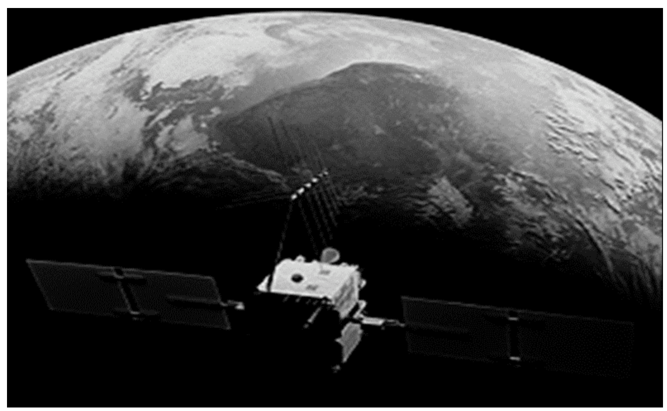
Towards Navigation Based on 120 Satellites

Understanding Galileo and Compass Signals



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A New Era for Global Navigation Satellite Systems (GNSS)

Nation	System	2002	2008	2020
USA	GPS	24 satellites	31 satellites	~31 satellites
EU	Galileo		2 satellites	~27 satellites
China	Compass		1 satellite	~35 satellites
Russia	GLONASS	8 satellites	16 satellites	~24 satellites
	Total	32 satellites	50 satellites	~120 satellites

Recently launched satellites provide opportunities to

- Study the benefit of redundancy on positioning accuracy and integrity
- Study the extent of interference among GNSS satellites
- Learn from the signal design of our international colleagues

Overview

Problem

Signal definitions for Galileo and Compass unpublished

Goal

Characterize new Galileo and Compass signals based on observations alone

Challenges

- Very weak signals (10^{-16} W) buried in thermal noise
- Complicated unknown signal structure
  - Unknown clock rate and code period
  - May broadcast data or use code overlays, composite codes, etc.
  - May use separate codes on inphase and quadrature channels
- Unsynchronized data collection apparatus
  - satellite clock drift, carrier phase, code phase and Doppler offset
- In presence of severe pulsed aeronautical interference

Outline

- Antenna setup
- Compass codes
  - Deciphering code chips
  - Deriving code generators
- Galileo codes
  - Differences from deciphering Compass codes
  - Validating codes using a software receiver

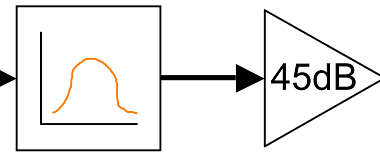
Antennas

Stanford GNSS Monitor Station with 1.8 m Dish Antenna

L-band Feed

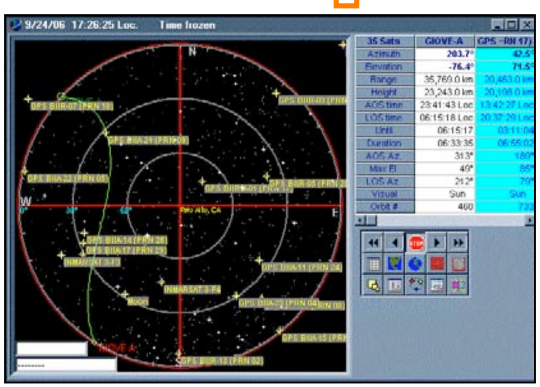
Cavity Filter

Low Noise Amplifier



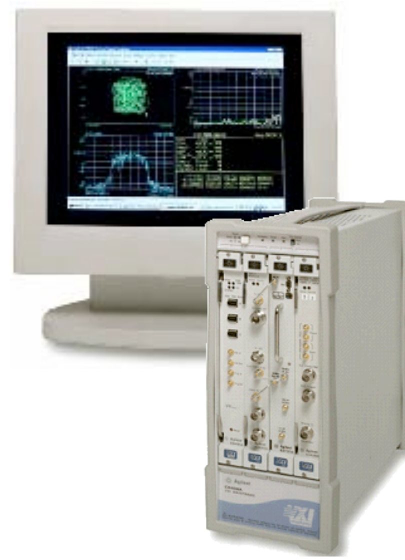
15 m cable

Azimuth/Elevation Control



Nova for Windows Satellite Tracking Software

- On-demand operation
- 1.8 m steerable dish antenna
  - High gain
  - Directional
- Flexible data collection system



Agilent Vector Signal Analyzer (VSA)

Outline

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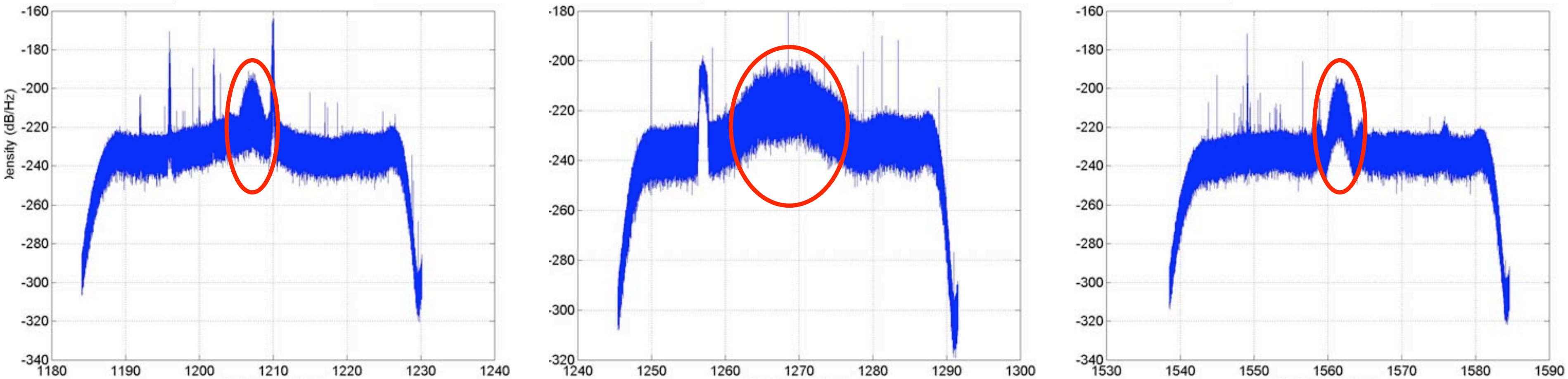
Compass-M1 Signal Spectra

