Performance Assessment of LunaNet's Augmented Forward Signal

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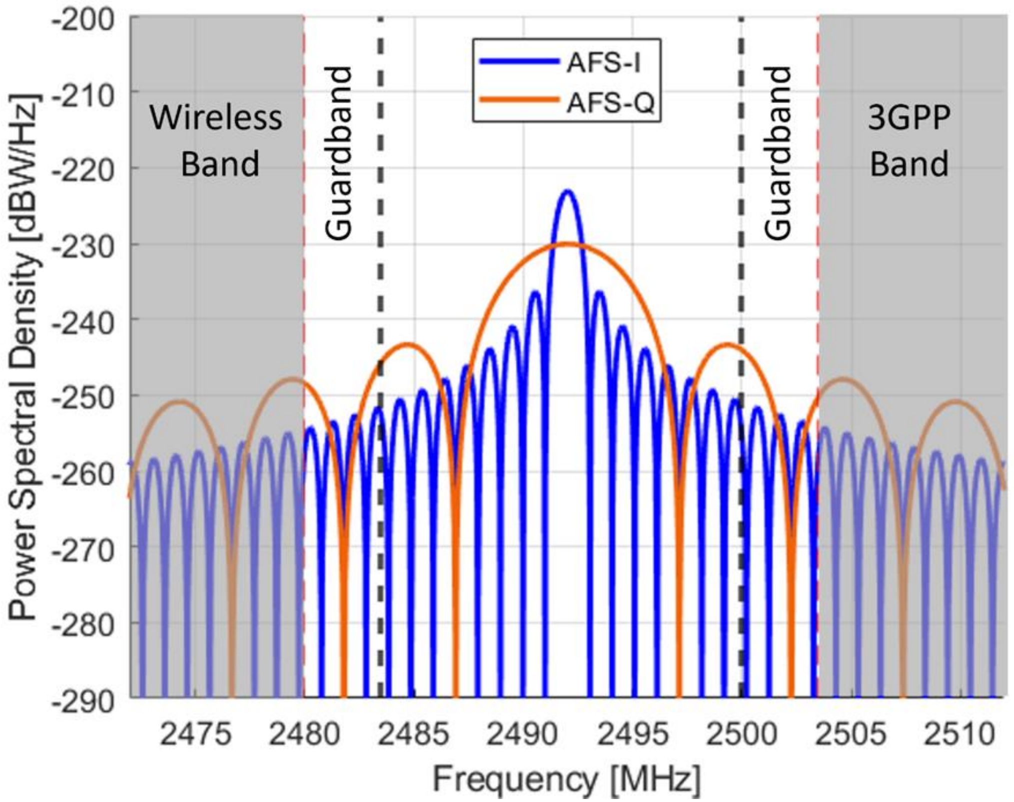
Acknowledgements

- This work was funded by the NASA LCRNS project to inform the LunaNet Interoperability Specifications (LNIS), funded under contract 80GSFC19D0011.

