Cross-Correlation of Existing & Evolving C/A System Signals

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Introduction and Background

Introduction

- In the late 1990s, the IGEB (predecessor to the EXCOM) commissioned studies to resolve disagreements related to the GPS C/A Code Cross Correlation
  - Yes, disagreements existed then as well
  - This was about the time when various SBASs (including WAAS) were being launched or proposed and the number of GPS SVs was being increased
    - There were those who supported the ITU WRC delegation that feared the number of C/A code signals, including SBAS signals, may cause excessive interference (Intra-System Interference)
  - Representing the FAA, Zeta Associates was awarded one of two IGEB studies and, then, a follow-on
    - This study not only involved analysis, but software and <u>hardware RF</u> receiver simulations
    - Results were published in a report and at least two ION papers (GNSS 1999 and GNSS 2000)
- Apparently, disagreements were <u>not</u> completely resolved

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- These early disagreements were between those supporting RTCA/FAA and the GPS Directorate/Aerospace Corp.
  - Primarily related to interference from WAAS GEO signals onto GPS
    - Later resolved when it was recognized that WAAS signals emulated long code signals because of the use of a high 250 bps data rate coupled with Forward Error Correction (FEC)
- Later disagreements arose when RTCA analysis differed from that being used in GPS/Galileo bilateral WG discussions
  - Not sure why – Galileo doesn't use short codes
    - It was something about maximizing GPS "margin" to allow for interference from Galileo

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- However, GPS C/A Codes <u>are</u> being proposed for Japanese QZSS and IMES systems
  - The GPS Directorate has allocated C/A PRN codes for those systems
  - IMES – for test purposes only
- Those bilateral WGs tried, or are trying, to apply long code interference methodology, along with the Aggregate Power Methodology, to the C/A-on-C/A code
  - That methodology doesn't work – covered in this presentation
  - The Aggregate Power Methodology is incorrect for short PRN codes
- An alternate C/A code interference methodology is also being considered by the ITU Working Party 4C
  - Developed by MITRE
  - Besides being incorrect, this alternate methodology is far too complicated to push forward in an international forum
- This long code and aggregate power methodology, if applied to the C/A code, artificially eats into RTCA/FAA's safety margins

Background

- C/A code Cross Correlation has been an topic within RTCA SC-159 tasking since the beginning of GPS Aviation MOPS development (and within GPS forever)
  - The GPS C/A Code signal is the only one available for using GPS in civil aviation, and will be for quite some time
  - The use of the C/A Code is nothing new to the Engineers involved, including
    - Cross Correlation Effects on Signal Acquisition
    - Cross Correlation Effects on Signal Fading (similar to multipath)
  - Consequently, the Aviation MOPS includes special requirements to mitigate or account for these effects
- GPS C/A code still works well for aviation and other applications
  - It is also the preferred signal for cell-phone applications
    - Presentation by Dr. Frank Van Diggelen, Broadcom, at Stanford PNT Symposium, 14 November 2013

C/A Code Cross Correlation is Not Noise

- It should <u>not</u> be treated as such; it is primarily Code Correlation Peak Distortion of the Desired Signal
  - Similar to the effect of multipath
  - In fact, for code tracking, it is partially mitigated using multipath mitigation technology
    - That is why tracking performance is captured in standard RTCA error budgets using carrier smoothing
  - Phase tracking is only affected due to signal fading (desired signal degradation)
    - Tends to be dominated by oscillator phase noise

The Bottom Line For RTCA/FAA

- Acquisition degradation is accommodated by raising detection thresholds above distorted correlation peak power
  - Rapid signal acquisition is not a requirement in aviation
- Code tracking errors could be worse than experienced in a multipath environment, but are mitigated using multipath mitigation techniques
  - Code tracking errors are no worse that group delay variations versus antenna aspect angle
  - Phase tracking (only used for code smoothing) errors are well within the RTCA/FAA error budget (dominated by oscillator effects)
- C/N_0 Estimators are affected, but are not used for navigation – only as a performance indicator
  - Effects vary with Estimator implementation
  - This was effectively the early disagreements issue with the Directorate and the Aerospace Corporation

