need 3D

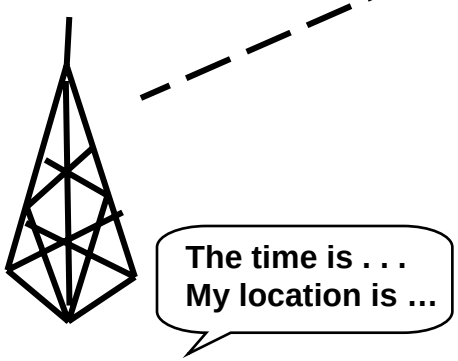
Success of the 621B, 3-D Ranging Test Program, 1968-71 lead to a space-based GPS

3-D Navigation: Perfect Clocks

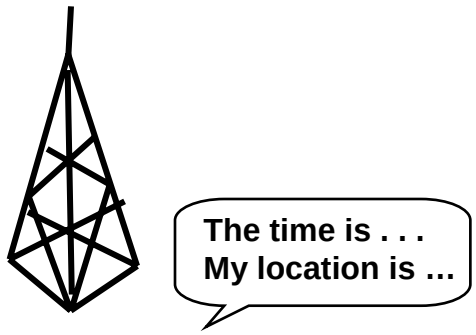
- Now OK for Flyers and Vehicles alike



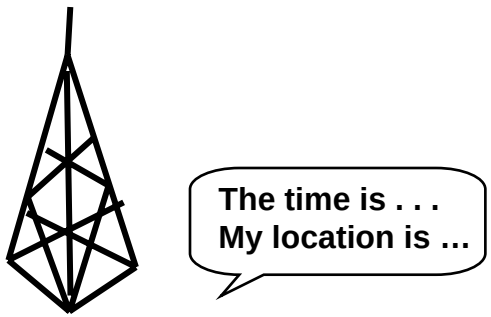
Ground-based Transmitters are put into Space



Transmitter (3)



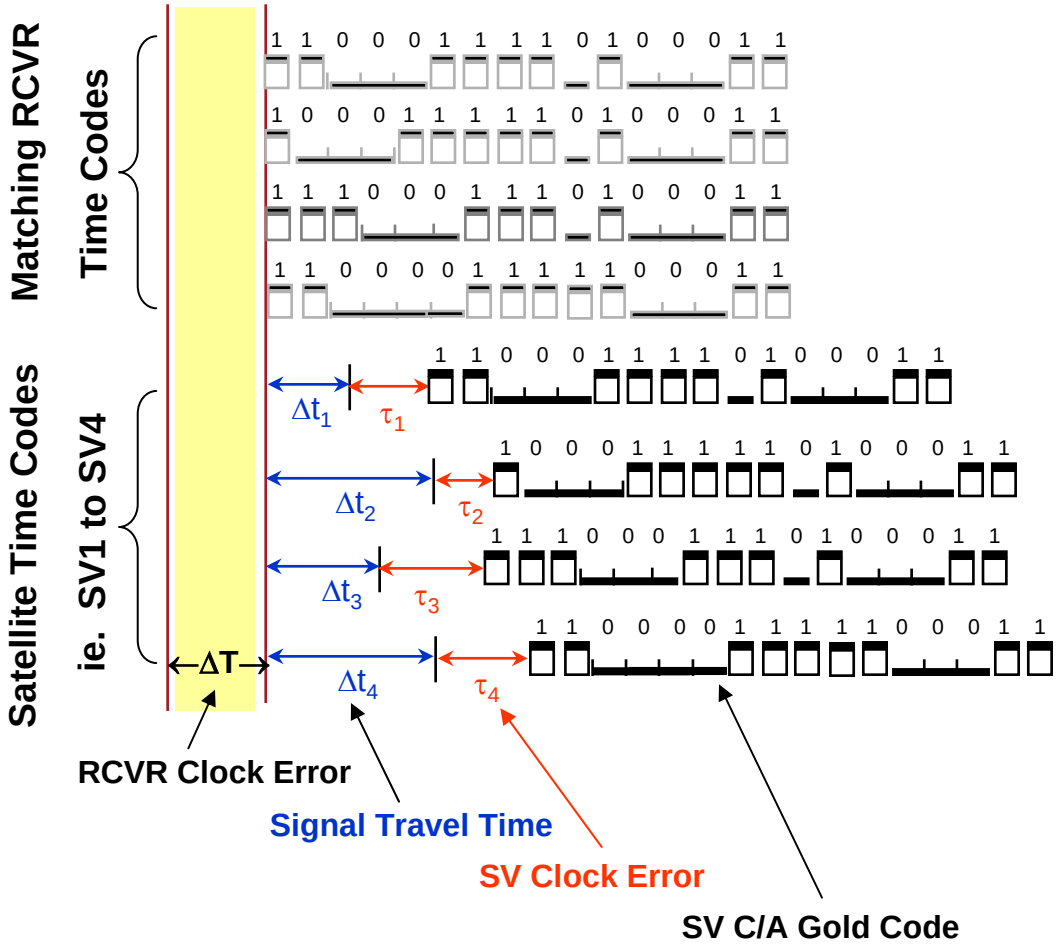
Transmitter (2)

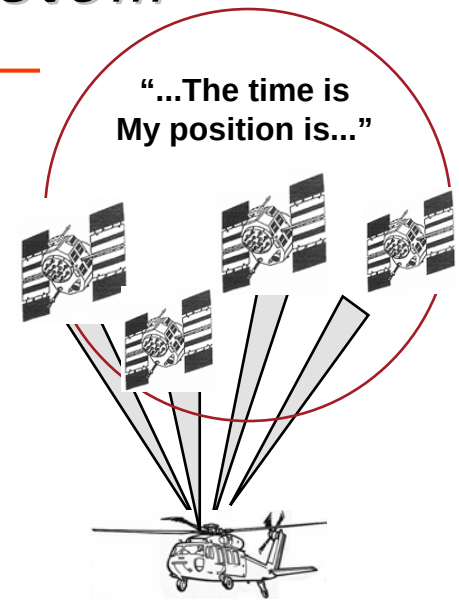


Transmitter (1)

Space Borne 1-Way 3D Ranging System

The Realistic GPS System





$R_1 = C(\Delta t_1 + \Delta T - \tau_1)$

$R_2 = C(\Delta t_2 + \Delta T - \tau_2)$

$R_3 = C(\Delta t_3 + \Delta T - \tau_3)$

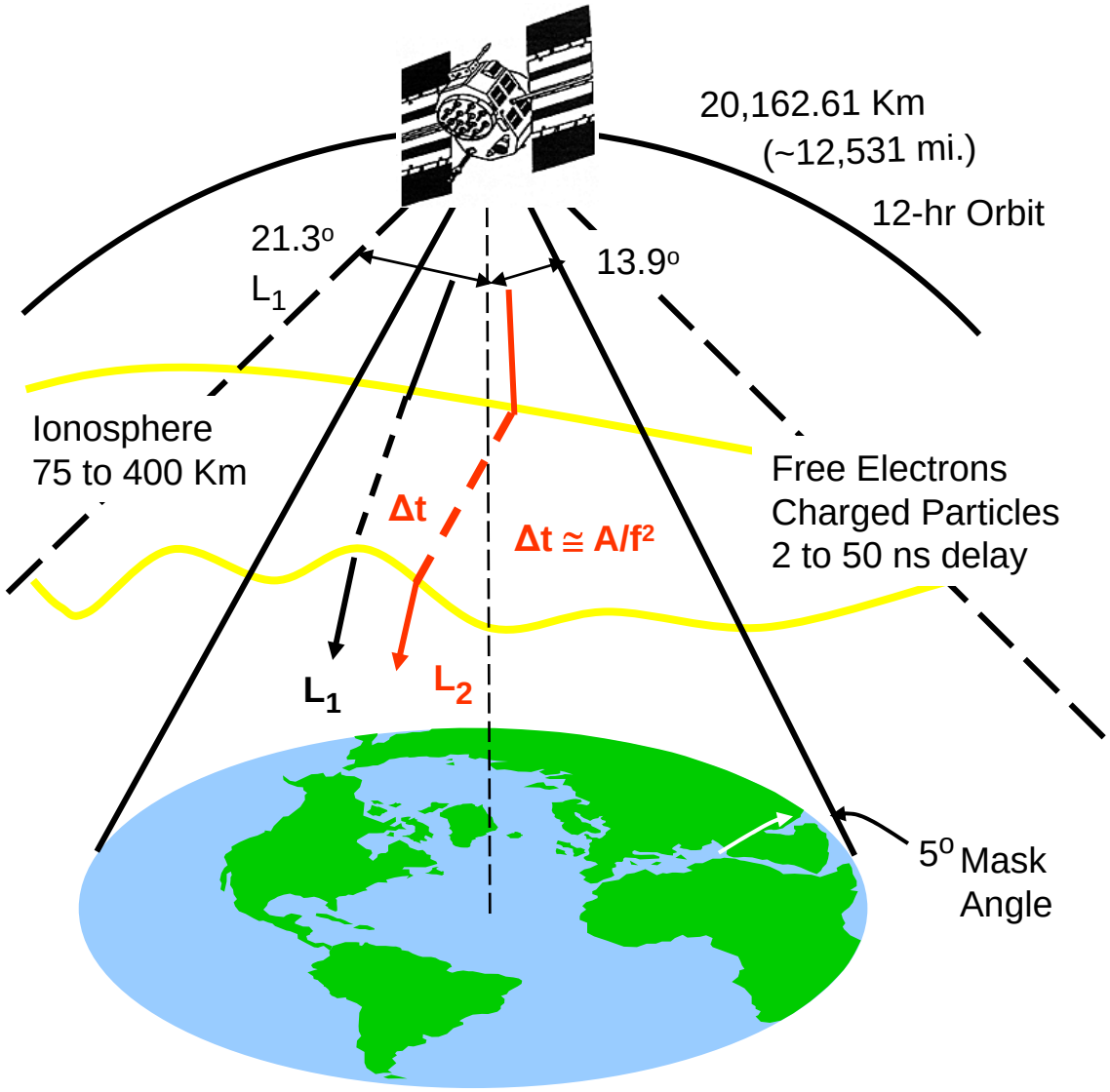
$R_4 = C(\Delta t_4 + \Delta T - \tau_4)$

4 Equations — 4 Unknowns

What is GPS?

- **A space-based satellite navigation system developed by the DoD in the mid 70's for military use, managed by a Joint Program Office (GPS-JPO) located at LAAFB, made up of the USAF, Navy, and other services,.**
- **A highly accurate 3-D navigation, positioning, and timing system, available 24 hours a day, 7 days a week, anywhere in the world.**
- **Has a clear (or coarse) acquisition signal (C/A-Code) to aid in the acquisition of the precision military signal (P-Code). Because the C/A-Code is in the clear, it serves as a civil navigation, positioning, and timing system, referred to as SPS (Standard Positioning Service), ~10m, 1σ, Spherical Error Probability (SEP).**
- **Also has a more accurate (precision) P-Code signal, available only to authorized cryptographic key users. When the P-Code is encrypted, it becomes the Y-Code. This is referred to as PPS (Precise Positioning Service), ~1m, 1 σ, SEP.**
- **SPS and PPS also provide an atomic time reference, accurate to ±100 ns of USNO - Master Clock, referenced to UTC (Universal Coordinated Time).**
- **The Satellite Constellation is controlled and maintained by the USAF from the Master Control Station (MCS) at Schriever AFB near Colorado Springs. The MCS is part of the Consolidated Space Operations Center (CSOC).**

GPS Satellite Signals



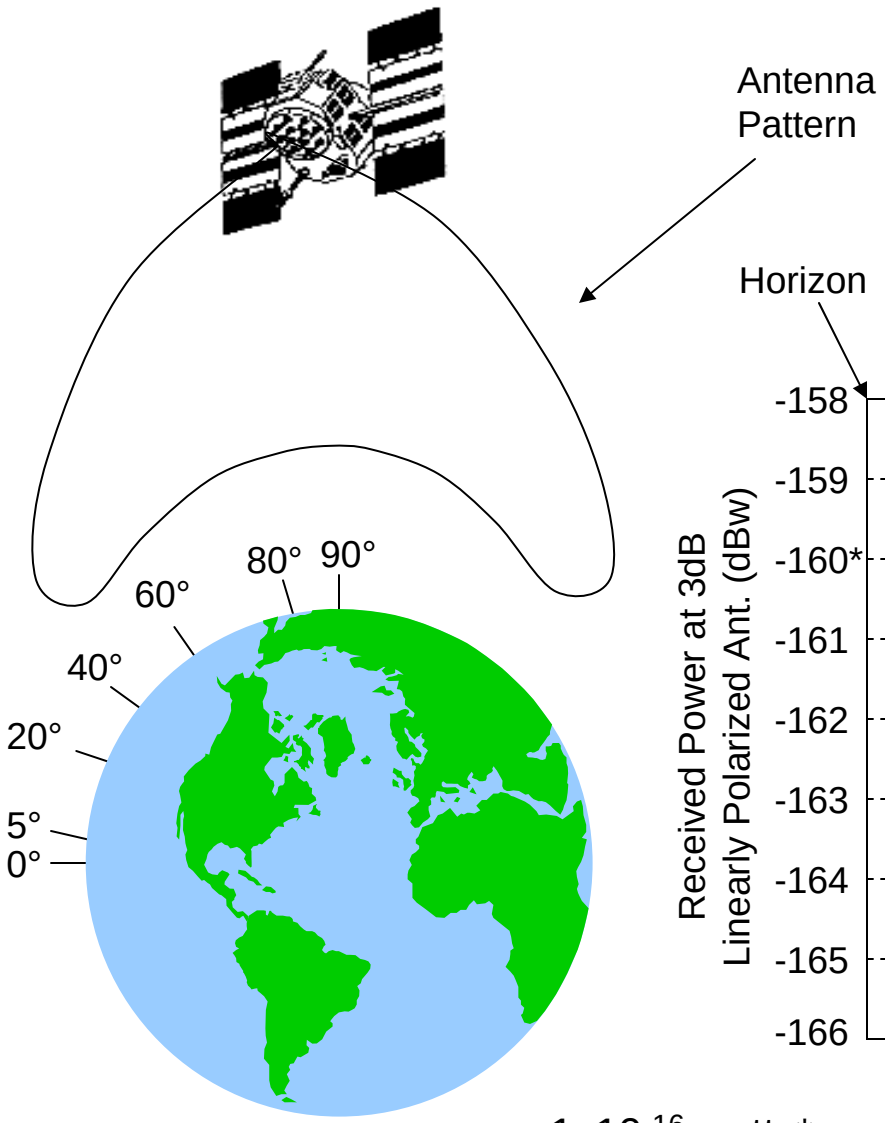
- **L_1 1575.42 MHz**
  C/A-Code 1.023 Mcps,
  P-Code 10.23 Mcps
  Data 50 bps

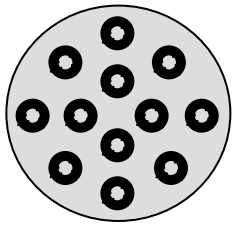
- **L_2 1227.6 MHz**
  P-Code 10.23 Mcps
  Data 50 bps