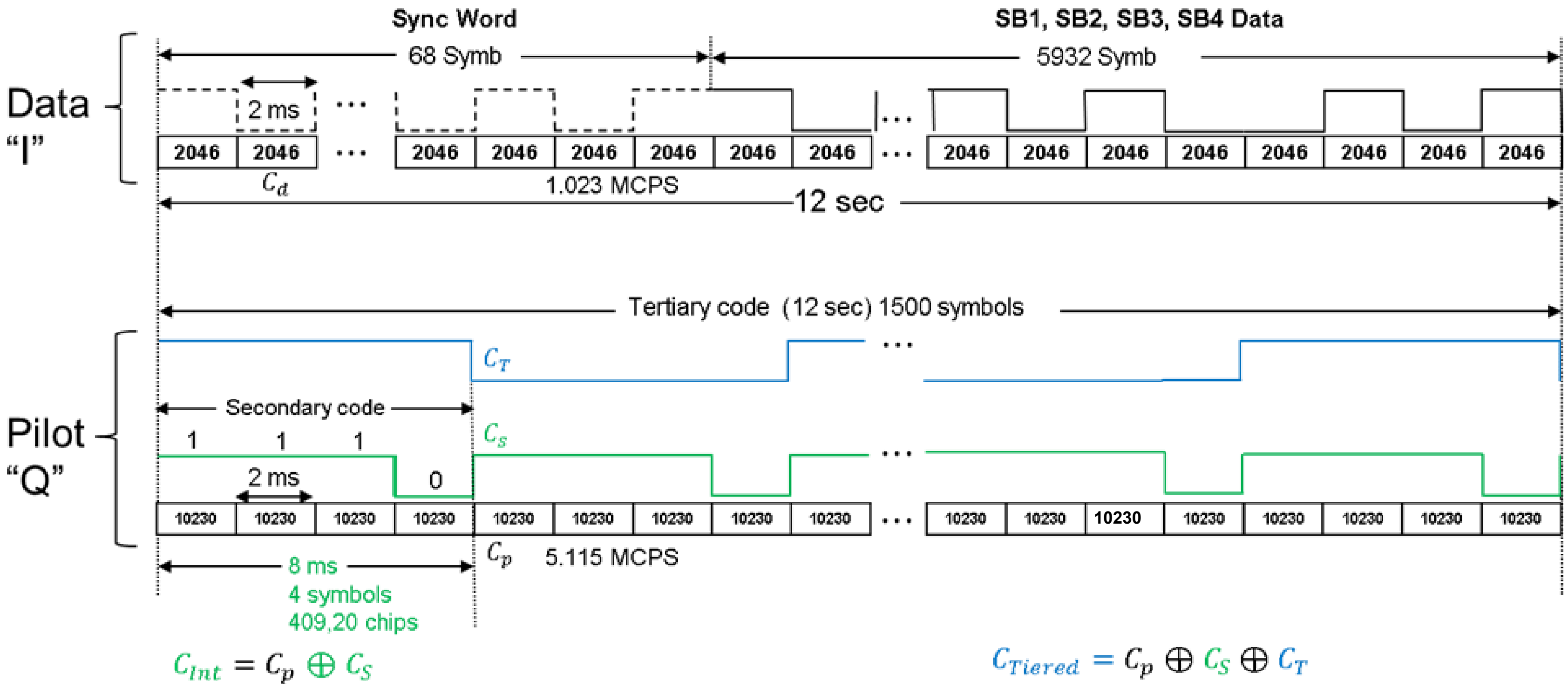
*LunaNet Signal Description**

- AFS-I: 1.023 MCPS BPSK Signal at -163 dBW
- AFS-Q: 5.115 MCPS BPSK Signal at -163 BW
- Center Frequency = 2492.028 MHz
  - *Between 2483.5 MHz and 2500 MHz*



*https://insidegnss.com/the-augmented-forward-signal-afs-defining-the-navigation-signal-standard-for-future-lunar-missions/

AFS's Tiered Code Structure



- Includes C/A-Like Data Channel Spreading Code with a 2046 length Gold Code
  - *Low complexity acquisition (twice that of C/A code)*
- Includes a tiered Pilot spreading code with a 2 ms primary code and an 8 ms secondary code for enhanced acquisition sensitivity
  - *Receiver can acquire 2 ms, 5.115 MCPS code with 1/2th the complexity of direct acquisition of the 1 ms L5 primary code (half the rate but same number of chips)*
    - ➢ having the same processing gain as L5
  - *Processing gain of 8 ms code at 5.115 MCPS is 6 dB greater than processing gain of L5 primary code at 10.23 MCPS*

Signal Design Considerations

- Spreading Modulation
  - ***Sensitivity to Adjacent Band Interference (Primary Driver for BPSK Signals over BOC Signals)***
  - *RMS Bandwidth*
  - *Multipath Rejection*
    - ➢ Improved by tracking 5.115 MCPS Pilot code

- Acquisition
  - *Code Length*
  - *Code Rate*

  Higher code length and rate Improve sensitivity at Increased Complexity
  - AFS I and Q signals balance this

  - *Autocorrelation side-lobes should be good enough to be well below noise level under normal operating conditions*
  - *Overlay Code provides absolute time for receivers with time to 12 sec*
    - ➢ Nearly eliminates the need to do a pure cold start under most conditions

- Tracking
  - *Available coherent integration*
    - ➢ 2 ms for data channel due to 2 ms data symbols
    - ➢ No limit for pilot channel after sync to tertiary code

