Signal Structure, Interoperability, and Geometry

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The Most Important Ingredient

- Only Navigation by Satellite can provide **excellent Geometry**
  - *Continuous, worldwide, four dimensional, with excellent accuracy*
  - *GDOP, Geometric Dilution of Precision, and its important children:*
    - PDOP, HDOP, VDOP, and TDOP
  - *Although the satellite signals may be weak, the geometry is strong*
- No <u>terrestrial</u> navigation aid delivers "the most important ingredient"
- Do users need better geometry than GPS alone can provide?
- The answer is a definite "YES" as demonstrated by:
  - *Widespread use of GLONASS in products from consumer mobile phones to commercial survey and machine control products*
    - In spite of the difficulty of using GLONASS FDMA with GPS CDMA
  - *Plus widespread development of receivers to use <u>all</u> available GNSS*
- Aircraft at altitude and ships at sea may not <u>need</u> more than GPS
  - *But integrity by A-RAIM requires many more satellites*
- Users subject to signal blockage or outage do need more satellites
- Thus, the second most important ingredient is signal interoperability
  - *<u>Enabling</u> the best geometry by using every interoperable satellite signal*

Signal Structure and Interoperability Considerations

- Interoperability is in the eye of the beholder
- For example, L1C and E1 OS have identical center frequencies and identical spectra, but almost everything else is different

Signal	Spreading Code Length (chips)	Spreading Code Duration	Modulation	Channel with BOC(6,1)	Data Power Percent	Pilot Power Percent	Symbol Rate	Bit Rate	Forward Error Correction	Pilot Overlay Code Duration	Message Frame Length
L1C	10,230	10 ms	TMBOC	Pilot	25%	75%	100 SPS	50 BPS	LDPC	18 sec	18 sec
E1 OS	4,092	4 ms	CBOC	Both	50%	50%	250 SPS	125 BPS	Convolutional	100 ms	720 sec

- Receivers will handle the differences and hide them from the user
  - *The user will experience better performance due to more satellites*
- However, different types of receivers will take advantage of some of the signal differences between systems
  - *Identical center frequency is important for high precision receivers and for bandwidth limited GNSS antennas on aircraft*
  - *Short spreading codes are important for consumer products, e.g., mobile phones, with less concern for a common center frequency*
    - With some signal combinations, e.g., fast signal acquisition with GPS C/A followed by using the better pilot carrier and message of L1C
    - The same could be true for fast acquisition with BeiDou B1-I followed by using the better pilot carrier and message of B1-C

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Interoperability Regrets

- Soon there will be many signals with common center frequencies and a common spectrum
  - *These may be the most important interoperability parameters*
- There remain many signal differences, including:
  - *Spreading codes, code lengths, data rates, forward error correction methods, message structures, etc.*
  - *GNSS receivers will carry the burden of these differences and provide what users will perceive as a seamless, fully interoperable GNSS*
- Little progress has been made toward providing a common "GNSS time reference" against which each system can reference itself
- There is not a common "middle frequency" signal to better enable interoperable, wide area, 10-cm navigation by tri-laning
  - *GPS has L2, BeiDou has B3, and Galileo has E6*

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Predicting the Future

- If there are three global interoperable GNSS constellations in 2020
  - *GPS, Galileo, and BeiDou, with a total of 72 to 90 operational satellites*

1. Use of GLONASS FDMA will decrease for precision applications
   - *The current demand for more satellites will be satisfied by interoperable CDMA signals, leaving little demand for the more difficult FDMA signals*
2. Use of GLONASS FDMA will continue for consumer applications
   - *Chip makers greatly value the 511 chip code for fast signal acquisition*
3. Users will not say "this is my GNSS" or "this is my BeiDou"
   - *There will be few <u>if any</u> GPS-only or BeiDou-only or Galileo-only receivers*
   - *Users won't know and they won't care where the signals originate*
   - *They will just enjoy the better performance provided by better geometry*
   - *And they probably will continue to call their device a "GPS" (sorry!)*
4. Special, unique, or "orphan" signals will be little used
   - *Use of GPS L2C will decline because no other GNSS provides it*
   - *The standard dual-frequency pair will become 1575.42 and 1176.45 MHz*
   - *E5b and B2b will be little used, whereas E5a and B2a will be widely used*
     - A lively discussion topic!
5. If and when E6 becomes free, it will be used extensively for tri-laning
   - *Could B3 ever be used this way?*