E5b PSD (dBHz) | E6 PSD (dBHz) | E2 PSD (dBHz)



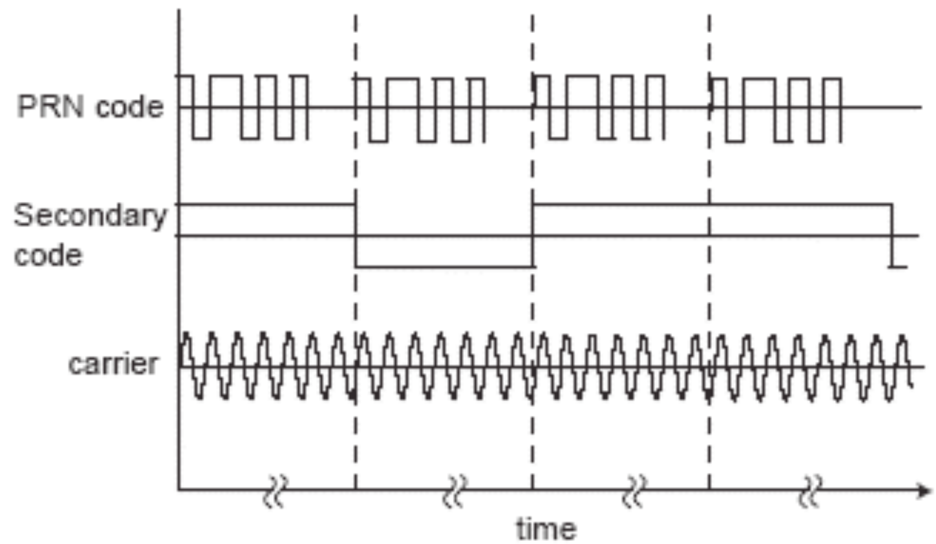
frequency (MHz)

E6 signal is more challenging to decipher than E5b or E2 signals

- Wider bandwidth
  (E6: 20 MHz vs. E5b/E2: 4 MHz)
- Faster chip rate
  (E6: 10.23 MHz vs. E5b/E2: 2.046 MHz)

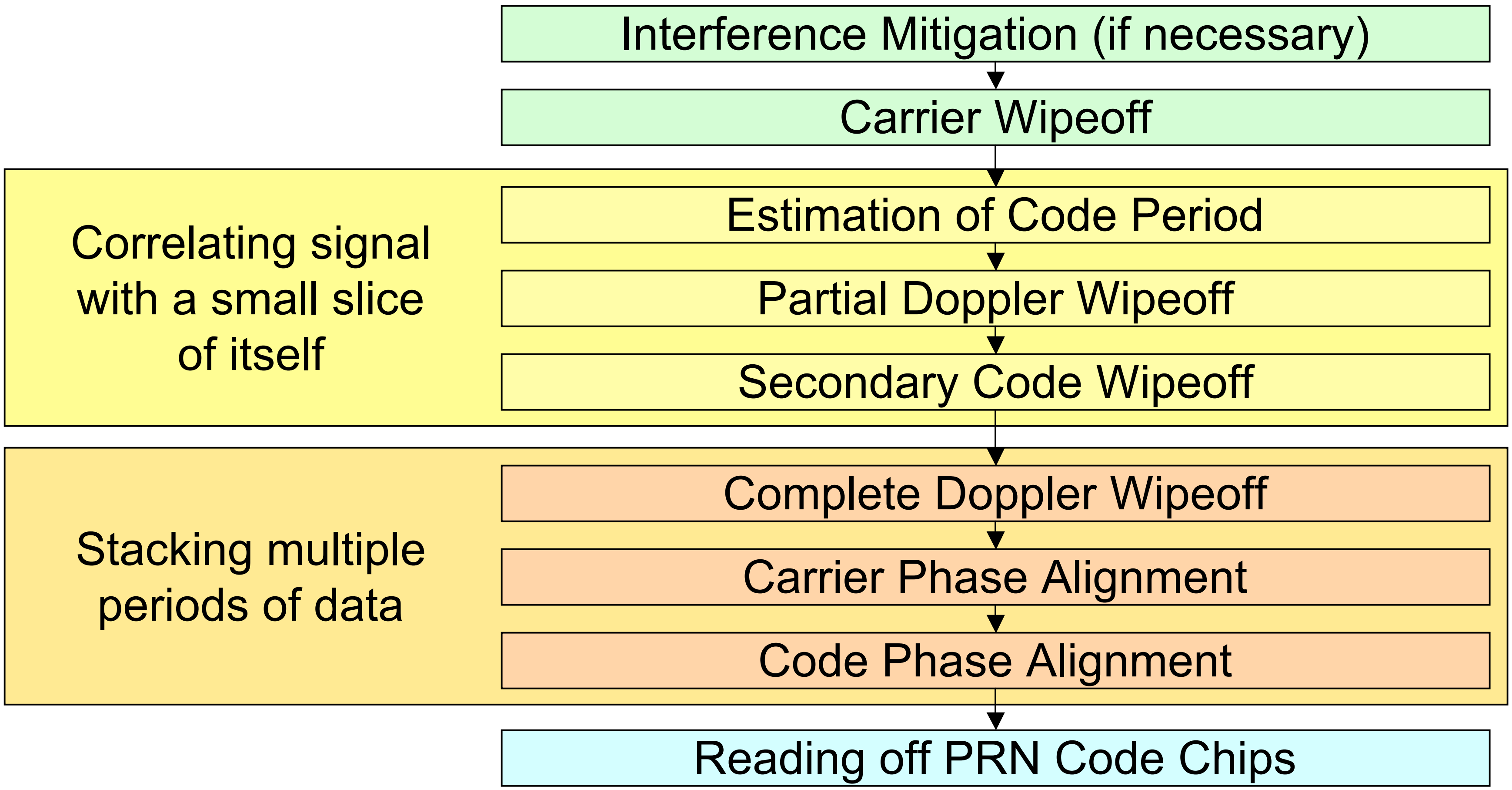
Received Signal Modeling

- Product of
  - Unknown periodic PRN code
  - Unknown secondary code (navigation data)
  - Carrier