- Pilot channel provides low cross-correlation to resist co-channel interference

I channel – AFS Data – Message and Code Correlation Performance

I Channel Code Correlation Performance

- 1.023 MCPS I channel allows 2 ms of coherent integration with no loss as compared to C/A code with bit boundary loss for coherent integration > 1 ms
  - *Limited by 500 bits/sec data rate*

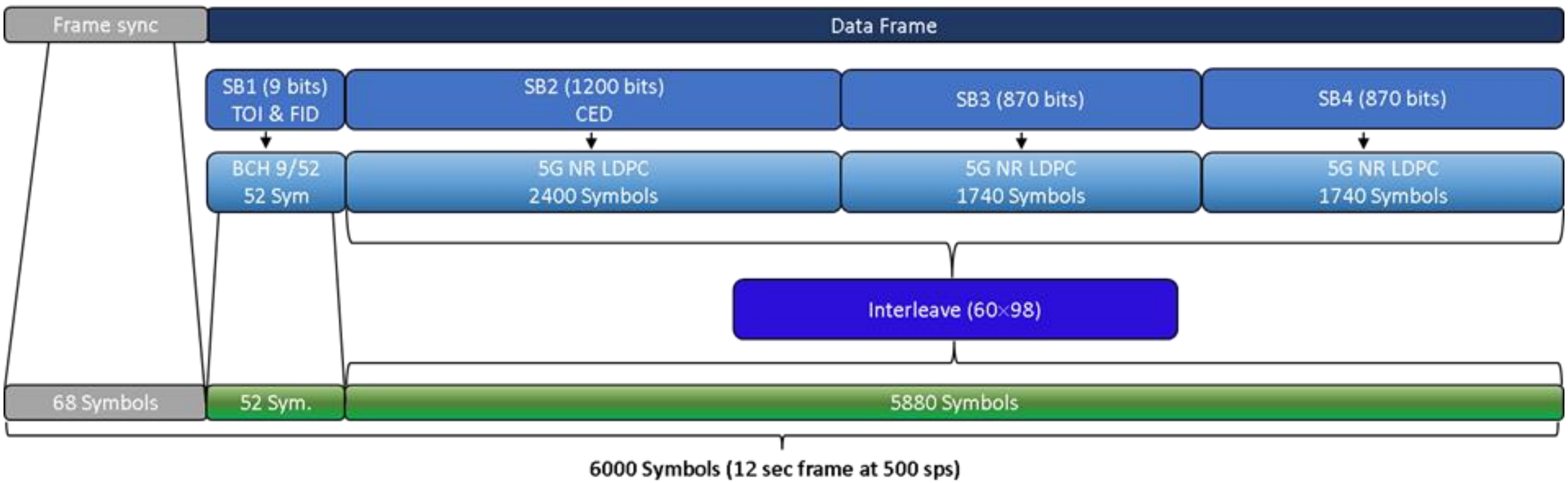
- Designed with 210 new Gold sequences

Code	C/A Acq.	C/A Track	AFS-I Acq./Track	AFS-I (Gold) Improvement over C/A Acq. (210 PRNs)	AFS-I (Gold) Improvement over C/A Track (210 PRNs)
PRNs	209	209	210		
Ti (ms)	1	2	2		
Code Length (chips)	1023	1023	2046		
Max (dB)	-16.5	-19.5	-19.6	3.1	0.1
RMS (dB)	-30.1	-31.4	-33.1	3.0	1.8
99% percentile (dB)	-22.7	-23.9	-25.5	2.9	1.6
99.9% percentile (dB)	-20.3	-22.6	-23.7	3.4	1.1

Provides 2-3 dB improvement over C/A cross-correlation performance for acquisition and 1-2 dB for tracking

