Update on GPS L1C Signal Modernization

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Glossary

- BOC = Binary Offset Carrier modulation
- C/A = GPS Coarse/Acquisition code
- dBW = 10 x log(Signal Power/1 Watt)
- E1 = Galileo designation for L1 band
- EU = European Union
- FEC = Forward Error Control
- L1C = GPS L1 Civil signal (at 1,575.42 MHz)
- L2C = GPS L2 Civil signal (at 1,227.6 MHz)
- L5 = GPS L5 Civil signal (at 1,176.45 MHz)
- LDPC = Low Density Parity Check
- MBOC = Multiplexed BOC, Generic for L1C and E1 OS
- Moore's Law = Performance of digital circuits doubles every 18 months, has become a "self-fulfilling prophesy"
- OS = Galileo Open Service signal
- Pilot Carrier = Signal without data
- TMBOC = Time Multiplexed BOC, GPS version of MBOC for L1C

Why L1C ?

- Why add another civil signal to L1 when millions of users benefit from C/A today
- In contrast with modernized L2 and L5 signals, C/A has deficiencies:
  - No pilot carrier
  - No forward error control (FEC)
  - Less precise message structure
  - Short 1023 chip code (relatively poor correlation performance)
- 2004 US/EU Agreement requires new GPS L1 signal to match E1 OS spectrum
- Better interoperability with Galileo

When ?

- L1C will be on all GPS III satellites
  - First GPS III launch planned for 2013
- L1C draft specification is available
  - IS-GPS-800
  - Interface Control Working Group (ICWG) met here last year to review specification
  - Another ICWG meeting tomorrow (9/25/07)
    - Several civil signal topics to be covered
    - 8:30 AM – 5:00 PM
    - Fort Worth Convention Center, Room 110
  - Final approval expected in a few months

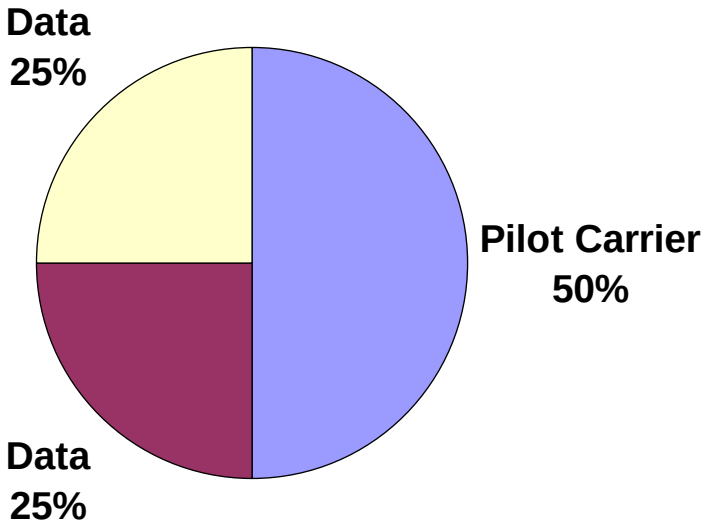
L1C Signal Design Philosophy

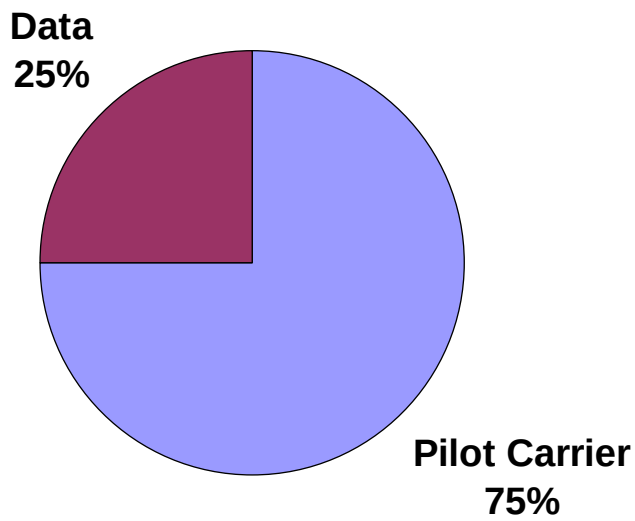
- Provide benefit to all users & applications
- Main attribute: Robustness
  - Signal acquisition and tracking
  - Code and carrier measurements
  - Spreading code correlation performance
  - Data demodulation, both speed and threshold
- Code/carrier phase measurements are vital
  - Dedicate most signal power to these functions
  - Auxiliary services better provided in other ways
    - Long lasting orbit and clock parameters
    - Differential corrections
    - Integrity messages

Experts Consulted on L1C Design

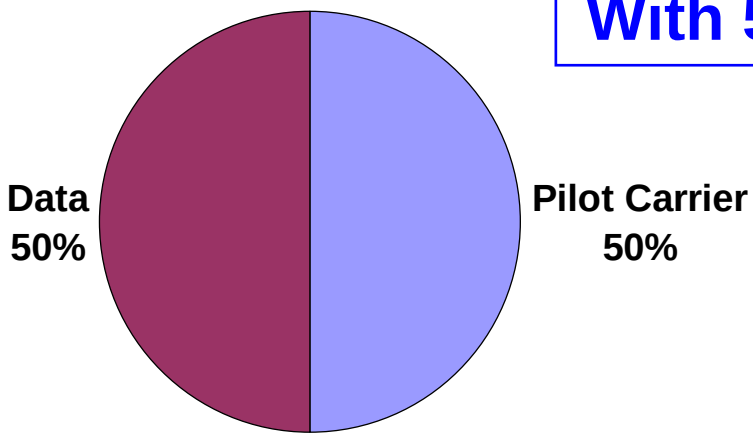
- The U.S. did a remarkable thing in designing L1C
- Asked what signal characteristics were preferred by worldwide GPS experts in:
  - Government
  - Industry
  - Academia

