Earth Science Applications of Space Based Geodesy

DES-7355

Tu-Th 9:40-11:05

Seminar Room in 3892 Central Ave. (Long building)

Bob Smalley
Office: 3892 Central Ave, Room 103
678-4929
Office Hours – Wed 14:00-16:00 or if I' m in my office.

http://www.ceri.memphis.edu/people/smalley/ESCI7355/ESCI_7355_Applications_of_Space_Based_Geodesy.html

Class 5

GPS Signals

GPS signals are broadcast on 2 L-band carriers

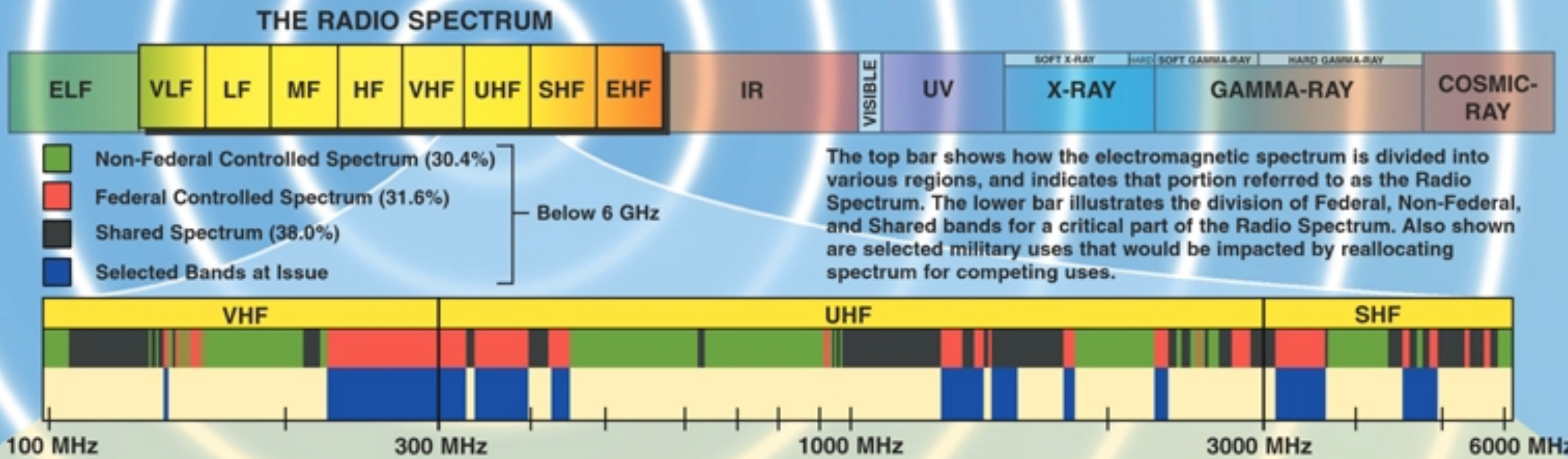
L1: 1575.42 MHz
Modulated by C/A-code & P-code
(codes covered later)

L2: 1227.6 MHz
Modulated by P-code only

(3rd carrier, L3, used for nuclear explosion detection)

A. Ganse, U. Washington , http://staff.washington.edu/aganse/
See http://en.wikipedia.org/wiki/Radio_spectrum for electromagnetic frequency band names

Electromagnetic Spectrum



The top bar shows how the electromagnetic spectrum is divided into various regions, and indicates that portion referred to as the Radio Spectrum. The lower bar illustrates the division of Federal, Non-Federal, and Shared bands for a critical part of the Radio Spectrum. Also shown are selected military uses that would be impacted by reallocating spectrum for competing uses.

Selected Bands at Issue

138 - 144 MHz

Military Uses	Competing Uses
Land Mobile Radio	Little LEOs
Tactical Air / Ground / Air	Public Safety

225 - 400 MHz

Military Uses	Competing Uses
Tactical Air / Ground / Air	Little LEOs
Data Links	Public Safety
Satellite Comm	Terrestrial DAB
Military ATC	CMRS
Search & Rescue	Space Research
Executive Comm	
Tactical Comm	

400.15 - 401 MHz

Military Uses	Competing Uses
DMSP (↓)	MSS

420 - 450 MHz

Military Uses	Competing Uses
BM Surveillance and Early Warning Radars	Auxiliary Broadcast
Shipboard / Airborne Early Warning Radars	CMRS
Missile / Air Vehicle Flight Termination	Biomedical Telemetry
Troop Position Location	WLL
Anti-Stealth Radar	MSS
Foliage Penetration Radar	EES (active)

1215 - 1390 MHz

Military Uses	Competing Uses
Long / Medium Range Air Defense	MSS
Radio Navigation	NLMCS
Air Route Surveillance Radars	Wind Profiler Radars
Tactical Communications	
Test Range Support	
Air / Fleet Defense	
Drug Interdiction	
GPS	
Remote Satellite Sensors	
Nuclear Detection	

1435 - 1525 MHz

Military Uses	Competing Uses
Telemetry Supporting Entire Aerospace Industry	DAB / DARS
	MSS
	NLMCS

1755 - 1850 MHz

Military Uses	Competing Uses
DoD Satellite TT&C (↑)	PCS
Point-to Point Microwave	MDS
Air Combat Training Systems	3G Wireless / IMT 2000
Tactical Comm	
Tactical Data Links	

2200 - 2290 MHz

Military Uses	Competing Uses
DoD Satellite TT&C (↓)	PCS
Guided Missile Telemetry	MDS
Point to-Point Microwave	WLL

3100 - 3650 MHz

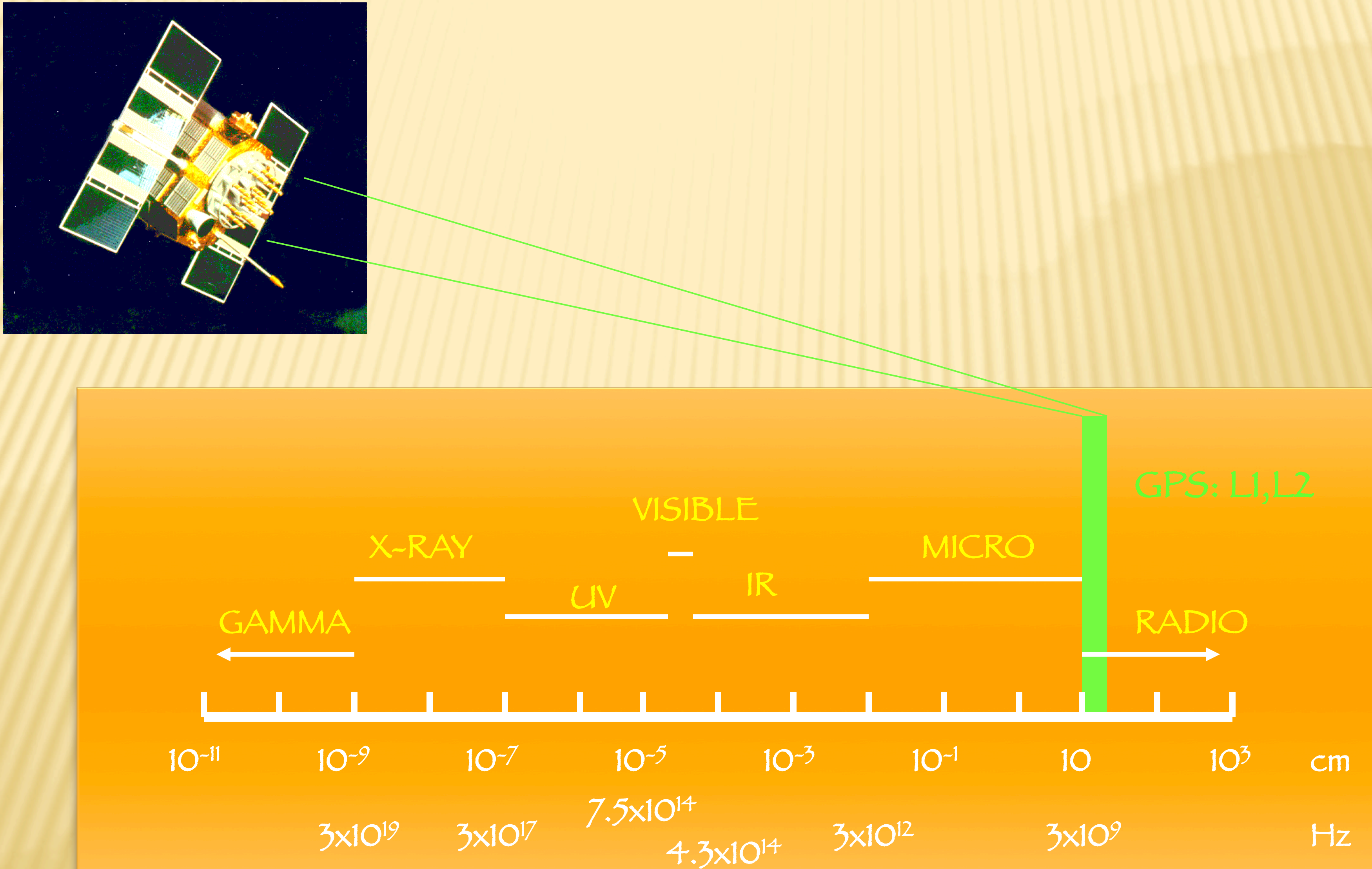
Military Uses	Competing Uses
High Power Mobile Radars	MDS
Shipboard ATC	WLL
Missile Links	FSS
Airborne Station Keeping	

4400 - 4940 MHz

Military Uses	Competing Uses
Fixed Wideband Comm	GWCS
Mobile Wideband Comm	FSS
Command Links	Public Safety
Data Links	

ATC -	Air Traffic Control
BM -	Ballistic Missile
CMRS -	Commercial Mobile Radio Service
DAB -	Digital Audio Broadcast - Terrestrial
DARS -	Digital Audio Radio Service - Satellite
DMSP -	Defense Meteorological Satellite Program
FSS -	Fixed Satellite Service
GPS -	Global Positioning Satellite
GWCS -	General Wireless Communications Service
IMT 2000 -	3rd Generation Mobile Telephony
LEO -	Low Earth Orbit
MDS -	Multipoint Distribution System
MSS -	Mobile Satellite Service
NLMCS -	New Land Mobile Communications Service
PCS -	Personal Communications Service
TT&C -	Tracking, Telemetry and Command
WLL -	Wireless Local Loop

Signal: Electromagnetic Spectrum



From Ben Brooks

GPS Signals

Most "unsophisticated" receivers only track L1

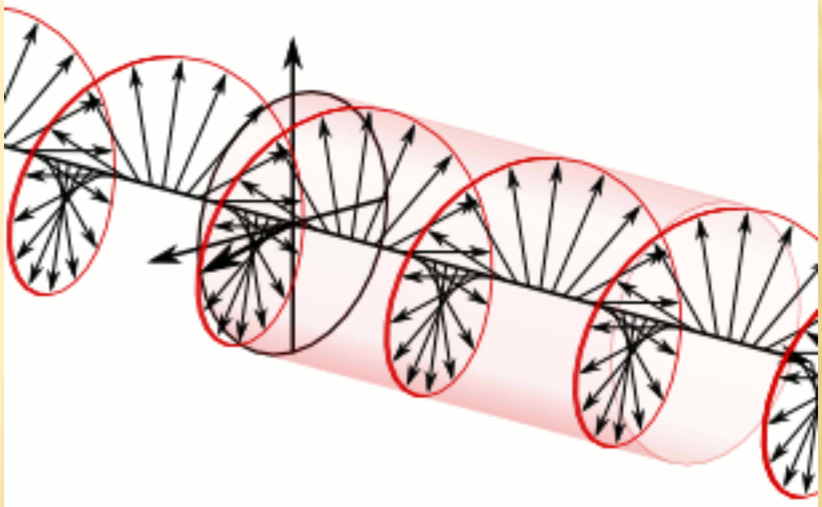
If L2 tracked, then the phase difference (L1-L2) can be used to filter out *ionospheric delay*.

This is true even if the receiver cannot decrypt the *P-code* (more later)

L1-only receivers use a simplified ionospheric correction model

For Signal-Heads Only

L1



Antenna Polarization: RHCP

Center Frequency: 1.57542 GHz

Signal Strength: -160 dBW

Main Lobe Bandwidth: 2.046 MHz

C/A & P-Codes in Phase Quadrature

A. Ganse, U. Washington , http://staff.washington.edu/aganse/
http://en.wikipedia.org/wiki/Circular_polarization

For Signal-Heads Only

L2

Center Frequency: 1.22760 GHZ

Signal Strength: -166 dBW

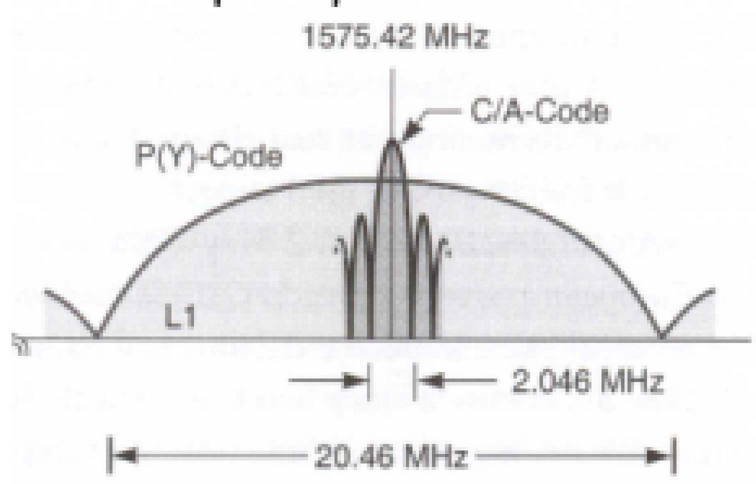
Code modulation is Binary, Biphase or Bipolar Phase Shift Key (BPSK)

Total SV Transmitted RF Power ~45 W

GPS Signal

- L-band carrier frequency was a compromise
  - At higher frequencies, ranging errors due to ionospheric effects reduce, but attenuation of signal power due to distance traveled increases