- **Four Satellites needed for 3-D navigation**

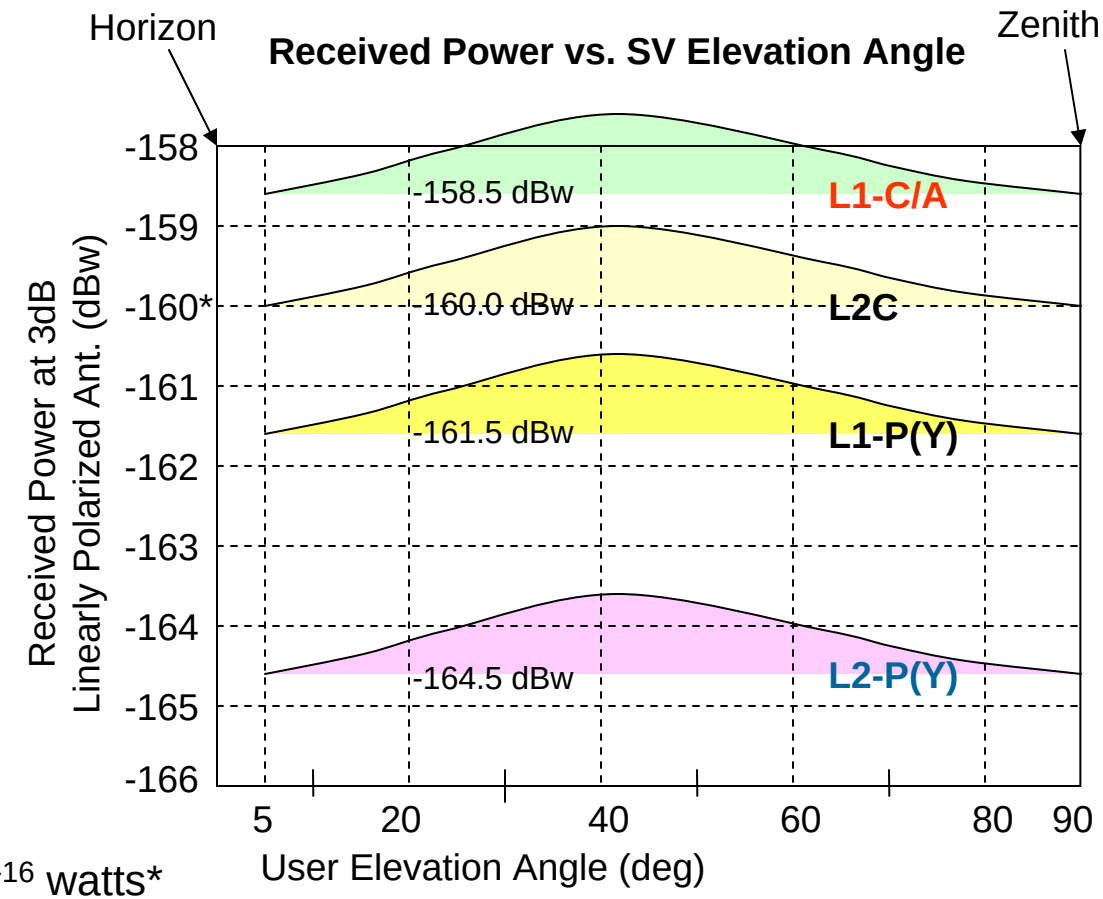
- **Maximum Doppler Shift between Satellites ~ ± 6KHz**

GPS Signal Realities



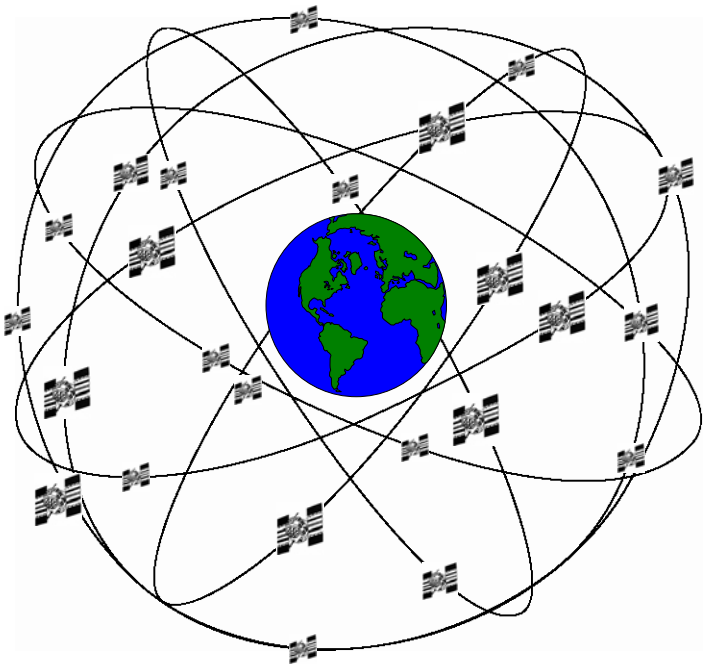


GPS Antenna:
12 Element
L-Band Helical
Phased Array
(On-axis view)



~1x10^{-16} watts*

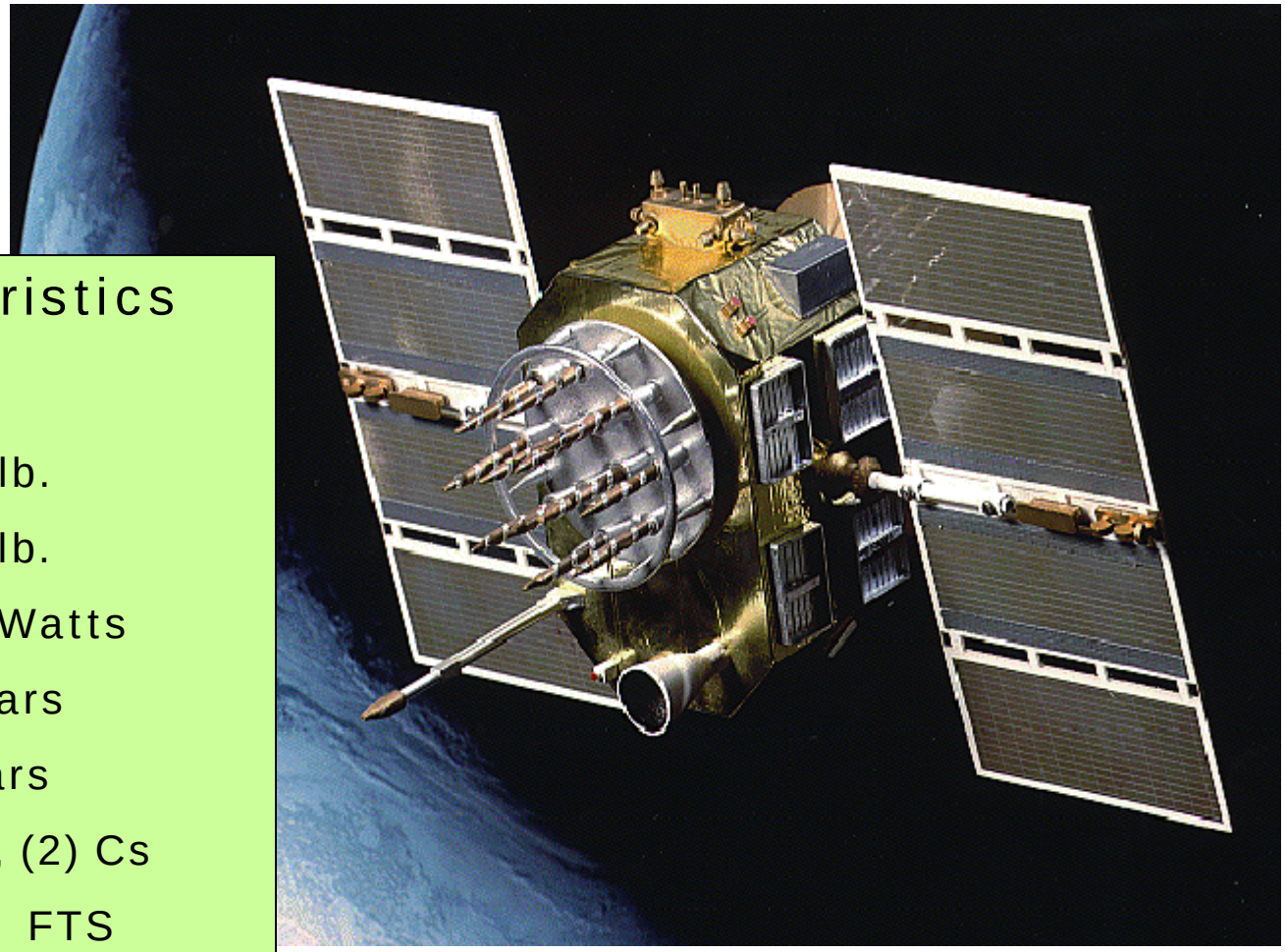
Satellite Constellation



- **All near perfect circular orbits**
- **21 to 24 Satellites required for 24 x 7 coverage**

30 GPS Satellites in Operation at present

GPS Satellite (Block II, IIA) – Rockwell (RI)



Major Characteristics

Launch mass	3,675 lb.
On-Orbit mass	1,862 lb.
Solar Array	1,000 Watts
Design Life	7.5 years
Consumables	10 years
Clocks	(2) Rb, (2) Cs
	RI-Efr FTS

All Have Been Launched

GPS Satellite (Block IIR) – Lockheed-Martin

Major Characteristics

Launch mass	4,480 lb.
On-Orbit mass	2,210 lb.
Solar Array	1,100 Watts
Design Life	7.5 years
Consumables	10 years
Clocks	(3) Rb
	EG&G*

***now Perkin-Elmer**

In Launching Phase

*GPS Satellite (Block IIF) – Boeing**

*** Was Rockwell International**

Major Characteristics

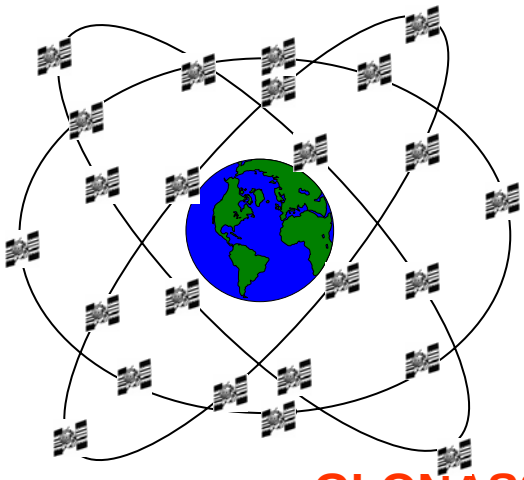
Launch mass	4,634 lb.
On-Orbit mass	~2,400 lb.
Solar Array	1,560 Watts
Design Life	15 years
Consumables	15 years
Clocks	(2) Rb, (1) Cs
	EG&G* FTS**

