Development of Long-Code Capability at Goldstone and Initial Results for NEA (357439) 2004 BL86, Venus, and Galilean Satellites

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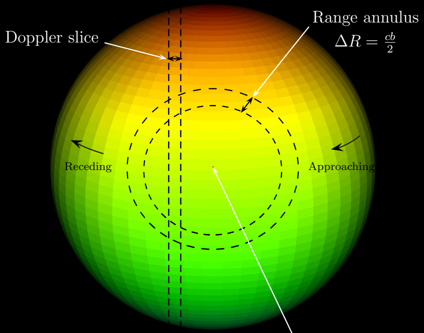
Motivation

- Implement capability to unambiguously measure range and generate unaliased delay-Doppler imagery of planetary targets.
  - Allows for rapid ranging estimation in a single observation.
  - Enables ranging of overspread targets not previously measurable, such as Galilean satellites.
  - Alleviates delay and Doppler folding of overspread targets.
- Currently supports science effort to detect subtle orbital changes due to tidal dissipation of Jupiter.
  - Fully-steerable Goldstone 70 meter antenna allows long-term ranging to the Galilean satellites for ephemeris refinement.
  - Improved orbit accuracy may allow Europa Clipper to skip initial distant flybys (1000 km).
- Future applications include range determination of newly discovered near-Earth asteroids (NEAs).
  - Large initial range uncertainties of tens of thousands of km unsuitable for standard techniques.
  - Helps satisfy US National Space Policy and Asteroid Robotic Retrieval Mission (ARRM) objectives.

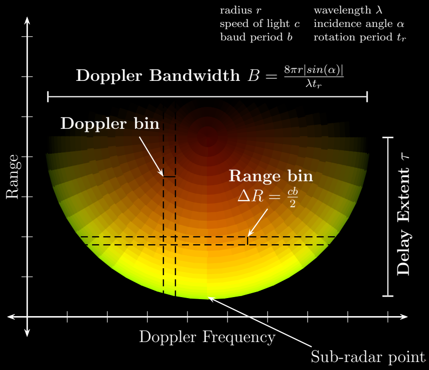
Background

- Planetary radar targets often simultaneously have large delay depth τ and limb-to-limb Doppler bandwidth B.
- These targets are said to be "overspread" if their time-bandwidth product is greater than one, $F = \tau B > 1$.

3-D View Showing Iso-Range & Doppler Contours



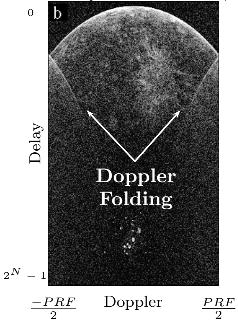
Range-Doppler Map View



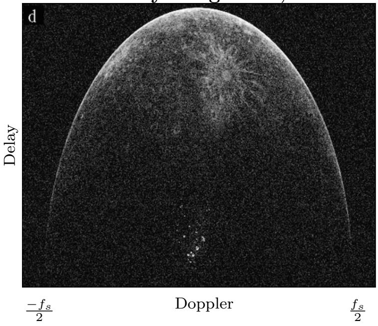
Limitations of Standard Short-Code

- Standard “short-code” waveforms with high repetition rates used for Near-Earth Asteroid observations are insufficient for resolving overspread targets.
- Backscatter images of terrestrial planets and the Galilean satellites are both Doppler aliased and wrapped in range.
- Multiple measurements are required to resolve inherent range ambiguities.

Mercury Short-Code, SC†



Mercury Long-Code, SC†



$$F = \tau B$$

Target	F
NEA 2004-BL86	2.2e-6
Mercury	5.6
Venus	8.3
Mars	617.4
Io	103.8
Europa	37.9
Ganymede	53.7
Callisto	19.3

Table 1. Typical overspreading factors F for various solar system bodies at 8.56 GHz.

† Observation by J. Harmon at Arecibo Observatory.