Five Signal Options Were Offered





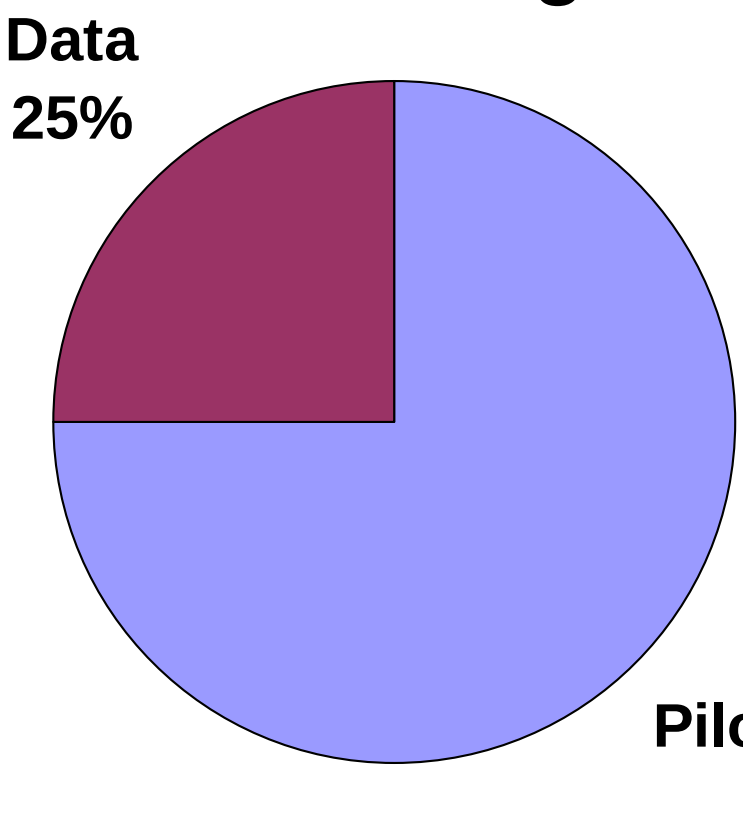
With 50 or 75 bps?