C/A Code Properties and Cross-Correlation

C/A Code Properties

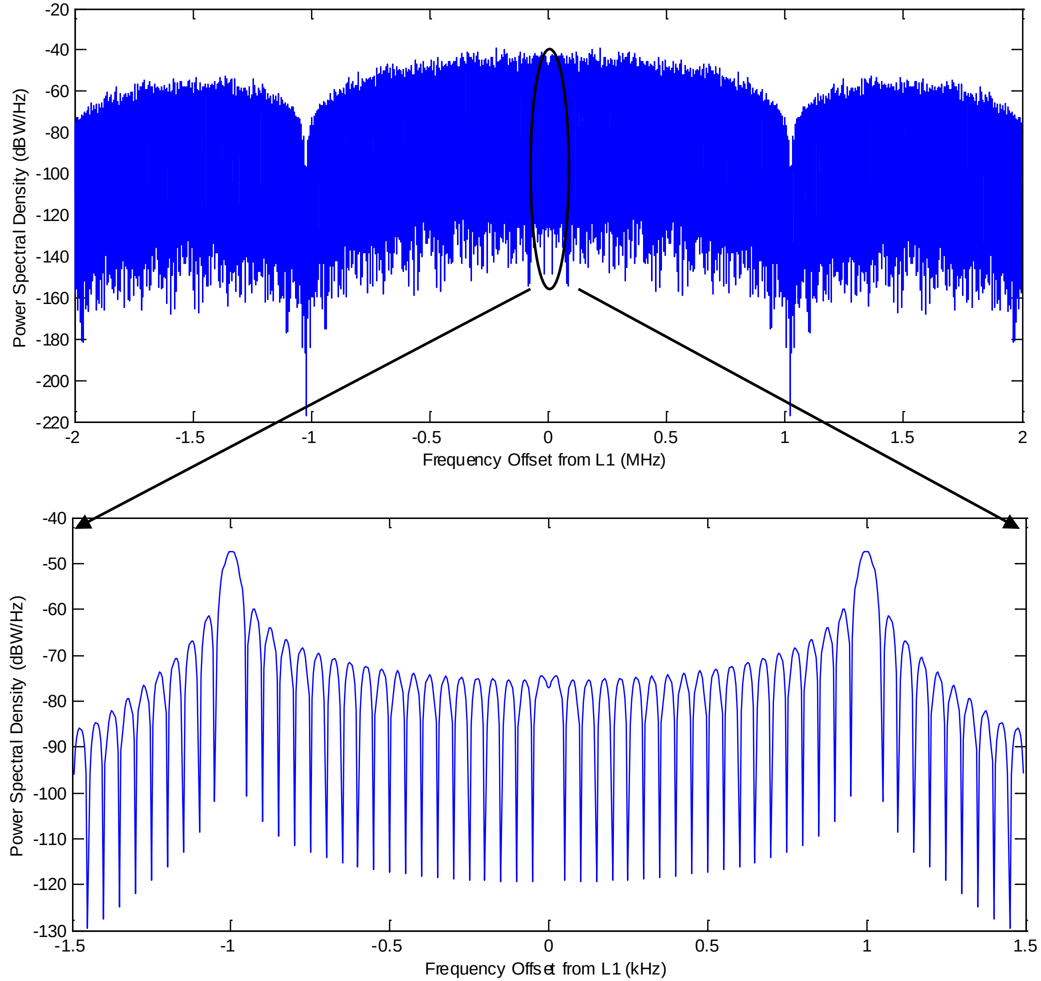
- 1023 chip Gold Codes @ 1.023 MHz chipping rate
- Code represented with a discrete Line Spectrum – 1,023 lines spaced 1 kHz apart
  - Because Code repeats every 1 ms
  - Spectral nulls at multiples of 1.023 MHz (the chipping rate)
  - Line magnitudes significantly vary about a Sinc^2 envelope
- Code is modulated with 50 bps data
  - WAAS signals modulated with 500 sps symbols
  - Thus, spectrum lines have a spectral width of the data/symbol rate

SPECTRAL PROPERTIES OF THE GPS C/A CODES

Why long-code analysis techniques do not work when analyzing C/A-to-C/A code interference.