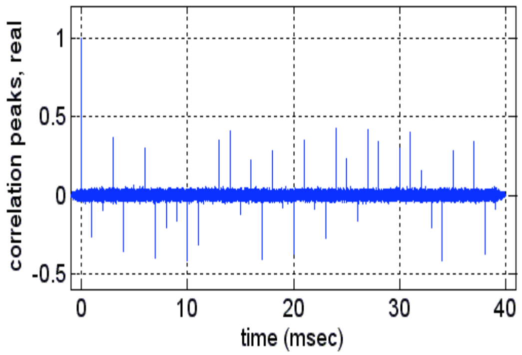
- Also contains
  - Unknown Doppler offset
  - Unknown carrier phase
  - Unknown code phase
  - Unknown satellite clock drift

Decoding Flow Chart

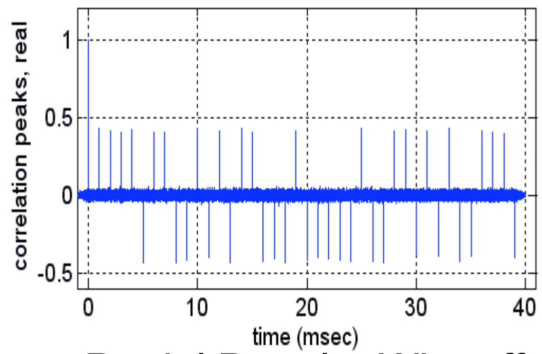


Major Decoding Steps

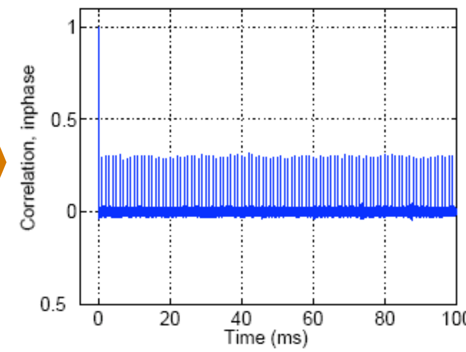
Correlating



Estimation of Code Period

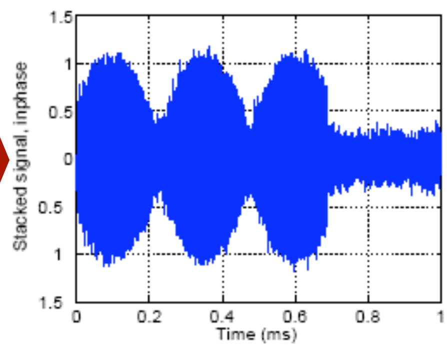


Partial Doppler Wipeoff

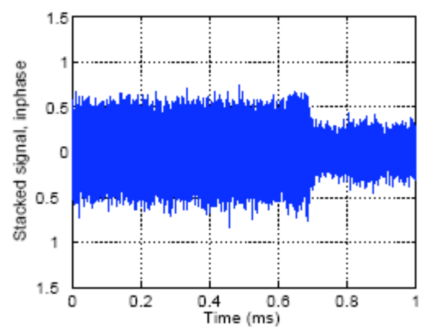


Secondary Code Wipeoff

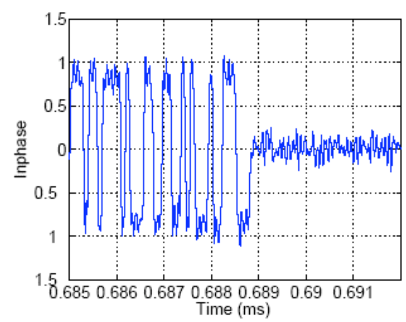
Stacking



Stacking



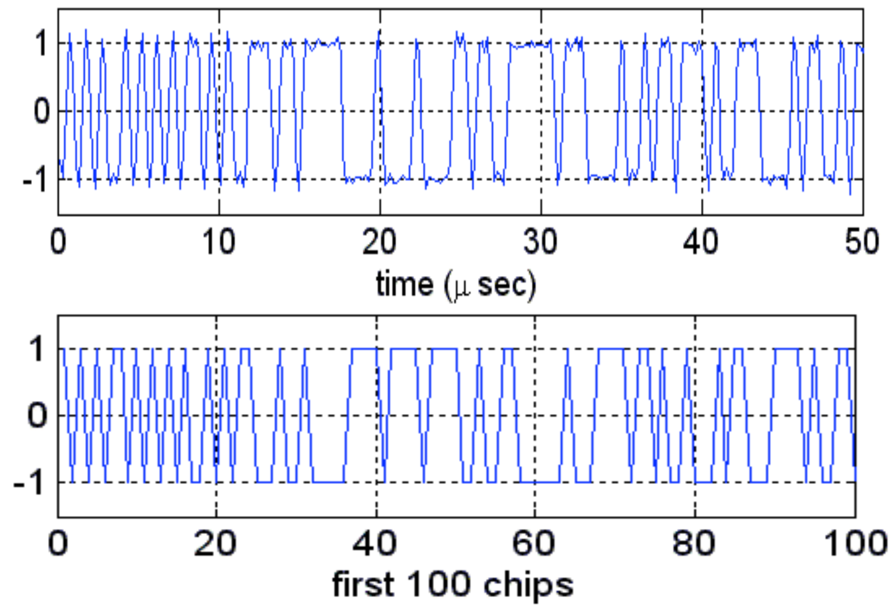
Complete Doppler Wipeoff



Zeroing initial phase

Reading off PRN Code Chips

Compass E6 PRN code chips revealed!