One Was the Clear Choice

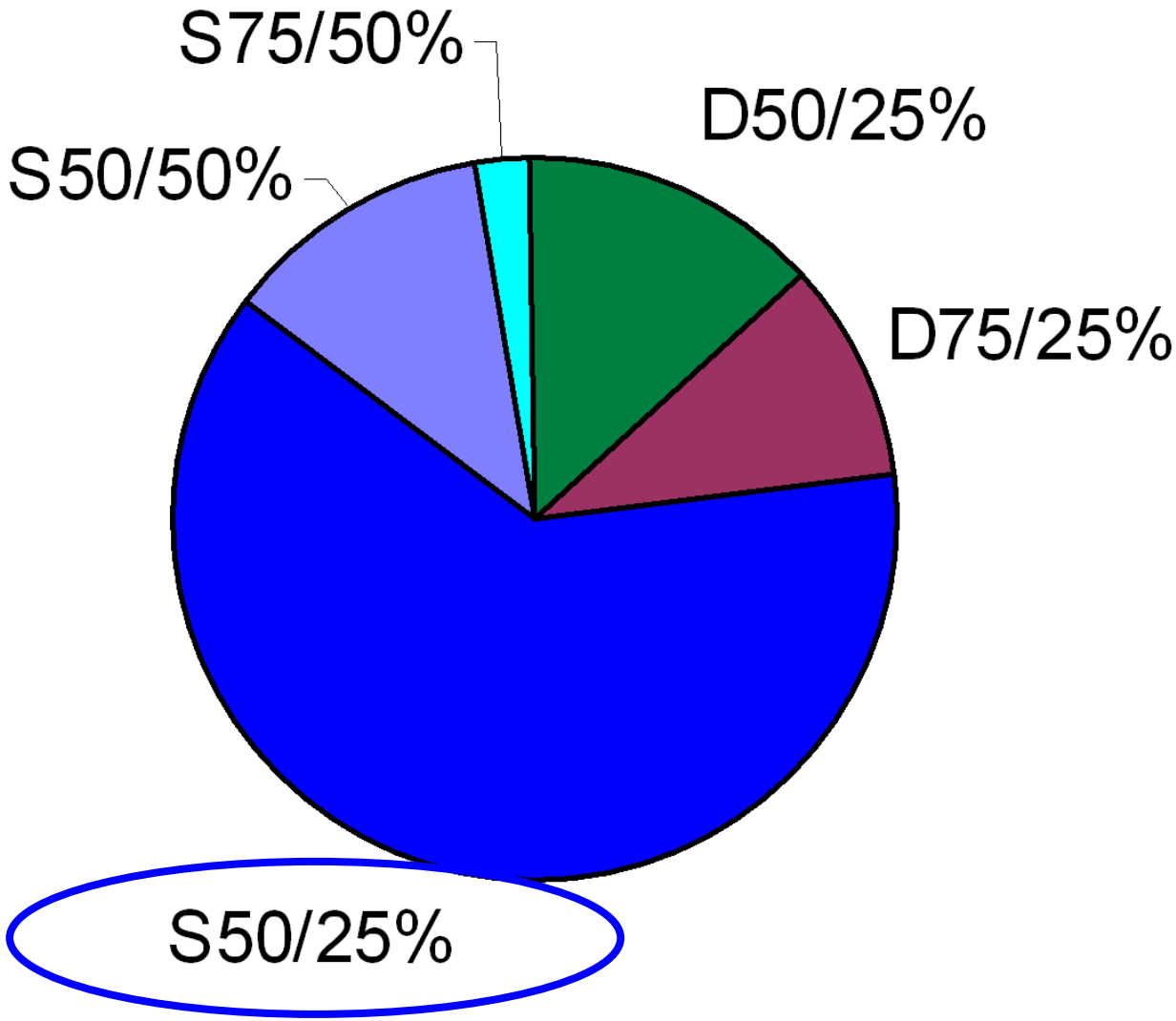
Data at 50 bps

Signal Power Split



Best Code & Carrier Track Threshold

Selected by a Large Majority



The Future L1C Environment

- GPS + Galileo provide better geometry
- UWB and other sources raise the noise floor
- Moore's law continues to apply
  - > 10 times digital improvement before L1C launch
  - Permits better receiver performance
- Proliferation of GPS communication sources
  - Cell phones, wireless internet, SBAS, GBAS, etc.
  - Alternate GPS message sources will provide
    - Long-lasting clock and ephemeris for all satellites
    - Integrity and differential correction messages
    - User alerts, e.g., software updates, system status, etc.

L1C Shares Earlier Improvements

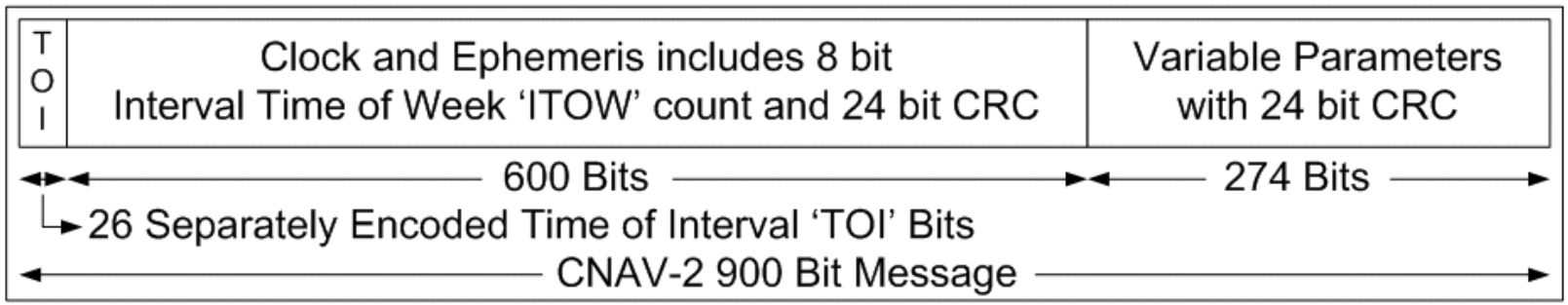
- L1C builds on improved characteristics of other (L2C and L5) modernized GPS signals:
  - Signal power split between data & data-less parts
  - Data-less part is a pilot carrier
    - Better tracking threshold
    - Eliminates ½ cycle phase ambiguities
  - Forward error control (FEC) improves (lowers) message demodulation threshold
  - Longer spreading codes
    - Reduce susceptibility to narrowband and cross-satellite interference
    - Resolve data timing ambiguity (no bit sync required)
  - Message slant range precision ~ 3 centimeters

L1C Message Improvements

- Achieves two conflicting objectives
  - Faster time to first fix
  - Demodulation of vital message data at the lowest signal tracking threshold
  - New message structure is called CNAV-2
    - L2C and L5 messages are called CNAV
- Other L1C message improvements
  - More powerful FEC improves demodulation
  - Interleaving minimizes effect of short fades
    - e.g., driving past trees or other obstructions

CNAV and CNAV-2 Formats

300 bit CNAV Type 10	300 bit CNAV Type 11	300 bit CNAV Type 3x



900 bits at 50 bps = 18 second message length
1800 chip overlay code on pilot carrier frames messages
Separate LDPC block encoding of 600 bit and 274 bit portions of the 900 bit message
Symbol interleaving of the LDPC block-encoded parts of the message to mitigate brief signal losses