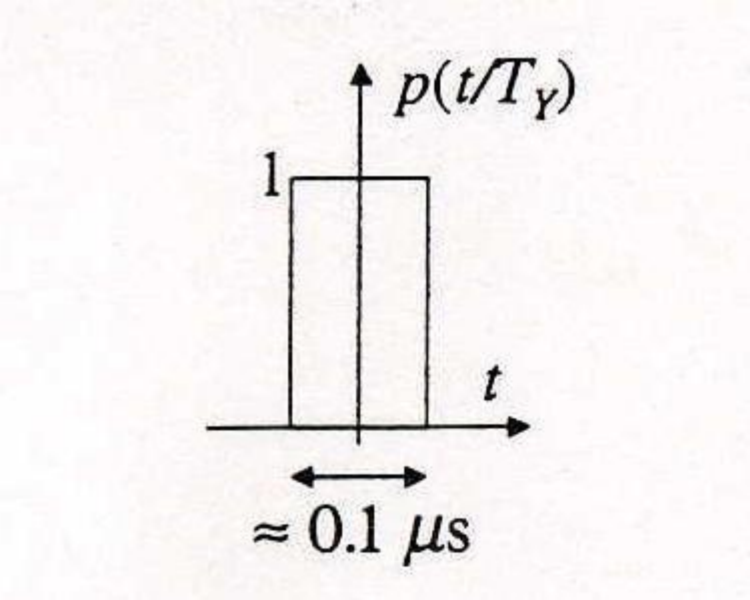
- GPS was first wide-spread use of spread spectrum technology
  - Code division multiple access (CDMA)
    - Allows multiple transmitters to use same frequency band
  - Adding code has the effect of "spreading" the signal
    - 2MHz (20MHz) band about the carrier at L_1 ~ 1575.42MHz

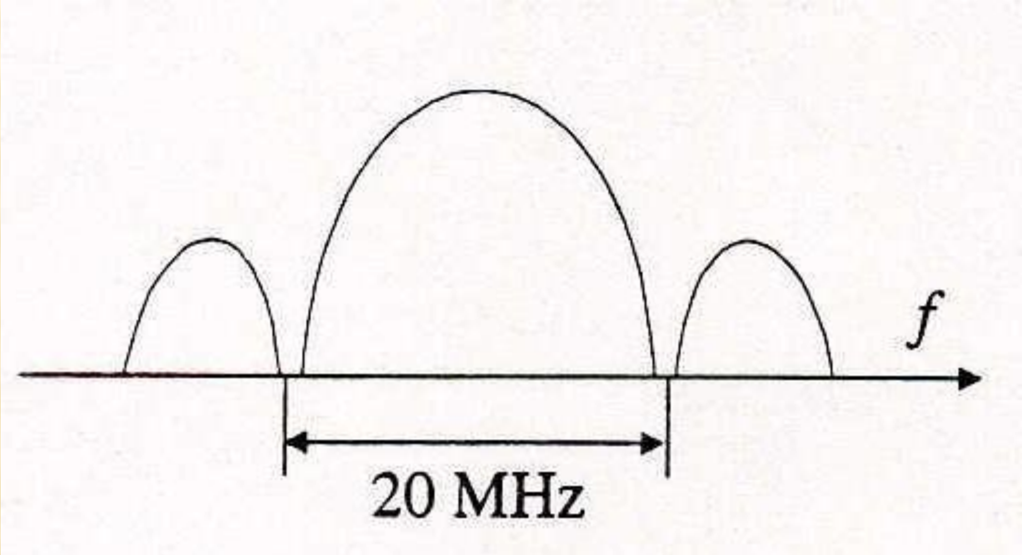


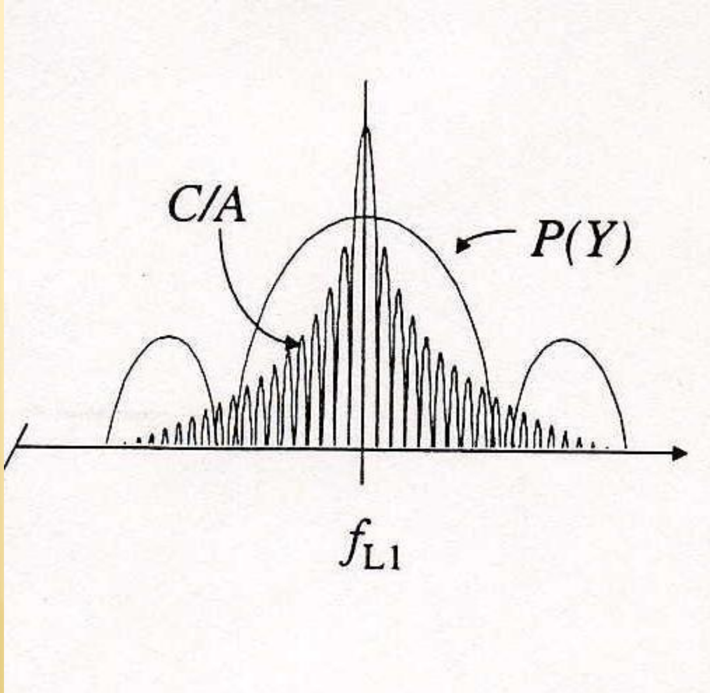
From J. HOW, MIT

Spectra of P and C/A code

(square wave in TD <--> sinc in FD)







http://www.colorado.edu/engineering/ASEN/asen5090/asen5090.html

Direct Sequence Spread Spectrum

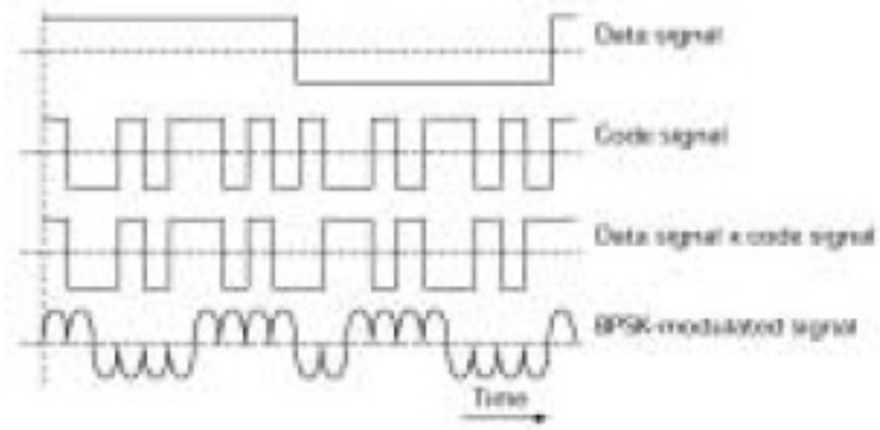


Fig 2: Generation of a DSSS Signal

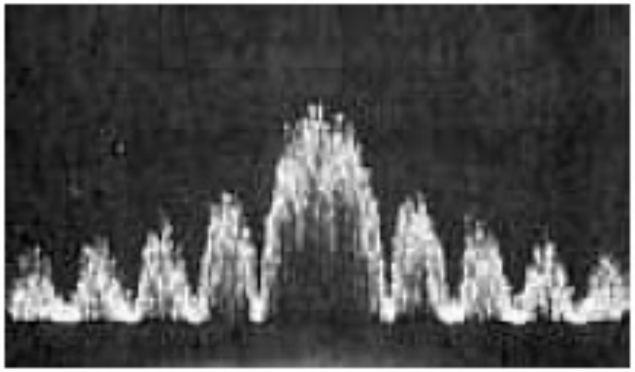


Fig 3: Spectrum of a DSSS Signal

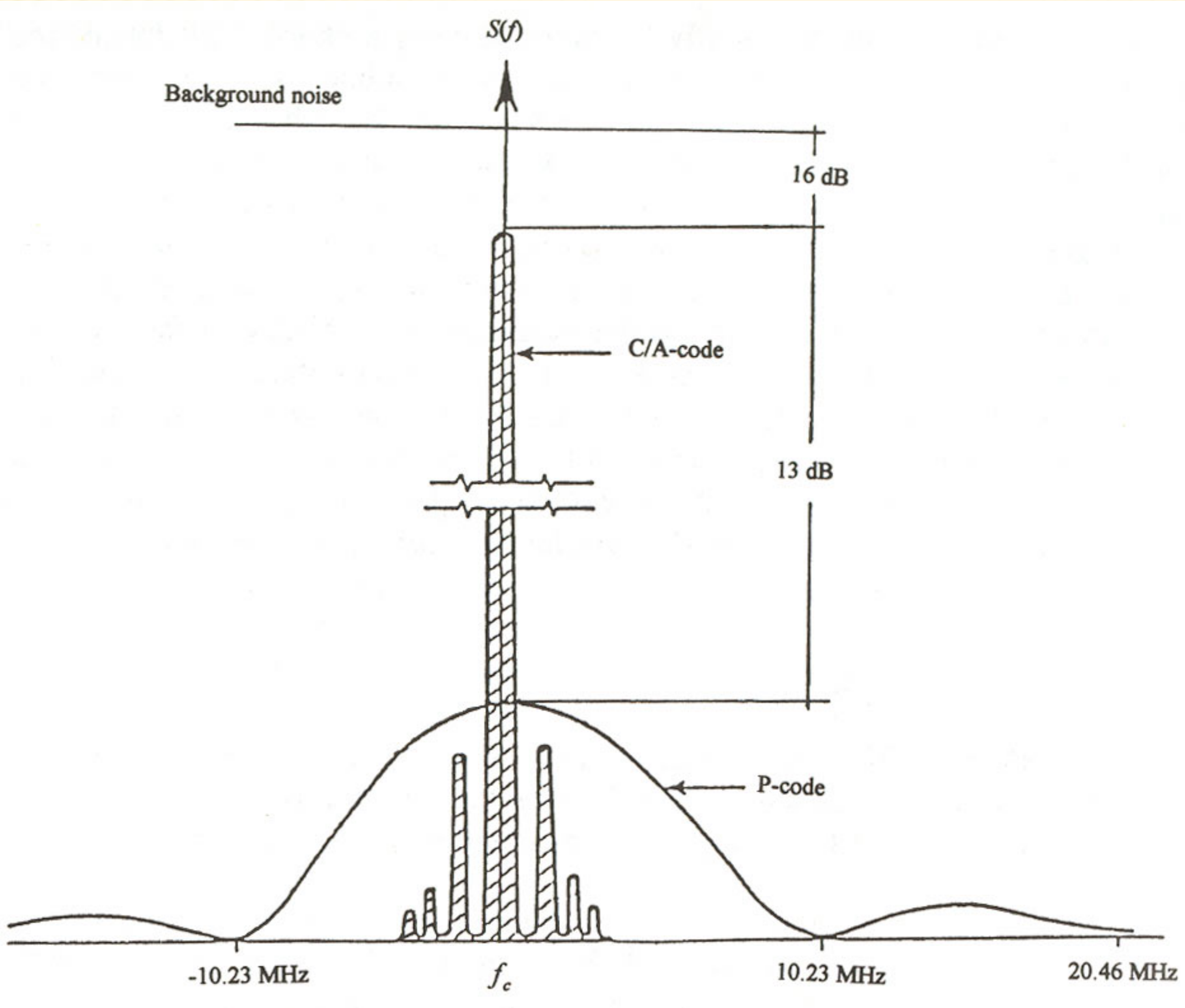
http://www.ieee.org/organizations/history_center/cht_papers/SpreadSpectrum.pdf

Frequency Hopped Spread Spectrum

Fig 5: Spectrum of a FHSS Signal

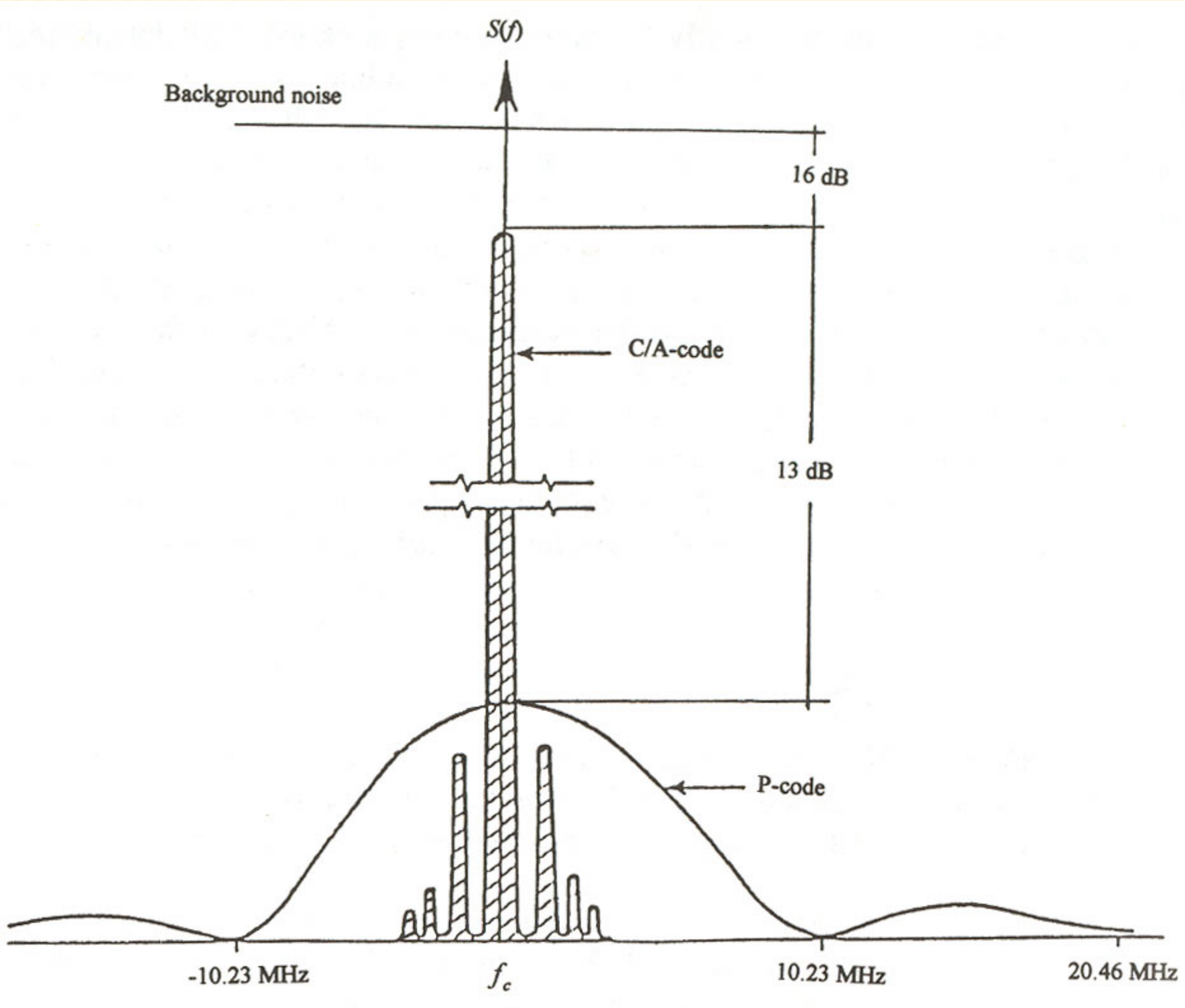
http://www.ieee.org/organizations/history_center/cht_papers/SpreadSpectrum.pdf
http://en.wikipedia.org/wiki/Hedy_Lamarr