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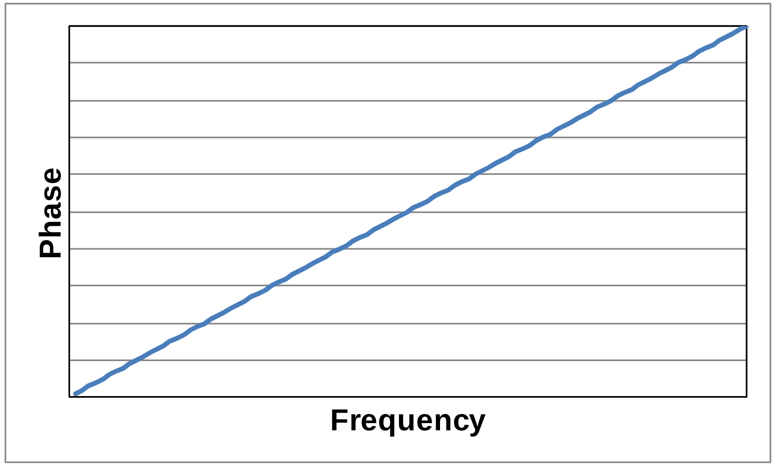
Future Decrease in High Precision FDMA Use

- A pure "time delay" Δt is characterized by a linear slope of phase versus frequency

$$\Delta\varphi / \Delta f = \Delta\varphi / (\Delta\varphi / \Delta t) = \Delta t$$



- However, a bandpass filter must rapidly attenuate signals outside the bandpass region
- This introduces nonlinearities in phase versus frequency, especially at the band edges
- In high precision applications it is desirable for every signal from every satellite to experience the same nonlinearities so there are no time delay differences between signals due to receiver filtering
- This will be true if every signal has the same center frequency
- Because this is not true for GLONASS FDMA signals, very careful calibration of each channel is required for near-precision results
- This is why high precision use of GLONASS FDMA will likely decrease substantially with deployment of Galileo and BeiDou

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Future Use of Short Code Signals

- Consumer device makers value low cost, low power consumption, and fast signal acquisition much more than precision
- This is why consumer device makers greatly appreciate GNSS signals with short spreading codes
- The shortest GNSS spreading codes are 511 (GLONASS FDMA), 1023 (GPS C/A) and 2046 (BeiDou B1-I)
- All of these signals have different center frequencies
- Therefore, consumer devices are expected to continue use of short code signals for billions of users
  - *Whereas high precision devices will rely primarily on CDMA signals with a common center frequency*
- Consumer products also may use modernized signals with longer codes after resolving time and position uncertainties
  - *Examples include using GPS L1C after acquiring C/A*
  - *Also, using BeiDou B1-C and Galileo E1 OS*

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Growth Continues and Should Accelerate

- Application growth is fueled primarily by the private sector
  - *Heavily regulated products, e.g., for aviation and the military, are slow to change and generally lag in innovation (sad but true)*
- Factors that encourage innovation and application growth:
  - *Competition, Moore's law, opportunity, fear, and the profit motive*
- What in the future will stimulate growth:
  - *Much better GNSS <u>geometry</u> improves availability, continuity, integrity, and accuracy, especially in difficult environments*
    - Urban canyons, real canyons, open pit mining, even aviation
  - *A-RAIM will become practical and begin to displace SBAS use*
  - *Ambiguity resolution for Real Time Kinematic (RTK) in survey and machine control will become almost instantaneous and more reliable*
    - Improved vertical accuracy will displace some laser plane requirements
  - *With free E6/B3 10 cm tri-laning could become a consumer application*
    - Car navigation lane-keeping, personal survey products, unmanned aircraft vehicles (UAV), unmanned lawnmowers, etc.
- Alternate means to communicate message parameters will promote "instant navigation" for all applications (push to navigate)

Backup Slides

Ionospheric Refraction Calculations

For L1 = 1575.42 MHZ and L2 = 1227.6 MHz

$$PR = (PR_{L1} \cdot 77^2 - PR_{L2} \cdot 60^2) / (77^2 - 60^2)$$

$$PR \approx 2.55 PR_{L1} - 1.55 PR_{L2}$$

For L1 = 1575.42 MHZ and L5 = 1176.45 MHz

$$PR = (PR_{L1} \cdot 154^2 - PR_{L5} \cdot 115^2) / (154^2 - 115^2)$$

$$PR \approx 2.26 PR_{L1} - 1.26 PR_{L5}$$

For L1 = 1575.42 MHZ and L5+ = 1191.795 MHz

$$PR = (PR_{L1} \cdot 154^2 - PR_{L5+} \cdot 116.5^2) / (154^2 - 116.5^2)$$

$$PR \approx 2.34 PR_{L1} - 1.34 PR_{L5+}$$

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Very Small Impact of Less Error Tracking L5+

For 1575.42 and 1227.6 MHz

$$\sqrt{2.55^2 + 1.55^2} \sim 2.98$$

For 1575.42 and 1176.45 MHz

$$\sqrt{2.26^2 + 1.26^2} \sim 2.59$$

For 1575.42 and 1191.795 MHz

$$\sqrt{2.34^2 + 1.34^2} \sim 2.69$$

For 1575.42 and 1191.795 MHz

$$\sqrt{2.34^2 + 0^2} \sim 2.34$$

Even if the pseudorange error tracking E5a+E5b were zero, the ionosphere corrected pseudorange error would be 90.35% of the error tracking only E5a

$$2.34 / 2.59 \sim 0.9035$$

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