X-band PN Delta DOR Signal Design and Implementation on the JPL Iris Transponder

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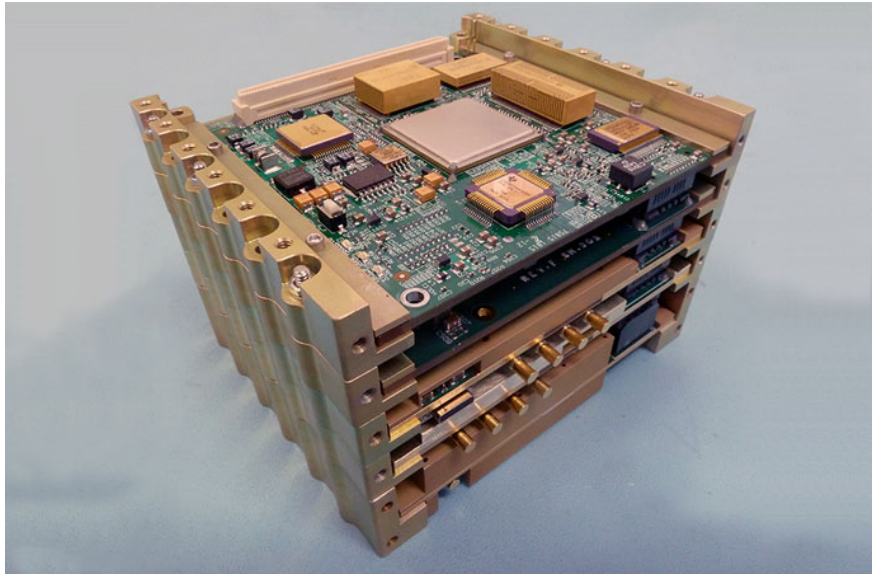
The JPL Iris CubeSat Transponder

- A version of the Iris radio was utilized onboard the MARCO spacecraft.
- The MARCO A and B are the first demonstration of cubesats in deep space
  - The MARCOs were used to relay Insight EDL data back to earth via the Iris radio.
- The Iris radio will soon be utilized for multiple EM-1 missions.



[1] M. M. Kobayashi, T. Dobreva, E. Satorius, S. Holmes, A. Yarlagadda, F. Aguirre, M. Chase, K. Angkasa, B. Burgett, and L. McNally, "The Iris Deep-Space Transponder for the SLS EM-1 Secondary Payloads," Submitted for publication.

[2] M. M. Kobayashi, "Iris Deep-Space Transponder for SLS EM-1 CubeSat Missions," in 2017 Small Satellite Conference, Logan, Utah, Aug. 2017, pp.1-7.

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Delta Differential One-Way Ranging (Delta-DOR)

- Differential One-Way Ranging (DOR)
  - Uses interferometry to measure spacecraft angular position in the radio reference frame:

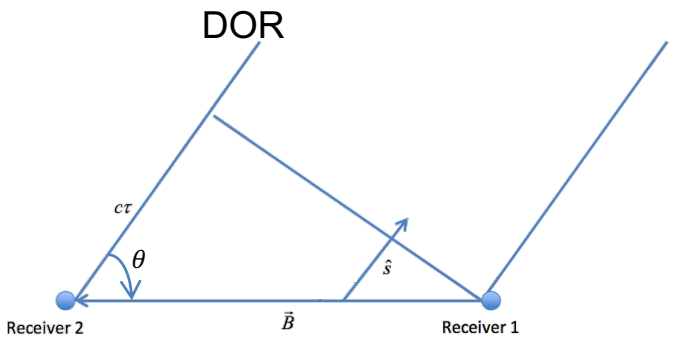
$$\cos(\theta) = \frac{c\tau}{B}$$

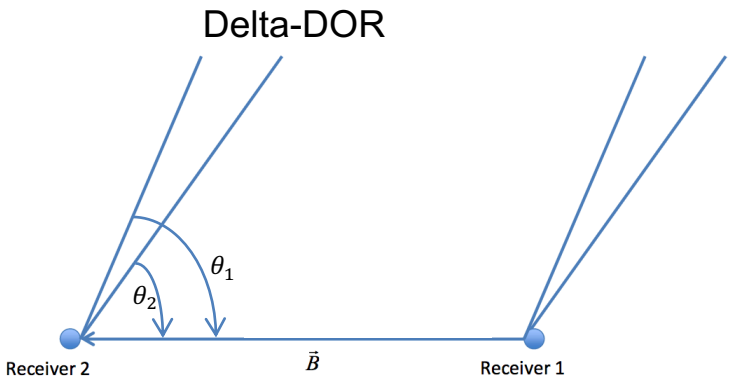
where c is the speed-of-light in a vacuum, τ is the estimated delay of the waveform between the receivers, and B is the separation distance between the receivers.

- Delta Differential One-Way Ranging (Delta-DOR)
  - Station clock offsets, instrumental group delays, and media effects will influence the measurement of τ in DOR, and these errors are accounted for by observing an object (quasar) with known angular position that is close (in angle) to the spacecraft (i.e., calibrated out):

$$\theta_1 - \theta_2 \approx \frac{c\sin(\theta_1)}{B}(\tau_1 - \tau_2)$$

- Observations from 2 (long) baselines are needed to measure both components of angular position.





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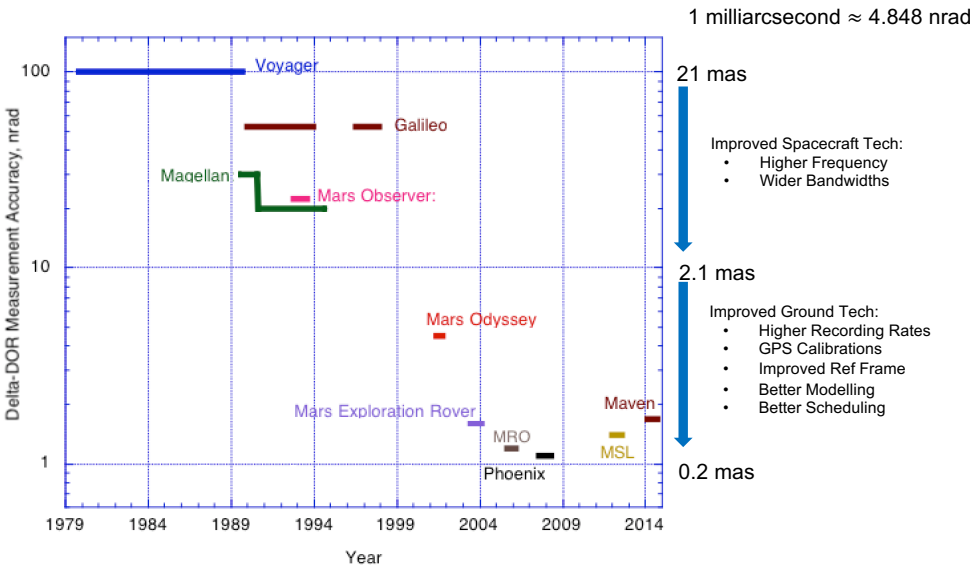
Improvement in Accuracy

- Accuracy has improved from 150 nrad in 1981 to 2 nrad today
- Primary use is to improve targeting in plane-of-sky coordinates for encounters and other critical events
  - 2 nrad is 300 m plane-of-sky position accuracy at Mars encounter distance
  - High accuracy is needed for Mars landing
- Plane-of-sky coordinate accuracy scales with Delta-DOR measurement accuracy