GPS signal strength - frequency domain



Note that C/A code is below noise level; signal is multiplied in the receiver by the internally calculated code to allow tracking. C/A-code chip is 1.023 Mhz, P-code chip is 10.23 Mhz

GPS signal strength - frequency domain



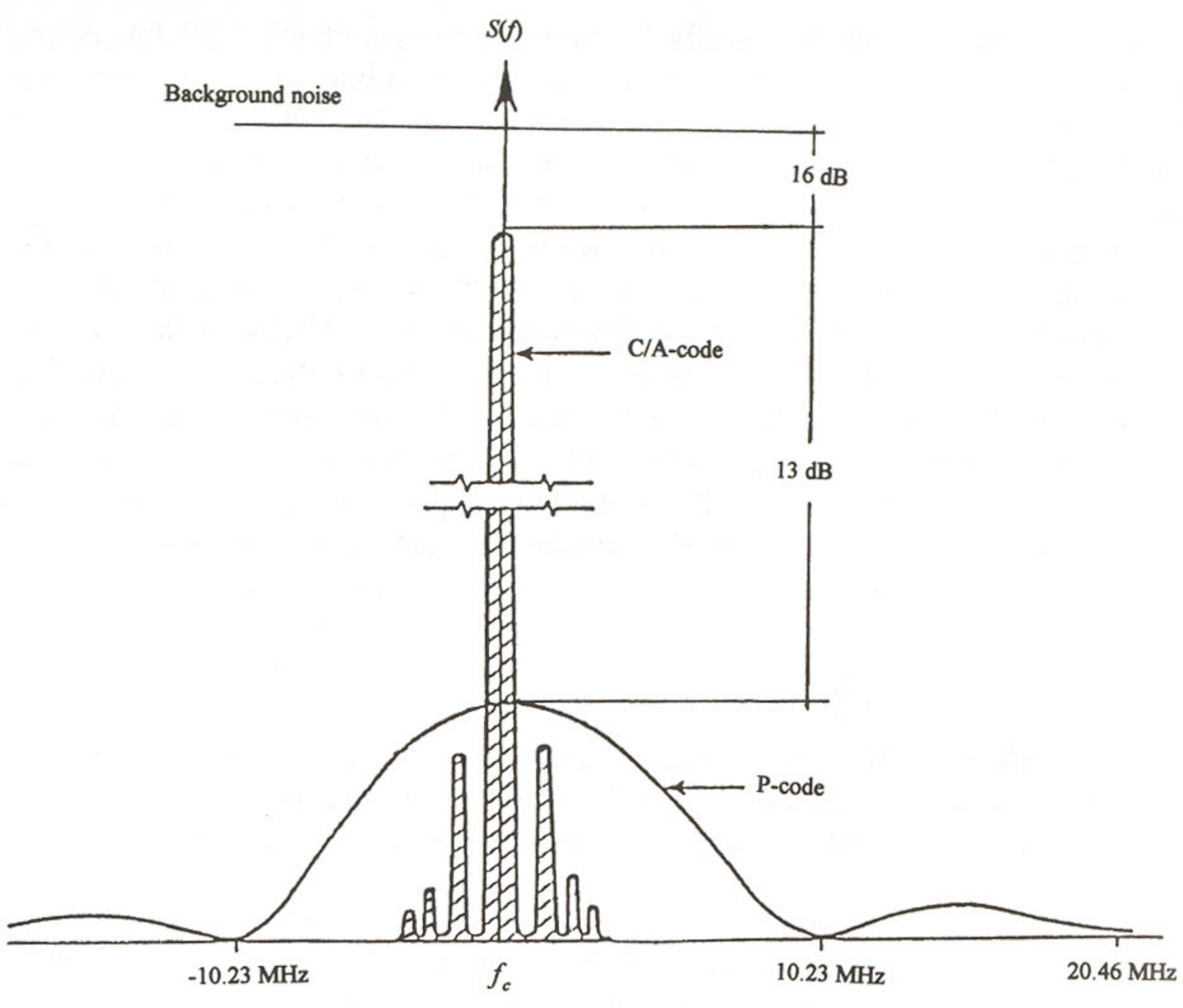
Power = P(t) = $y^2(t)$

$$\text{Bandwidth} \equiv B \approx \frac{1}{T}$$

where

$T \equiv$ is chip duration

GPS signal strength – frequency domain



The calculated power spectrum derives from the Fourier transform of a square wave of width 2π and unit amplitude.

FD shape – common function in DSP called the "sinc" function.

PRN Codes

GPS signals implement *PseudoRandom Noise* Codes

- Enables very low power (below background noise)
- A form of *direct-sequence spread-spectrum*
- Specifically a form of Code Division Multiple Access (CDMA), which permits frequency sharing

Pseudo random numbers/sequences

What are they?

Deterministic but "look" random

Example – digits of π

3.14159265358979323846264338327950288419716939937510

Looks like a random sequence of single digit numbers.

But you can compute it. Is perfectly deterministic.

Frequency of individual digits (first 10,000 digits)
This list excludes the 3 before the decimal point

Digit	Frequency
0	968
1	1026
2	1021
3	974
4	1012
5	1046
6	1021
7	970
8	948
9	1014
Total	10000

http://www.ex.ac.uk/cimt/general/pi10000.htm

PRN Codes

Codes are known “noise-like” sequences

Each bit (0/1) in the sequence is called a *chip*

Each GPS SV has an assigned code

Receiver generates equivalent sequences internally and matches signal to identify each SV

There are currently 32 reserved PRN’ s
(so max 32 satellites)

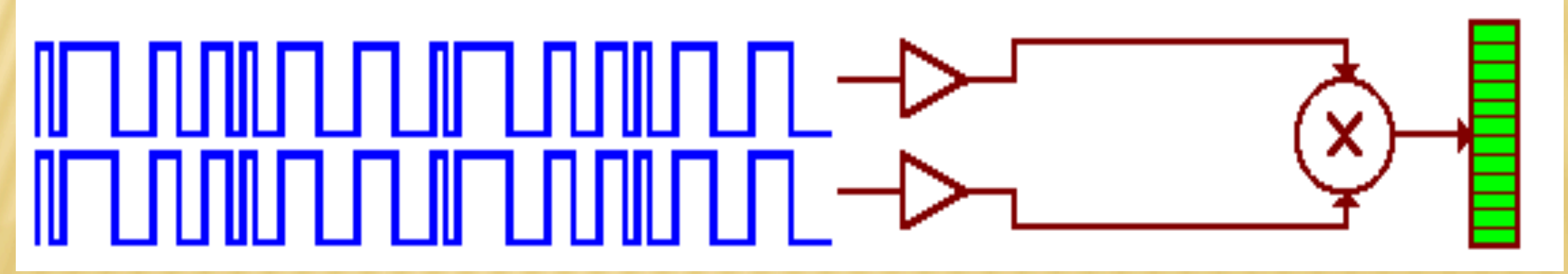
PRN Code matching

Receiver slews internally-generated code sequence until full "match" is achieved with received code

Time data in the nav message tells receiver when the transmitted code went out

Slew time = time delay incurred by SV-to-receiver range Minus clock bias and whole cycle ambiguities

Receiver/Signal Code Comparison



A. Ganse, U. Washington , http://staff.washington.edu/aganse/

Coarse Acquisition (C/A) Code

1023-bit Gold Code

Originally intended as simply an acquisition code for *P-code* receivers

Modulates L1 only

Chipping rate = 1.023 MHz
(290 meter "wavelength")

Coarse Acquisition (C/A) Code

Sequence Length = 1023 bits, thus Period = 1 millisec

~300 km range ambiguity: receiver must know range to better than this for position solution

Provides the data for *Standard Positioning Service* (SPS)

The usual position generated for most civilian receivers

Modulated by the Navigation/Timing Message code

A. Ganse, U. Washington , http://staff.washington.edu/aganse/

Precise (P) Code

P code is known, but encrypted by unknown (secret) *W* code into the *Y-code*

Requires special chip to decode

Modulates both L1 & L2

Also modulated by Nav/Time data message

Chipping rate = 10.23 MHz

Precise (P) Code

Sequence Length (*Y* code?) = BIG (Period = 267 days)

Actually the sum of 2 sequences, *X1* & *X2*, with sub-period of 1 week

Precise (P) Code

P-code rate is the fundamental frequency (provides the basis for all others)

P-Code (10.23 MHz) /10 = 1.023 MHz (C/A code)

P-Code (10.23 MHz) X 154 = 1575.42 MHz (L1).

P-Code (10.23 MHz) X 120 = 1227.60 MHz (L2).

Code Modulation

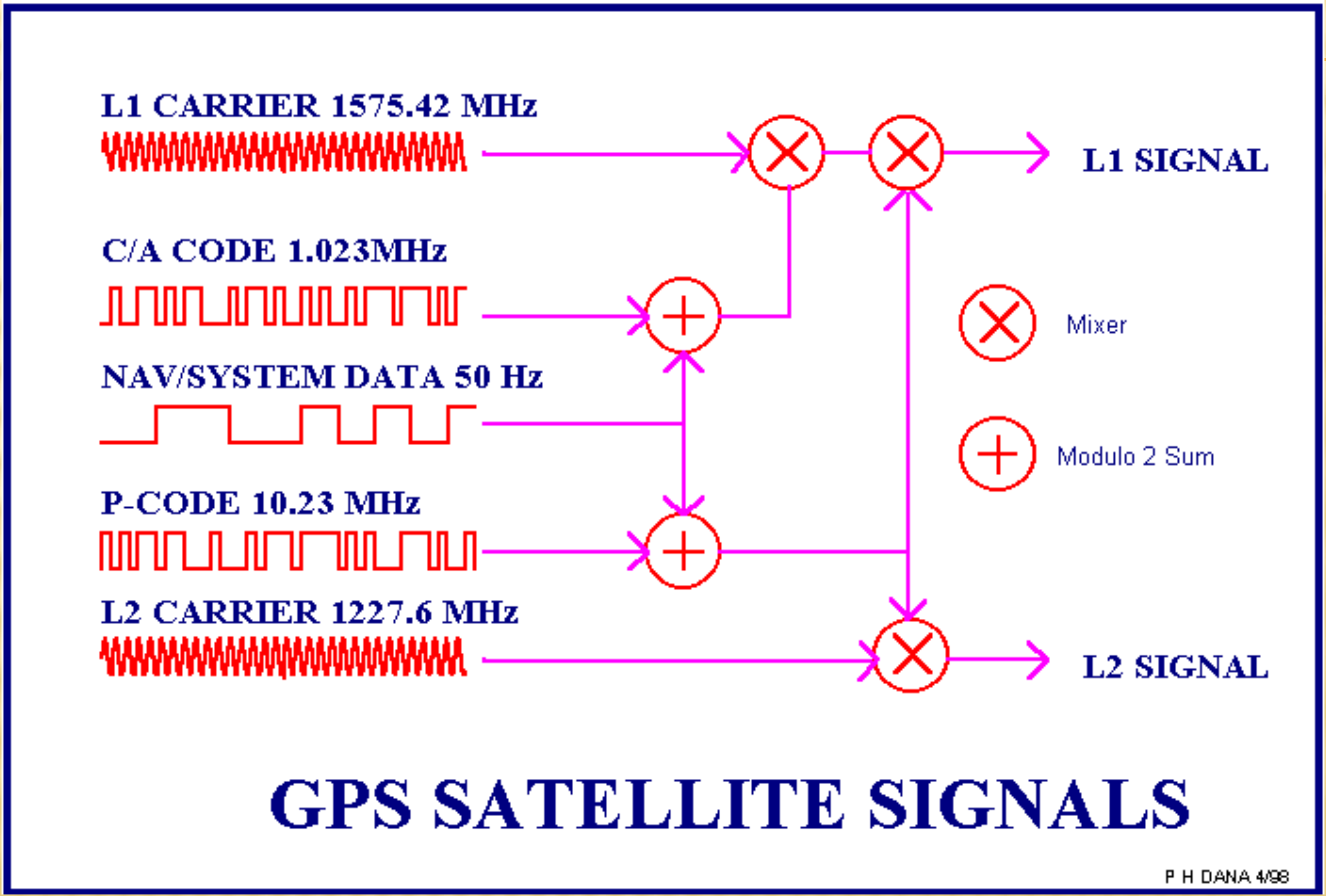
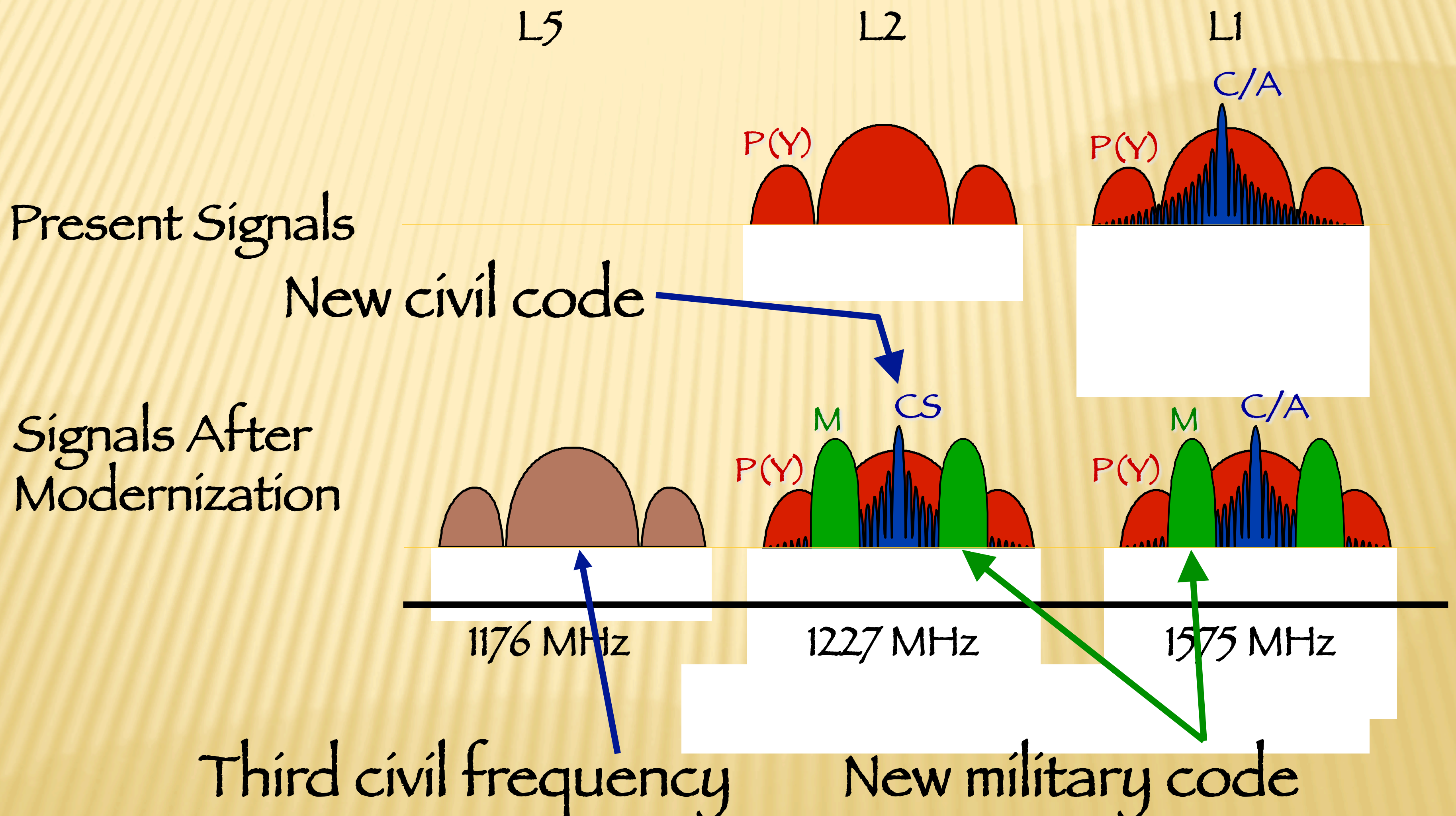


Image courtesy: Peter Dana, http://www.colorado.Edu/geography/gcraft/notes/gps/gps_f.html

Modernized Signal Evolution



DGPS overview, www.edu-observatory.org/gps/BostonSection.ppt , Dierendonck

Why Modernize?