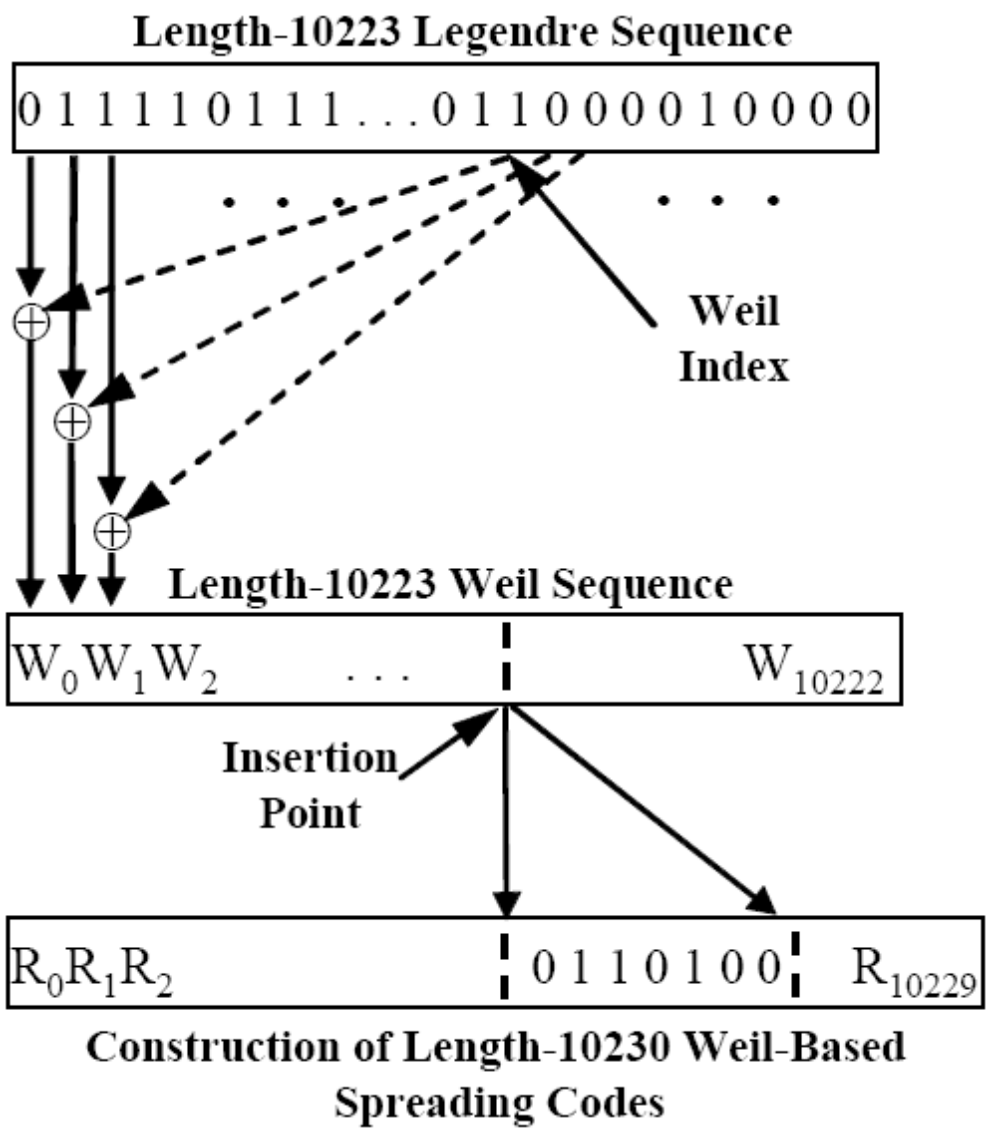
CNAV-2 Message Characteristics

- TOI symbols are identical from all satellites
  - Symbols can be combined from multiple satellites
  - Only one TOI is needed to set the receiver clock
- Clock & Ephemeris symbols repeat identically (remain fixed) for at least 15 minutes
  - LDPC block encoding
  - Combine symbols from multiple messages
- Variable Parameters change each time
  - If variable parameters have the same timing in the same orbit plane, symbols also can be combined

Spreading Code Characteristics

- Primary codes are length 10,230 chips
  - On both Pilot and Data signal components
  - Based on Weil sequences, derived from length-10,223 Legendre sequences
  - Fixed 7-chip sequence inserted in each
  - Approaches ideal correlation properties
- Overlay code also applied to Pilot
  - Satellite-unique 1800 chip overlay code
  - Improves correlation separation
  - Frames the data messages

Generating L1C Spreading Codes



Construction of Length-10230 Weil-Based Spreading Codes

Each Weil sequence is the component-wise exclusive-or of the Legendre sequence and a circular shift of the Legendre sequence. The value of this shift is the Weil index. The resulting Weil sequence is also length 10223. A fixed seven-bit sequence is inserted into a Weil sequence to create a length-10230 L1C spreading code, which is specified by the value of the Weil index and the insertion point. All spreading codes are based on the Legendre sequence and the same seven-bit sequence. The construction, summarized in the Figure, involves simple logical operations on the Legendre sequence and the seven-bit sequence.

Code Correlation Comparisons

Correlation Sidelobes at 0 Hz Frequency Shift for Various 10230-Length Spreading Codes

Code Family	Max. Auto Even Sidelobe (dB)	Max. Cross Even Sidelobe (dB)	99.9999% Auto Even/Odd Sidelobe (dB)	99.9999% Cross Even/Odd Sidelobe (dB)
L1C TMBOC	–31.1	–27.7	–29.4	–28.7
L5 (I5 and Q5)	–28.6	–26.0	–26.9	–27.0
L2C CM	–27.0	–25.4	–27.0	–25.4

Overlay Code Characteristics

Maximum Sidelobes at 0 Hz Frequency Shift for the Overlay Codes

Overlay Codes	Even Auto-Correlation	Even Cross-Correlation
Index 1 to 63	–24.8 dB	–19.6 dB
Index 1 to 210	–22.7 dB	–19.6 dB