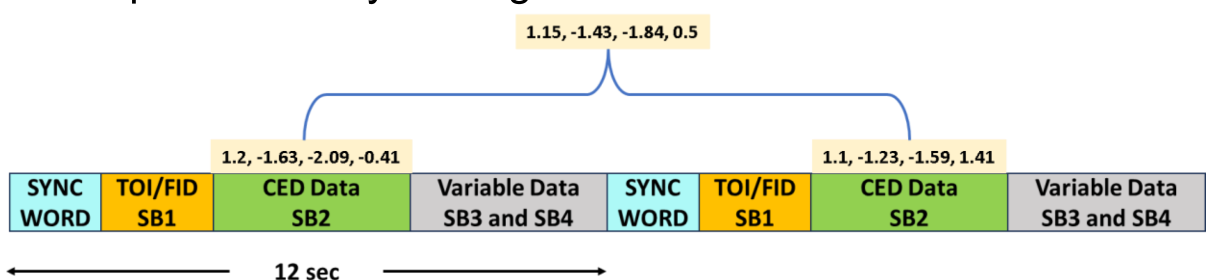
AFS Data Message Structure

- 12 sec Data Frame - 5G New Radio (5GNR) Forward Error Control Coding
  - *Subframe Block 1 (SB1) : Includes BCH coded Time of Interval (TOI) and Frame ID*
  - *SB2: Clock and Ephemeris Data*
  - *SB3: Almanac, Coordinate frame conversions, etc.*
  - *SB4: LunaNet Network Access Information (MSG-G1), etc.*



Time of Interval (TOI) in SB1 Is intended to informs receiver when CED data changes

- Fixed repeating data for 20 min to enable CED data symbol combining for robust warm start
- e.g., 4.8 dB improvement by waiting 36 sec to read data



Data Message Minimum C/N_0 Threshold to Achieve 95% Probability of a Fix

Navigation System	GPS				Galileo		LunaNet
Signal	CA	L1C	L2C	L5	E1B/E5b	E5a	AFS
Encoding	None	Custom LDPC, rate 1/2	Conv rate 1/2, k=7	Conv rate 1/2, k=7	Conv rate 1/2, k=7	Conv rate 1/2, k=7	5GNR rate 1/2 LDPC
Bit Rate (bits/sec)	50	50	25	50	125	50	250
Message/Block Size (Symbols)	300	1200	600	600	520	512	2400
Message/Block Size (Bits)	300	600	300	300	260	256	1200
Number of Messages Required to Read CED	3	1	3	3	3	3	1
Required BER for 95 % Probability of a fix	7.1E-06	1.1E-05	7.1E-06	7.1E-06	8.2E-06	8.3E-06	5.3E-06
Required MER for 95 % Probability of a Fix	2.1E-03	6.4E-03	2.1E-03	2.1E-03	2.1E-03	2.1E-03	6.4E-03
Eb/No for Required BER/MER	9.74	2.3	4.64	4.64	4.58	4.57	1.8
Implementatin Loss+ Data Pilot Split	1	7	4	4	4	4	4
*Minimum C/No into receiver for a warm start data read time ≤ 60 sec (db-Hz)	27.73	21.52	22.62	25.63	29.55	25.56	22.79
*Minimum C/No into receiver for a warm start data read time ≤ 36 sec (db-Hz)	27.73	23.29	22.62	25.63	29.55	25.56	25.01
*Minimum C/No into receiver for a warm start data read time ≤ 30 sec (db-Hz)	27.73	26.29	22.62	25.63	29.55	25.56	26.77
Min Time to Read data without CED Combining	18	18	60	30	30	30	12
*Minimum C/No to read data at Min. data read time (db-Hz)	27.73	26.29	22.62	25.63	29.55	25.56	29.78

LunaNet AFS provides data at Lower C/No than C/A with 5 times the data rate!

Enables Comparable performance to L1C/L2C for CED while providing high-rate paged data

Q channel – AFS Pilot- Performance

*Initial AFS Q Channel – “Pilot’” Design**

- Initial Pilot channel Design
  - *Relied on L1Cp for 210 Spreading Codes of length 10230*
  - *Leveraged a 4 chip secondary code (Orthogonal Barker sequences) as a secondary code to enable the first signal with variable pilot acquisition performance/complexity modes*
  - *Employed length 1500 Weil sequences for the tertiary overlay code to determine frame sync and absolute time*

- A desire to remove dependency on GPS L1C and make the AFS signal open for collaboration motivated development of a new set of 10230 bit Spreading codes

- The remainder of this presentation describes the design of the new set of codes and the methodology used to optimize the selection from new code families