Typical C/A-Code Power Spectral Density (PSD)

- Spectral nulls at multiples of 1.023 MHz
- Spectral Lines spaced 1-kHz apart
  - Lines are not really lines, but are data sinc^2 spectral densities
- Spectrum centered at carrier frequency plus Doppler, including a Doppler difference shift between SVs
- ***<u>There is Spectral Separation between SVs – do not fully overlap</u>***



Cross-Correlation Issues

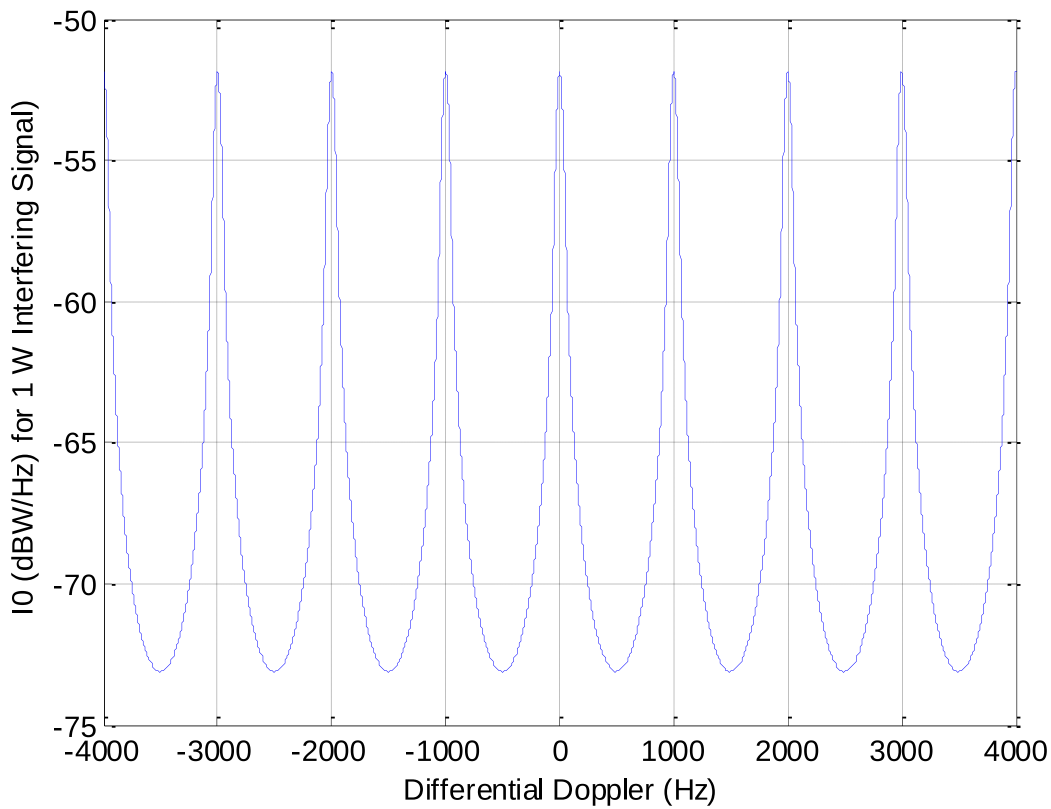
- Unfortunately, only 1,023 possible PRN code patterns, resulting in some cross-correlation between codes
  - 256 of those are really bad (not balanced)
    - These are not assigned
- Cross-Correlation magnitude levels of 63/1023 or -65/1023, relative to full correlation level of 1
  - Happens at near zero Doppler difference (modulo 1 kHz)
  - At code-alignments (25% of the time)
  - Otherwise, at level of -1/1023