Origin of Long-Code Processing

1986 — Long-code developed by Sulzer at Arecibo Observatory for ionospheric radar observations. Eliminates range and Doppler ambiguities by transmitting non-repeating pseudo-noise waveform.

1992 — Method applied to planetary radar observations by Harmon et al. at Arecibo.

1994 — First successful radar range measurements to Ganymede and Callisto published by Harmon et al. at Arecibo.

2001 — Harcke et al. carry out long-code observations of Mercury from Goldstone Solar System Radar (GSSR) using equipment borrowed from Arecibo. Capability later lost during hardware upgrades.

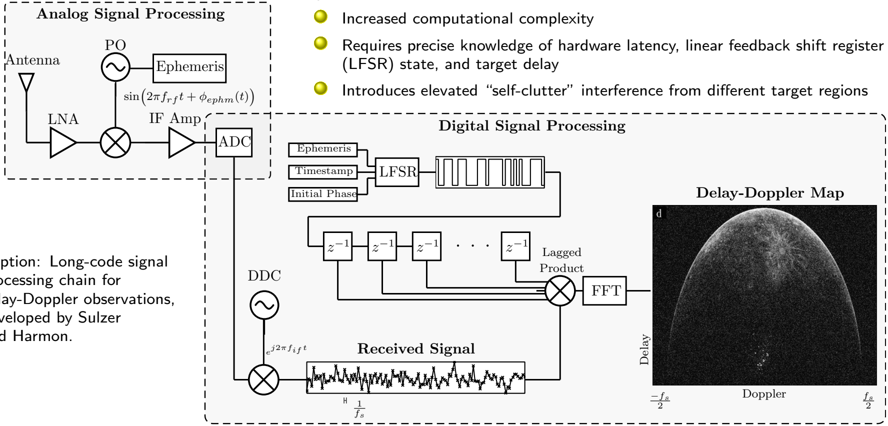
2015 — Long-code implemented on next generation of radar hardware at GSSR. Operation verified through successful range measurements of Galilean satellites, Mercury, Venus, and NEAs. Confirmed detections in bistatic configuration with Green Bank Telescope (GBT).

Long-Code Signal Processing Chain

- Long-code method eliminates range ambiguities by transmitting non-repeating pseudo-noise waveform and forming a separate matched filter for each delay.
- Doppler aliasing issues are alleviated by performing spectral analysis at full sample rate f_s.

Complications:

- Increased computational complexity
- Requires precise knowledge of hardware latency, linear feedback shift register (LFSR) state, and target delay
- Introduces elevated "self-clutter" interference from different target regions



Caption: Long-code signal processing chain for delay-Doppler observations, developed by Sulzer and Harmon.

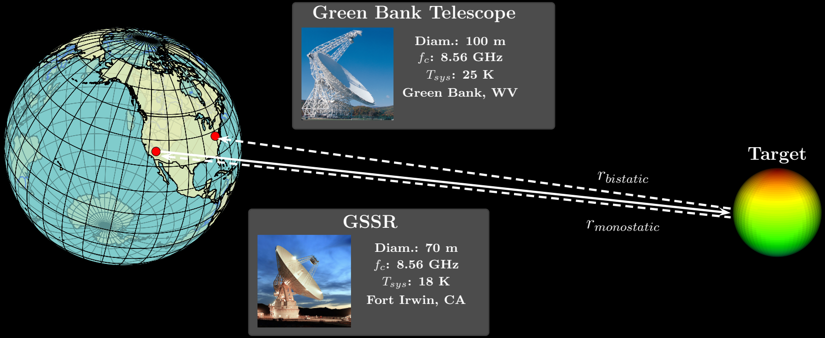
Long-Code Modifications

- The GSSR waveform generator and control software were modified to support binary phase code (BPC) modulation of length $2^{63} - 1$.
  - Control software records initial condition of linear feedback shift register.
  - Loopback test performed at 0.125 us baud period to characterize hardware delay ($\tau_{hw} \approx 15.003625$ ms).
  - Currently using BPC modulation of length $2^{40} - 1$, which repeats every 1.59 days at 0.125 us baud, giving unambiguous range of 138 AU.
- Long-code correlation image processor developed for forming delay-Doppler imagery.
  - Processor initially validated with Arecibo observations of Galilean satellites collected by L. Harcke (JPL) in 2000.
  - Forming individual matched filters for each lag adds computational complexity.
  - Unlike short-code, any timing uncertainty greatly expands search space.