***Now Perkin-Elmer**

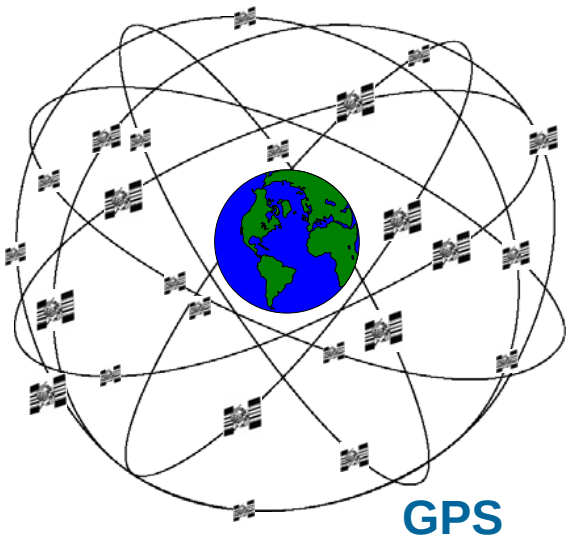
****Now Symmetricom**

In Launching Phase

Comparison of GPS and GLONASS



GLONASS

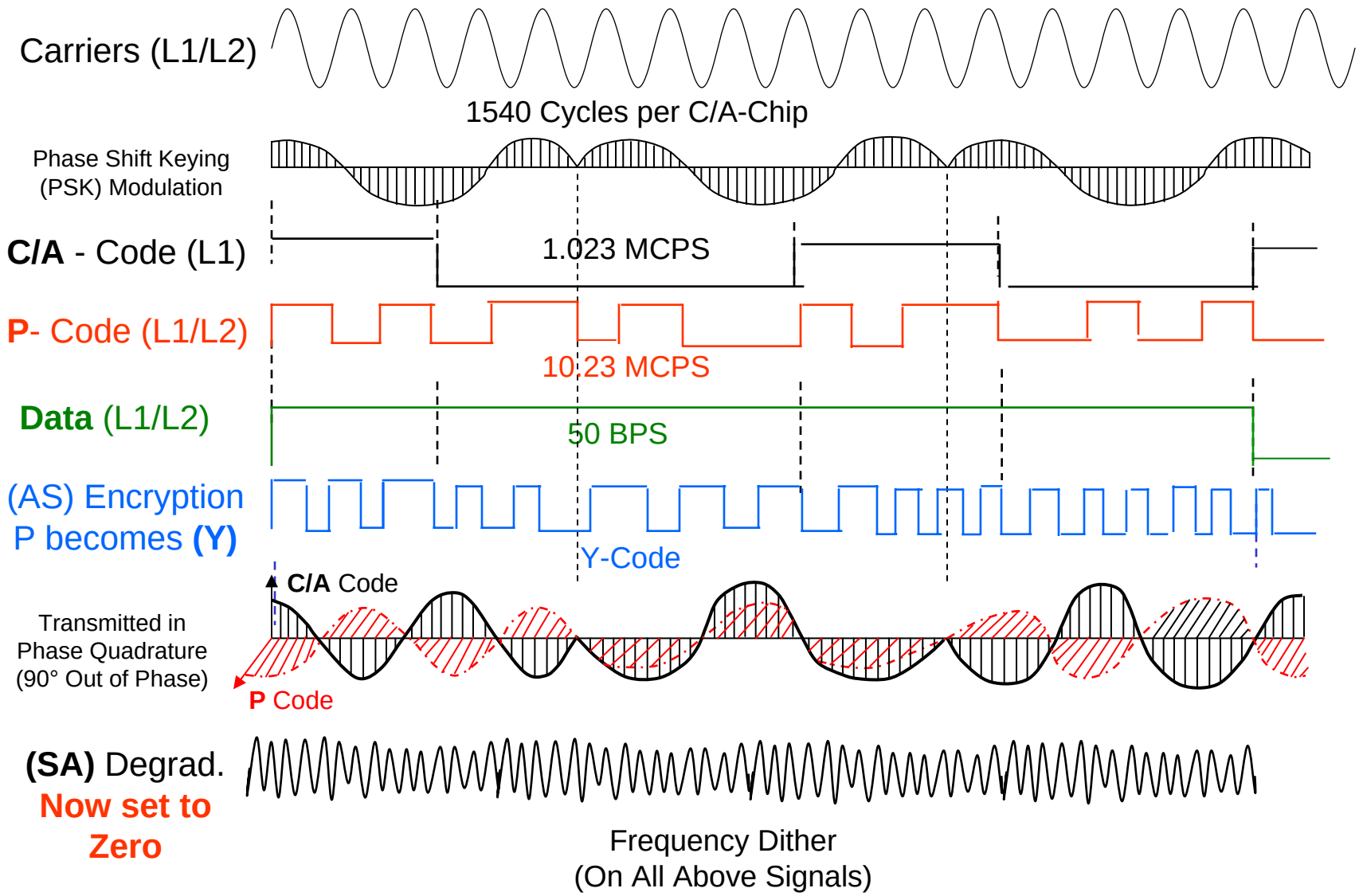


GPS

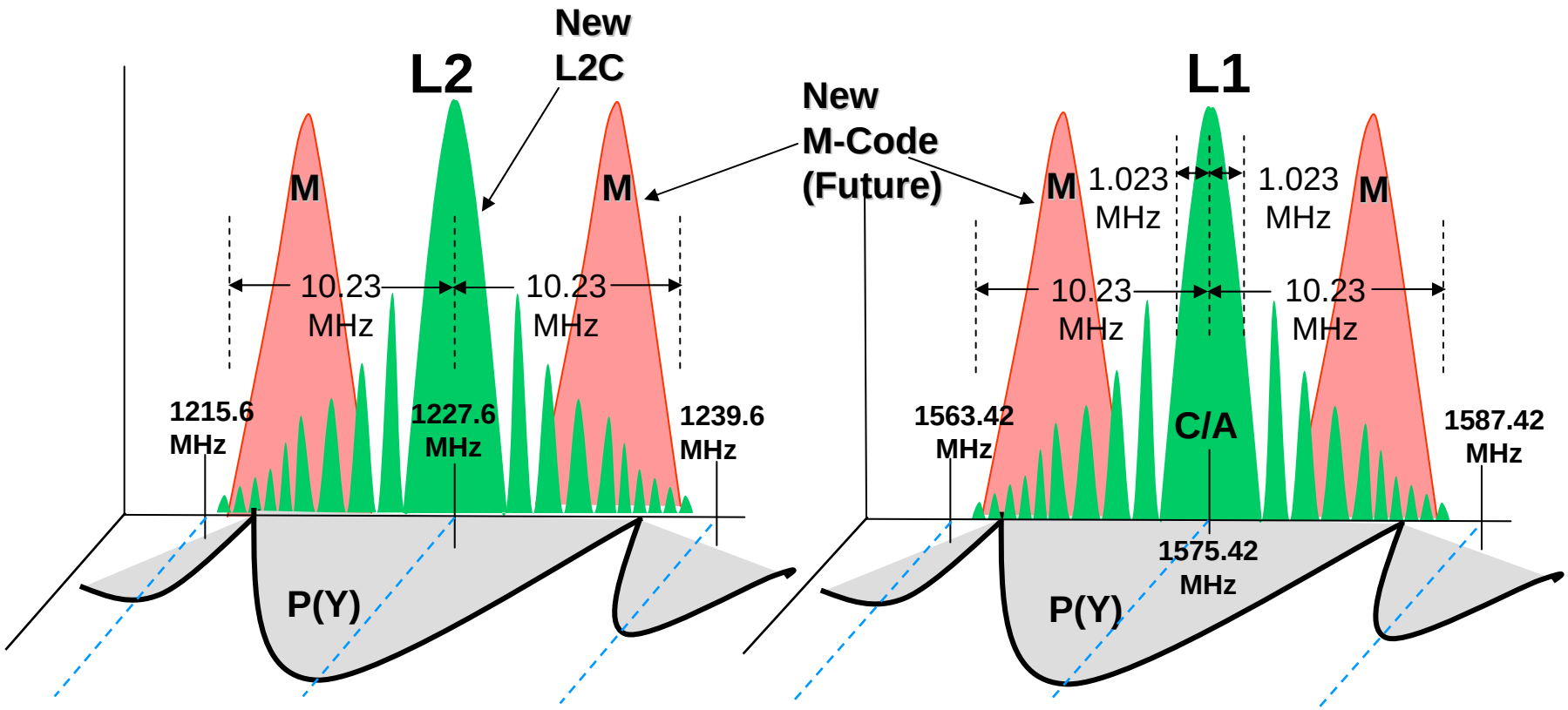
Parameter	GLONASS	GPS
Ephemeris information presentation method	9 parameters of s/c motion in the geocentric rectangular rotated coordinate system	Interpolation coefficients of satellite orbits
Geodesic coordinate system	SGS 85	WGS 84
Referencing of the ranging signal phases	To the timer of GLONASS system	To the timer of GPS system
System time corrections relative to the Universal Coordinated Time (UTC)	UTC (SU)	UTC (USNO)
Duration of the almanac transmission	2.5 min	12.5 min
Number of satellites in the full operational system	21 + 3 spares	21 + 3 spares
Number of orbital planes	3	6
Inclination	64.8°	55°
Orbit altitude	19100 km	20180 km
Orbital period	11 h 15 min	12 h
Satellite signal division method	Frequency Division	Code Division
Frequency band allocated (L1)	1602.5625-1615.5 ± 0.5 MHz	1575.42 ± 1MHz
Type of ranging code	PRN-sequence of maximal length	Gold Code
Number of code elements	511	1023
Timing frequency of code (C/A)	0.511 MHz	1.023 MHz
Crosstalk level between two neighboring channels	-48 dB	-21.6 dB
Synchrocode repetition period	2 sec	6 sec
Symbol number in the synchrocode	30	8

GPS Signal Structure

The GPS Carrier Modulation Signals



GPS Signal Structure



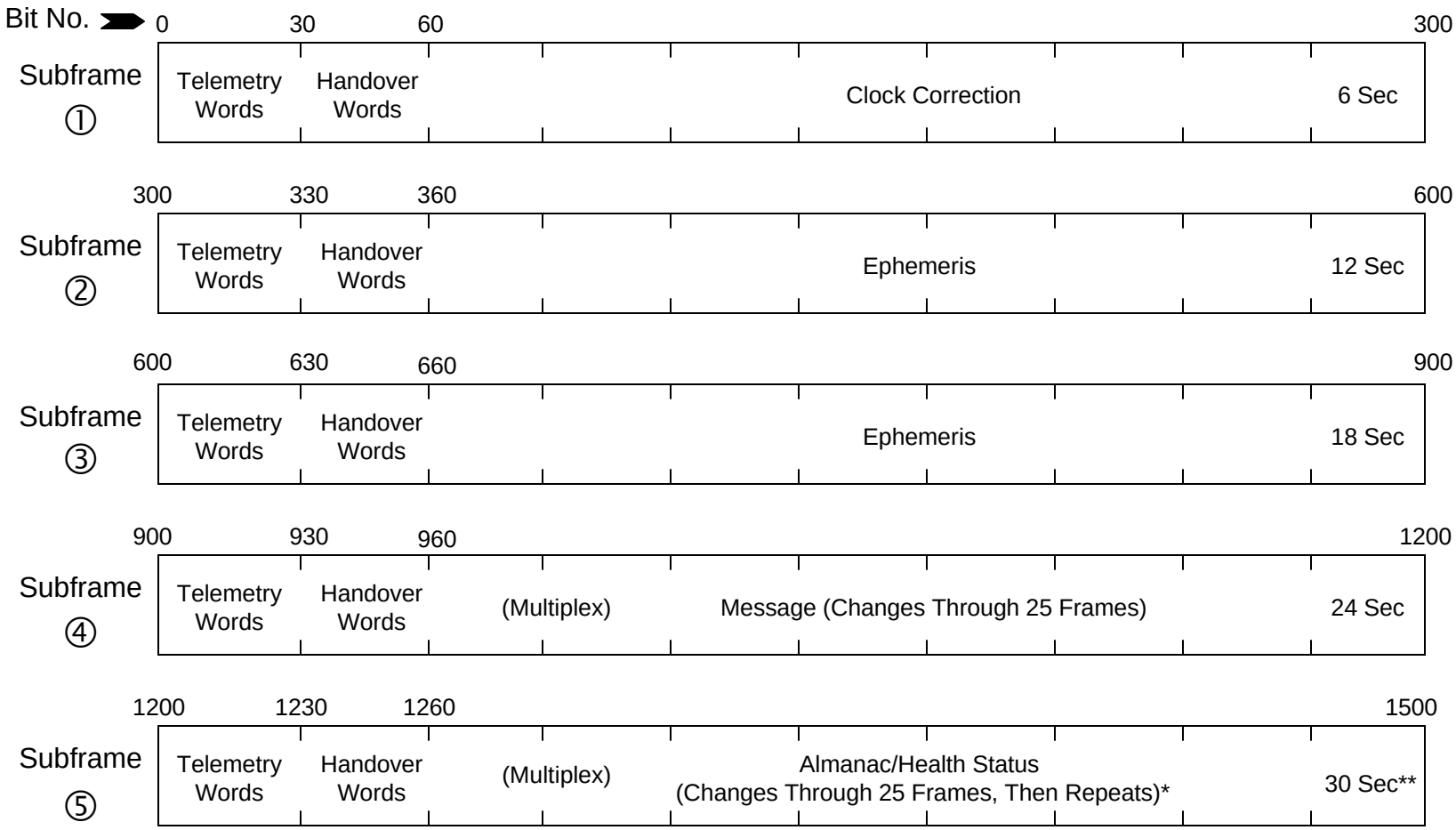
Spread Spectrum Signal, ~30 dB below the receiver ambient noise level

(Said to represent energy of a 25 watt light bulb at 11,000 miles distance)

GPS Signal Structure Overview

Carrier-Frequency	C/A Code	P-Code	(+) Encryption	Data	(S/A) Degradation
L1 1575.42 MHz	1.023 MHz Chipping Rate	10.23 MHz Chipping Rate	NSA/JPO Crypto Keys For Authorized Users Only	50 BPS	Selective Availability of C/A Signal
	Code Period 1023 Chips	Code Period 2.35469×10^{14} Chips (~38 weeks)		1500 Bit Frame, 5 subframes (30S); Each Subframe 300 Bits (6S); 30 Bits Word, 24 Bearer Bits, 6 Bits Parity; Total 12.5 Minutes	Dither at Output of Sat Clocks
	Code Repeats Every 1 ms ~1microsec Time Per Chip	Code is Reset Every Week			Degradation Level of C/A Selectable by Grd. Comd.
	Different Gold Code I.D.'s Each Sat	6.19658×10^{12} Chips/Week		"How" Word For P-Code Acq. (Each Subframe)	**NOW set to Zero**
	Spatial Length per bit: 290 m, 960 ft.	~0.1microsec Time Per Chip		Clock and UTC Correction	
		Same Code for Each Sat, But Different 7-day Section		User Range Accur. (URA)	
				Sat Health	
		37, 7-day Sections Available		Sat Configuration	
				Ionospheric Correction Model	
		Spatial Length per bit: 29 m, 96 ft.		Ephemeris	
				Coordinate Sys.	
				Almanac	
L2 1227.6 MHz	No-C/A	P-Only	Yes	Yes	Yes

GPS Data Message - 50 Bits Per Second



* Format of frame twenty-five changes

** 12.5 minutes before the entire message repeats

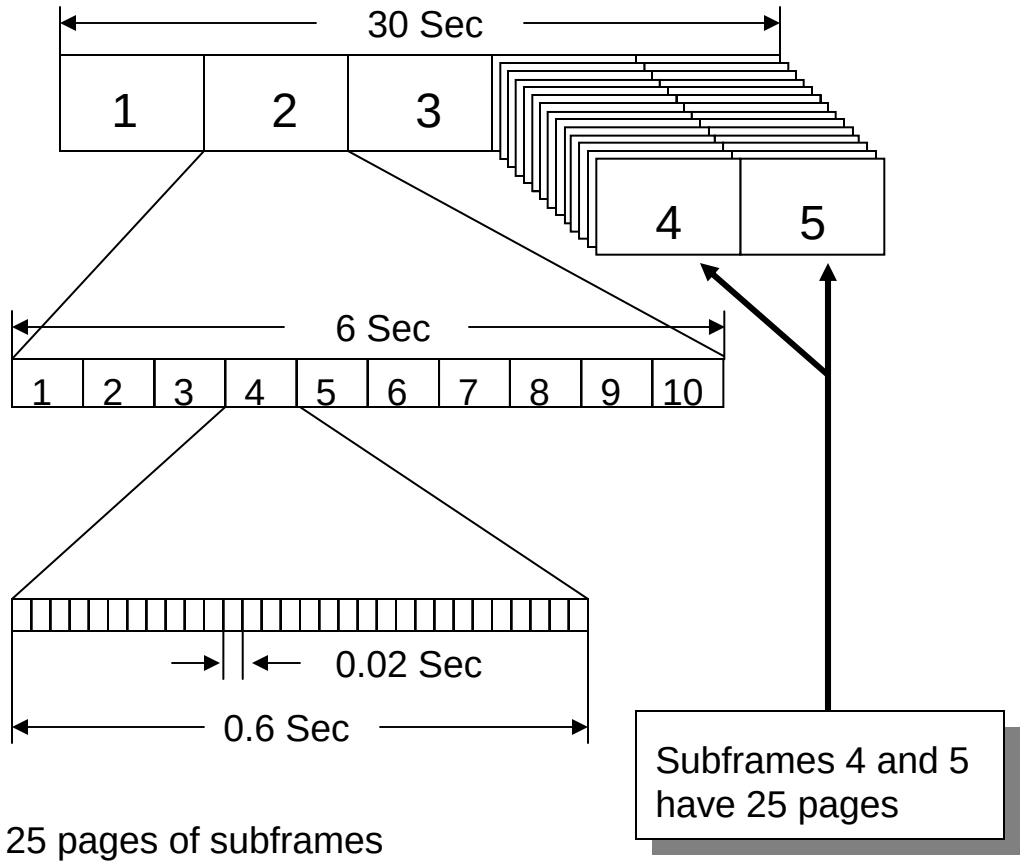
GPS Data Message Format

Basic message unit is one frame (1500 bits long)

1 frame = 5 subframes

1 subframe = 10 words

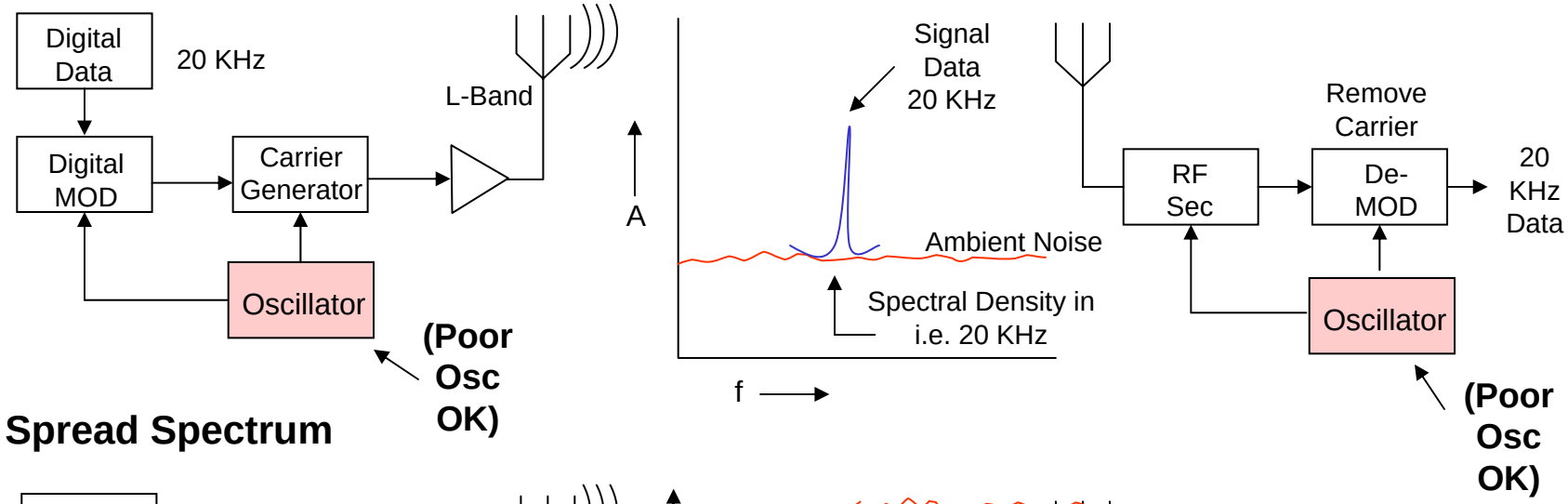
1 word = 30 bits



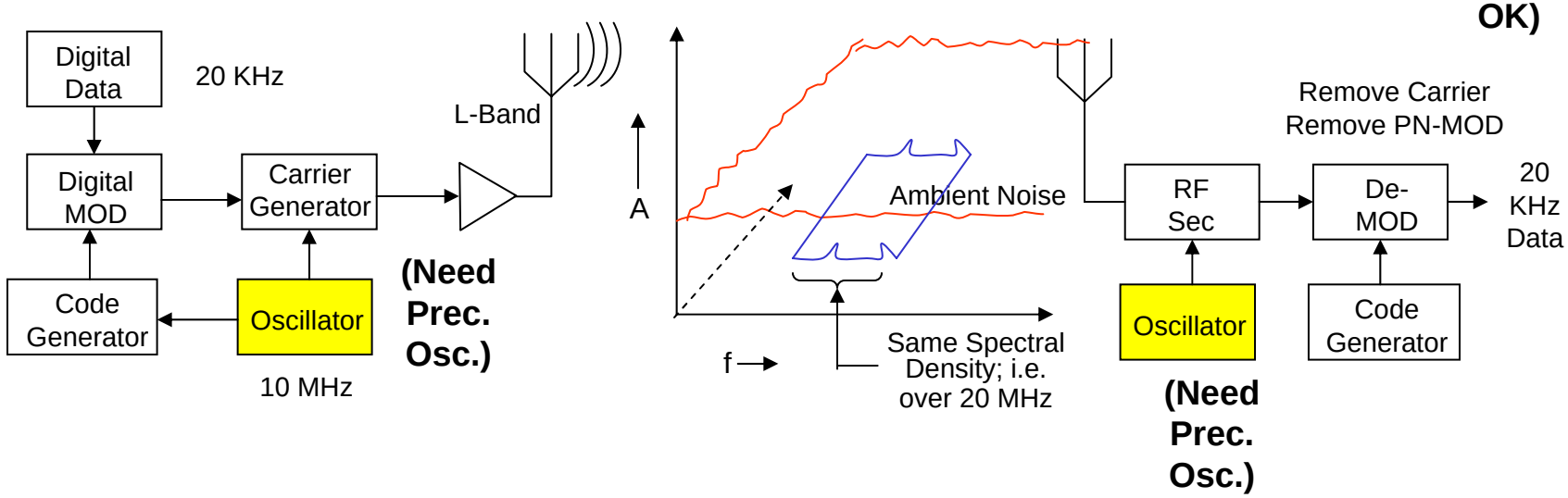
One MASTER FRAME includes all 25 pages of subframes 4 and 5 = 37,500 bits taking 12.5 minutes to transmit