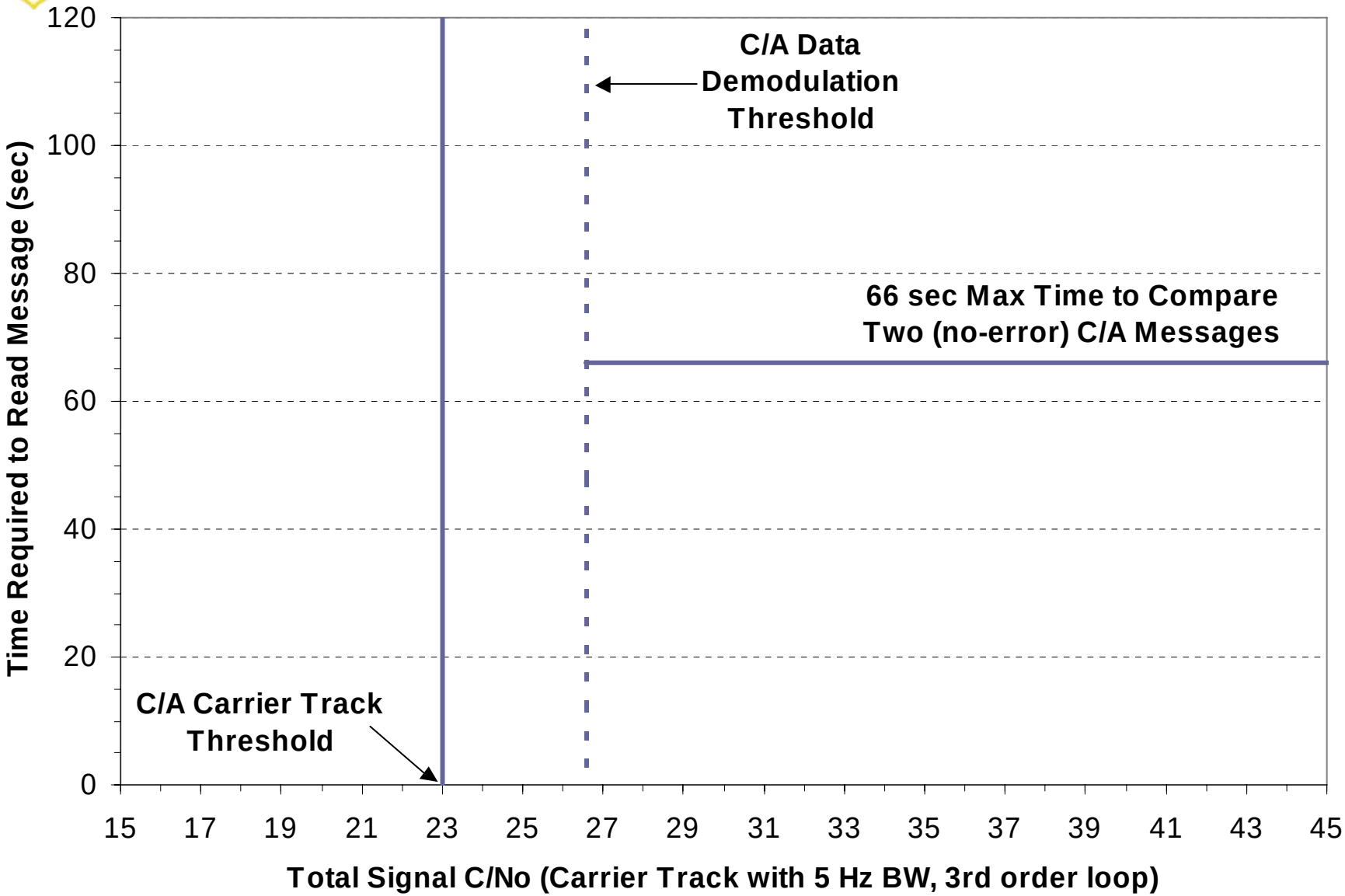
- **Increased Pilot correlation protection**
- **Rapid synchronization**

Each overlay code is 1800 bits long, aligned to the data message boundary. Overlay codes indexed 1 to 63 are reserved for GPS and are truncated m-sequences. The remaining overlay codes, indexed 64 to 210, are truncated Gold sequences. The even autocorrelation properties of the overlay codes are shown in the Table. The codes were also chosen to have good correlation properties for small window sizes. For 100 symbols (1 s), the sidelobes are below –7 dB, while for 200 symbols (2 s), the sidelobes are below –10.5 dB. These low sidelobes provide more reliable synchronization to an interval, and thus to the data message.