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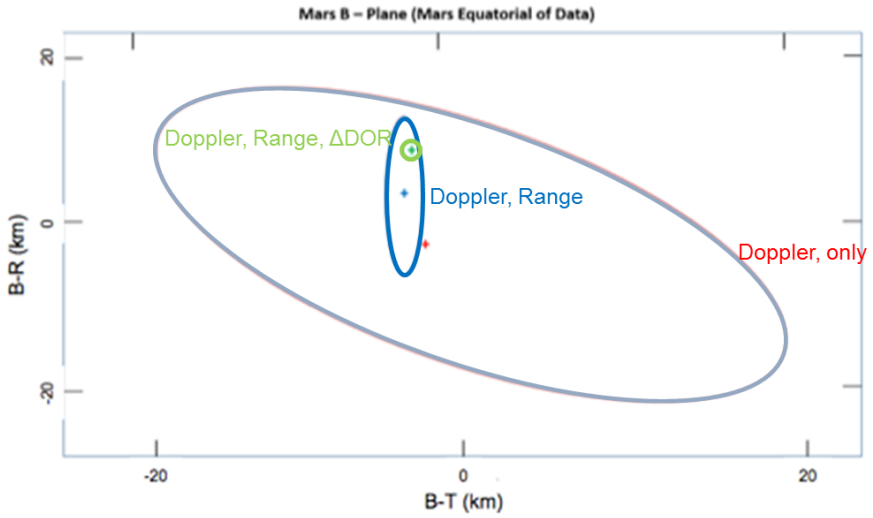
Why Improvement is Still Necessary

- Improved Delta-DOR measurement accuracy provides the following benefits:
  - Would lessen need for long Doppler and range passes
  - Would enable targeting of a more narrow target corridor
  - Can avoid necessity for performing a late maneuver, if a high targeting accuracy is achieved at an earlier time
- Other opportunities for technology improvements:
  - Current 1 MHz DOR tone provides ambiguity resolution of just 1 μs. For missions with lower a priori position knowledge, larger ambiguity resolution is desired.



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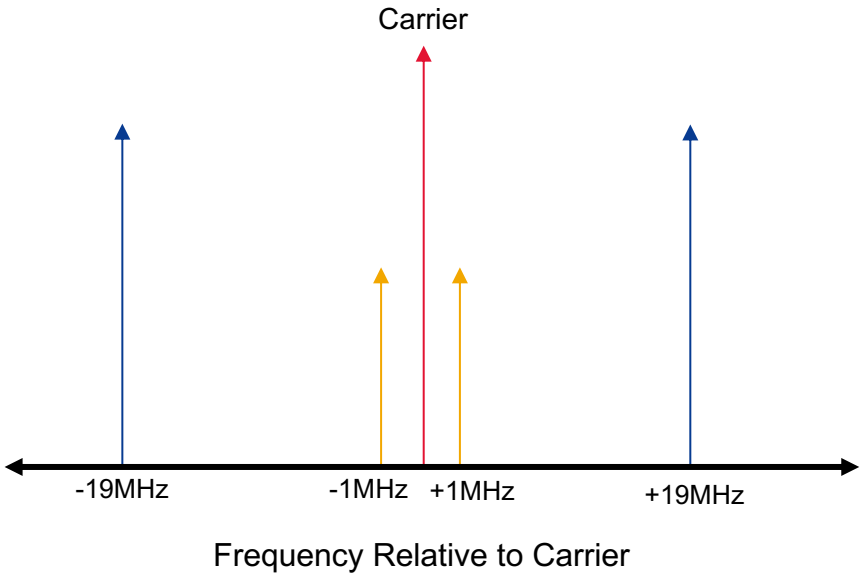
The Classic Delta-DOR Spectrum

- The Delta-DOR spectrum generated by the transponder includes “DOR” tones at approximately $\pm 19\mathrm{MHz}$.
- The $\pm 1\mathrm{MHz}$ tones are used for ambiguity resolution of up to $1\mu s$.