Spectral Separation

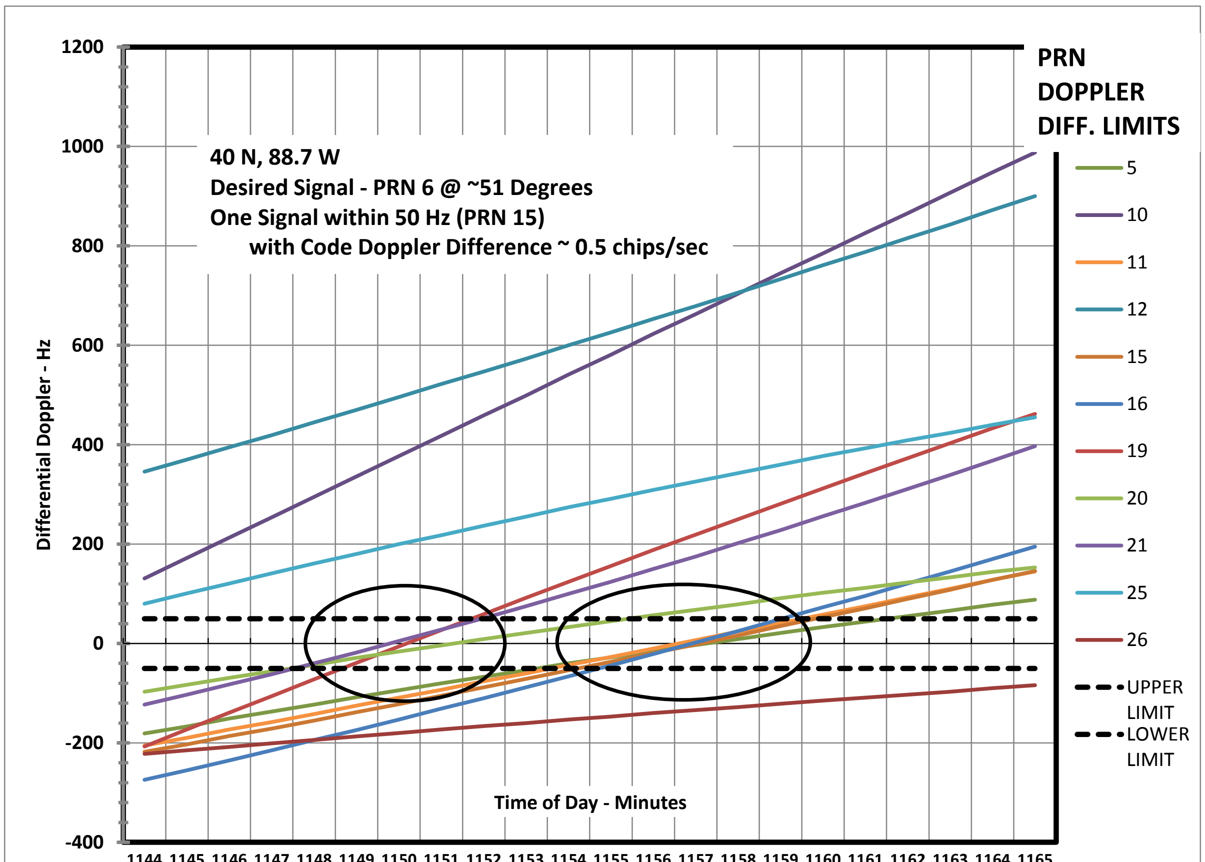
- Short/Long Code Differences
  - Spectral lines for long codes are very close – separated by 1/(code-length)
    - Line magnitudes do not vary much
    - Practically, results in continuous spectral density
- Spectral Separation Coefficient (SSC)
  - An analytical measure of PSD overlap of an “interfering” code onto the “desired” code
    - The integral of the product of the two PSDs
  - For long codes, PSDs almost fully overlap, but are generally lower in magnitude
    - Doppler difference is not significant relative to “wide” spectrum
  - For C/A code, PSDs only overlap significantly near Doppler crossings