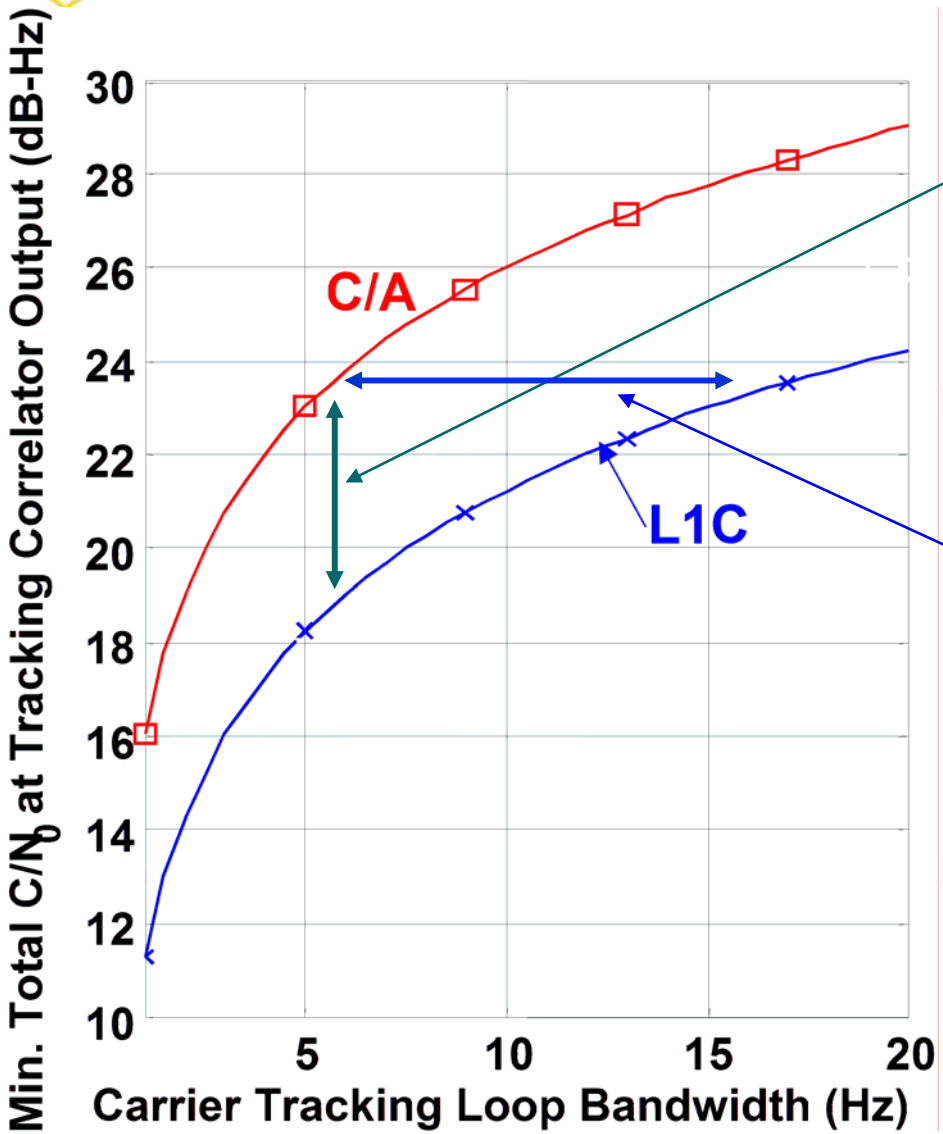
Spreading Code Improvements

- New code structure
- Code length is identical on pilot carrier and message channel(s) so 100% of signal power can be used for acquisition
  - Similar to L5 but not L2C
- Secondary codes on pilot carriers
  - Frame the messages
  - Data demodulation can start anywhere
  - Improves protection against narrowband and cross-satellite interference