Observation Configuration

- Goldstone's 70 m antenna operated in monostatic and bistatic configuration with the 100 m Green Bank Telescope.
- For observations of the same duration, the larger GBT antenna is expected to improve SNR by approximately 1.47 times (1.7 dB).
- Recordings longer than single RTT possible in bistatic operation (add $\sqrt{\frac{T_{rec}}{RTT}}$).

$$\Delta_{SNR} = 10\ \log_{10}\left(\frac{\overbrace{5655\ \text{m}^2}^{a_{eff,GBT}}}{\underbrace{2771\ \text{m}^2}_{a_{eff,GSSR}}}\right) - 10\ \log_{10}\left(\frac{\overbrace{25\ \text{K}}^{T_{sys,GBT}}}{\underbrace{18\ \text{K}}_{T_{sys,GSSR}}}\right) \approx 1.7\ \text{dB}$$

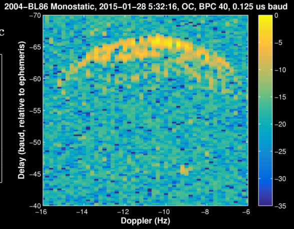


NEA 2004-BL86

- Hardware modifications first successfully tested on NEA (357439) 2004-BL86.
- Estimated ephemeris correction of 7 us in agreement with earlier measurements.
- GBT latency calibrated with back-to-back monostatic and bistatic observations.

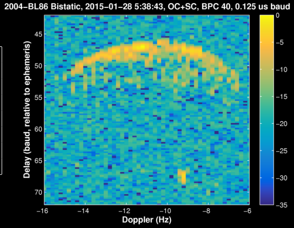
2004-BL86 Monostatic Long-Code

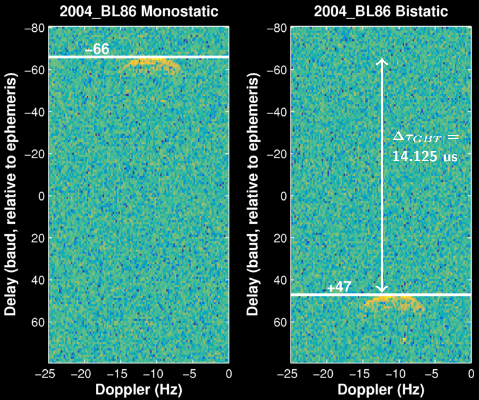
Range	0.02 AU
Baud	0.125 us
Range Res.	18.75 m
Dopp Res.	0.2 Hz
RTT	16.1 s
Duration	10 s
Channels	OC
Ephemeris	S62



2004-BL86 Bistatic Long-Code

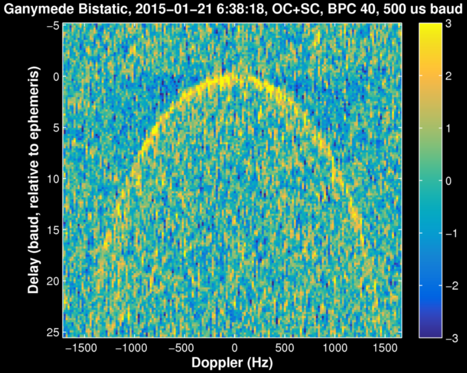
Range	0.02 AU
Baud	0.125 us
Range Res.	18.75 m
Dopp Res.	0.2 Hz
RTT	16.1 s
Duration	10 s
Channels	OC+SC
Ephemeris	S62