Generic C/A on C/A SSC versus Doppler Difference

- This figure covers all possible Doppler differences
  - Not just those between “interfering” and “desired” signals
  - Insignificant interference in the “valleys”

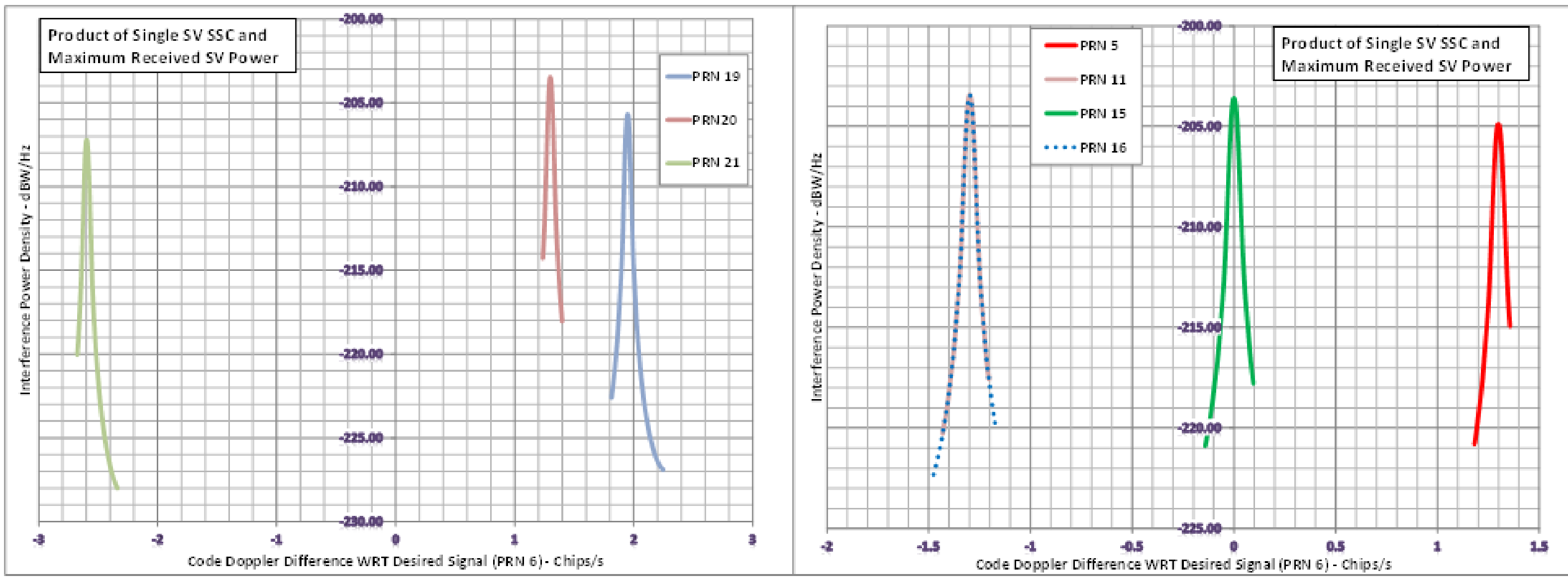


Example Scenario of 36 SVs with Doppler Crossings within 50 Hz (mod 1 kHz)



Scenarios Have Significant Spectral Separation

- C/A-on-C/A Interference is scenario dependent
  - Interfering SVs only, converted to dBW/Hz versus Code Doppler (i.e., SSC added in dB to worst case received power)