National policy - GPS is a vital dual-use system

For civil users, new signals/frequencies provide:

More robustness against interference, compensation for ionospheric delays and wide/tri-laning

For military users, new signals provide:

Enhanced ability to deny hostile GPS use, greater military anti-jam capability and greater security

For both civil/military, system improvements in accuracy, reliability, integrity, and availability

DGPS overview, www.edu-observatory.org/gps/BostonSection.ppt , Dierendonck generation of code - satellite and receiver

Time
Seconds

```
00000000001111111111222222222233333333334444444444555555
01234567890123456789012345678901234567890123456789012345
```

(Genesis - sent by satellite 1 and generated in receiver)
In the beginning God created the heavens and thIn the beg

(Exodus - sent by satellite 2 and generated in receiver)
These are the names of the sons of Israel who wThese are

(Leviticus - sent by satellite 3 and generated in receiver)
Yahweh called Moses, and from the Tent of MeetiYahweh cal

code

(repeats)

"chip"

Reception of code in receiver

The time of the reception of the code is found by lining up the known and received signals

```
Time
Seconds

000000000011111111112222222222333333333344444444445555555
012345678901234567890123456789012345678901234567890123456

              In the beginning God created the heavens an
              ^14 seconds

     These are the names of the sons of Israel who wThese
     ^5 seconds
                      Yahweh called Moses, and from the T
                      ^22 seconds
```

GPS Signals (Code)

- Coarse/Acquisition (C/A) codes enable:
  - Simultaneous measurements from many satellites (CDMA)
  - Accurate absolute range (10-100m) using signal propagation delay

A Short Repeating PRN Code Sample

- Each satellite has a unique C/A code
  - One of a repeating sequence 1023 **chips** long
  - Rate of 1.023MHz (period of 1ms)
  - Appear random (pseudo random - PRN), but one of the deterministic "Gold Codes"

GPS Code Signal Acquisition

- Receiver replicates the *C/A* code to **correlate** with the measured signal
- What is **correlation**?
  - *Mathematics:*

$$\Psi_{ij}(\tau) = \frac{1}{T}\int_0^T \left[c_i(t)c_j(t-\tau)\right]dt$$

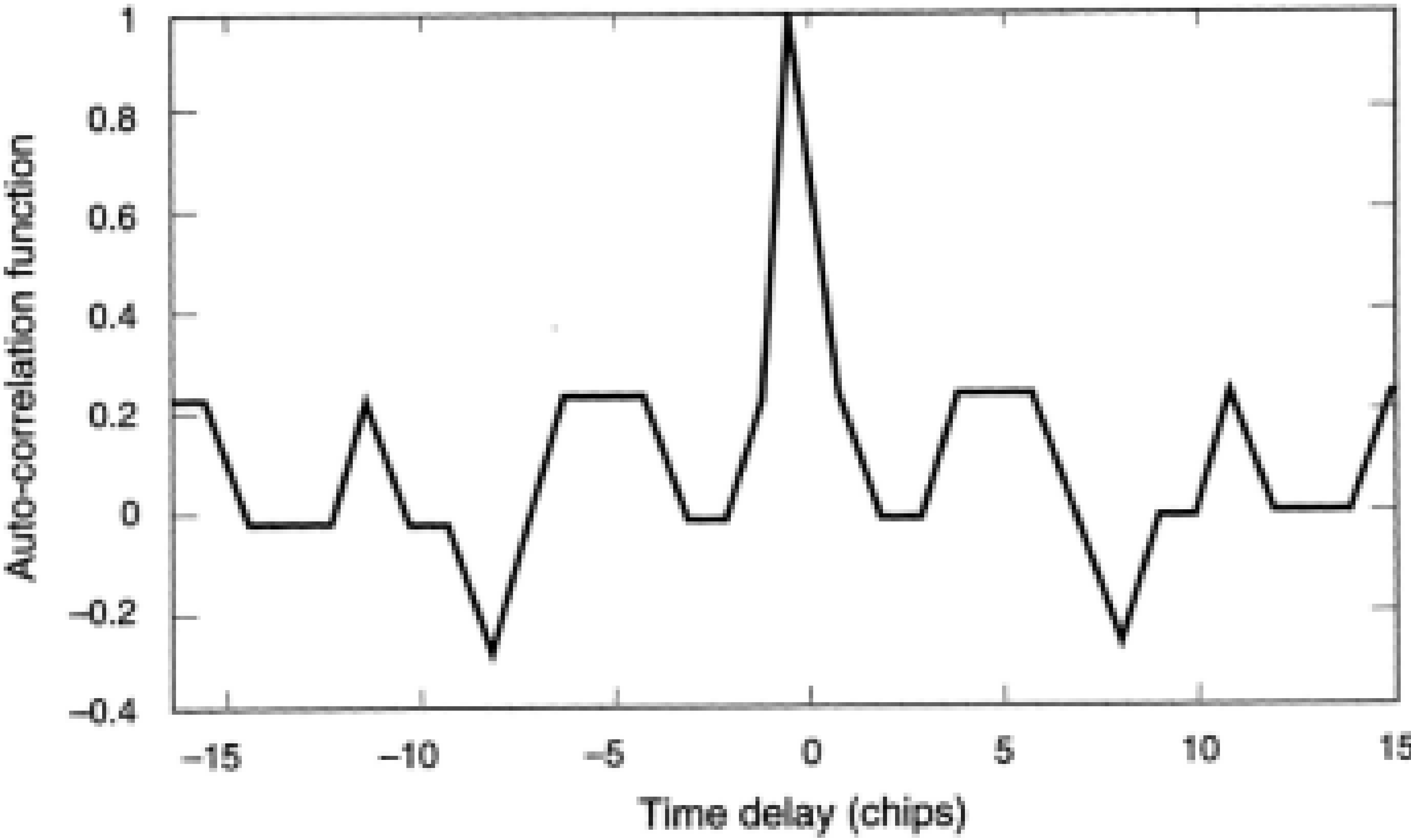
- Receiver slides code replica (τ) until strong correlation found with transmitted signal
  - With N "chips" in the signal period

    ➔ Correlation ≈ (# Agree - # Differ)/N

- Comparison with wrong code will produce very low agreement for all τ
  - Right code, wrong τ also produces low agreement

From J. HOW, MIT

Correlation Visualization



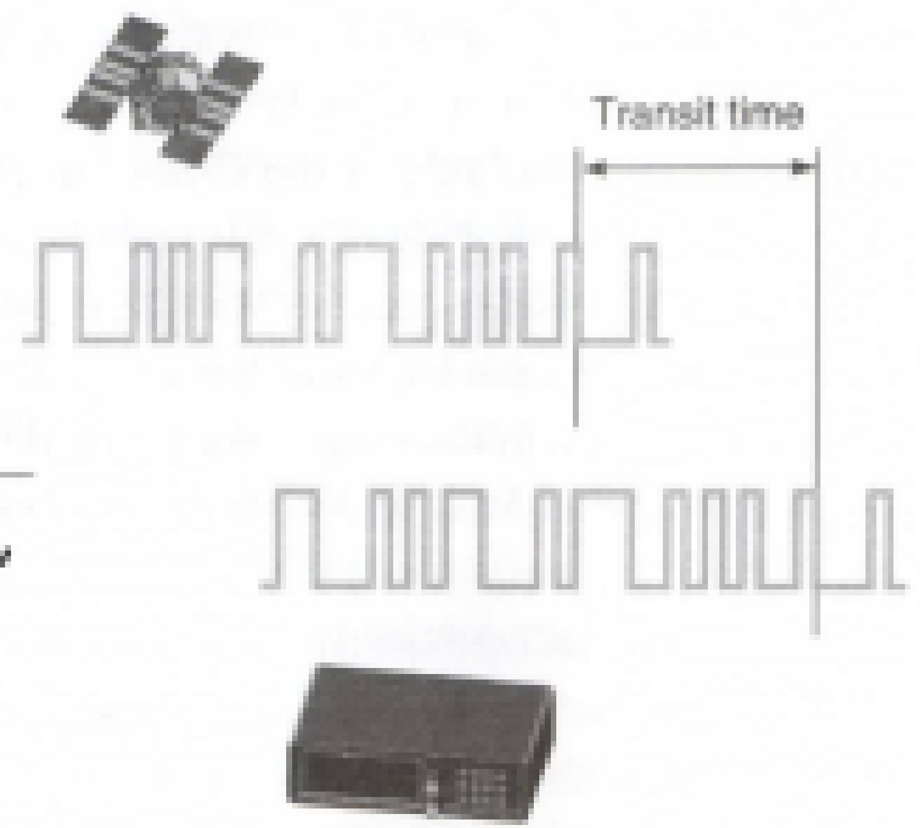
Full Correlation (Code Phase Lock) of Receiver and Satellite PRN Codes

From J. HOW, MIT

GPS Signal Processing

- Correlation:
  - Allows receiver to pick up the very weak signal
  - Allows us to determine the time offset of the incoming signal

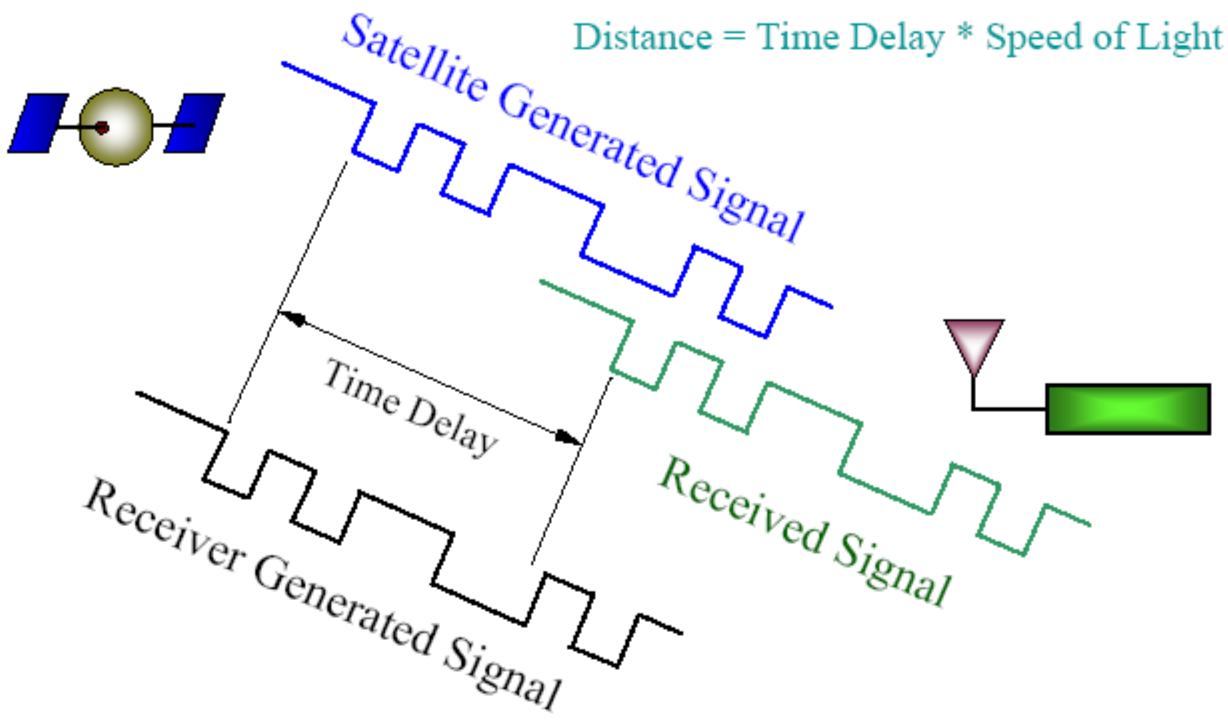
  → **Transit Time**



- Transit time will be off by the **user clock error**, but we can solve for & remove that term