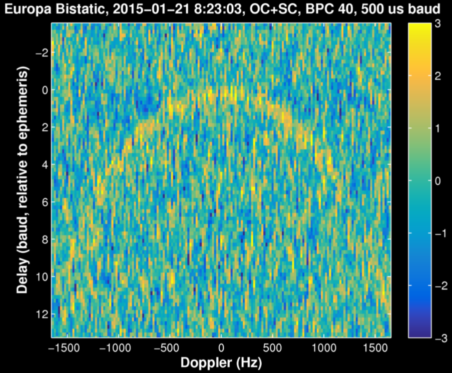




Ganymede & Europa

- First-ever ranging detection of Galilean satellites from GSSR.





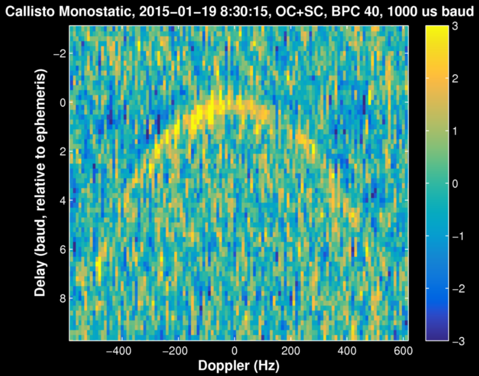
Ganymede Bistatic Long-Code

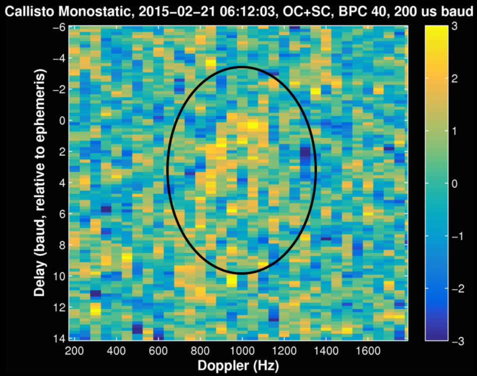
Range	4.39 AU
Baud	500 us
Range Res.	75 km
Dopp Res.	20 Hz
RTT	73.0 min
Duration	1.3x RTT
Channels	OC+SC
Ephemeris	JUP310

Europa Bistatic Long-Code

Range	4.39 AU
Baud	500 us
Range Res.	75 km
Dopp Res.	20 Hz
RTT	72.9 min
Duration	2.5x RTT
Channels	OC+SC
Ephemeris	JUP310

Callisto





Callisto Monostatic
Long-Code

Range	4.40 AU
Baud	1000 us
Range Res.	150 km
Dopp Res.	10 Hz
RTT	73.2 min
Duration	1.0x RTT
Channels	OC+SC
Ephemeris	JUP310

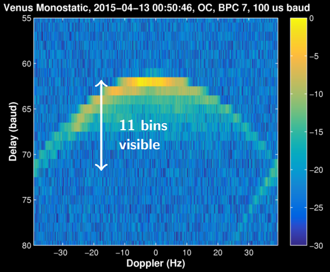
Callisto Monostatic
Long-Code

Range	4.39 AU
Baud	200 us
Range Res.	30 km
Dopp Res.	50 Hz
RTT	73.0 min
Duration	1.0x RTT
Channels	OC+SC
Ephemeris	JUP310

Venus

Venus Monostatic Short-Code

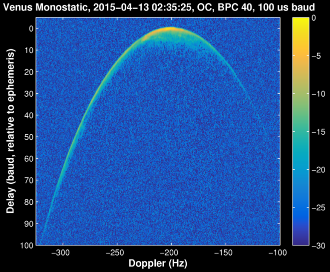
Range	1.13 AU
Baud	100 us
Range Res.	15 km
Dopp Res.	0.1 Hz
RTT	18.7 min
Duration	1.0x RTT
Channels	OC
Ephemeris	DE430