- AFS hot and warm start acquisition sensitivity margin is also compared to GPS L1 C/A and L5

*https://www.nasa.gov/wp-content/uploads/2025/02/lunanet-signal-in-space-recommended-standard-augmented-forward-signal-vol-a.pdf?emrc=0f6993

Development of a Unique Unpatented Code Family for AFS-Q Primary Codes

- The L1C GPS and B1C BeiDou Weil sequences are generated from a Legendre Polynomial which is passed on a prime number representing the sequence length
  - *GPS L1C Weil sequences are based on the prime number 10223*
    - Initially patented but while patent is not enforced, requires periodic approval by GPS spectrum office
  - *Beidou B1C sequences are based on the prime number 10243*
  - *These Primes are directly below and above the code length of 10230*

- After studying alternatives, we decided to select a family of 210 PRN Weil codes using the prime number P=10247; there are 5123=(P-1)/2 possible Weil sequences
  - *Perfectly selecting 210 codes from 5123 requires examining* $\binom{5123}{210} = \frac{5123!}{(5123-210)!210!}$ *yielding* 1.69×10^{571} Possibilities!
    - This is an NP Hard problem, which means it is not feasible to find the best set by brute force
  - *Selecting 420 codes out of 3123 requires examining* 2.43×10^{1131} possibilities!
  - **Key point**: In theory, short cycling by 10247-10230= 17 chips should result in significantly poorer cross-correlation performance than BeiDou or GPS L1C since there is greater deviation from the natural code length that guarantees low cross-correlation

- Initial P=10247 codes were found to be comparable to L1C
  - Later refined to exceed performance of L1C and other code families

Results: *New AFS Pilot Code Exceeds Performance of other 10230 Length Codes*

- Up to 420, 10230 chip spreading codes have been identified for future AFS use
- New AFS codes meet or exceed performance of most other length 10230 codes
  - *Lowest max cross-correlation compared to any other length 10230 spreading code set*
  - *Lowest 99th and 99.9th percentile cross-correlation than any other length 10230 code set*
  - *Lower max autocorrelation sidelobe than L1C or L5 (sufficient for any acquisition scenario)!*