Basic Spread Spectrum Concept

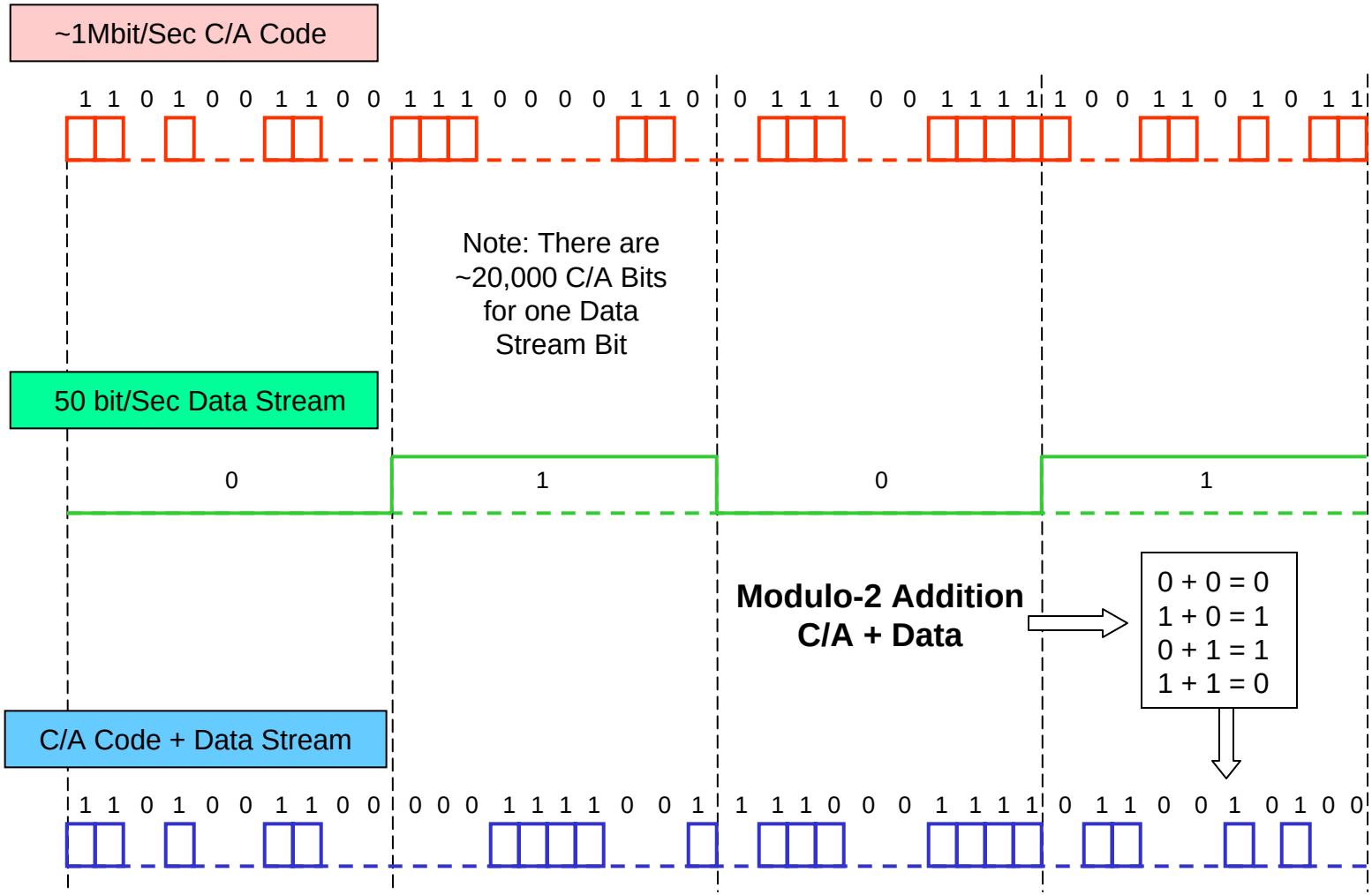
Conventional



Spread Spectrum



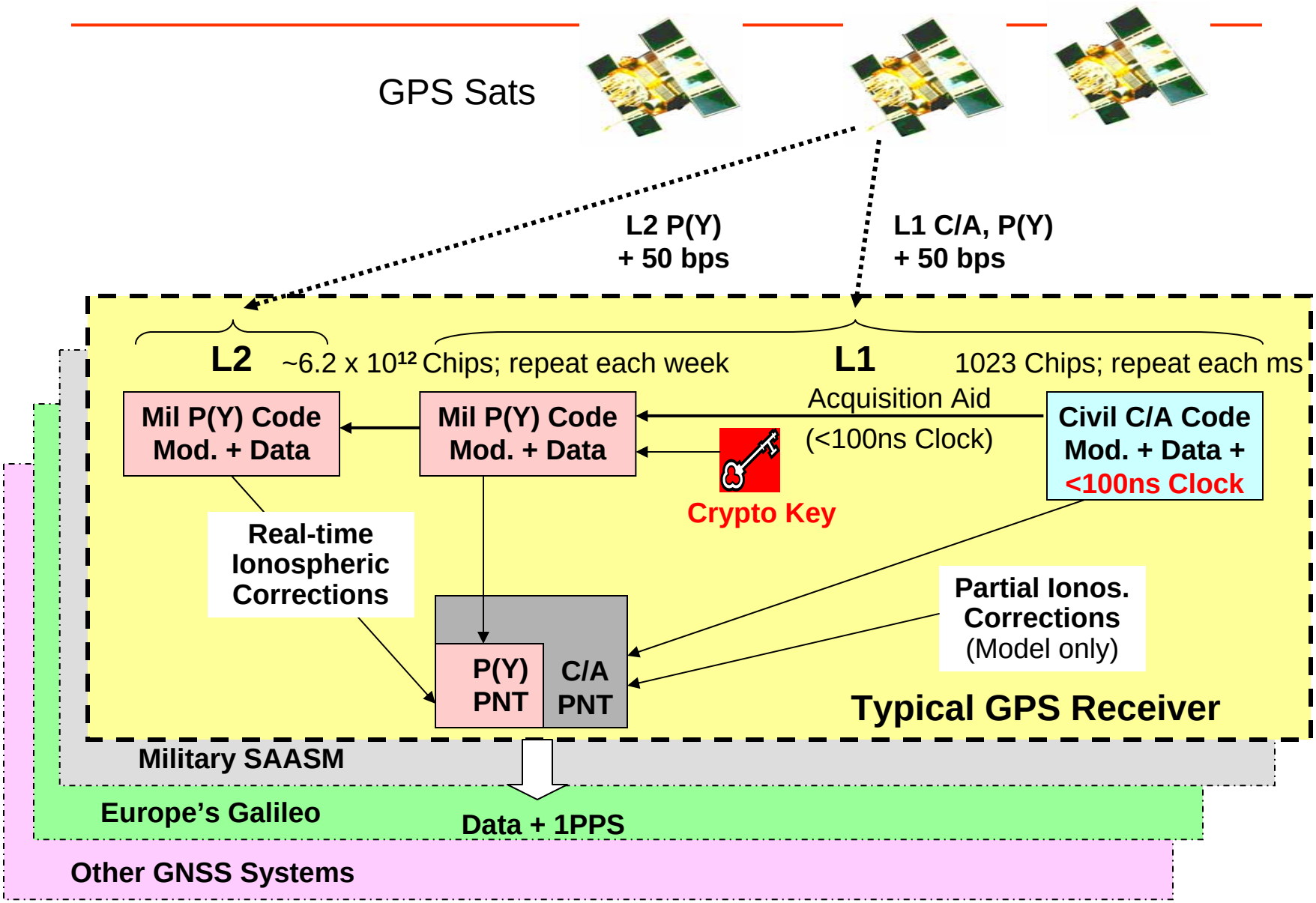
C/A-Code with Data Stream Superimposed



Note: The Data Stream is superimposed on both the ~1Mbit/Sec C/A-Code and the ~10 Mbit/Sec P-Code

GPS Signal Acquisition

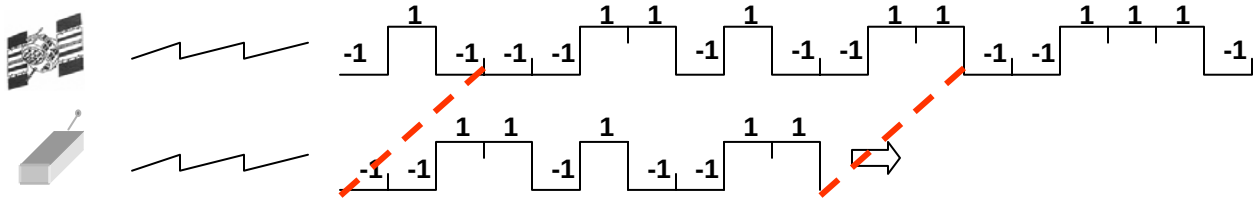
Civil and Military Signal Relationships



The Autocorrelation Function

Satellite C/A-Code

User Set matching C/A-Code



Autocorrelation Function $\frac{1}{N}\sum_{S=U}^{N} X_S \bullet X_U$

In the case above:

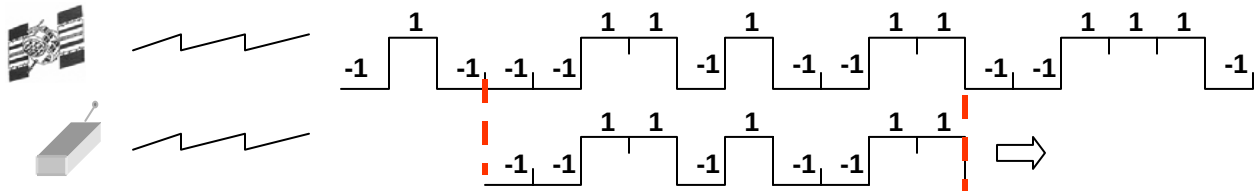
$$\frac{1}{10}\sum_{S=U}^{10} X_S \bullet X_U = (-1)(-1)+(1)(-1)+(-1)(1)+(-1)(1)+(-1)(-1)+(1)(1)+(1)(-1)+(-1)(-1)+(1)(1)+(-1)(1)$$

$$= \frac{1}{10}(+1-1-1-1+1+1-1+1+1+1-1) = 0$$

Shifting 3 bits (time) to the right gives:

Satellite

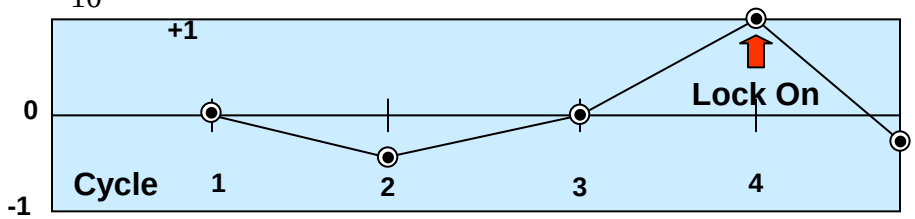
User Set



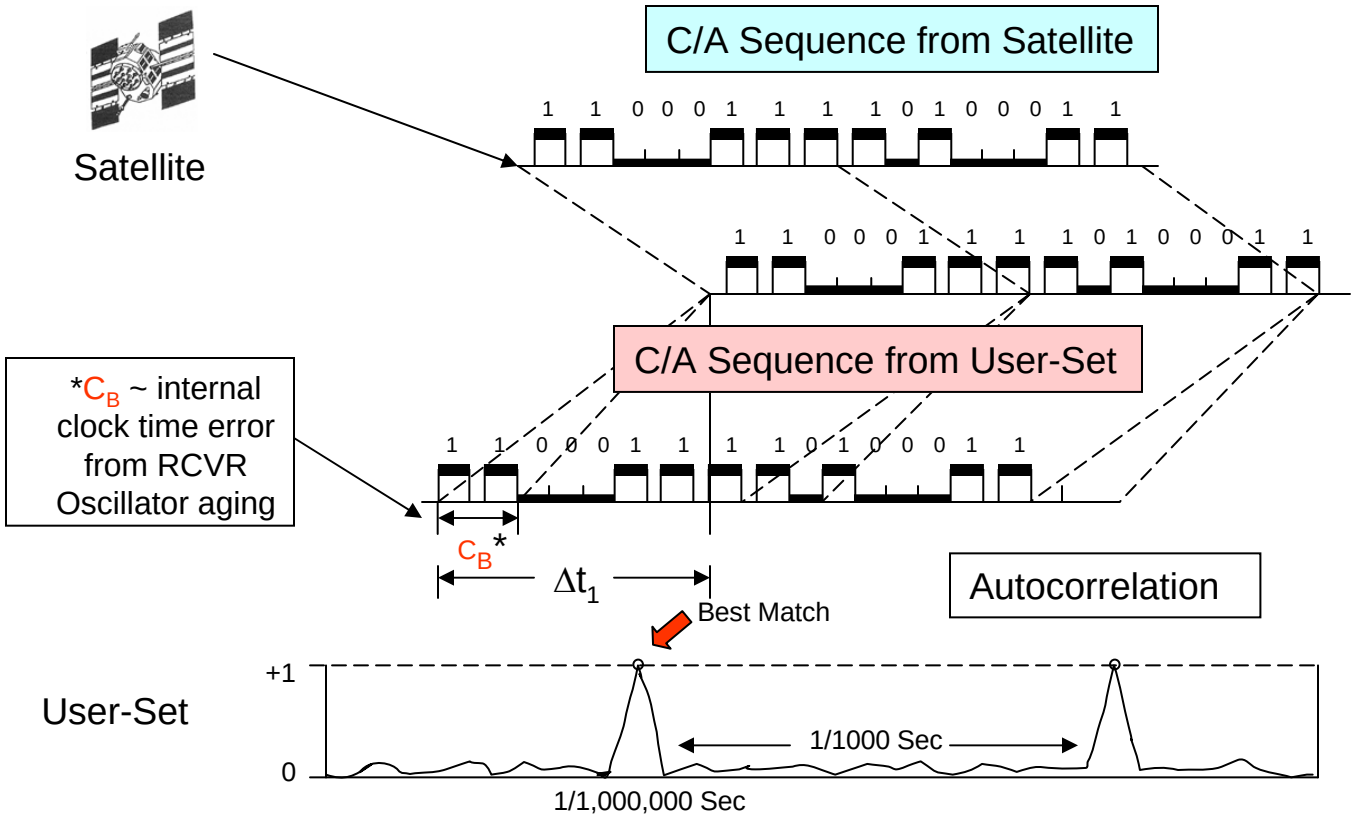
$$\frac{1}{10}\sum_{S=U}^{10} X_S \bullet X_U = (-1)(-1)+(-1)(-1)+(1)(1)+(1)(1)+(-1)(-1)+(1)(1)+(-1)(-1)+(-1)(-1)+(1)(1)+(1)(1)$$

$$= \frac{1}{10}(1+1+1+1+1+1+1+1+1+1) = 1$$

Autocorrelation Value



Acquiring the Clear Civil C/A Signal



Pseudo Ranges:

$R_1 = C\Delta t_1$

$R_2 = C\Delta t_2$

$R_3 = C\Delta t_3$

$R_4 = C\Delta t_4$

Position Equations:

$$(X_1 - U_X)^2 + (Y_1 - U_Y)^2 + (Z_1 - U_Z)^2 = (R_1 - C_B)^2$$

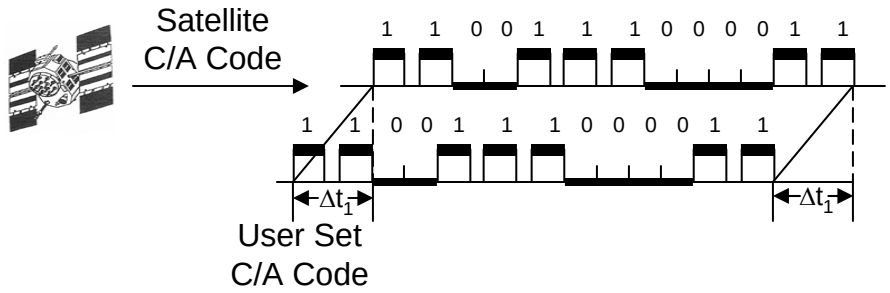
$$(X_2 - U_X)^2 + (Y_2 - U_Y)^2 + (Z_2 - U_Z)^2 = (R_2 - C_B)^2$$