From J. HOW, MIT

Measuring Distance



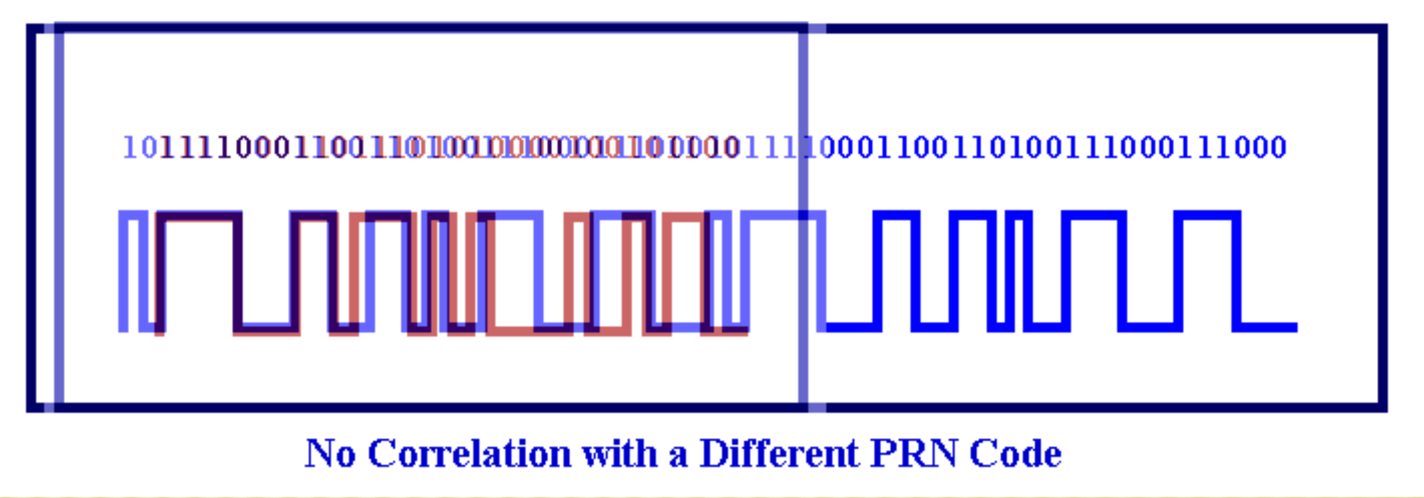
http://www.unav-micro.com/about_gps.htm

GPS Signal Acquisition Process

- Determine which satellites are visible
  - Approximate time/position, GPS almanac ➔ skyplot
- Determine approximate Doppler for each satellite
  - Reduces time-to-first-fix since defines frequency search space (estimate of receiver clock drift required)
- Must search **both** frequency and C/A code phase
  - Large velocity of GPS satellites, so the received signals can have a large Doppler shift (+/- 5 KHz) that can vary rapidly
  - Accurate frequency knowledge required to "strip off" the carrier part of the signal
    - Estimate frequency range to search using Doppler shift
    - Search frequency range using ~20 *frequency bins* of 500 Hz

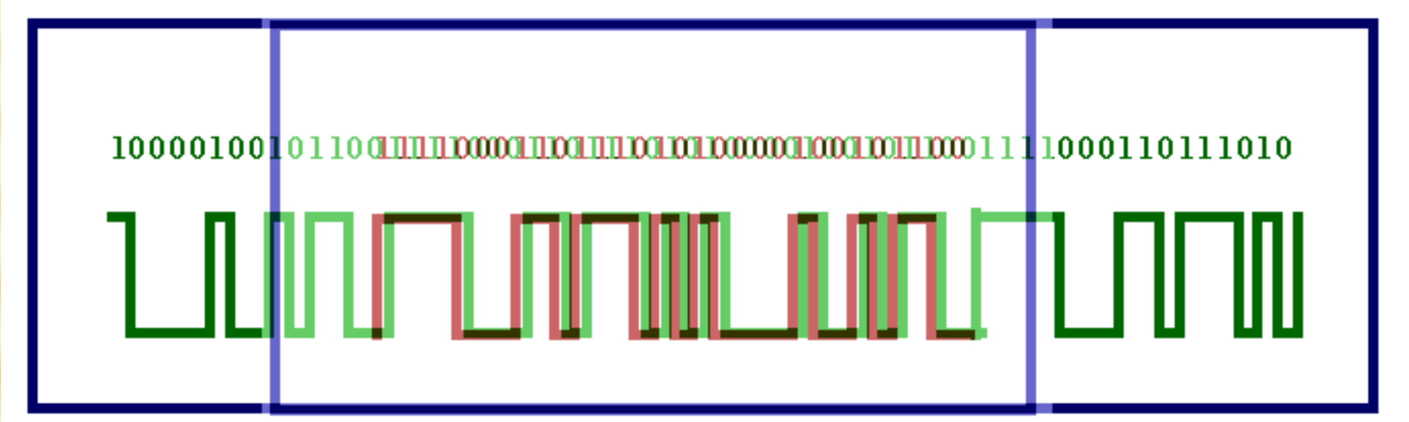
From J. HOW, MIT

if receiver applies different PRN code to SV signal …no correlation



Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Dana

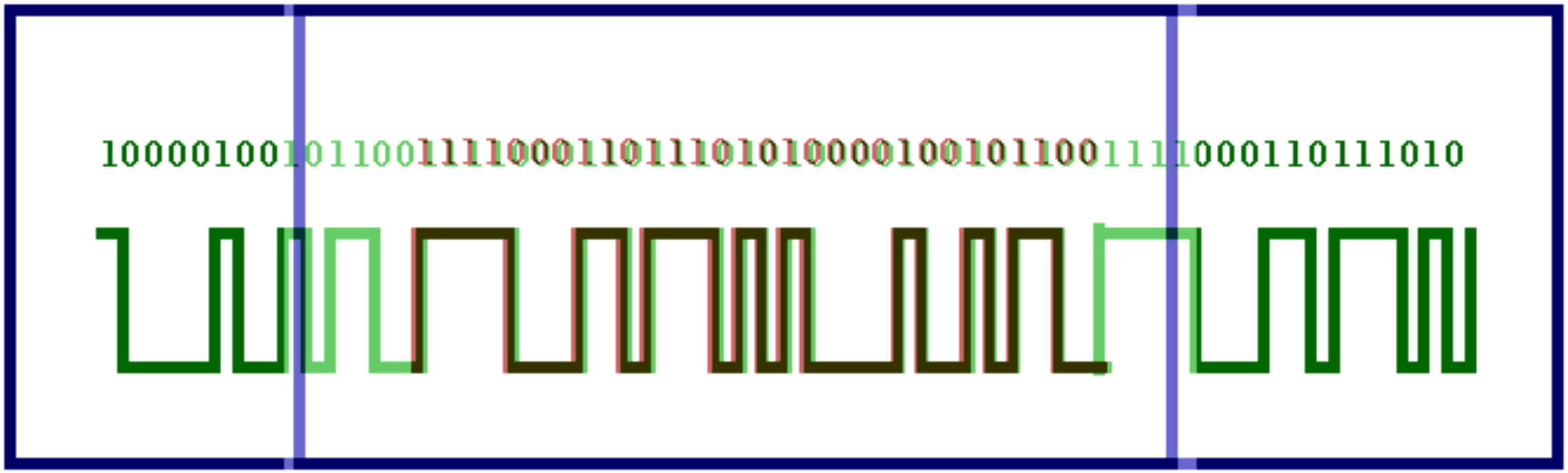
when receiver uses same code as SV and codes begin to align
…some signal power detected



Partial Correlation of Identical Receiver and Satellite PRN Codes

Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Dana

when receiver and SV codes align completely
...full signal power detected



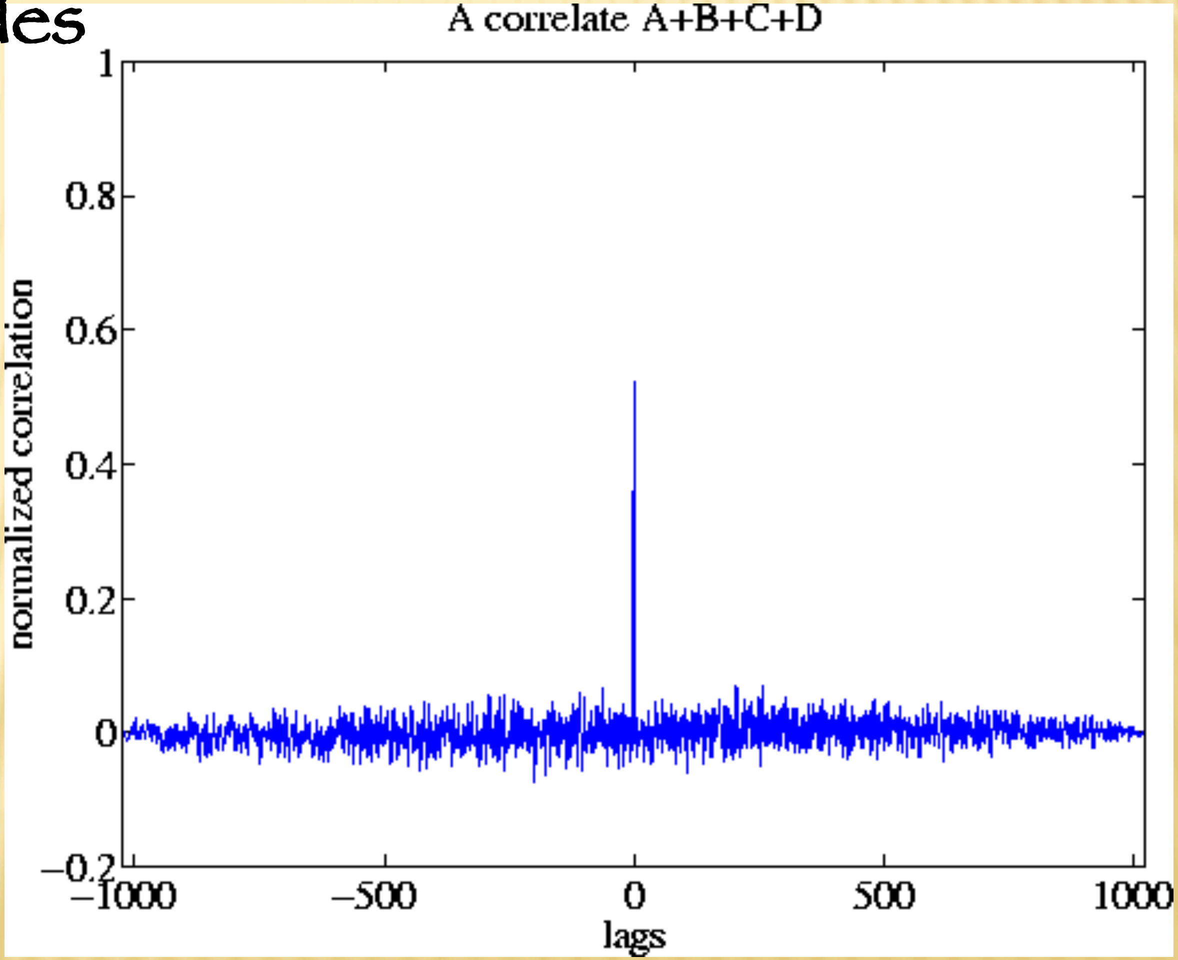
Full Correlation (Code-Phase Lock) of Receiver and Satellite PRN Codes

usually a late version of code is compared with early version
to insure that correlation peak is tracked

Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Dana

PRN Cross-correlation

Correlation of receiver generated PRN code (A) with incoming data stream consisting of multiple (e.g. four, A, B, C, and D) codes



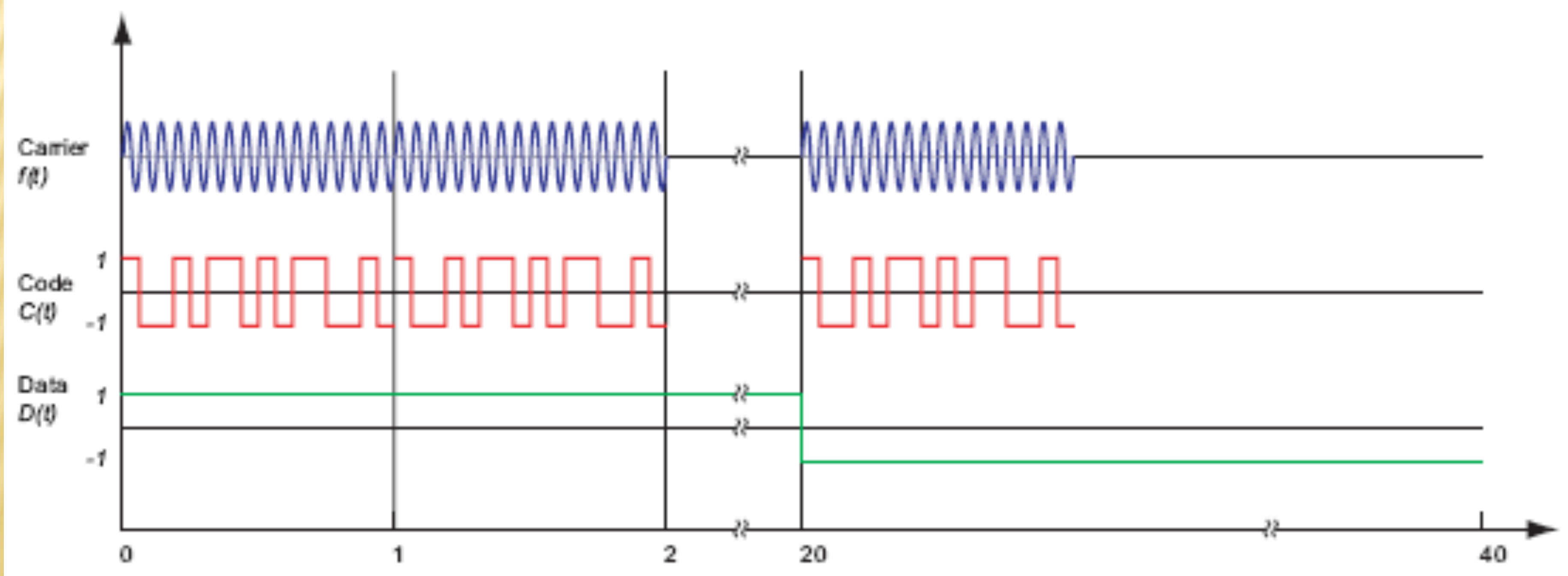
Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html