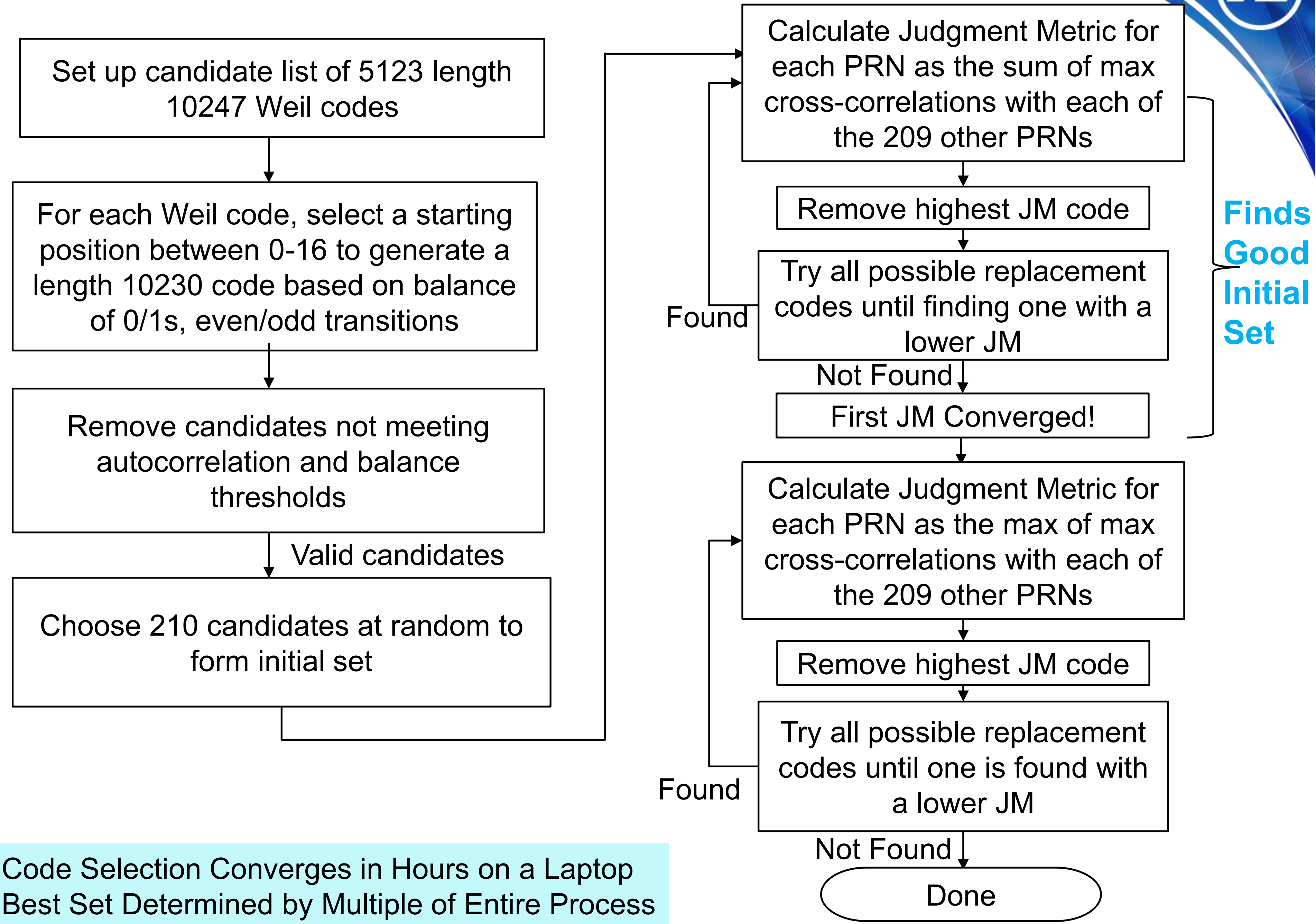
Code Family-No. Codes:	E5 - 50	L1C - 210	L5I - 210	L5Q - 210	IZ4L1P - 64	IZ4L1D - 64	Beidou Pilot -63	Beidou Data-63	Lunanet- 210
P(Max):	3.99E-08	2.90E-08	2.23E-09	2.23E-09	1.21E-07	4.85E-08	1.25E-07	5.01E-08	3.56E-08
Max (dB):	-25.23	-26.22	-25.49	-25.74	-26.50	-26.50	-27.45	-27.29	-27.65
Mean (dB):	-42.18	-41.93	-41.98	-41.98	-42.03	-42.04	-41.86	-41.86	-41.85
RMS (dB):	-40.10	-40.10	-40.10	-40.10	-40.11	-40.10	-40.10	-40.10	-40.10
99% percentile (dB):	-31.70	-32.31	-32.24	-32.24	-32.17	-32.10	-32.52	-32.52	-32.52
99.9% percentile (dB):	-29.67	-30.26	-30.26	-30.26	-30.54	-30.48	-30.54	-30.54	-30.71
Autocorr Max Sidelobe(dB):	-28.56	-28.03	-26.98	-26.22	-29.83	-29.83	-31.19	-31.19	-28.47

	LunNet Improvement Compared to Other length 10230 PRN Codes							
Code Family-No. Codes:	E5 - 50	L1C - 210	L5I - 210	L5Q - 210	IZ4L1P - 64	IZ4L1D - 64	Beidou Pilot -63	Beidou Data-63
Max (dB):	2.42	1.43	2.16	1.91	1.15	1.15	0.20	0.36
Mean (dB):	-0.33	-0.08	-0.13	-0.13	-0.18	-0.19	-0.01	-0.01
RMS (dB):	0.00	0.00	0.00	0.00	-0.01	-0.01	0.00	0.00
99% percentile (dB):	0.82	0.21	0.28	0.28	0.35	0.42	0.00	0.00
99.9% percentile (dB):	1.04	0.45	0.45	0.45	0.17	0.23	0.17	0.17
Autocorr Max Sidelobe(dB):	-0.09	0.44	1.49	2.25	-1.36	-1.36	-2.73	-2.73