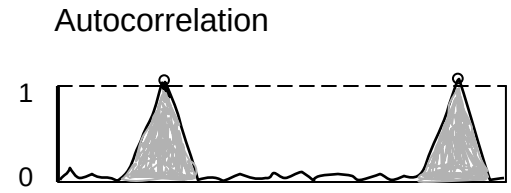
$$(X_3 - U_X)^2 + (Y_3 - U_Y)^2 + (Z_3 - U_Z)^2 = (R_3 - C_B)^2$$

$$(X_4 - U_X)^2 + (Y_4 - U_Y)^2 + (Z_4 - U_Z)^2 = (R_4 - C_B)^2$$

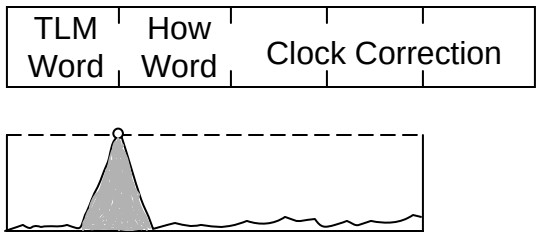
Acquiring the Military P(Y)-Code Signal

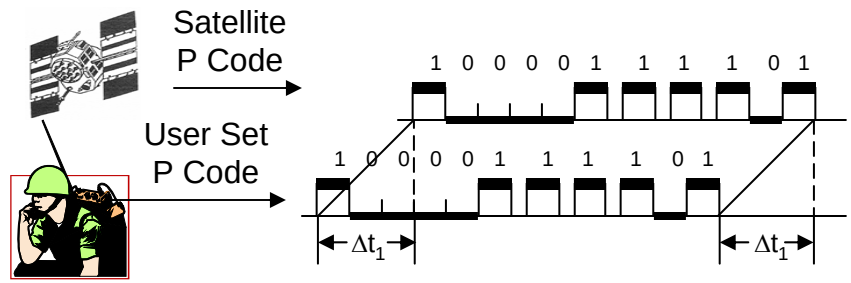
User-Set Matches the C/A Code





Strips off the Data - "How" Word Gives Address of P-Code Match





Pseudo Ranges:

$R_1 = C\Delta t_1$

$R_2 = C\Delta t_2$

$R_3 = C\Delta t_3$

$R_4 = C\Delta t_4$

Position Equations:

$$(X_1 - U_X)^2 + (Y_1 - U_Y)^2 + (Z_1 - U_Z)^2 = (R_1 - C_B)^2$$

$$(X_2 - U_X)^2 + (Y_2 - U_Y)^2 + (Z_2 - U_Z)^2 = (R_2 - C_B)^2$$

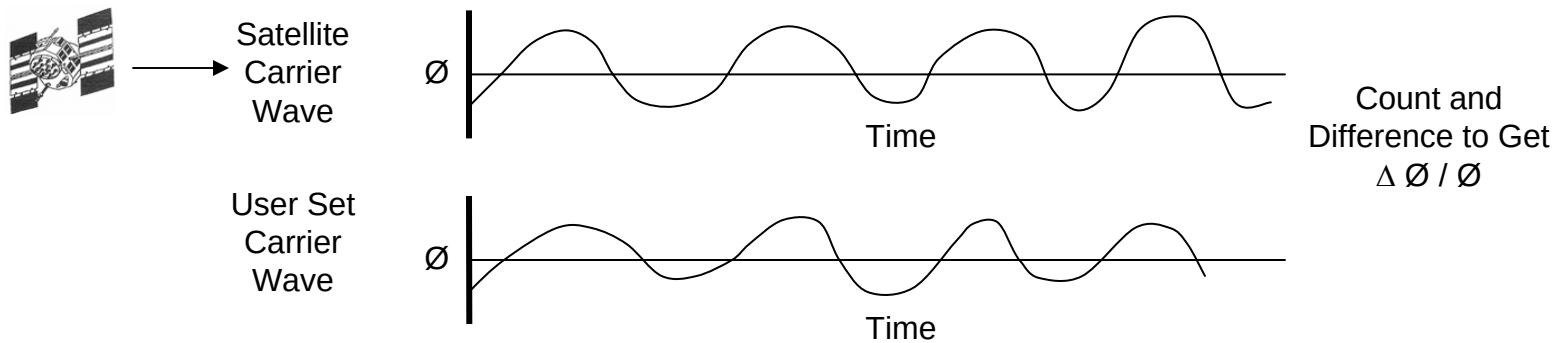
$$(X_3 - U_X)^2 + (Y_3 - U_Y)^2 + (Z_3 - U_Z)^2 = (R_3 - C_B)^2$$

$$(X_4 - U_X)^2 + (Y_4 - U_Y)^2 + (Z_4 - U_Z)^2 = (R_4 - C_B)^2$$

*C_B ~ 1/100 Sec for one week of user-set drift

Obtaining the Velocity Components

User-Set Locks onto Carrier to Obtain Doppler Shift



User-Set Performs the Navigation Solution for Velocity

Range Rates:

$\dot{R}_1 = \Delta Ø_1 / Ø_1 \, c$

$\dot{R}_2 = \Delta Ø_2 / Ø_2 \, c$

$\dot{R}_3 = \Delta Ø_3 / Ø_3 \, c$

$\dot{R}_4 = \Delta Ø_4 / Ø_4 \, c$

Velocity Equations:

$$(X_1 - U_X)(\dot{X}_1 - \dot{U}_X) + (Y_1 - U_Y)(\dot{Y}_1 - \dot{U}_Y) + (Z_1 - U_Z)(\dot{Z}_1 - \dot{U}_Z) = R_1(\dot{R}_1 + \dot{C}_B)$$

$$(X_2 - U_X)(\dot{X}_2 - \dot{U}_X) + (Y_2 - U_Y)(\dot{Y}_2 - \dot{U}_Y) + (Z_2 - U_Z)(\dot{Z}_2 - \dot{U}_Z) = R_2(\dot{R}_2 + \dot{C}_B)$$

$$(X_3 - U_X)(\dot{X}_3 - \dot{U}_X) + (Y_3 - U_Y)(\dot{Y}_3 - \dot{U}_Y) + (Z_3 - U_Z)(\dot{Z}_3 - \dot{U}_Z) = R_3(\dot{R}_3 + \dot{C}_B)$$

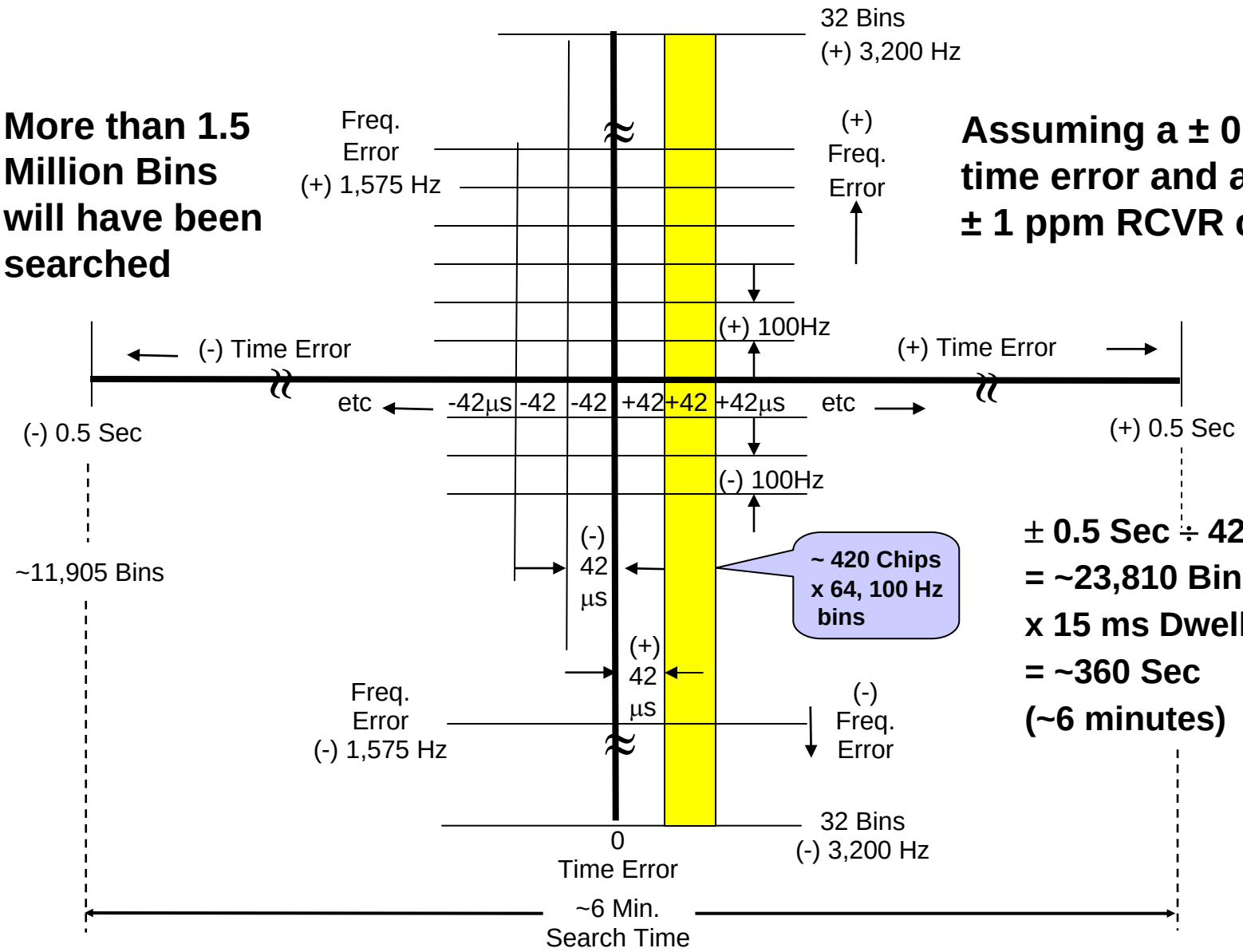
$$(X_4 - U_X)(\dot{X}_4 - \dot{U}_X) + (Y_4 - U_Y)(\dot{Y}_4 - \dot{U}_Y) + (Z_4 - U_Z)(\dot{Z}_4 - \dot{U}_Z) = R_4(\dot{R}_4 + \dot{C}_B)$$

Where $\dot{C}_B$ = Frequency Drift in the User-Set Clock

Rough example of a typical search process

More than 1.5 Million Bins will have been searched

Assuming a ± 0.5 sec time error and a ± 1 ppm RCVR clock



± 0.5 Sec ÷ 42 µs/Bin
= ~23,810 Bins
x 15 ms Dwell Time
= ~360 Sec
(~6 minutes)

Elements Involved in GPS Acquisition

External Factors

- **Jamming or ambient noise level**
- **Signal blocking (canyons, buildings, trees, etc.)**
- **Civil (C/A) signal availability (level of SA, if on)**
- **Number of satellites in view**
- **Position of satellites (GDOP)**
- **Motion (and frequency of change) of GPS platform**
- **Velocity (Doppler) of GPS platform**
- **Vibration and Shock forces**
- **Initialization Parameters (Time and Position)**

Internal Factors (RCVR)

- **Acquisition sequence with C/A and P-Codes**
- **Signal Processing Architecture and Mfr's SW savvy**
- **Type of Key, if using PPS receiver**
- **Age of the ephemeris and Almanac**
- **Averaging Time of PVT Solutions**
- **RCVR noise level**
- **RCVR oscillator spec**

GPS Dilution of Precision

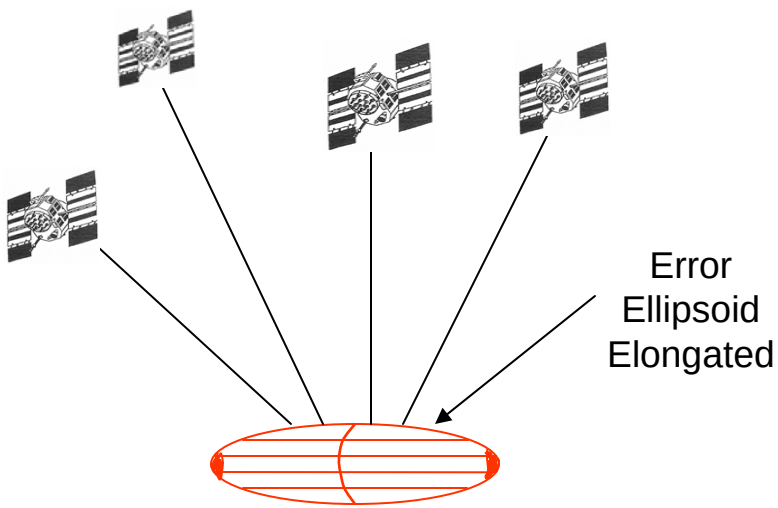
Satellite Geometry and GDOP

$$\sigma_p = DOP * \sigma_m$$

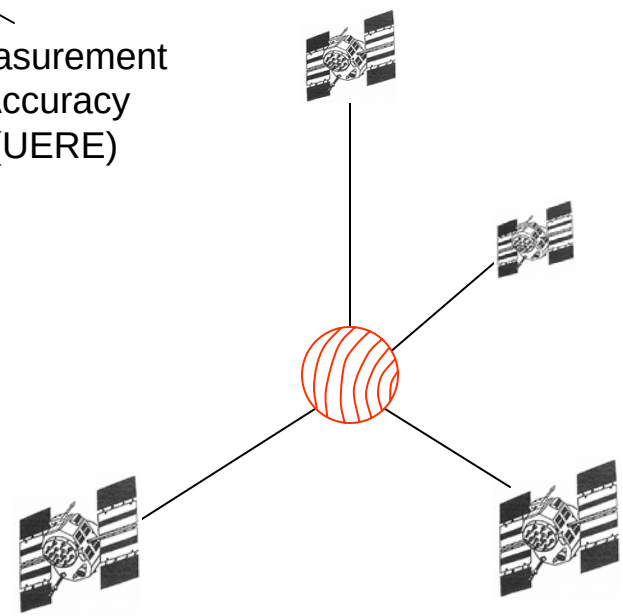
Positioning Accuracy (X, Y, Z)

Geometry (Dilution of Precision)

Measurement Accuracy (UERE)



Poor GDOP
Satellites bunched together

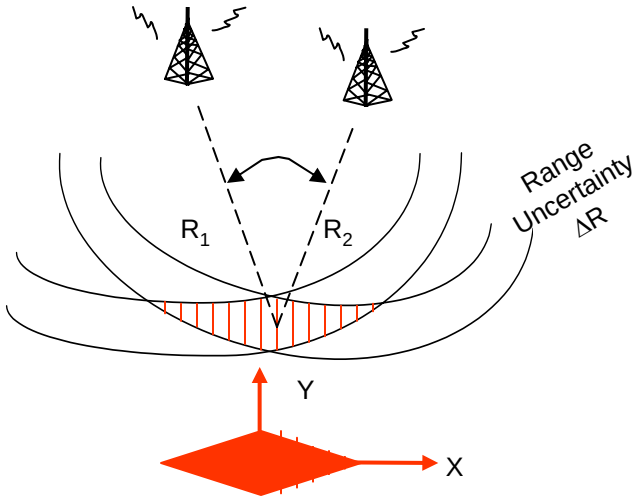


Good GDOP
(ideal case)

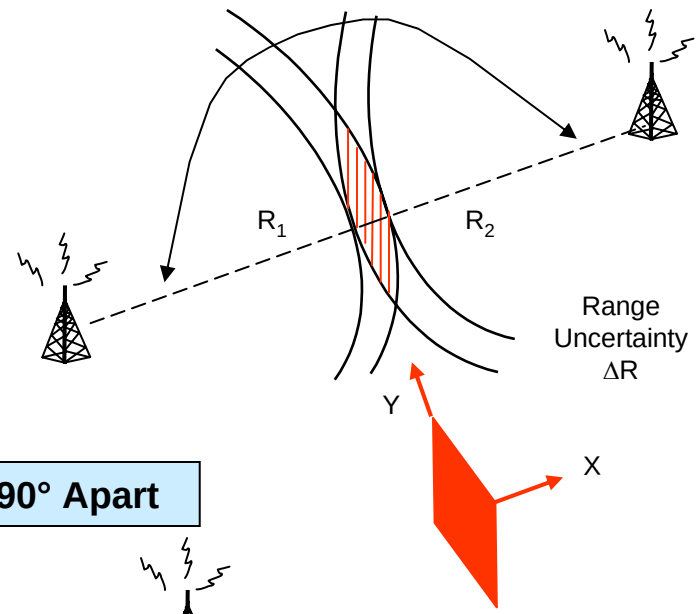
- One satellite overhead
- 3 on horizon, 120° apart in azimuth

What is Geometric Delusion of Precision (GDOP)?