Baseline C/A Signal Performance

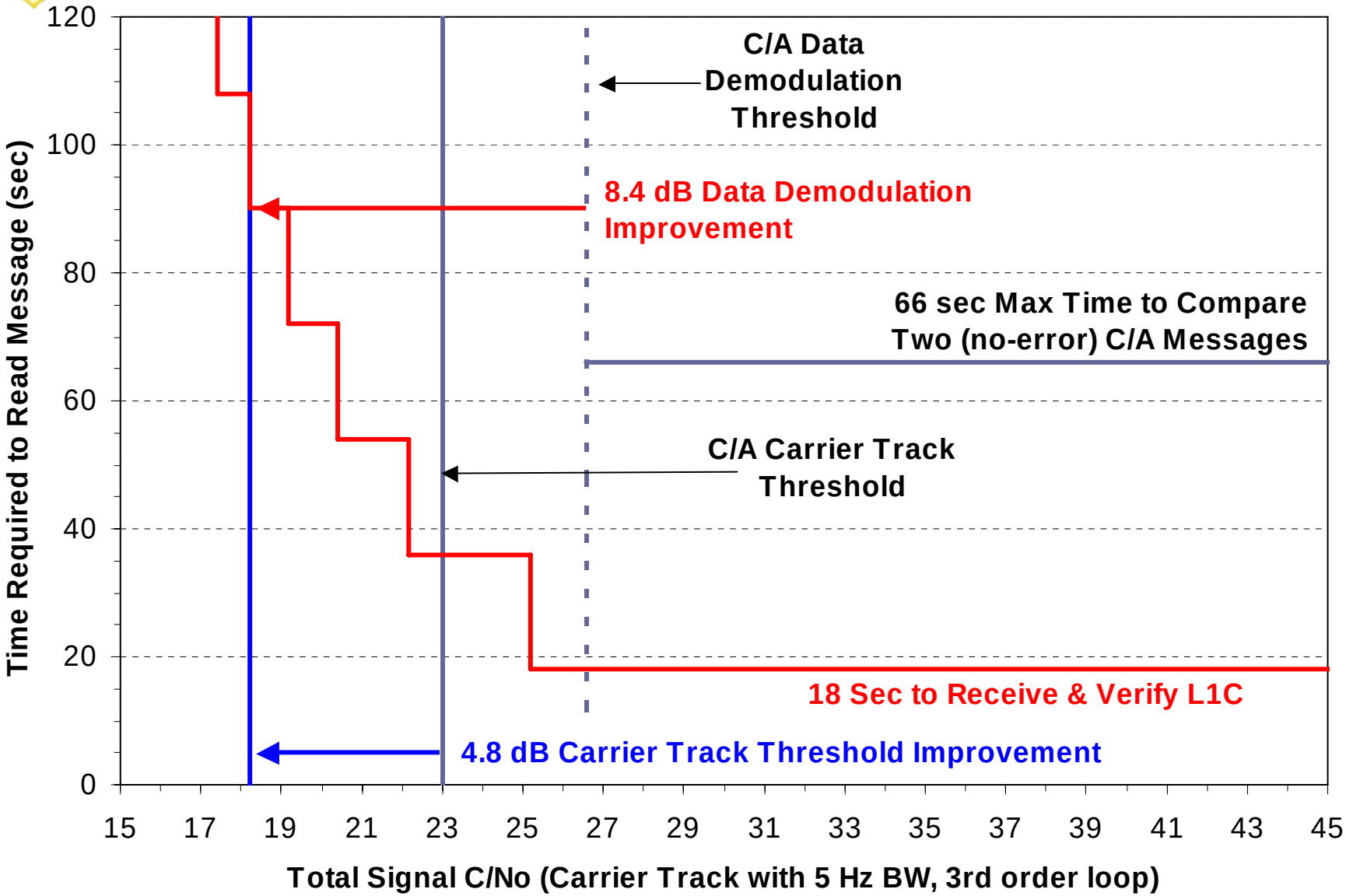


Better Carrier Tracking Threshold



- L1C carrier tracking threshold is 4.8 dB better than a C/A signal of equal power
- A 4.8 dB (3 times) wider loop bandwidth permits tracking nine times higher G forces
  - 27 times higher Jerk
- Min L1C power also specified to be 1.5 dB higher than C/A

L1C Performance Comparison



US and EU Choose MBOC

The United States Mission to the European Union

http://useu.usmission.gov Brussels, Belgium

U.S., EU Announce Final Design for GPS-Galileo Civil Signal

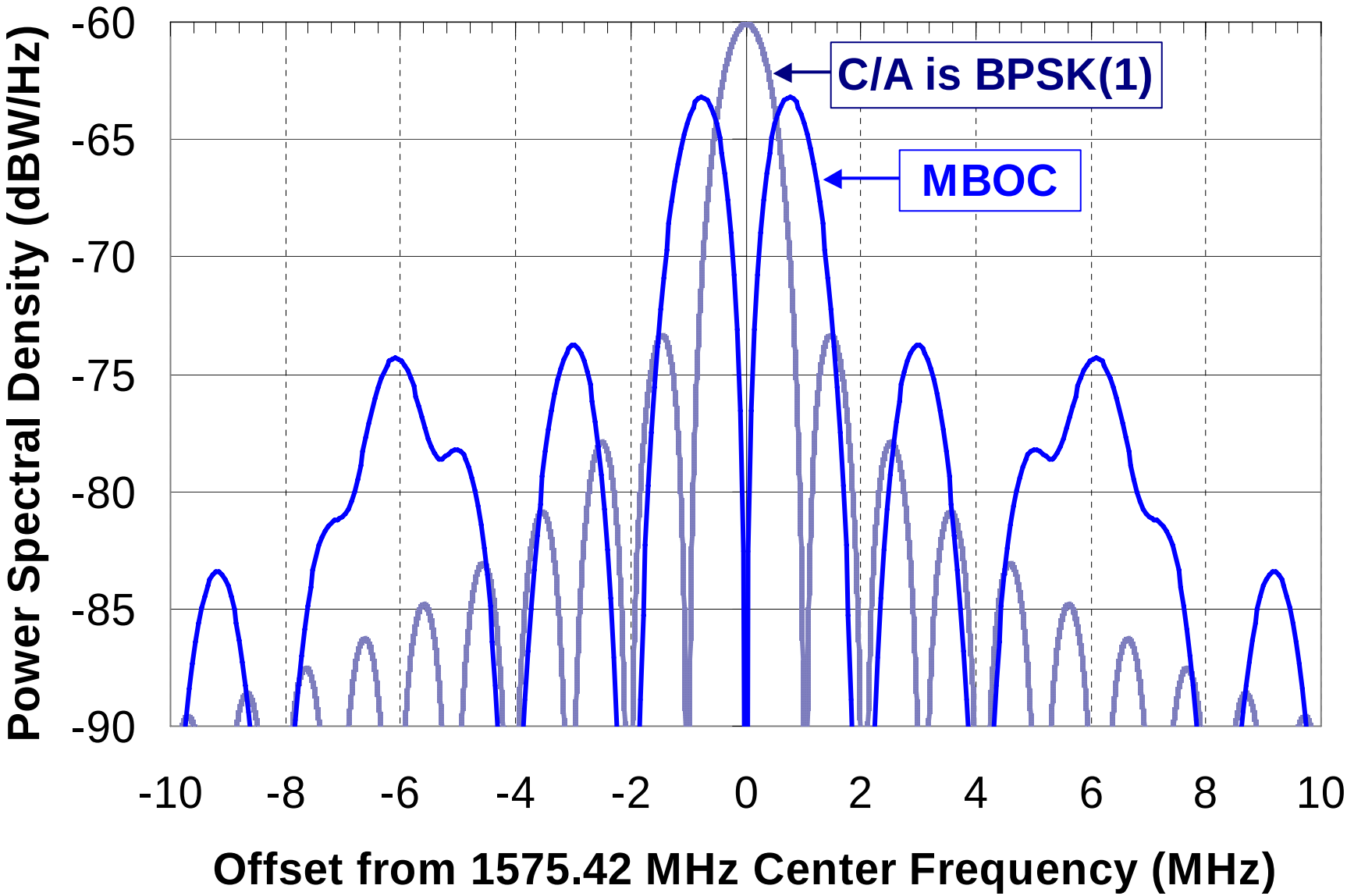
July 26, 2007

The United States and the European Union announced July 26 an agreement for a common GPS-Galileo signal -- called MBOC -- for civilian use. In the future, this will allow receivers to track the GPS and/or Galileo signals with higher accuracy, even in challenging environments.