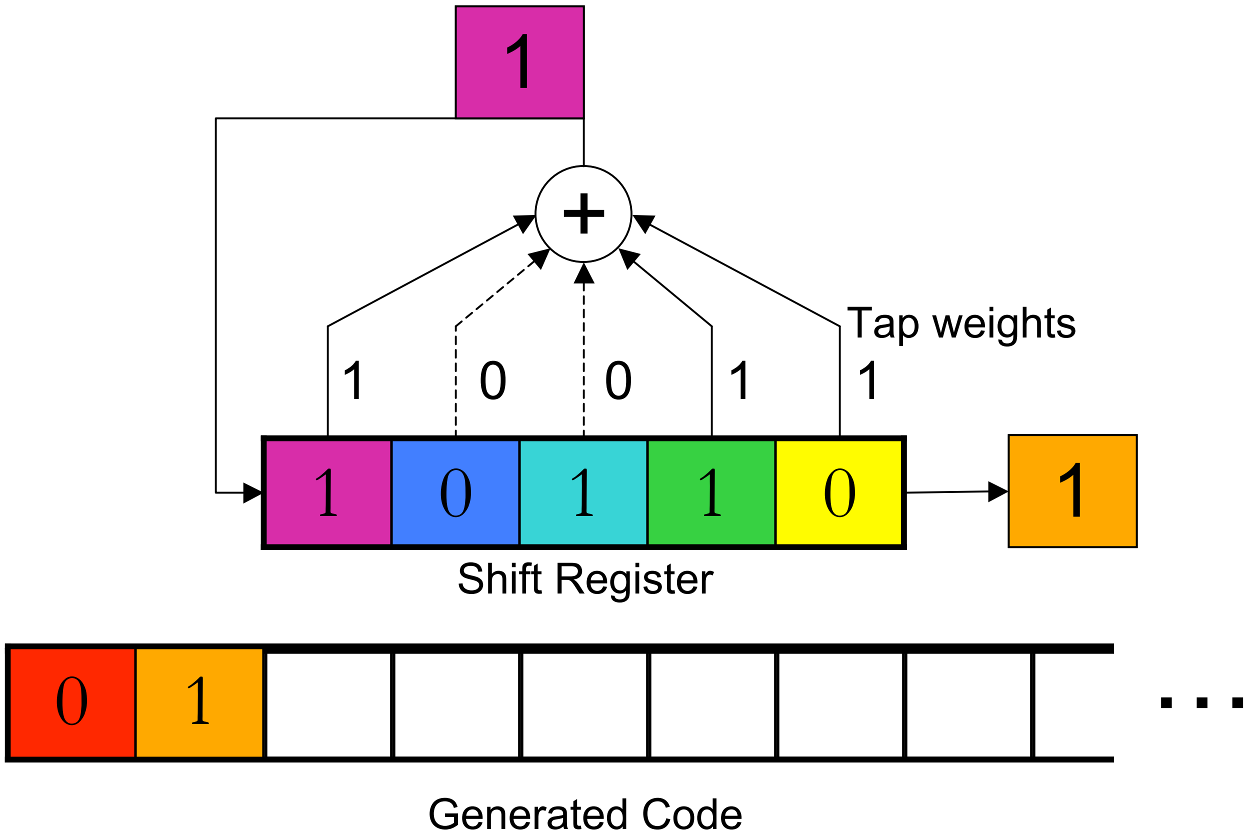
- There is still ambiguity in overall polarity to be resolved later
- Compass E6 secondary code is 20 bit Neuman-Hoffman code

  [-1 -1 -1 -1 -1 1 -1 -1 1 1 -1 1 -1 1 -1 -1 1 1 1 -1]

Deriving Code Generator

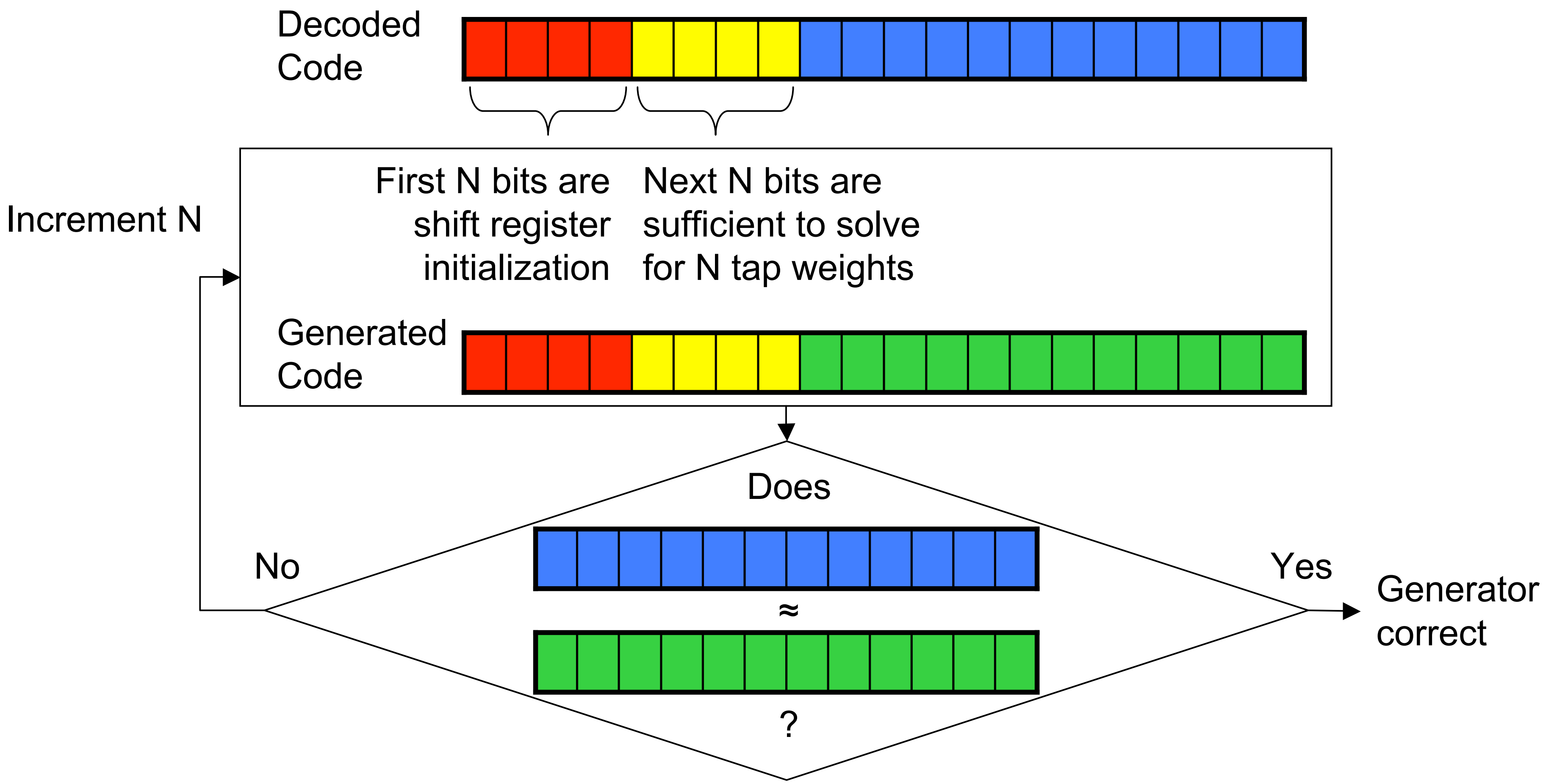
- Why seek the code generator?
  - To build better receivers
  - To analyze code structure
  - To resolve overall polarity ambiguity
- Educated guess: code generator is a linear feedback shift register (LFSR)
  - Efficient representation (10s of bits vs. 1000s)
  - Easy to implement and run in hardware
  - Just like GPS codes