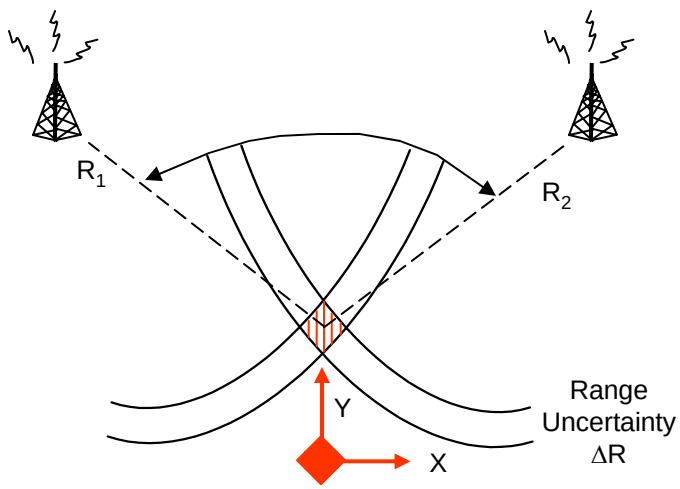
Two Transmitters Near Side by Side



Two Transmitters Near 180° Apart



Two Transmitters 90° Apart



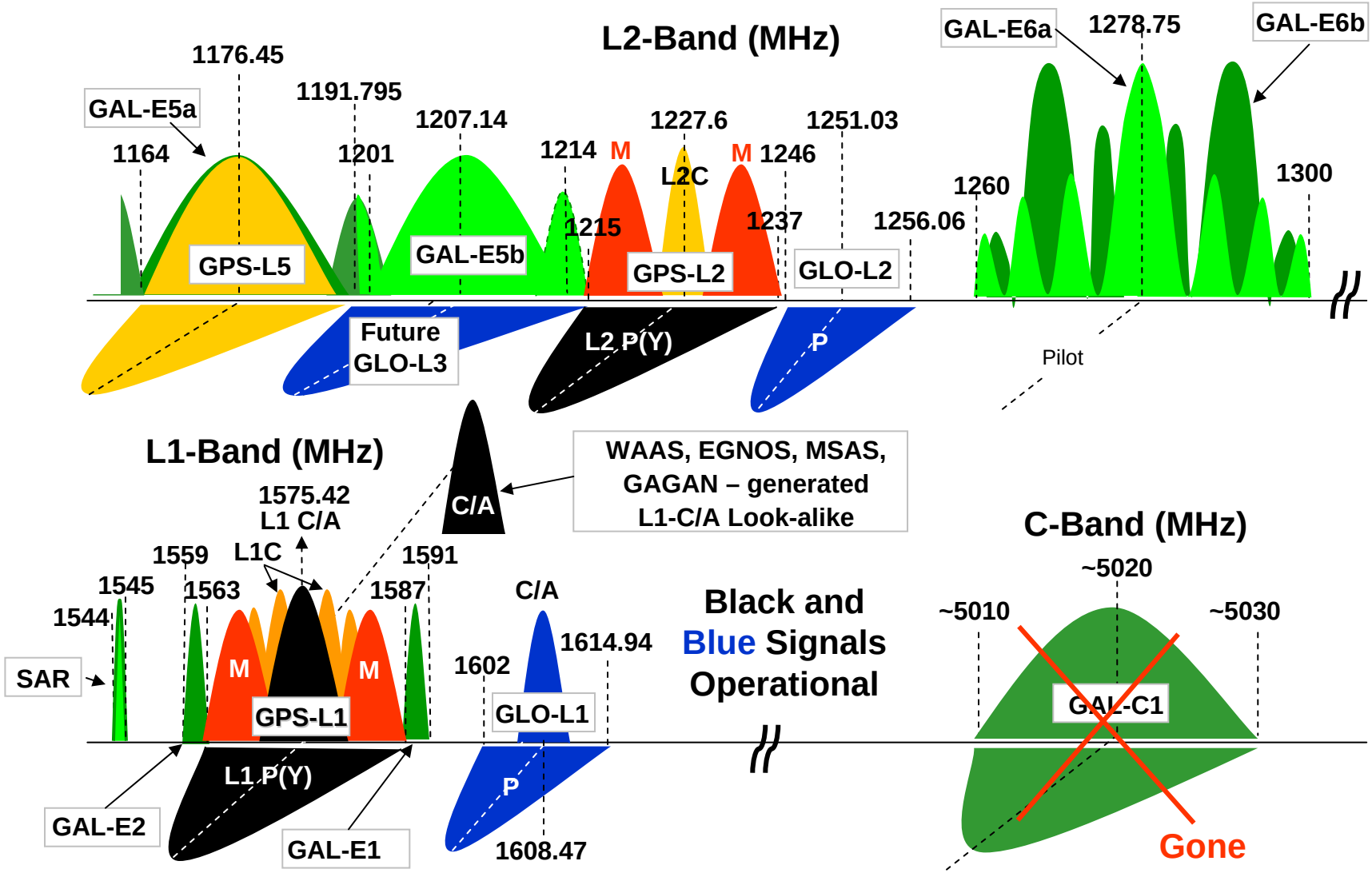
Optimum

$$\Delta X = \Delta Y$$

$$\sim \sqrt{2}(X)(\Delta R)$$

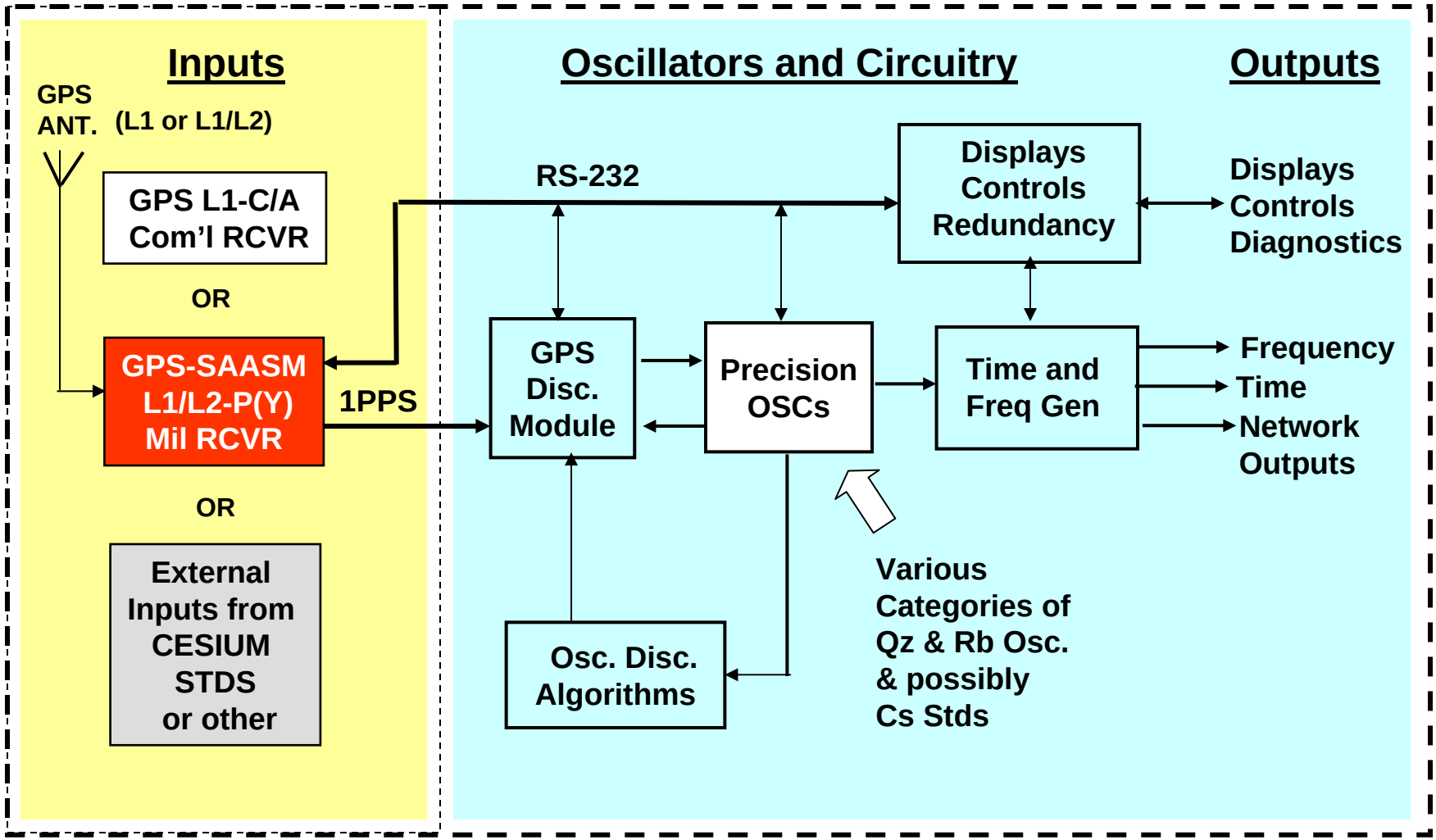
Future Signal Structure

Present & Upcoming GPS, Glonass & Galileo Signals

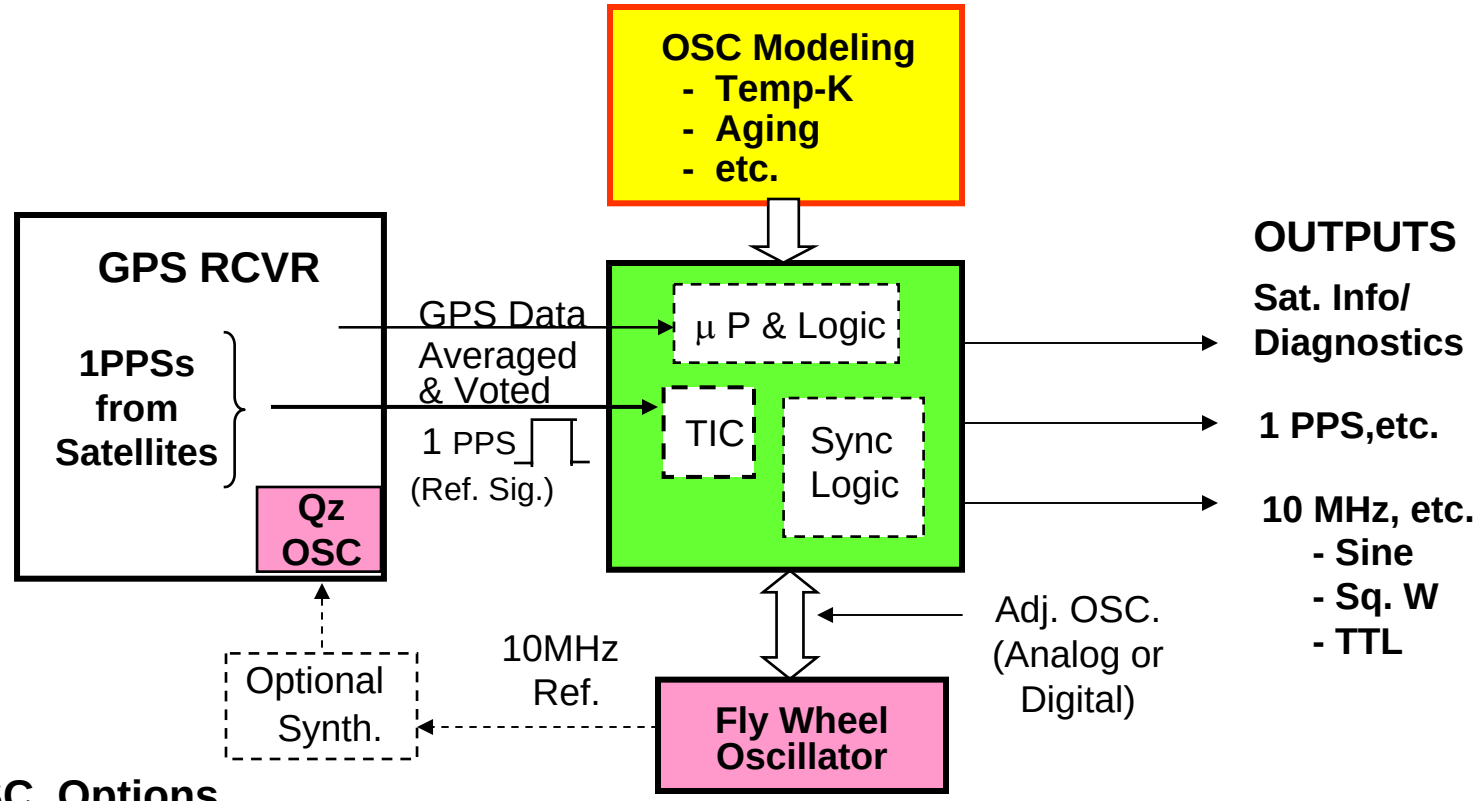


The GPS Sync Engine

Time & Frequency System Building Blocks



Typical GPS Sync Engine Details

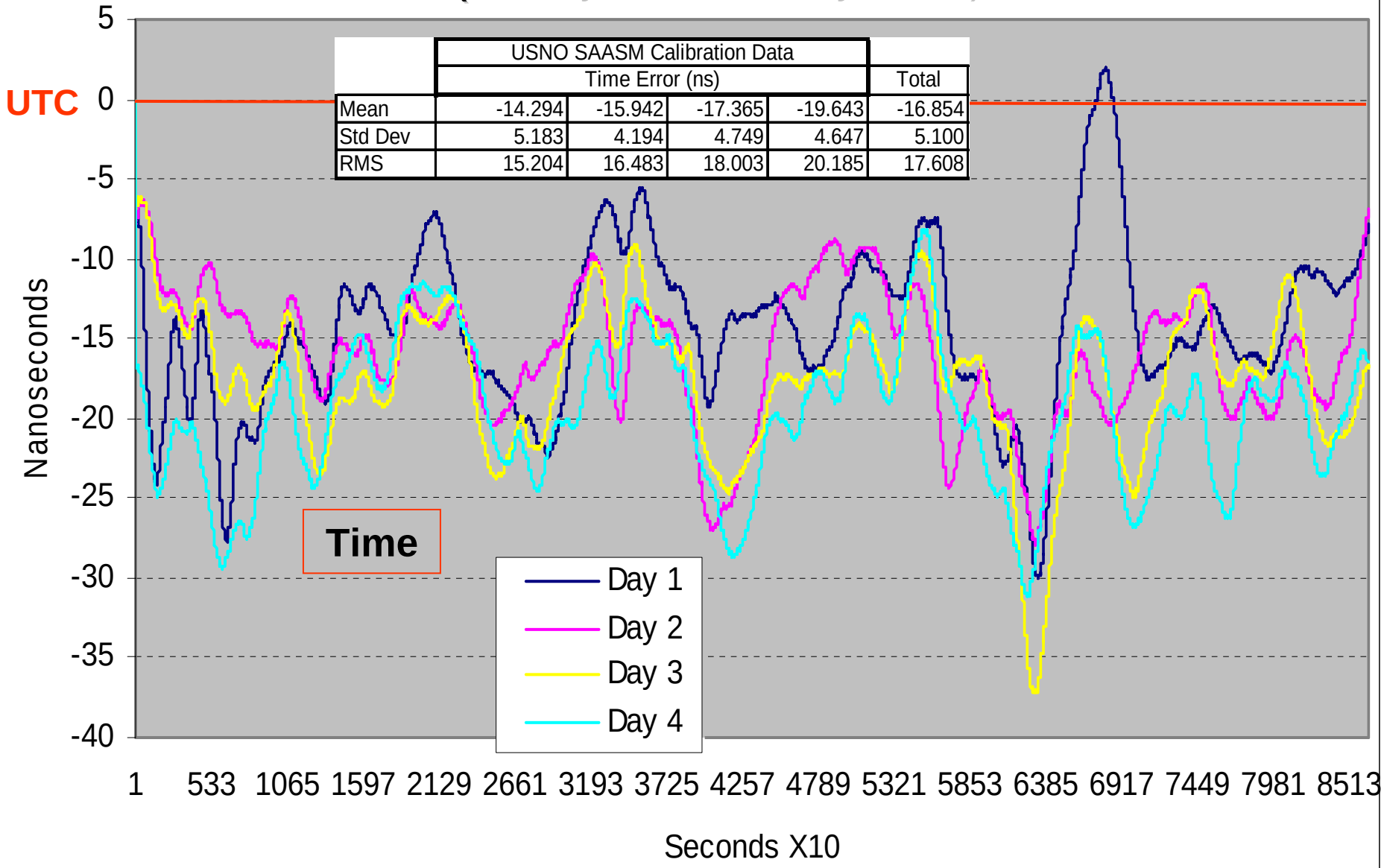


OSC. Options

TCXO	**no-holdover**	**average performance**
OCXO	**good holdover**	**good performance**
DOCXO	**better holdover**	**better performance**
Rubidium	**best holdover**	**best performance**