420 New AFS 10230 Lenth Codes Were Selected From Short-Cycled Length 10247 Weil Sequences

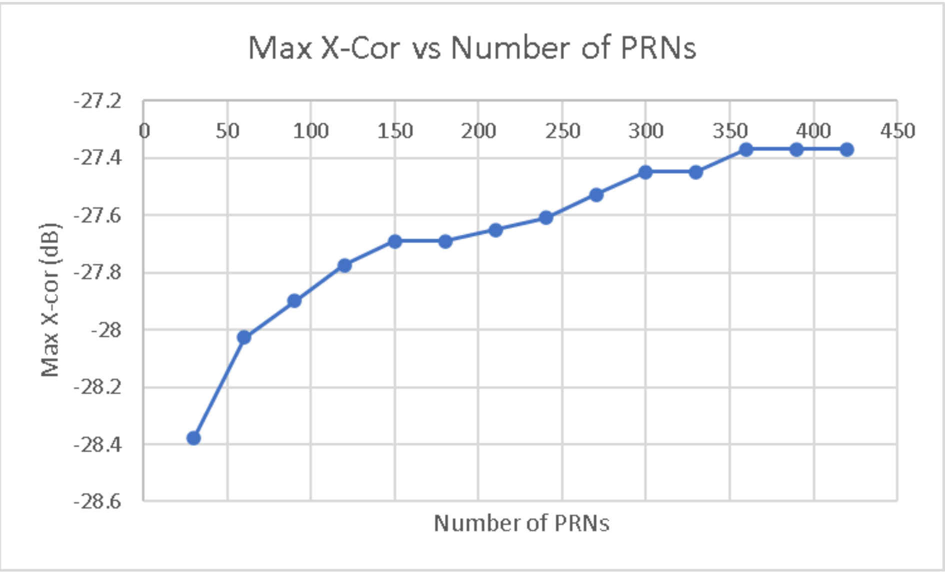
- Shown to Outperform All Other Length 10230 Codes in Relevant Cross-Correlation Performance
- Autocorrelation sidelobes are lower than L1C and L5
  - More than adequate since thermal noise floor is above this level

Code Selection Process



Code Selection Converges in Hours on a Laptop
Best Set Determined by Multiple of Entire Process

A Total of 420 PRN Codes of Length 10230 were selected and Ordered by performance in Groups of 30 Codes
- 210 AFS-Q Primary codes and 210 reserved for future use



Num PRNs	Max	Mean	RMS	99% perce	99.9% percentile
30.00	-28.38	-41.85	-40.10	-32.52	-30.71
60.00	-28.03	-41.85	-40.10	-32.52	-30.71
90.00	-27.90	-41.85	-40.10	-32.52	-30.71
120.00	-27.77	-41.85	-40.10	-32.52	-30.71
150.00	-27.69	-41.85	-40.10	-32.52	-30.71
180.00	-27.69	-41.85	-40.10	-32.52	-30.71
210.00	-27.65	-41.85	-40.10	-32.52	-30.71
240.00	-27.61	-41.85	-40.10	-32.59	-30.66
270.00	-27.53	-41.85	-40.10	-32.59	-30.66
300.00	-27.45	-41.85	-40.10	-32.52	-30.71
330.00	-27.45	-41.85	-40.10	-32.52	-30.71
360.00	-27.37	-41.85	-40.10	-32.52	-30.71
390.00	-27.37	-41.85	-40.10	-32.52	-30.71
420.00	-27.37	-41.85	-40.10	-32.52	-30.66

- Performance only degrades in the 99.9th percentile by < 0.1 dB
- Max degrades by up to 1 dB but negligible since Max occurs once in 28 million trials

Practical performance is invariant over the 420 selected codes

Application of AFS Code Search Algorithm to Selection of an Improved Set of 210 new L5 Codes

Code Family-No. Codes:	L5-I 210	L5-Q 210	L1CP-210	New L5-210 L5 Using AFS Optimization Algorithm
P(Max):	2.23E-09	2.23E-09	2.90E-08	4.23E-08
Max (dB):	-25.49	-25.74	-26.22	-26.94
Mean (dB):	-41.98	-41.98	-41.93	-41.98
RMS (dB):	-40.10	-40.10	-40.10	-40.10
99% percentile (dB):	-32.24	-32.24	-32.31	-32.24
99.9% percentile (dB):	-30.26	-30.26	-30.26	-30.26
Autocorr Max Sidelobe(dB):	-26.98	-26.22	-28.03	-28.47