Background: Linear Feedback Shift Register (LFSR)



- For Nth-order LFSR, first N bits of code are initial contents of shift register
- Next N bits can be used to solve for unknown tap weights

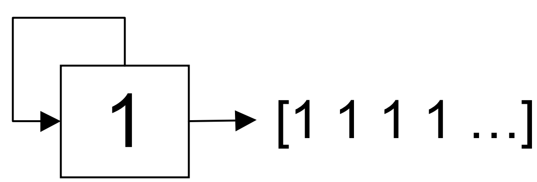
Error-Tolerant Berlekamp-Massey Algorithm



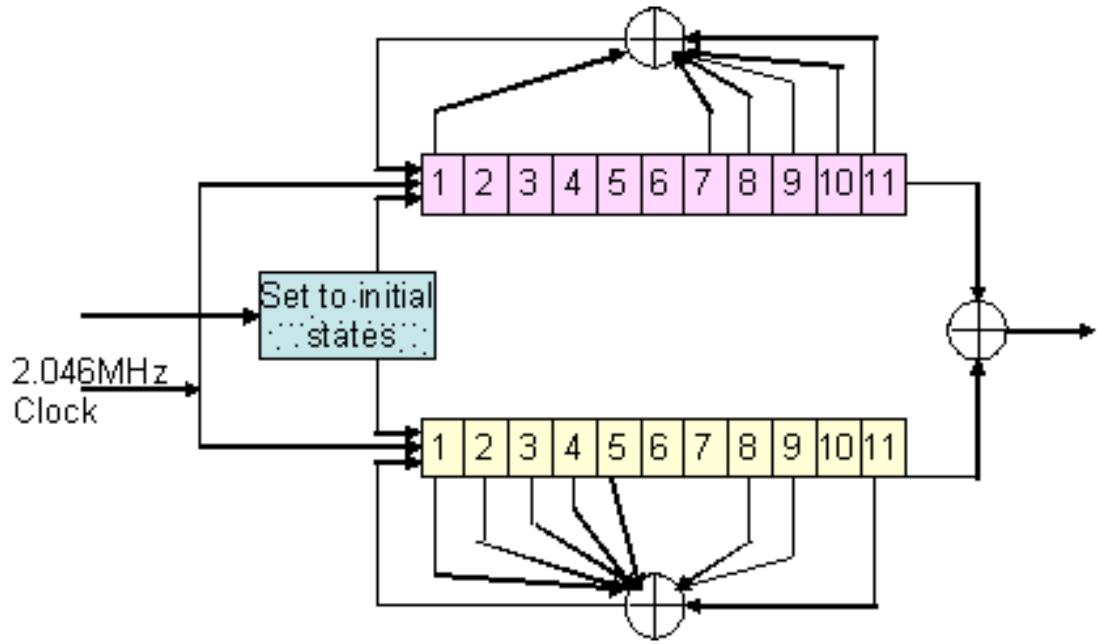
[Berlekamp, 1968] [Massey, 1969]

Deriving E2/E5b Code Generator

- Compass E2 and E5b codes are identical
- Generator is a 22nd-order LFSR
  - Can also be represented as modulo 2 sum of pair of 11th-order LFSRs
  - Gold codes [Gold, 1967]
- Overall polarity ambiguity is resolved
  - Flipped code requires additional 1st-order LFSR to output a string of 1s



Compass E2/E5b Generator



E2/E5b I-channel code (2046 bits, 1msec, 11-stage Gold code)	
Polynomial_1	$X^{11}+X^{10}+X^{9}+X^{8}+X^{7}+X+1$
Initial State_1	[0 1 0 1 0 1 0 1 0 1 0]
Polynomial_2	$X^{11}+X^{9}+X^{8}+X^{5}+X^{4}+X^{3}+X^{2}+X+1$
Initial State_2	[0 0 0 0 0 0 0 1 1 1 1]

Compass E6 Generators

E6 I-channel code (Head)	
Polynomial_1	$X^{13}+X^{12}+X^{10}+X^{9}+X^{7}+X^{6}+X^{5}+X+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 0]
Polynomial_2	$X^{13}+X^{4}+X^{3}+X+1$
Initial State_2	[1 1 1 1 1 1 1 1 1 1 1 1 1]