Construction of L1 signal

Carrier – blue

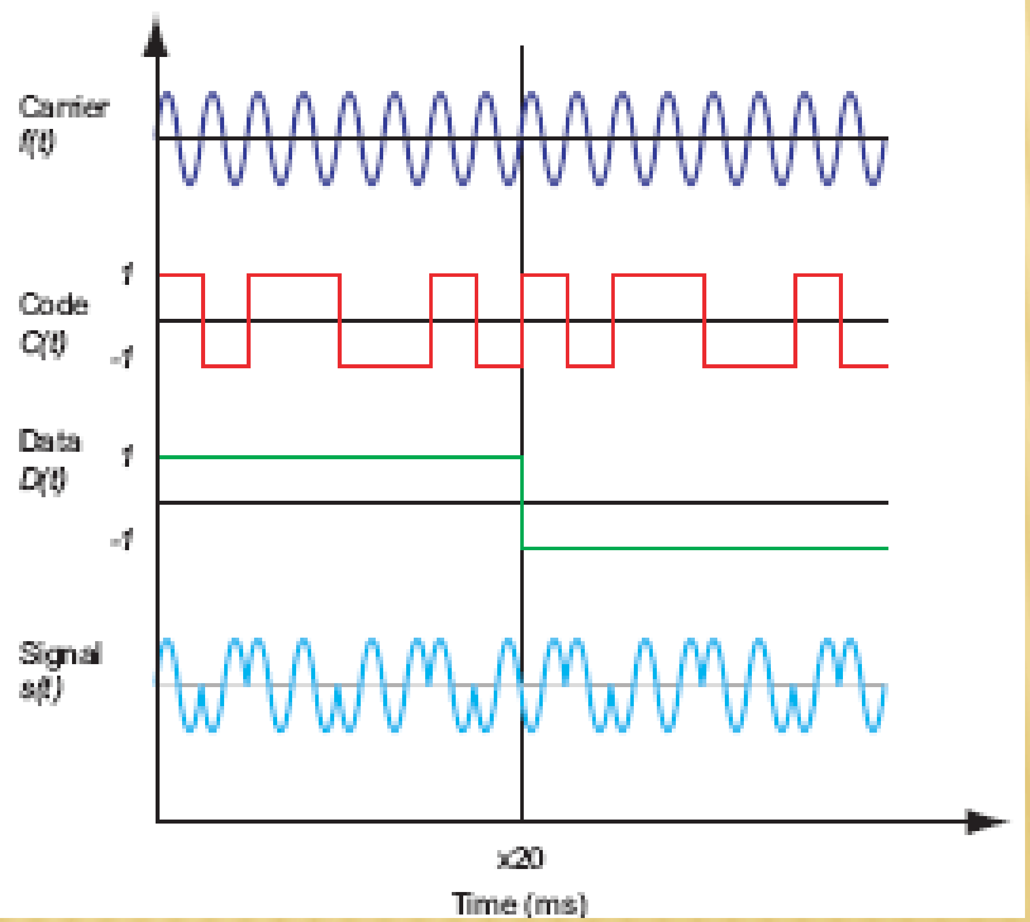
C/A code sequence – red, 1 bit lasts ~1 μsec, sequence of ~1000 bits repeats every 1 ms

Navigation data – green, one bit lasts 20 ms (20 C/A sequences)



Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Construction of L1 signal
BPSK modulation
(Carrier) x (C/A code) x (navigation message) = L1 signal



Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Digital Modulation Methods

Amplitude Modulation (AM) also known as amplitude-shift keying. This method requires changing the amplitude of the carrier phase between 0 and 1 to encode the digital signal.

Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Dana

Digital Modulation Methods

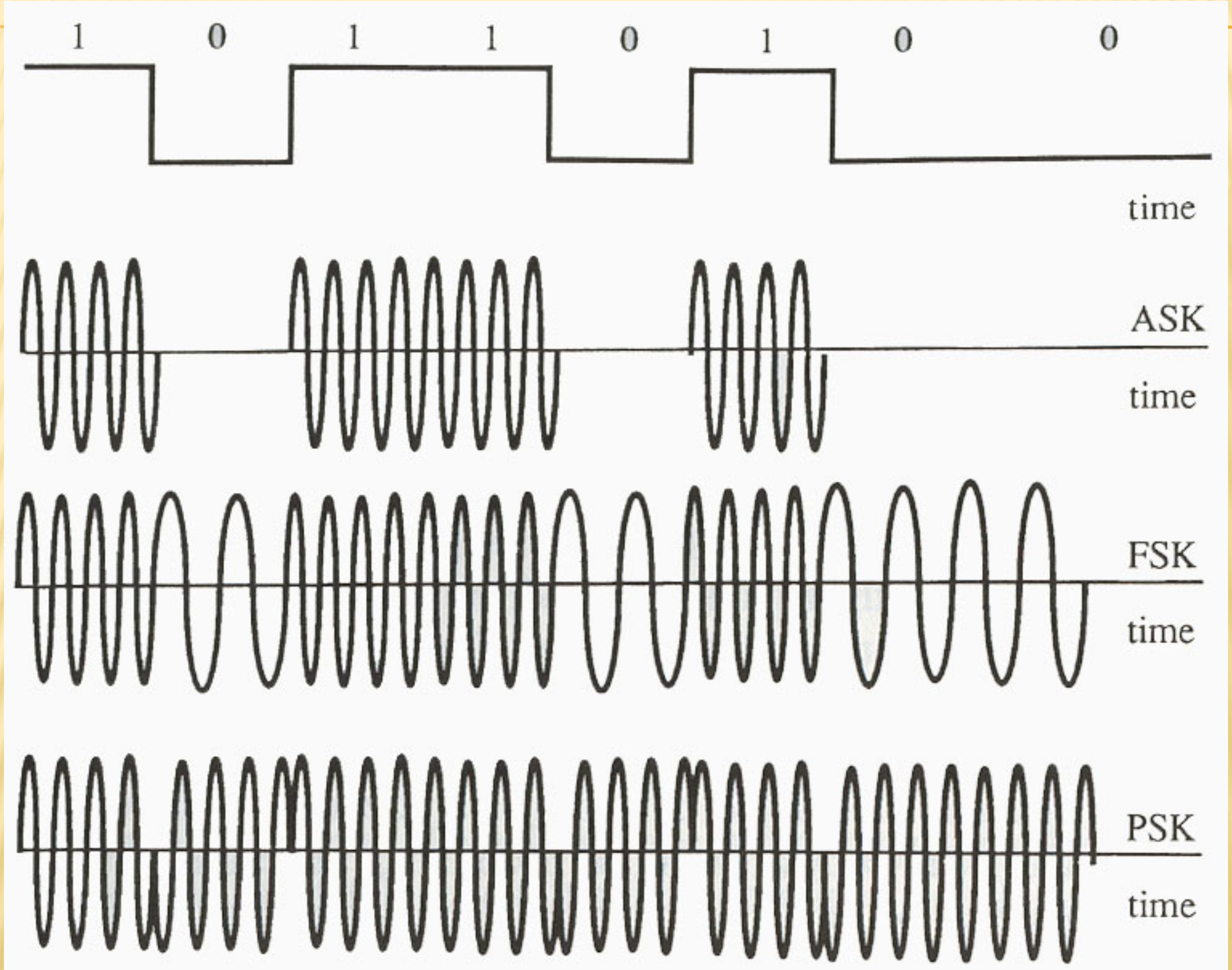
Frequency Modulation (FM) also known as frequency-shift keying. Must alter the frequency of the carrier to correspond to 0 or 1.

Digital Modulation Methods

Phase Modulation (PM) also known as phase-shift keying. At each phase shift, the bit is flipped from 0 to 1 or vice versa. This is the method used in GPS.

Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Dana

Modulation Schematics



Mattioli-http://comp.uark.edu/~mattioli/geol_4733.html and Dana

Nearly no cross-correlation.

C/A codes nearly uncorrelated with one another.

$$R_{ik}(n) = \sum_{l=0}^{1022} c^i(l)\, c^k(l+n) \approx 0, \ \forall n, i \neq k$$

Nearly no auto-correlation, except for zero lag

C/A codes nearly uncorrelated with themselves, except for zero lag.

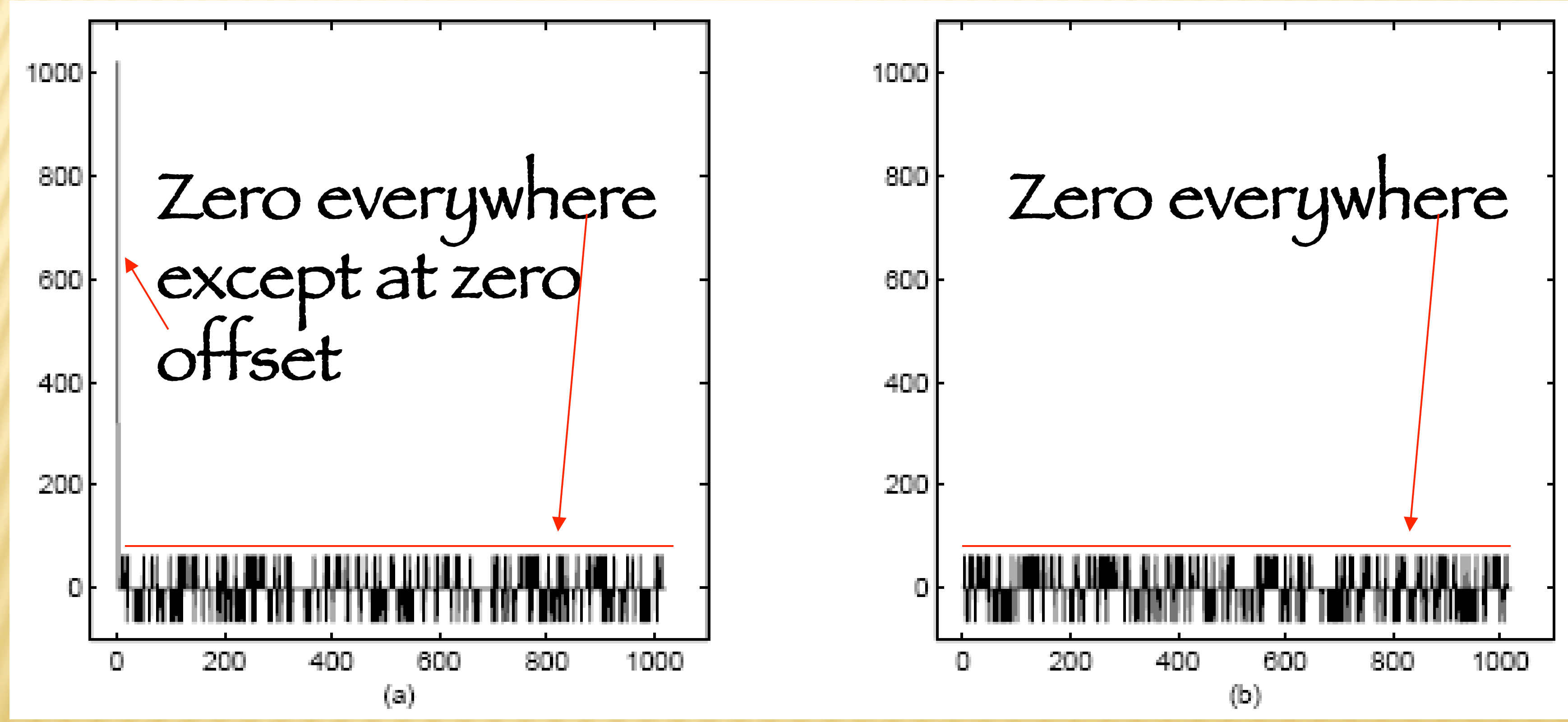
$$R_{kk}(n) = \sum_{l=0}^{1022} c^k(l)\, c^k(l+n) \approx 0, \ \forall |n| \geq 0$$

Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Gold Code correlation properties

Auto-correlation with itself (narrow peak, 1023)