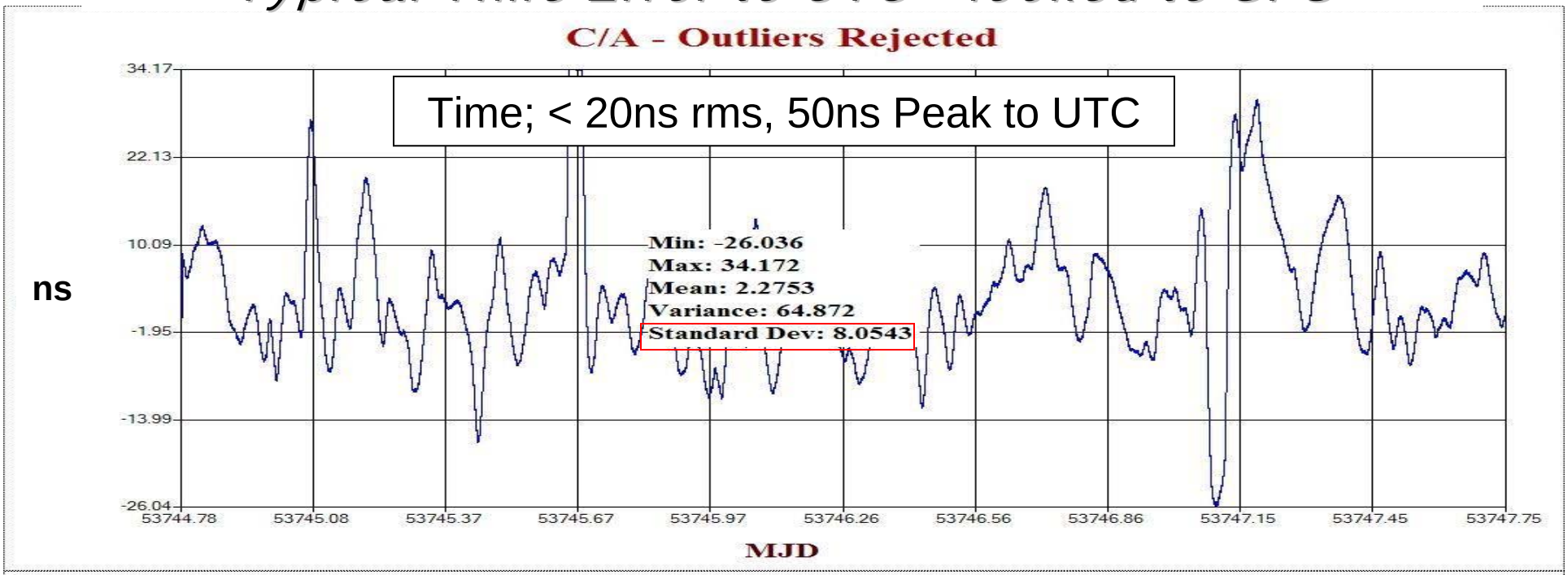
Typical Time Error to UTC – locked to GPS

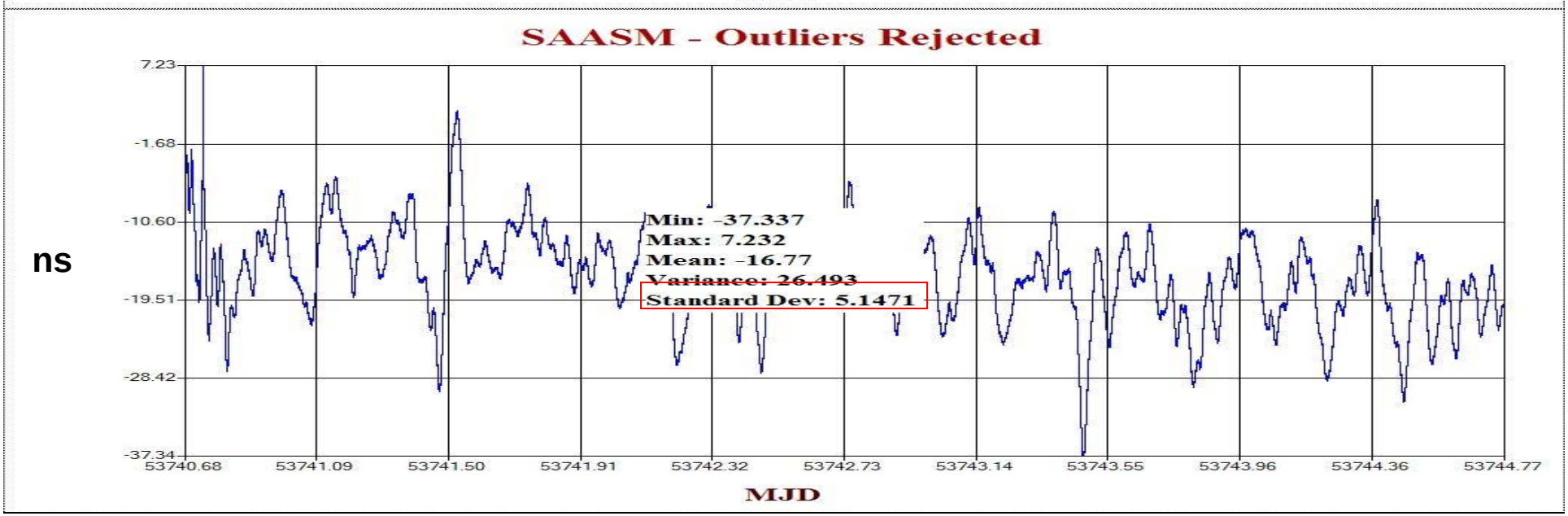
(T/F System, 4-Day Test)



	USNO SAASM Calibration Data				
	Time Error (ns)				Total
Mean	-14.294	-15.942	-17.365	-19.643	-16.854
Std Dev	5.183	4.194	4.749	4.647	5.100
RMS	15.204	16.483	18.003	20.185	17.608

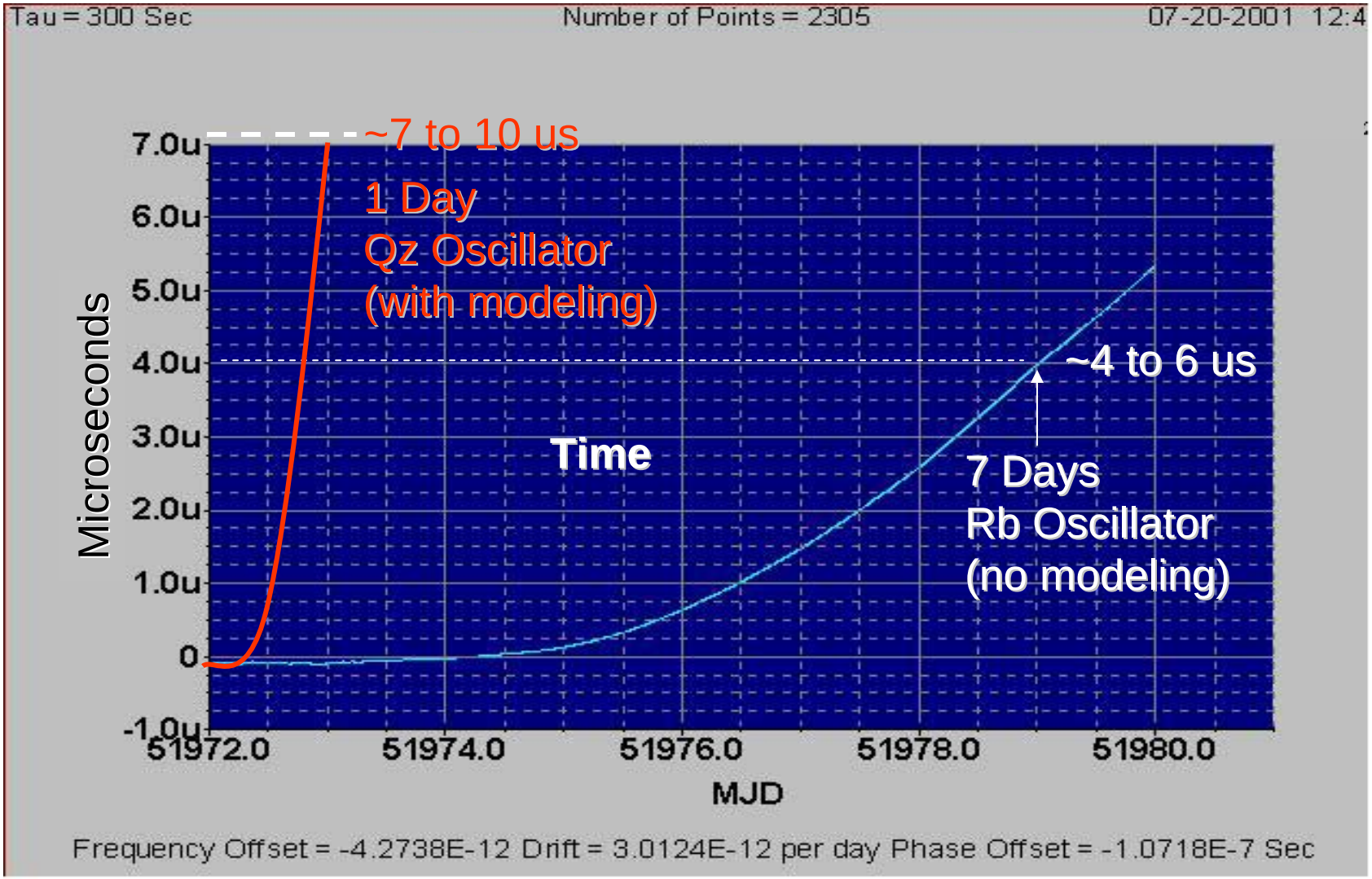
Typical Time Error to UTC – locked to GPS





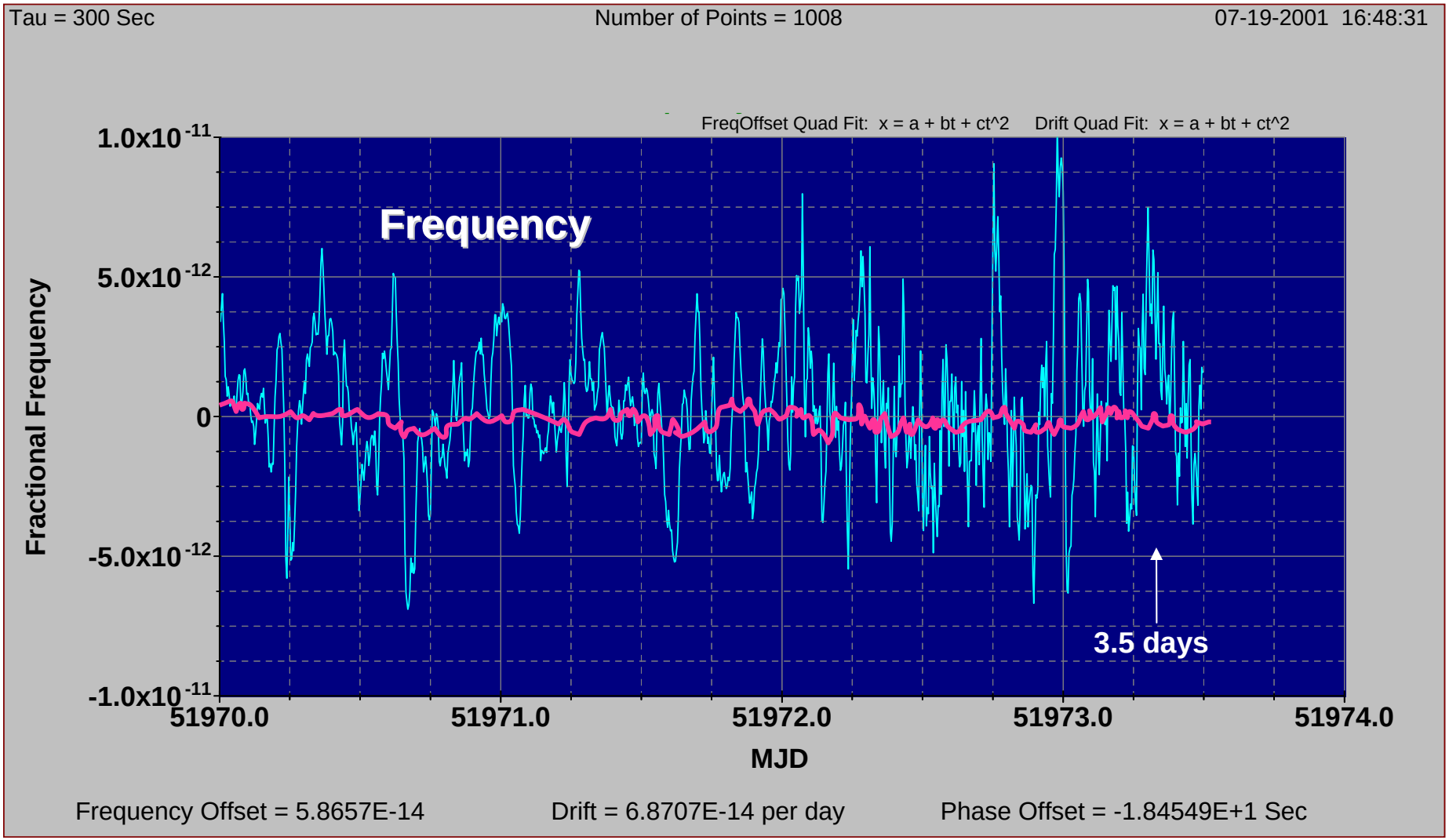
Typical Holdover Time Error to UTC – unlocked

(T/F System)