E6 I-channel code (Tail)	
Polynomial_1	$X^{13}+X^{12}+X^{10}+X^{9}+X^{7}+X^{6}+X^{5}+X+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{13}+X^{4}+X^{3}+X+1$
Initial State_2	[1 1 1 1 1 1 1 1 1 1 1 1 1]

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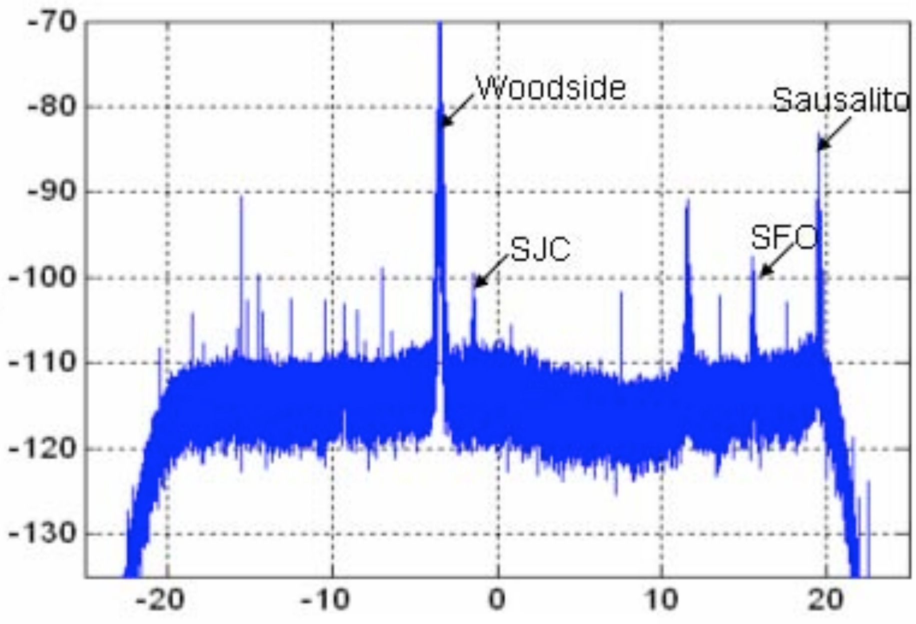
E5 Band Suffers from DME/TACAN Interference

- Distance Measurement Equipment (DME)
  - Provides distance measurement between aircraft and a ground station
- Tactical Air Navigation (TACAN)
  - Additionally provides azimuth information and is a military system
- DME/TACAN signals are pulsed interference to Galileo E5 band

Airport	Transmitter frequency (MHz)
Woodside	1173
Moffett	1210
SFO	1192
SJC	1175
OAK	1202
Sausalito	1196

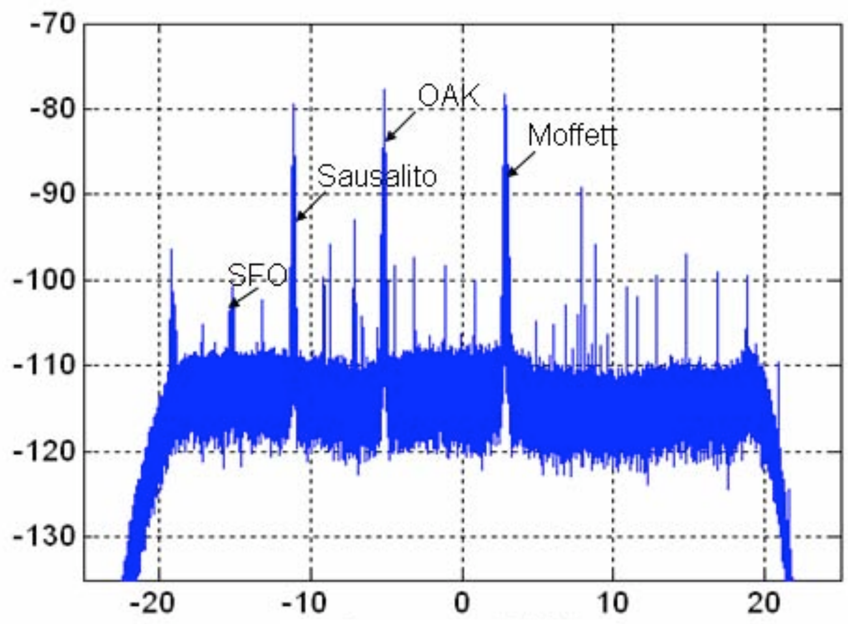
Received E5a and E5b Spectra

E5a PSD (dBHz)