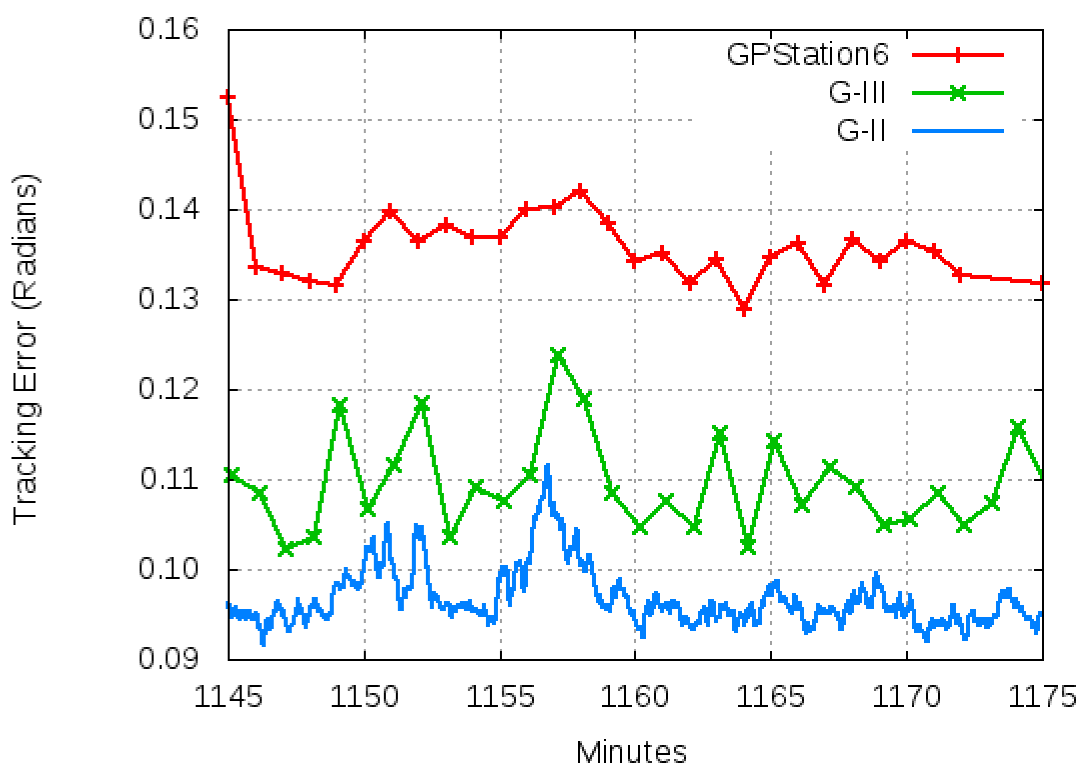
- If compared to “other” interference and thermal noise at ≈-198 dBW/Hz, added interference is tolerable -- not that significant

C/A to C/A Code Interference Only Partially Aggregates

- Long Code Methodology aggregates interference fully from all visible SVs
  - With each at maximum received power
  - This is because PSDs essentially fully overlap
- Previous charts show that C/A code interference does not aggregate
  - Mainly because C/A code PSDs only partially overlap, and at or near Doppler crossings

Hardware Simulation Tests of Example Scenario – All Results Well Within RTCA MOPS Specified Requirements

- US Navy SPAWAR Simulator
- Three Different Receivers
- Carrier Phase Tracking Errors
- Errors dominated by Oscillator Phase Noise



Summary and Conclusions

- Effects of CA-to-CA Code Interference (Cross-Correlation) are over-stated
  - Yes, there is cross-correlation, but receiver designers work around the effect
  - Long Code methodology used in most bilateral discussions is not appropriate
    - Because C/A code interference power does not significantly aggregate
- Because of its simplicity and legacy, many commercial applications prefer the C/A code