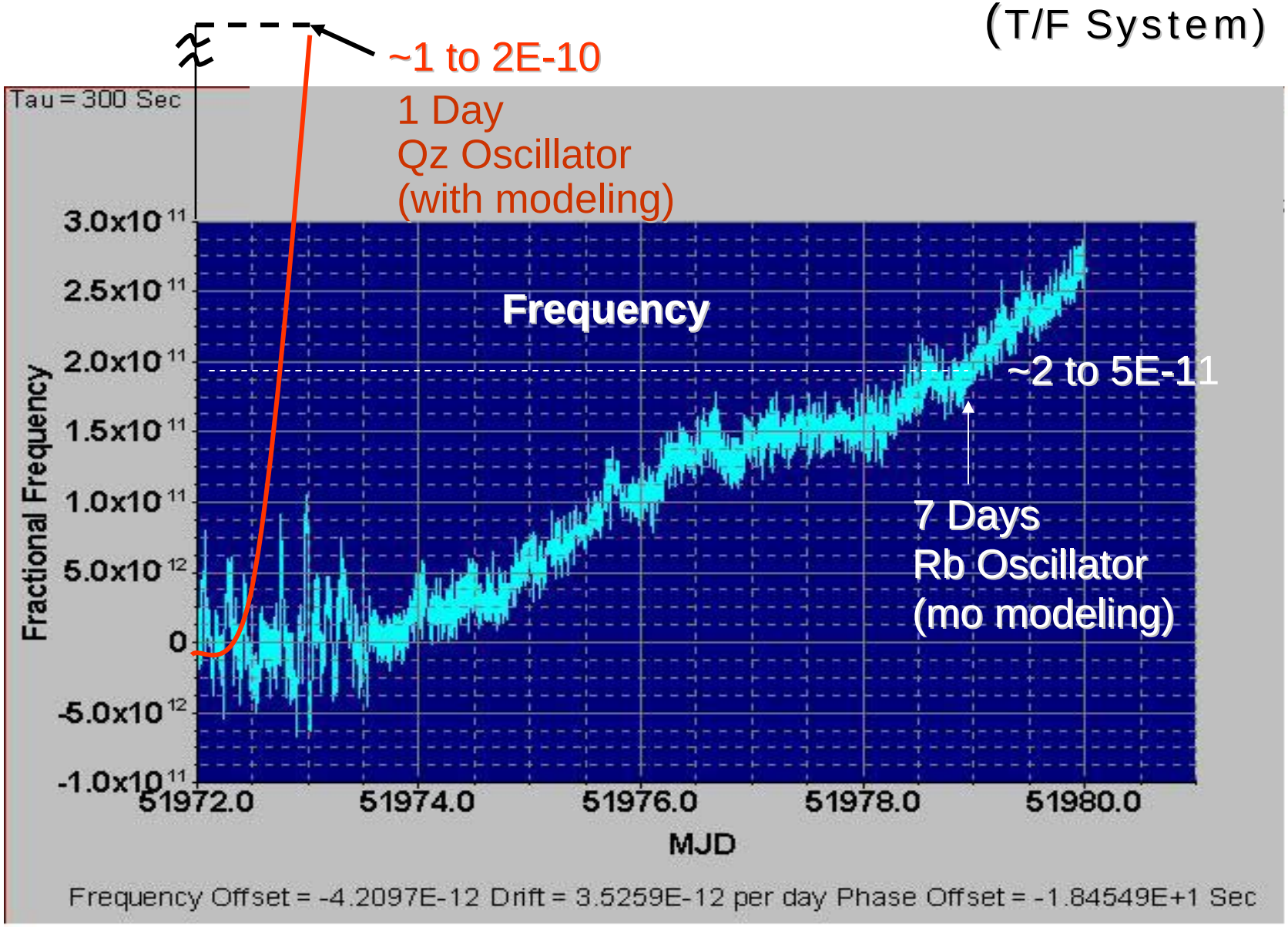
Typical Frequency Error to UTC – locked to GPS

(T/F System)

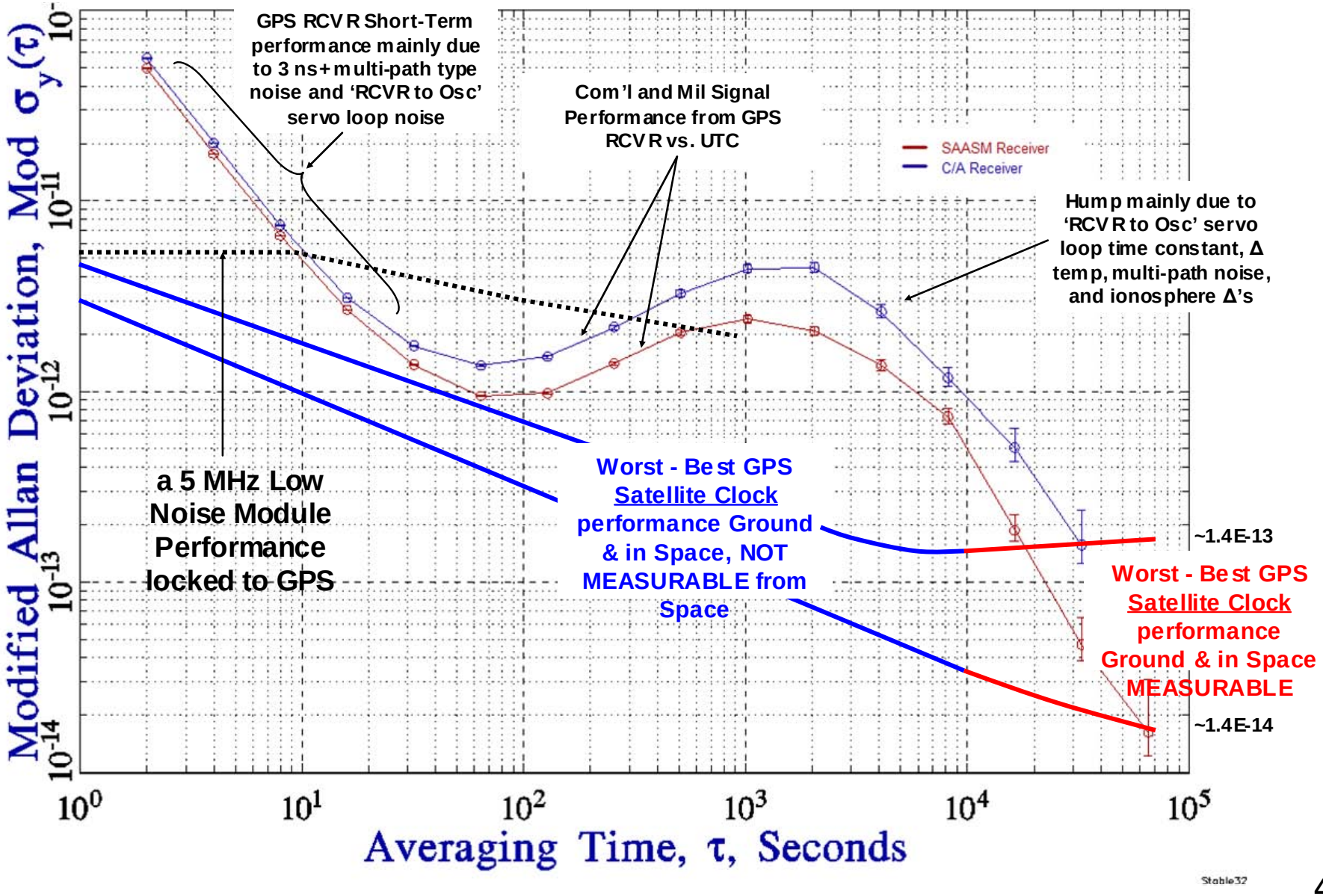


Typical Holdover Freq. Error to UTC – unlocked

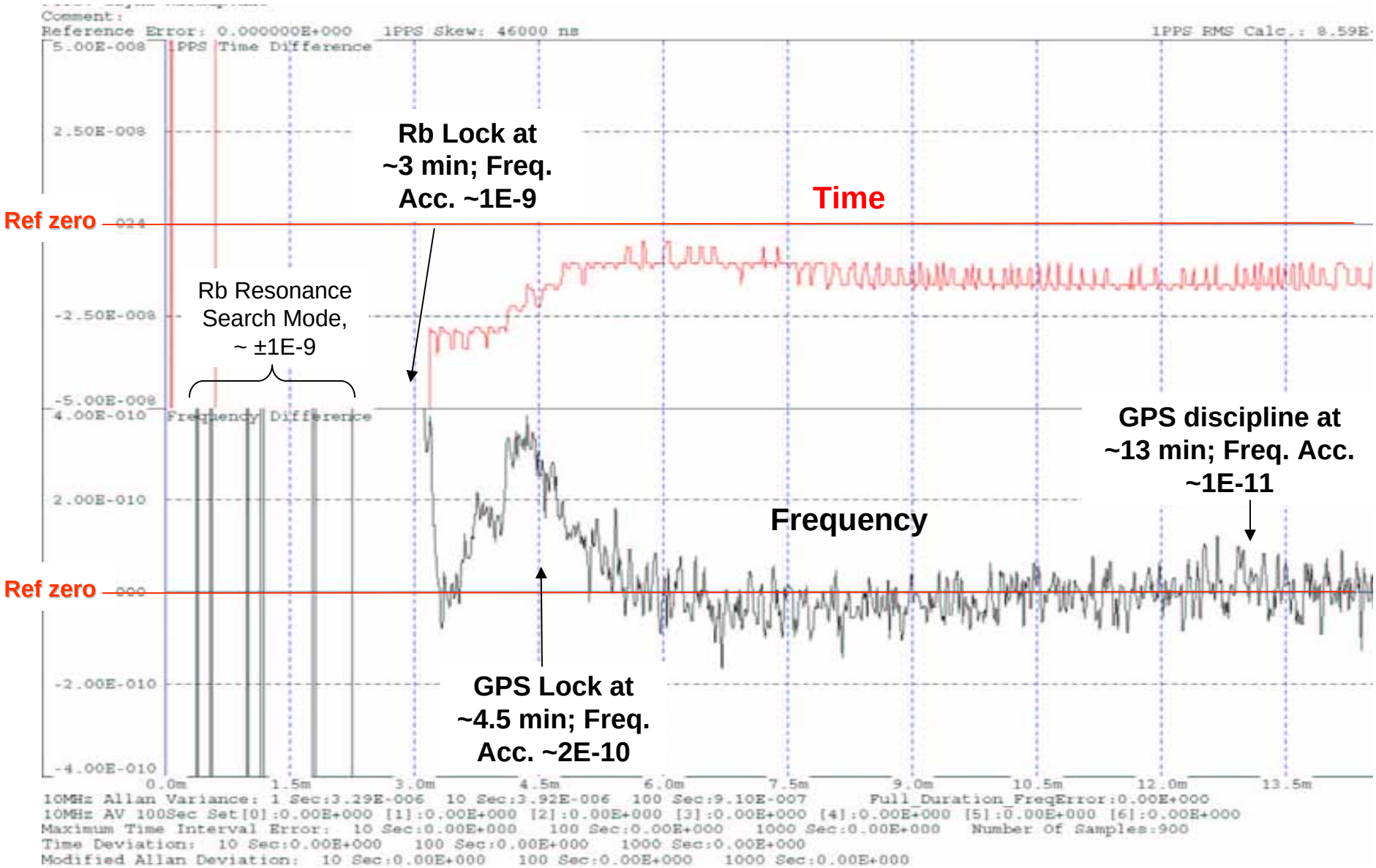
(T/F System)



Frequency Stability – GPS disciplined Oscillator



Typical Freq. & Time Accuracy vs. Warm-up Time



What *"is" (was)* SA?

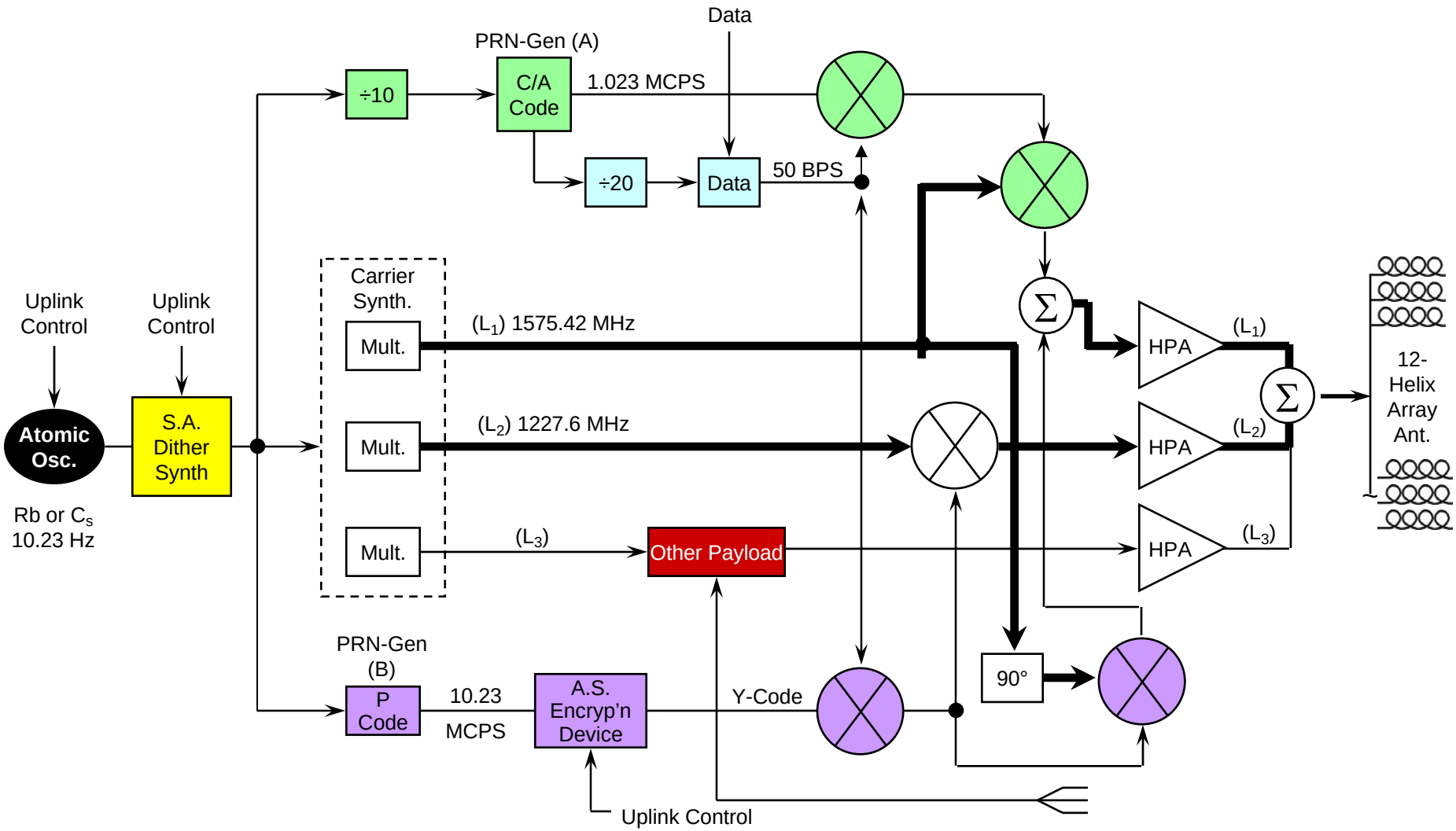
SA Origin

- **The initial GPS Block-I Satellites were launched in the late ’70’s early ’80’s**
  - These did not have SA capability
- **After testing the initially deployed satellite constellation, it was realized that the “in-the-clear” C/A signal PVT Solutions (Position, Velocity, and Time) were far more accurate than expected (20 to 30m vs. expected >100m)**
  - Hence, the need to protect our forces against the use of C/A by our adversaries during times of conflict
  - All GPS satellites thereafter had SA capability and activated to ~100m, 340ns, 3σ
    Starting 1983 (per Federal Radio Navigation Plan)

What is SA?

- A deliberate signal distortion affecting the accuracy of the C/A-Code derived PVT
- When activated, the effects are worldwide and cannot easily be implemented in selected geographic areas
- The distortion is generated by each satellite and the magnitude of the distortion is set by a ground station uplink command.
- SA basically consists of:
  - SA induced **"Range"** uncertainty of C/A-derived PVT solution
  - **Range** distortion can be set from zero (no SA effect) to 1000s of meters and many microseconds

Simplified GPS Satellite Navigation Package



How is SA Generated?

- **The SA Error consists of the sum of two elements:**
  - EPSILON, a bias component (reporting an incorrect SV position in the Nav message)
  - DITHER, a rapidly varying component (Dithering the clock output)
  - The period of oscillations is 2 to 5 minutes
  - Works well, degrading the PVT accuracy of the un-aided, moving C/A-Code user
- **For the authorized crypto-key P(Y)-Code user:**
  - Computes EPSILON error to obtain true SV position
  - Computes DITHER offsets to obtain true time of transmission
  - All done in SW in the PPS receiver

Problems with SA

- **The SA Clock dither has a de-correlation time of 300 – 400 seconds (D. Allan, W. Dewey)**
  - For averaging times shorter than 300s, clock dither can be modeled as a random walk phase modulation
  - For averaging times greater than 300s, clock dither can be modeled as white noise phase modulation
- **SA is routinely defeated by the World's Communications infrastructure, having stationary terminals**
  - Long averaging times with a non-repositioning terminal will allow algorithms to filter out SA
- **SA is routinely defeated with DGPS networks which, through some form of RF link, can send differential corrections (with SA filtered out) to the moving platforms**