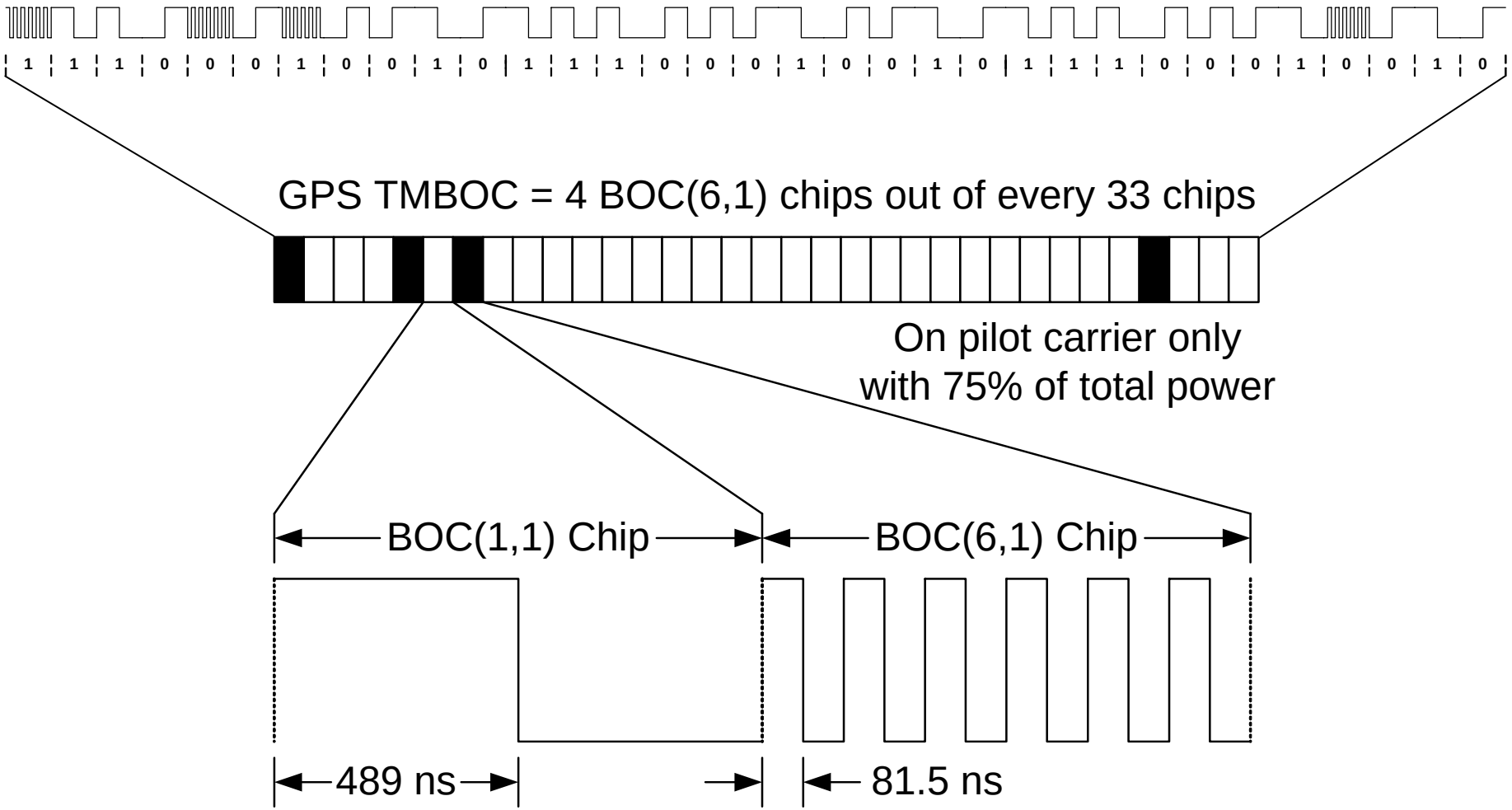
The agreement to jointly use MBOC on these interoperable civil signals demonstrates the close U.S.-EU cooperation since 2004 to ensure that GPS and Galileo are compatible and interoperable at the user level.

- Baseline US/EU agreed waveform for GPS L1C and Galileo E1 OS was BOC(1,1)
- US/EU compatibility and interoperability working group (WGA) recommended MBOC

L1C & E1 OS Have Same Spectrum



GPS TMBOC Version of MBOC



Galileo MBOC has a different "CBOC" implementation

TMBOC Gives More Transitions

- The main purpose of TMBOC is to provide more code waveform transitions
  - C/A has 0.5 average transitions/code chip
  - BOC(1,1) has 1.5
  - BOC(6,1) has 11.5
- Over 33 chips, on average:
  - C/A has 0.5 x 33 = 16.5 transitions
  - BOC(1,1) alone has 1.5 x 33 = 49.5
  - TMBOC has 1.5 x 29 + 11.5 x 4 = 89.5
- Relative to C/A or BOC(1,1), TMBOC has:
  - 5.4 times or 7.3 dB more transitions than C/A
  - 1.8 times or 2.6 dB more transitions than BOC(1,1)

L1C Summary

- Overcomes deficiencies of C/A code
- More interoperable with Galileo E1 OS
- Satisfies US/EU Agreement
- Will be on all GPS III satellites
- Significant performance improvements:
  - Code and carrier tracking threshold
  - Code correlation, interference Protection
  - Time to first fix
  - Data demodulation to tracking threshold
  - Lower code tracking noise
  - Less multipath interference