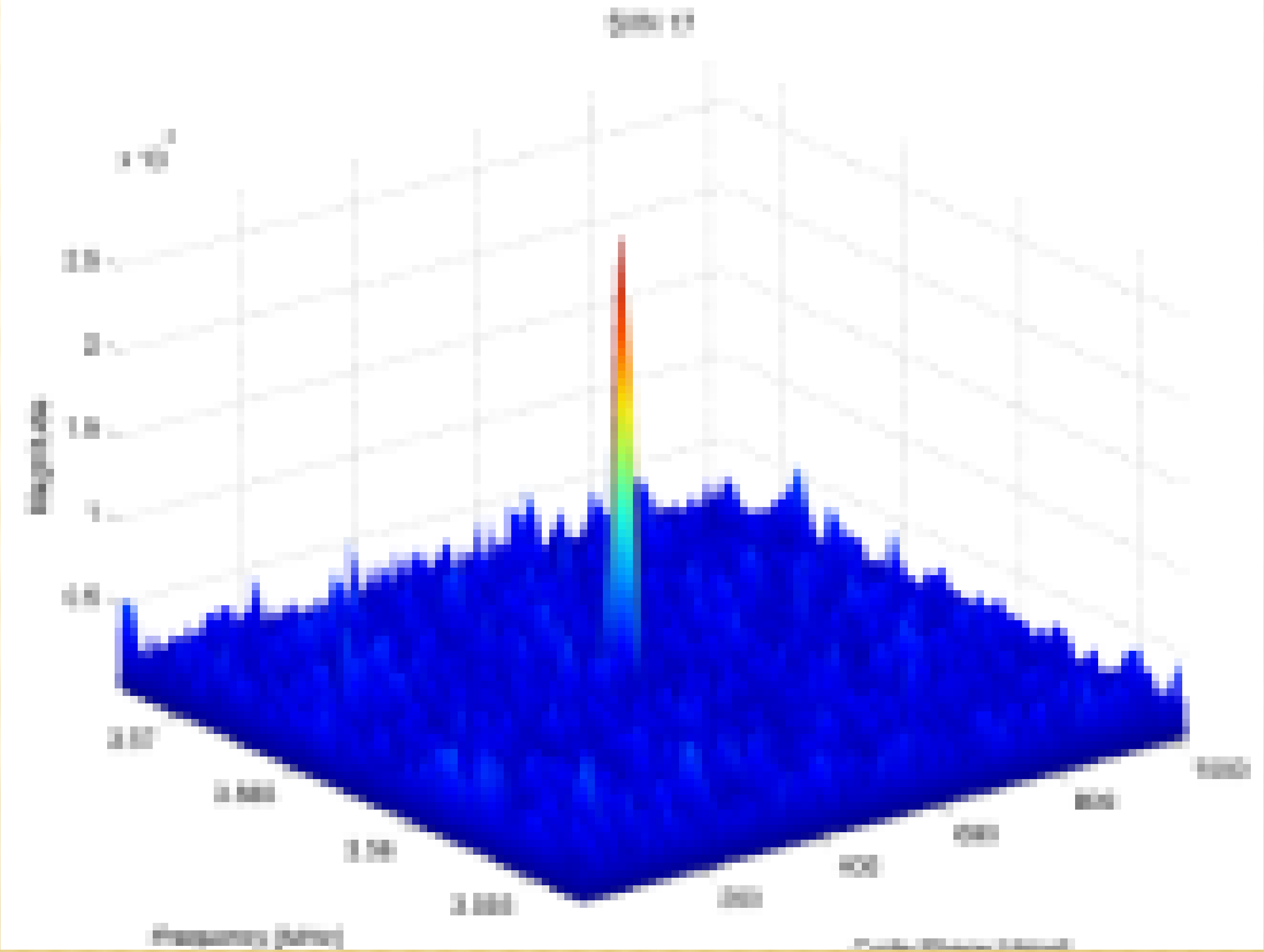
Cross-correlation with another code



Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Signal acquisition

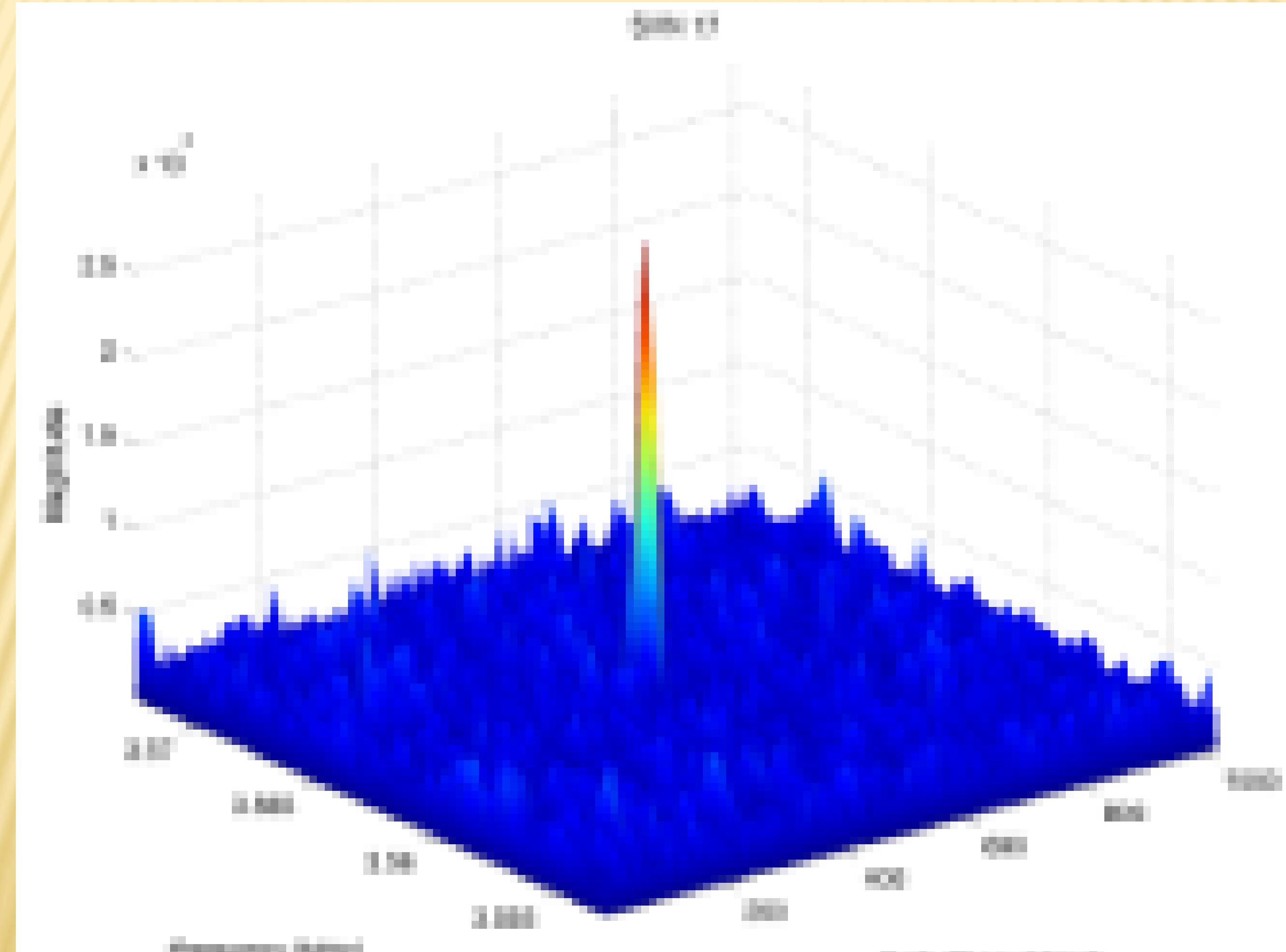
Is a search procedure over correlation by frequency and code phase shift



kom.aau.dk/~rinder/AAU_software_receiver.pdf

Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

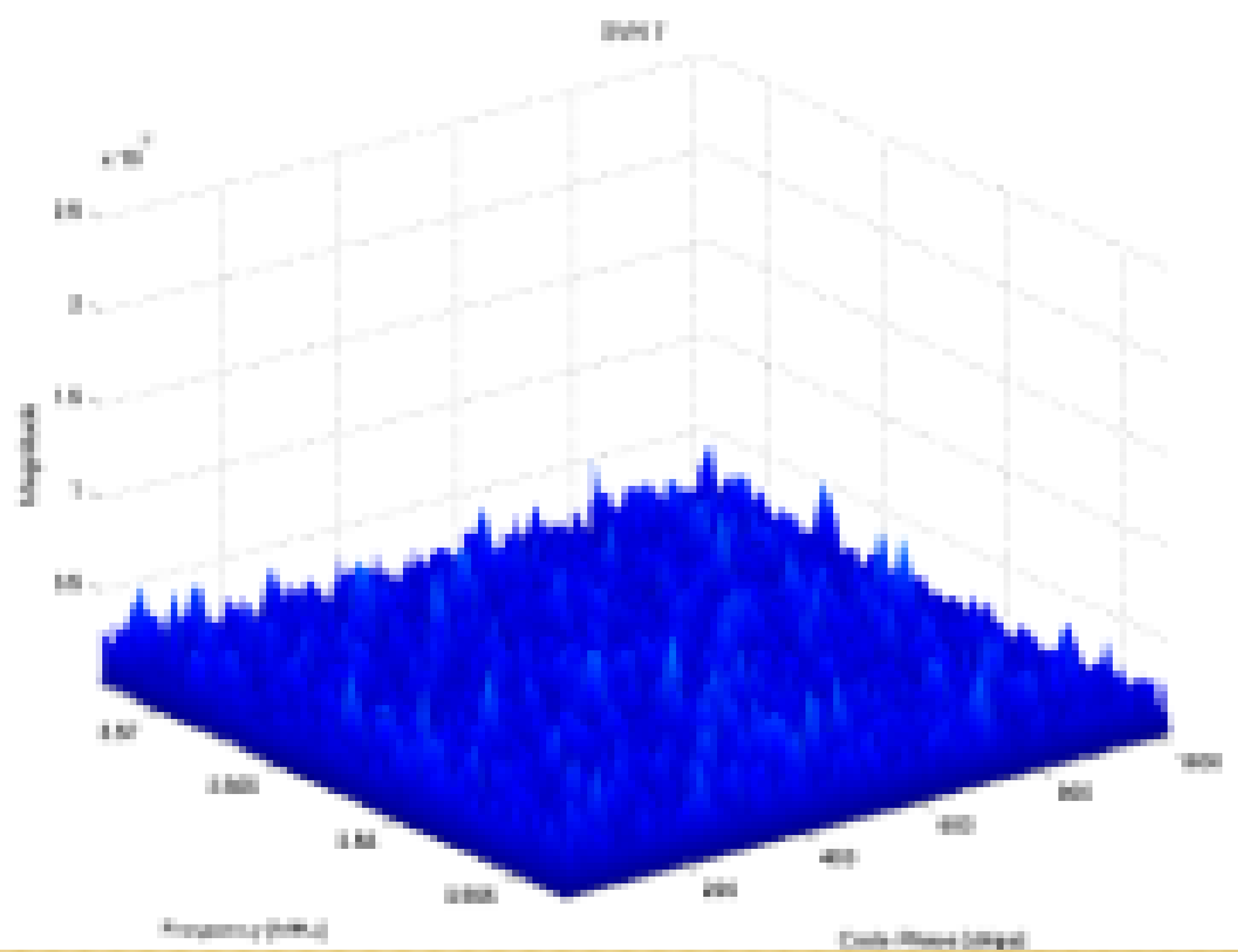
Search resulting grid of correlations for maximum, if above some threshold signal has been detected at some frequency and phase shift.



kom.aau.dk/~rinder/AAU_software_receiver.pdf

Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Search resulting grid of correlations for maximum, if it is small everywhere, below threshold, no signal has been detected.



Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

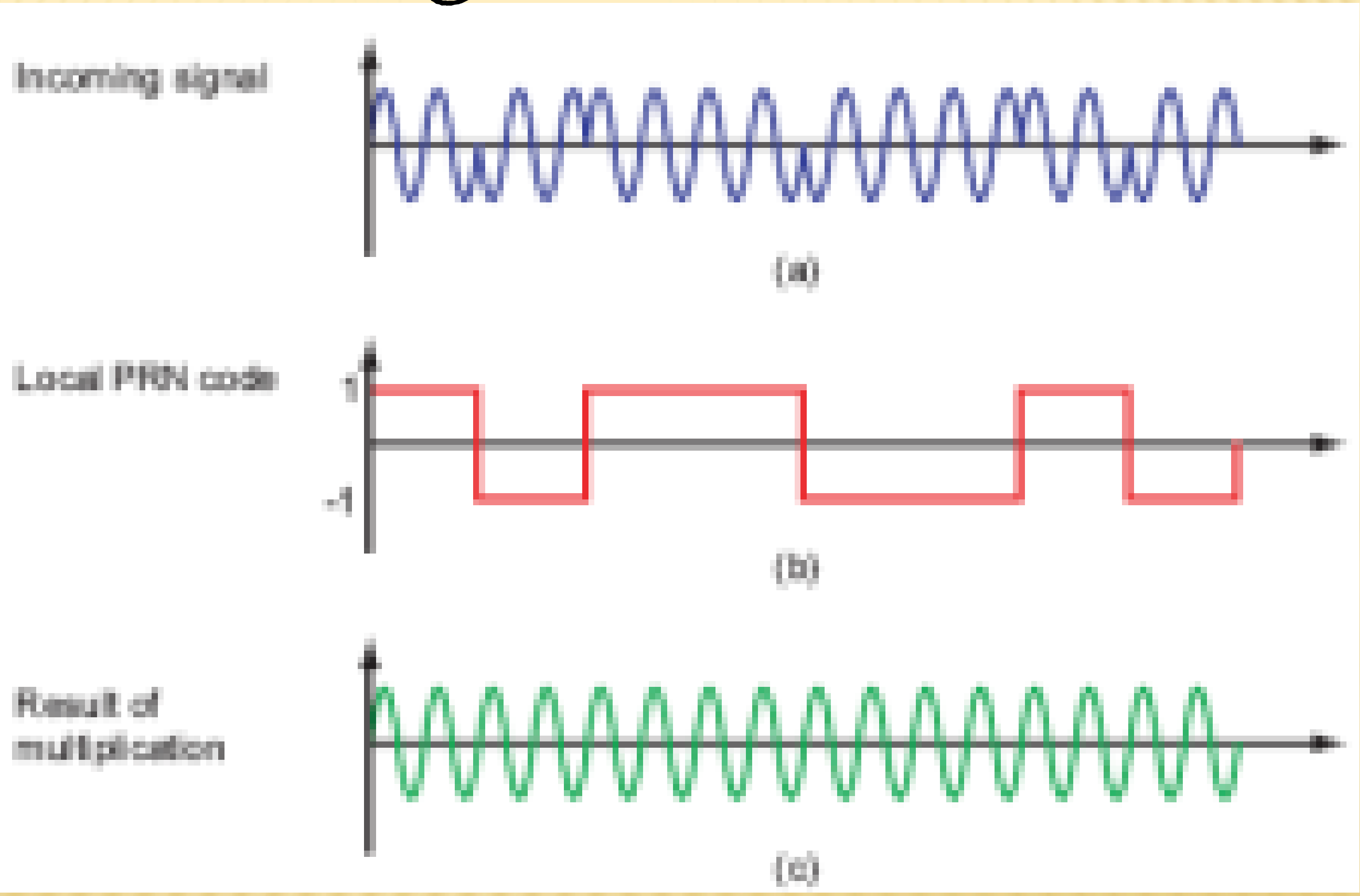
This method,

while correct and useful for illustration,

is too slow for practical use

Recovering the signal

What do we get if we multiply the L1 signal by a perfectly aligned C/A code?

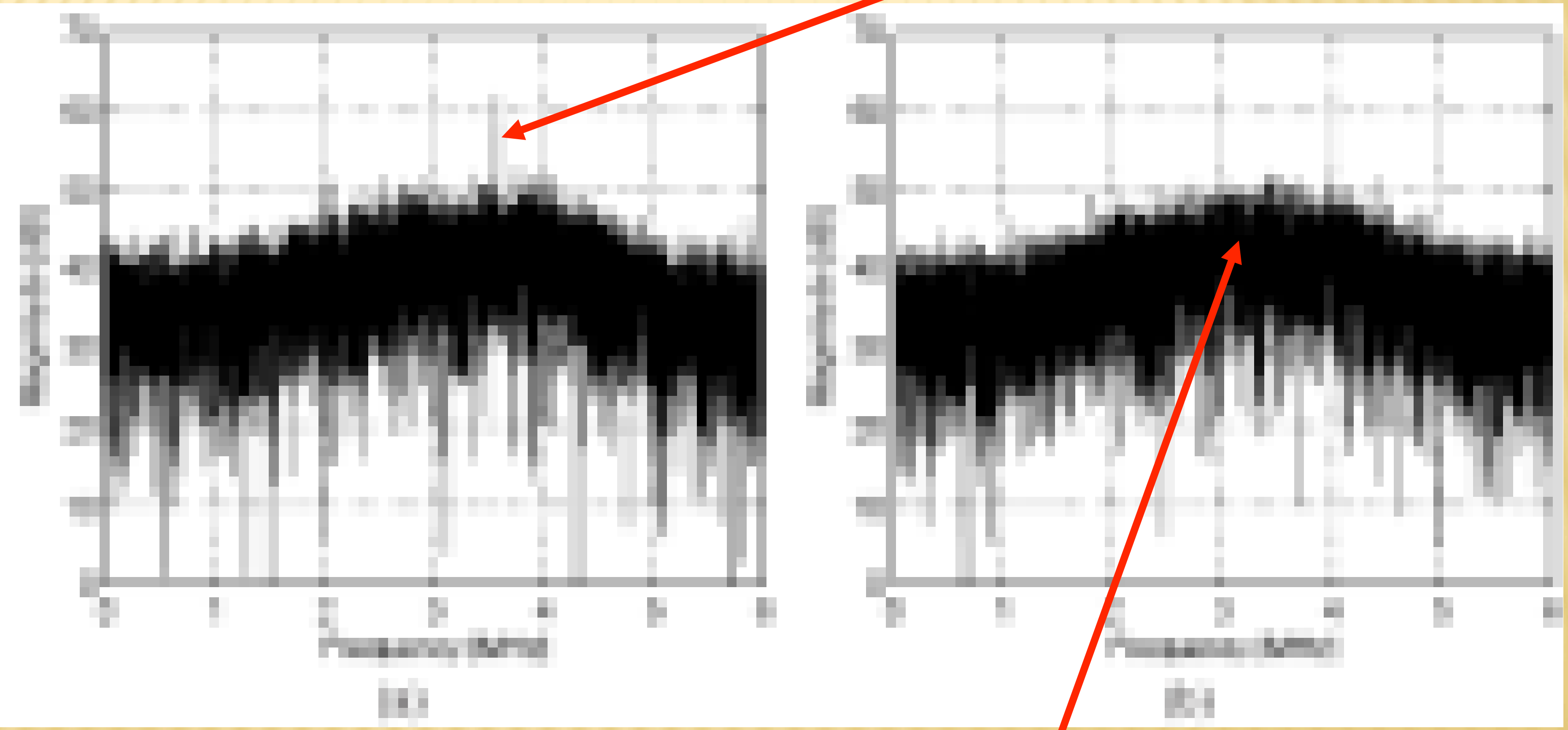


A sine wave!

Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Recovering the signal

Fourier analysis of this indicates the presence of the signal and identifies the frequency



No signal

Rinder and Bertelsen, kom.aau.dk/~rinder/AAU_software_receiver.pdf

Additional information included in GPS signal
Navigation Message

In order to solve the user position equations, one must know where the SV is.

The navigation and time code provides this

50 Hz signal modulated on L1 and L2

Navigation Message

The SV' s own position information is transmitted in a 1500-bit data frame (broadcast orbits)

Pseudo-Keplerian orbital elements, fit to 2-hour spans

Determined by control center via ground tracking

Receiver implements orbit-to-position algorithm

Navigation Message

Also includes clock data and satellite status

And ionospheric/tropospheric corrections

Additional information on GPS signal

The Almanac

In addition to its own nav data, each SV also broadcasts info about ALL the other SV’ s

In a reduced-accuracy format

Known as the *Almanac*

The Almanac

Permits receiver to predict, from a cold start, “where to look” for SV’ s when powered up

GPS orbits are so predictable, an almanac may be valid for months

Almanac data is large

12.5 minutes to transfer in entirety

Selective Availability (SA)

To deny high-accuracy realtime positioning to potential enemies, DoD reserves the right to deliberately degrade GPS performance

Only on the C/A code

By far the largest GPS error source

Selective Availability (SA)

Accomplished by:

1) "Dithering" the clock data

Results in erroneous pseudoranges

2) Truncating the navigation message data

Erroneous SV positions used to compute position

Selective Availability (SA)

Degrades SPS solution by a factor of 4 or more

Long-term averaging only effective SA compensator

FAA and Coast Guard pressured DoD to eliminate

ON 1 MAY 2000: SA WAS DISABLED BY PRESIDENTAL DIRECTIVE

How Accurate Is GPS?

Remember the 3 types of Lies:
Lies, Damn Lies, and Statistics…

Loosely Defined "2-Sigma" Repeatable Accuracies:

All depend on receiver quality

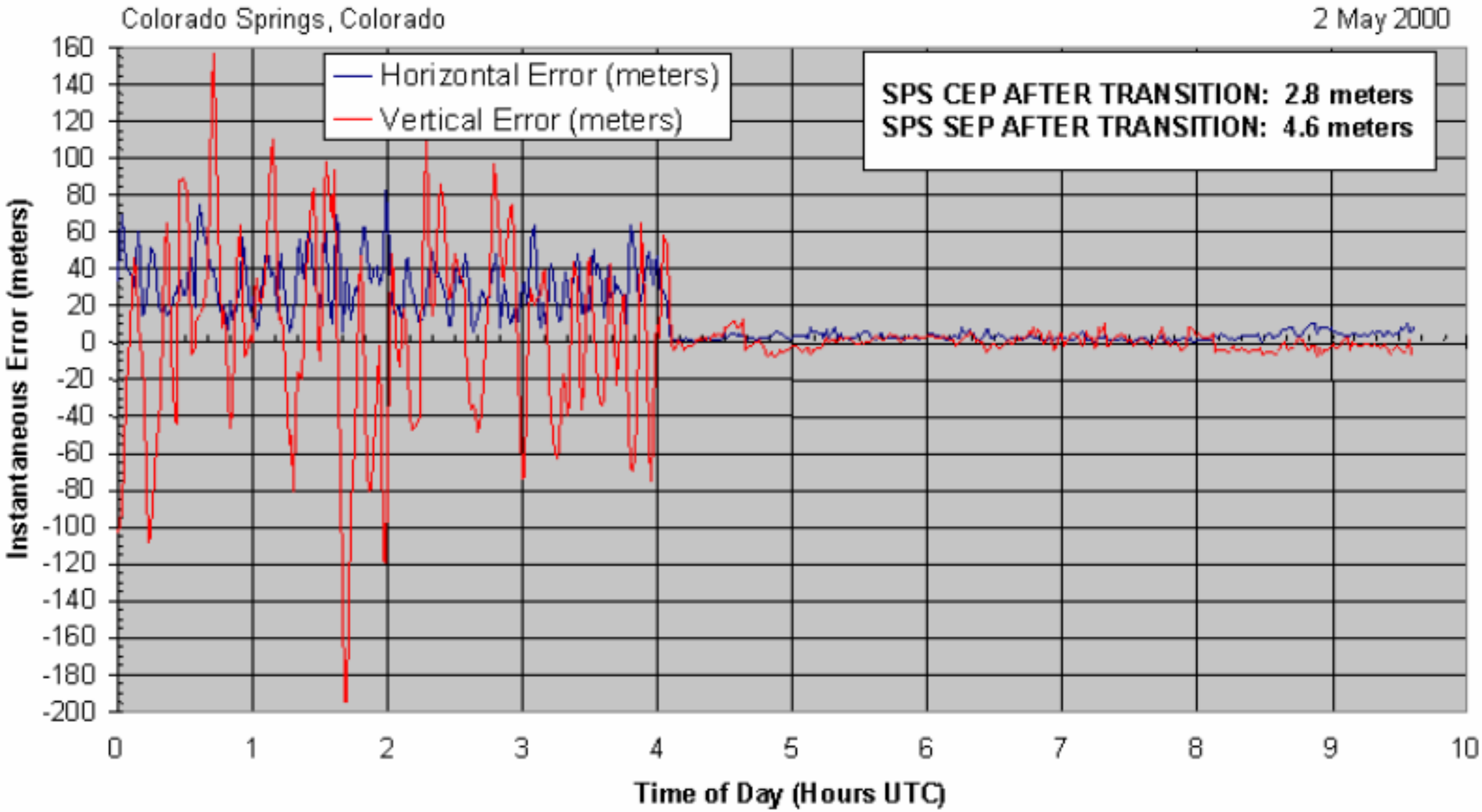
How Accurate Is GPS?

SPS (C/A Code Only)

S/A On:
Horizontal: 100 meters radial
Vertical: 156 meters
Time: 340 nanoseconds

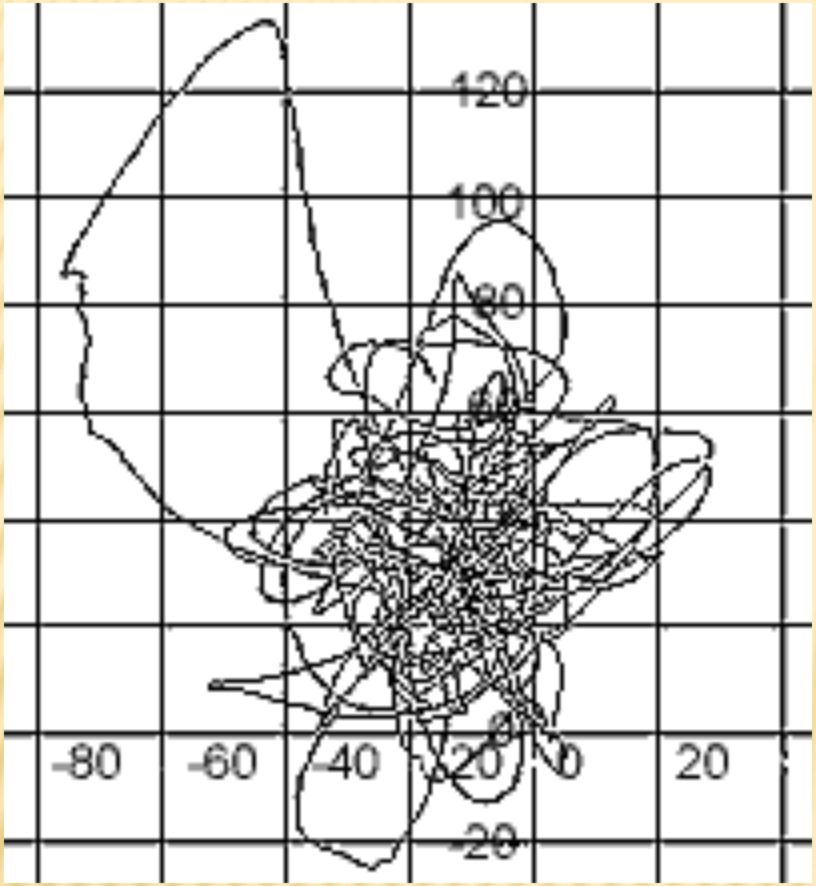
S/A Off:
Horizontal: 22 meters radial
Vertical: 28 meters
Time: 200 nanoseconds

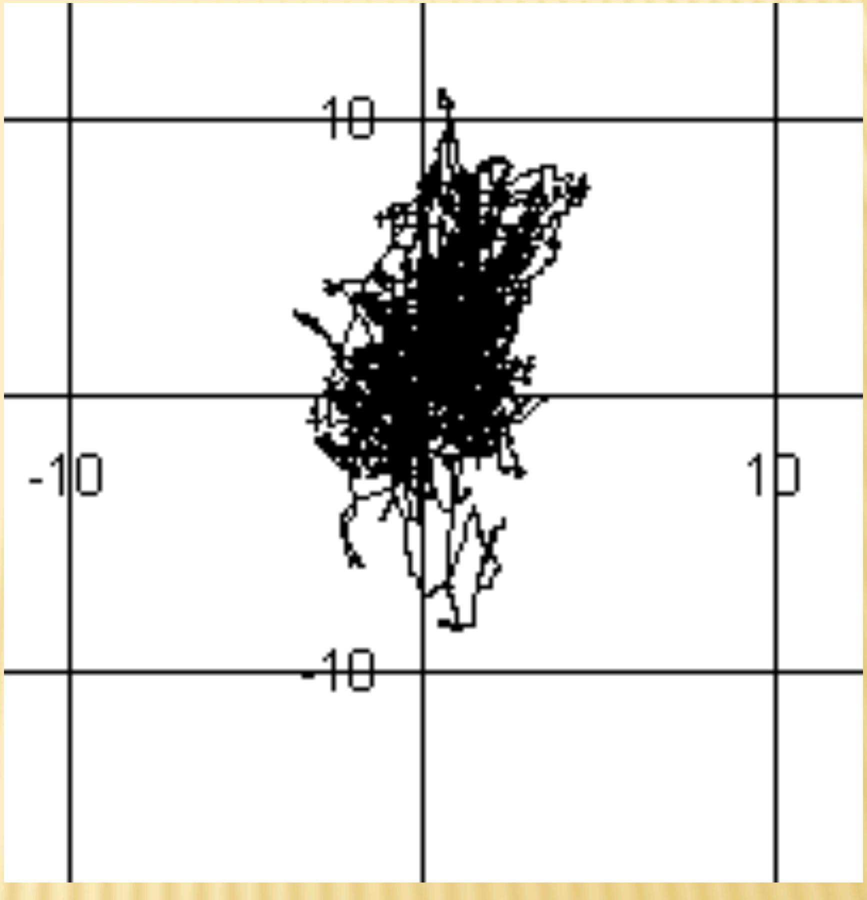
SA Transition -- 2 May 2000



From J. HOW, MIT

Position averages





5.5 hours S/A on

8 hours S/A off

Note scale difference

How Accurate Is It?

PPS (P-Code)

Slightly better than C/A Code w/o S/A (?)

Differential GPS

A reference station at a known location compares predicted pseudoranges to actual & broadcasts corrections: "Local Area" DGPS (LAAS)

Broadcast usually done on FM channel

Corrections only valid within a finite range of base
User receiver must see same SV's as reference.

USCG has a number of DGPS stations operating (CORS network)

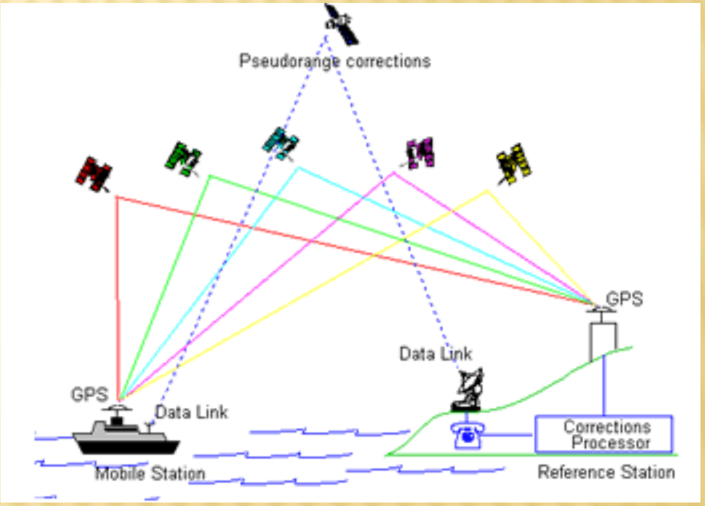
Differential GPS

Base stations worldwide collect pseudorange and SV ephemeris data and "solve-for" time and nav errors

"Wide Area" DGPS -- WAAS

Available conterminous US
Not yet globally available

DGPS can reduce errors to < 10 meters



A. Ganse, U. Washington , http://staff.washington.edu/aganse/

WAAS

Wide Area Augmentation System

is a satellite navigation system consisting of equipment and software which augment the GPS Standard Positioning Service (SPS).