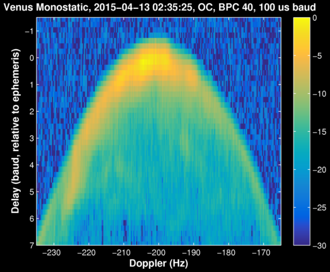


Short-code processing clips visible response

Venus Monostatic Long-Code

Range	1.13 AU
Baud	100 us
Range Res.	15 km
Dopp Res.	0.3 Hz
RTT	18.7 min
Duration	1.0x RTT
Channels	OC
Ephemeris	DE430

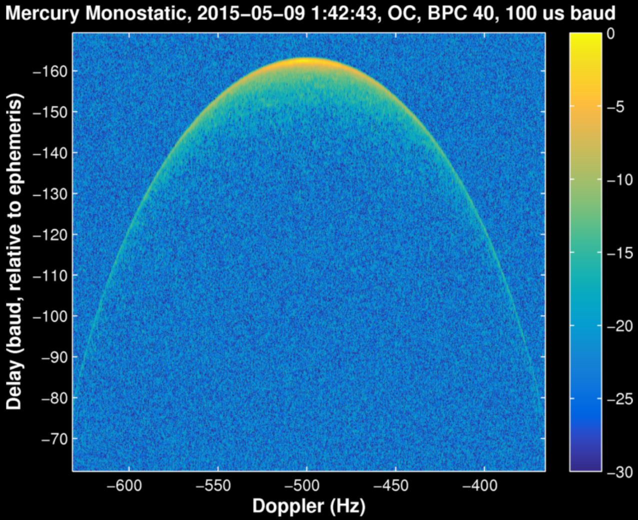




Mercury

Mercury Monostatic Long-Code

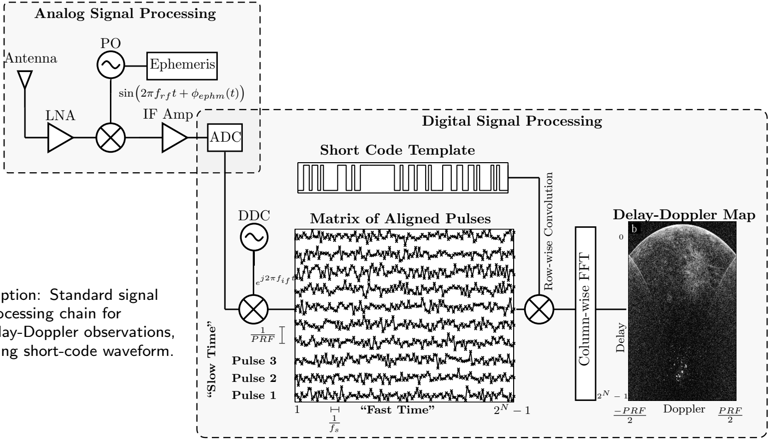
Range	0.80 AU
Baud	100 us
Range Res.	15 km
Dopp Res.	0.3 Hz
RTT	13.4 min
Duration	1.0x RTT
Channels	OC
Ephemeris	DE431