By applying the AFS Search algorithm to L5's code family, 210 new codes were found with performance that exceeds L5 Max cross-correlation by > 1 dB and max autocorrelation sidelobe by > 1.5 dB

Performance of the optimized L5 is now also comparable or better than L1Cp

Code Selection Approach is More Important Than Mathematical Properties of The Code Family For an NP-Hard Search Problem

Acquisition performance of AFS I and Q Compared to C/A and L5

- Hot Start Performance Assuming TTFF < 10 sec

Signal	Rc (MCPS)	Code Length	Complexity Realtive to C/A	Min C/N_0 (dB-Hz)	Received Power (dBW)	N_0 (dB-Hz)	Nominal C/N_0 (dB-Hz)	Margin (dB)
AFS I Only	1.023	2046	2	25.52	-166	-202	36	10.48
C/A Code	1.023	1023	1	25.28	-158.5	-202	43.5	18.22
AFS-Q -2 ms primary	5.115	10230	50	27.87	-166	-202	36	8.13
AFS-Q - 8 ms Tiered	5.115	40920	200	22.02	-166	-202	36	13.98
L5 Pilot Only 1 ms Primary	10.23	10230	100	32.65	-157	-202	45	12.35

- Warm Start Performance Limited by Min C/No to Read Data Message

Signal	Rc (MCPS)	Code Length	Complexity Realtive to C/A	Data Rate (BPS)	Min C/N0 (dB-Hz)	Received Power (dBW)	N_0 (dB-Hz)	Nominal C/N_0 (dB-Hz)	Margin (dB)
AFS I Only	1.023	2046	2	250	25.52	-166	-202	36	10.48
C/A Code	1.023	1023	1	50	27.73	-158.5	-202	43.5	15.77
AFS-Q -2 ms primary	5.115	10230	50	NA	23.77	-166	-202	36	12.23
AFS-Q - 8 ms Tiered	5.115	40920	200	NA	23.77	-166	-202	36	12.23
L5 Pilot Only 1 ms Primary	10.23	10230	100	NA	22.63	-157	-202	45	22.37

Even with 9 dB less Power, AFS Q enables Hot Start acquisition with 1.6 dB more Margin than acquisition of L5 Primary Code with only 2x More complexity

AFS Warm Start Acquisition Margin is limited by having 5X the data rate as CA/L5 - Min C/No is comparable to L5

Summary and Conclusion

- We have described the benefits of the LunaNet Augmented Forward Signal including I/Q design approach and tiered code structure

- The I channel – AFS Data Message and Code Correlation Performance was shown to exceed that of C/A code with only 2 times the complexity

- A new family of 420 of 10230 AFS Pilot codes was determined using an efficient code selection methodology to determine codes from short-cycled 10247 length Weil sequences
  - *Can Find a code family with good correlation properties in hours and runs on a standard laptop PC*
  - *Defined new set of publicly available 10230 Weil sequences with performance better than other length 10230 codes*
  - *Methodology was applied to L5 and shown to produce a set of 210 length 10230 codes that are comparable to or better than the set of 210 L1CP codes*

- AFS hot start acquisition performance margin exceeds L5 with only a factor of 2 complexity difference and 9 dB less power than L5!
  - *Warm start margin is limited by higher data rate but min C/No is comparable to GPS L5*

Backup Charts

Pilot Code Acquisition Performance

- C/No Calculation Assumptions
  - *Assumes 95 % certainty in TTFF*
  - *Assumes a hot start is needed in within 5 sec*
    - C/No is limited by max noncoherent integration
  - *Assumes a warm start is needed within 30 sec*
    - C/No is limited by lowest C/No for which data can be read
- Receivers having time to 12 seconds can achieve a virtual Cold start by acquiring and tracking the Pilot code and resolving time by searching the pilot overlay in < 1 sec after acquisition of primary or tiered (primary+ secondary) Q channel code
  - *Very feasible with high performance MEMs oscillators*
    - SiTime 7190 real time clock can achieve a holdover time of +/- 30 ms in one week with temp compensation (consumes << 1 mW)