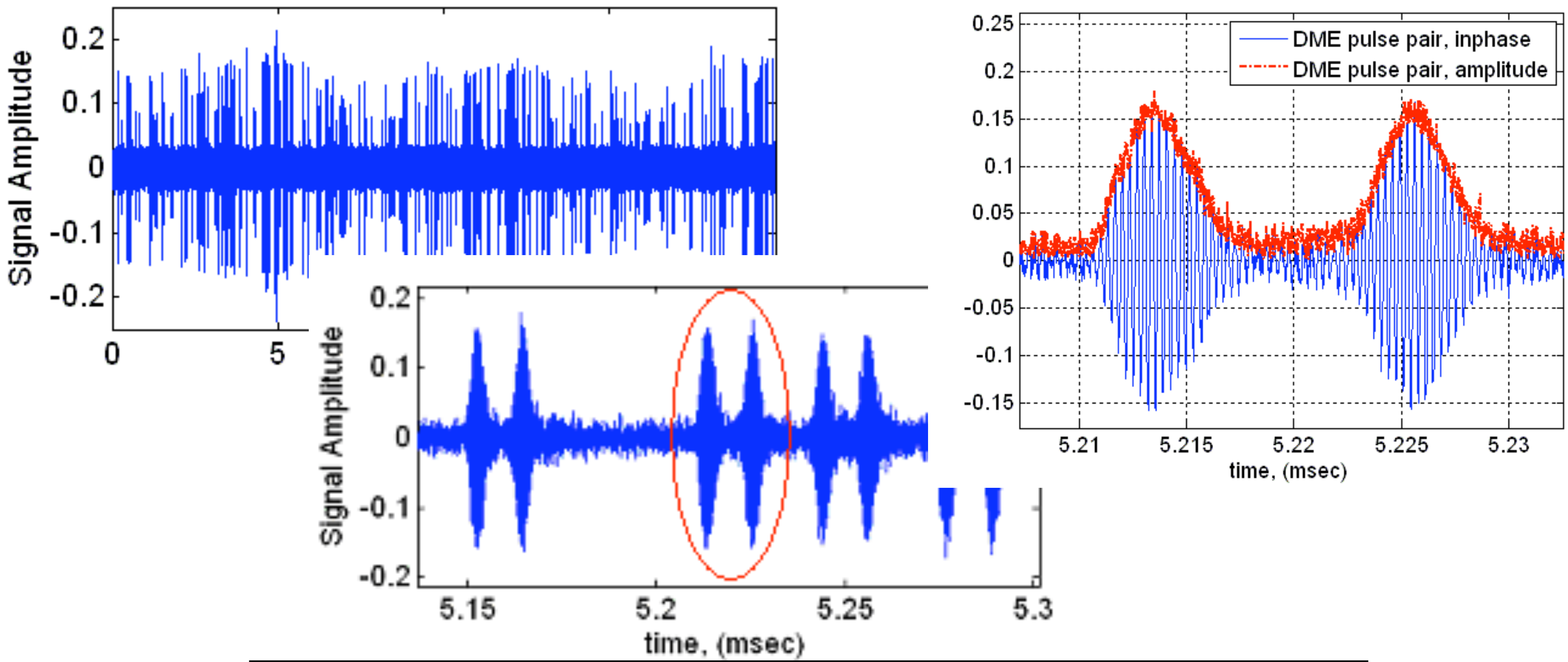
frequency (MHz)

E5b PSD (dBHz)



frequency (MHz)

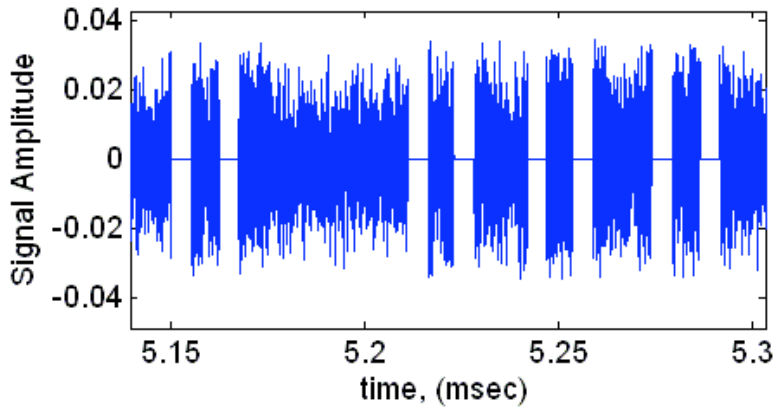
Received E5b Inphase Samples

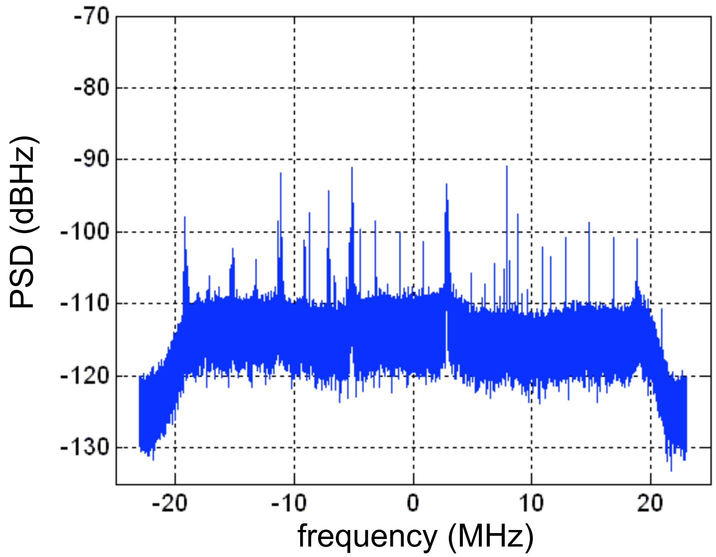


- DME pulse amplitude is 5-100 times greater than noise floor
- DME interference occurs 10-14% of the time
- DME pulses come in pairs with inter-pulse interval of 12 μsec
- E5b signal is completely buried in noise