Further Reading

Short-Code Signal Processing Chain

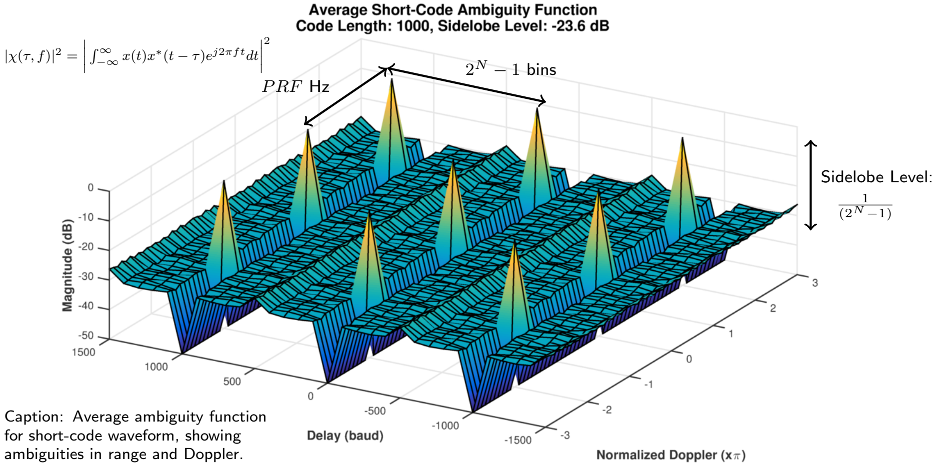
- In standard short-code operation, radar transmits repetitive waveform and analyzes received pulse-to-pulse phase progression to discriminate Doppler.
- Pulse repetition frequency (PRF) can be chosen to accommodate target bandwidth, but the time-bandwidth product is constrained to be unity: $\tau = \frac{1}{B}$.



Caption: Standard signal processing chain for delay-Doppler observations, using short-code waveform.

Short-Code Ambiguity Function

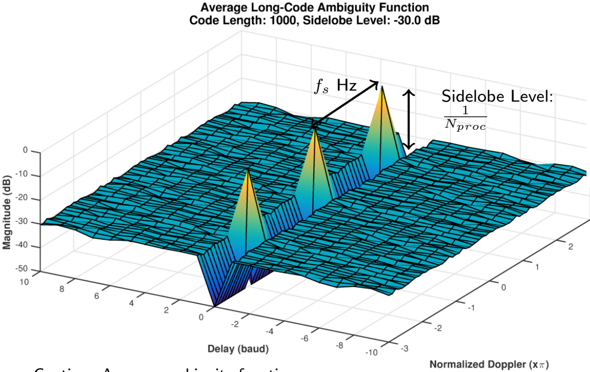
- Ambiguity function is a measure of the matched filter response for a given waveform at different delay and Doppler offsets.
- Short-code waveforms result in ambiguities closely spaced in range and Doppler.



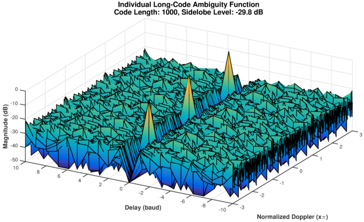
Caption: Average ambiguity function for short-code waveform, showing ambiguities in range and Doppler.

Long-Code Ambiguity Function

- Ambiguity function for long-code does not contain range ambiguities.
- Doppler ambiguities are still present, but are spaced much more distantly at intervals of f_s instead of PRF.



Caption: Average ambiguity function for long-code waveform, showing ambiguities in range and Doppler.



Caption: Ambiguity function for individual section of long-code waveform.

$$|\chi(\tau, f)|^2 = \left| \int_{-\infty}^{\infty} x(t)x^*(t-\tau)e^{j2\pi f t}dt \right|^2$$

Radar Range Equation for Imaging Mode

- Imaging SNR can be predicted by accounting for target surface area contained in each pixel.
  - P_{tx} : transmit power (watts, joules/sec)
  - G_{tx} : transmit antenna gain (unitless)
  - R : one-way distance to target (meters)
  - σ : radar cross section (m^2), depends on baud rate and Doppler resolution
  - $A_{eff,rx}$: receive antenna effective area (m^2)
  - k : Boltzmann constant (joules/kelvin)
  - T_{sys} : System temperature (kelvin)
  - t_{coh} : Coherent integration time (sec)
  - N_{incoh} : Number of incoherent summations

$$SNR = 10\ \log_{10}\left(P_{tx}G_{tx}\frac{1}{4\pi R^2}\sigma\frac{1}{4\pi R^2}A_{eff,rx}\frac{t_{coh}}{kT_{sys}}\sqrt{N_{incoh}}\right)$$

References

References:

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