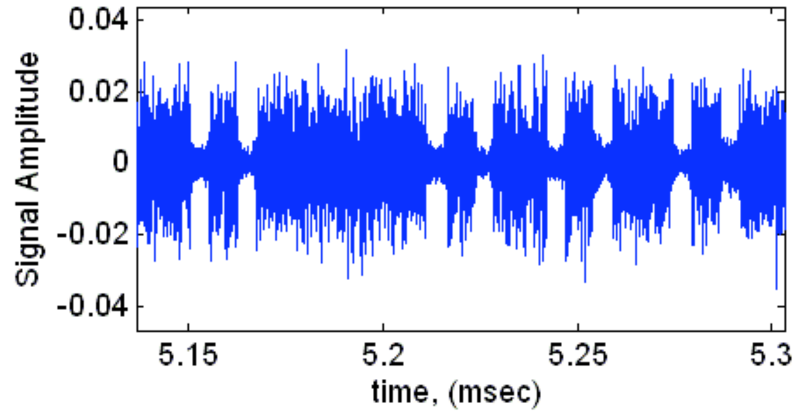
Interference Mitigation for E5b

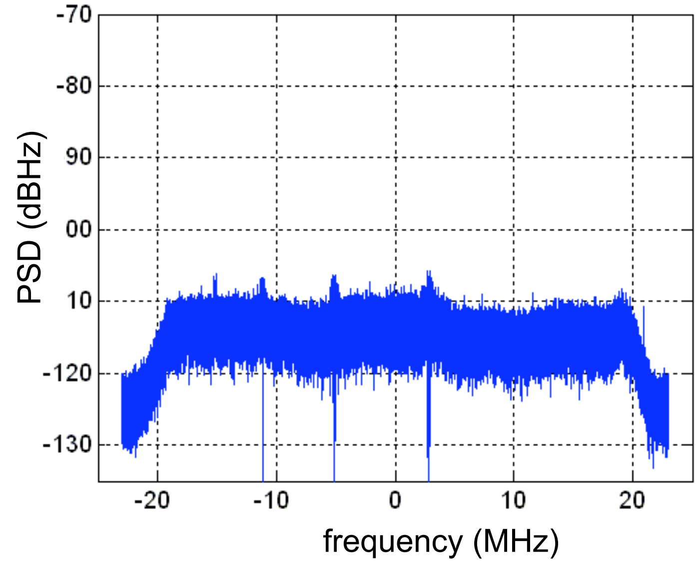
Pulse Blanking





Notch Filtering





Other Differences Between Galileo and Compass Signals

- Galileo L1 band uses Binary Offset Carrier (BOC) modulation

- Galileo L1 band overlaps GPS L1 band

- All Galileo bands have two codes superimposed

GIOVE-A L1 and E6 Generators

L1-B code (4092 bits, 4msec, 13-stage Gold code)	
Polynomial_1	$X^{13}+X^{10}+X^9+X^7+X^5+X^4+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{13}+X^{12}+X^8+X^7+X^6+X^5+1$
Initial State_2	[1 1 0 1 1 1 0 0 0 0 0 1 1]
L1-C code (8184 bits, 8msec, 14-stage Gold code)	
Polynomial_1	$X^{14}+X^{13}+X^{11}+X^4+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14}+X^{12}+X^9+X^8+X^5+X^2+1$
Initial State_2	[1 1 0 0 0 0 0 0 0 0 0 1 0 0]

E6-B code (5115 bits, 1ms,13-stage Gold Code)	
Polynomial_1	$X^{13}+X^{12}+X^{11}+X+1$
Initial State_1	[0 1 0 1 0 1 1 1 0 0 0 0 0]
Polynomial_2	$X^{13}+X^{10}+X^8+X^5+1$
Initial State_2	[1 1 1 1 1 1 1 1 1 1 1 1 1]
E6-C code (10230 bits, 2ms,14-stage Gold Code)	
Polynomial_1	$X^{14}+X^{11}+X^6+X+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14}+X^8+X^7+X^4+X^3+X^2+1$
Initial State_2	[0 1 1 0 1 0 0 0 0 1 1 1 0 1]

GIOVE-A E5 Generators

E5b-I code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14}+X^{13}+X^{11}+X^4+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14}+X^{12}+X^9+X^8+X^5+X^2+1$
Initial State_2	[1 1 1 0 0 0 1 0 1 0 0 0 1 0]
E5b-Q code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14}+X^{13}+X^{11}+X^4+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14}+X^{12}+X^9+X^8+X^5+X^2+1$
Initial State_2	[1 1 0 0 0 0 0 0 0 0 0 1 0 0]

E5a-I code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14}+X^8+X^6+X+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14}+X^{12}+X^8+X^7+X^5+X^4+1$
Initial State_2	[1 1 1 0 1 0 1 0 1 1 1 1 1 1]
E5a-Q code (10230 bits, 1msec, 14-stage Gold code)	
Polynomial_1	$X^{14}+X^8+X^6+X+1$
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Polynomial_2	$X^{14}+X^{12}+X^8+X^7+X^5+X^4+1$
Initial State_2	[0 1 1 0 1 1 0 0 1 0 1 0 1 0]

GIOVE-B L1/E5 Generators

All GIOVE-B codes have the same polynomials as the respective GIOVE-A codes, but different initial states.

E5a-I code (10230 bits, 1msec, 14-stage Gold code)	
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Initial State_2	[1 0 0 1 1 0 0 1 0 0 0 0 0 0]
E5a-Q code (10230 bits, 1msec, 14-stage Gold code)	
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Initial State_2	[1 0 0 0 1 1 1 0 1 0 1 1 0 0]

L1-B code (4092 bits, 4msec, 13-stage Gold code)	
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1]
Initial State_2	[1 0 0 1 1 1 1 1 1 1 1 0 0]
L1-C code (8184 bits, 8msec, 14-stage Gold code)	
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Initial State_2	[0 1 0 0 0 1 0 1 1 1 1 1 1]

E5b-I code (10230 bits, 1msec, 14-stage Gold code)	
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Initial State_2	[0 0 0 1 0 1 0 1 1 0 0 1 0]
E5b-Q code (10230 bits, 1msec, 14-stage Gold code)	
Initial State_1	[1 1 1 1 1 1 1 1 1 1 1 1 1 1]
Initial State_2	[0 1 0 1 0 0 0 0 0 1 0 1 1 1]

Summary of Contributions

- Designed algorithms for deciphering unknown pseudo-random-noise (PRN) codes of new GNSS satellites
  - Very weak signals (10^{-16} W) buried in thermal noise
  - Complicated unknown signal structure
    - Unknown clock rate and code period
    - May broadcast data or use code overlays, composite codes, etc.
    - May use separate codes on inphase and quadrature channels
  - Unsynchronized data collection apparatus
    - Unknown satellite clock drift, carrier phase, code phase and Doppler offset
  - In presence of severe pulsed aeronautical interference
- Characterized Galileo GIOVE-A and GIOVE-B and Compass-M1 satellite signals
  - Codes already implemented in commercial receivers
    - Trimble tracked GIOVE-A in March 2007 and GIOVE-B in May 2008
    - Septentrio tracked Compass-M1 signals in May 2007
    - Javad used my codes in their receivers since May 2007

Thank you!

Acknowledgement

- FAA
- My co-authors:

  Alan Chen, Dave De Lorenzo, Sherman Lo, Dennis Akos, Todd Walter and Per Enge