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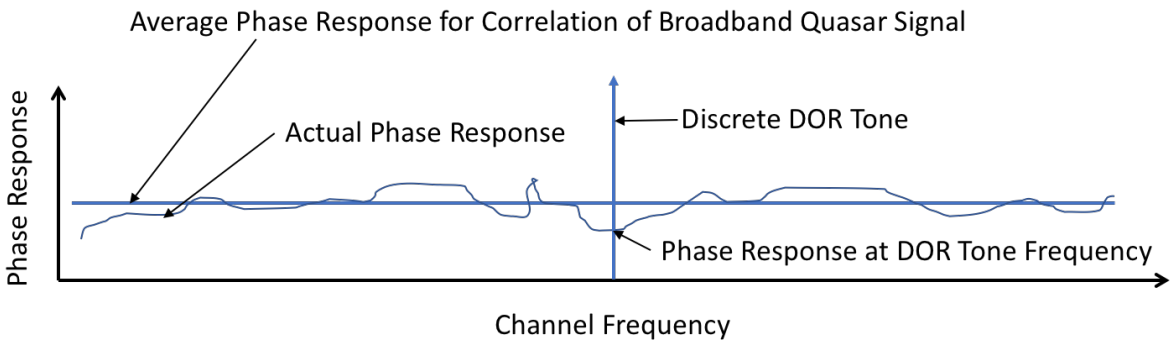
The Dominant Error: Phase Dispersion



- Dispersive phase is a result of the frequency dependent instrumental phase shift of the recorded signals.
- Not common to spacecraft and quasar due to difference in spectrum (discrete tones vs wideband spectrum), and thus cannot be calibrated out easily.
- Remains as key error source in Delta-DOR measurements.
- **Solution**: Let transponder mimic the spectrum of the quasar!

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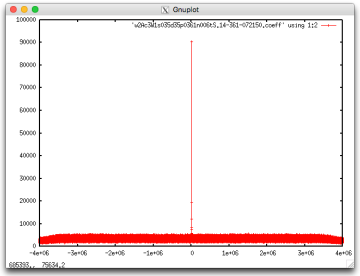
Pseudo-Noise (PN) Delta-DOR

- The spacecraft DOR tone can be spread by a PN sequence.
  - The resulting spectrum is spread by chip rate of the PN code, and further flattened by use of a pulse shaping filter, such as the root-raise-cosine filter.
  - Estimated cancellation of ~90% of the dispersion error.
  - A long sequence (~1 ms) can be used for ambiguity resolution.
  - CDMA techniques can measure multiple frequency-overlapped spacecraft simultaneously.

Sinusoidal DOR Signal



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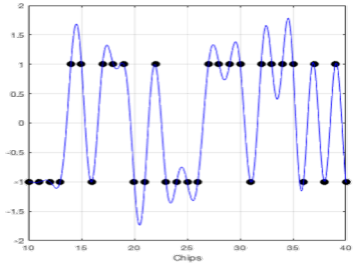
8 Mcps PN Sequence



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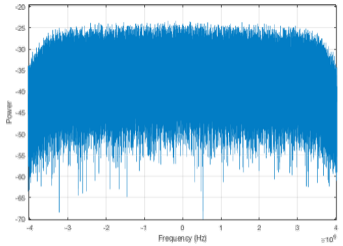
8 MHz PN-DOR Signal



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Design Specifications

- The bandwidth of the X-band PN Delta-DOR implementation is required to be 8MHz.
  - This is due to limits of spectrum allocation at X-band.
- The code period is required to be at least 1ms.
  - This boosts the ambiguity resolution capability by a factor of 1000 from $1\mu s$ for classic Delta-DOR implementation.
- Code must have good autocorrelation properties in order to improve the time resolution during the DDOR processing.
  - It is also desirable that the code have good cross-correlation properties. This is useful when multiple spacecraft utilize the same frequency channel simultaneously (i.e., can perform Delta-DOR for multiple spacecraft simultaneously with the same antennas).
- A small roll-off factor of < 0.3 must be used on the pulse-shaping filter in order to make the spectrum as flat as possible in the pass-band, with a span of 16-chips.

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Code Length Determination

- Using the following inequality:

$$T_c = \frac{2^N - 1}{R_c} \geq \frac{2^N - 1}{BW} = \frac{2^N - 1}{8\text{MHz}} > 1\text{ms}$$

  where

  - N denotes the shift-register length in bits
  - BW is the desired bandwidth in Hertz
  - T_c is the code period in seconds
  - R_c is the code rate in chips per seconds
- We have that the code length in chips is lower-bounded by:

$$2^N - 1 \geq 8000$$

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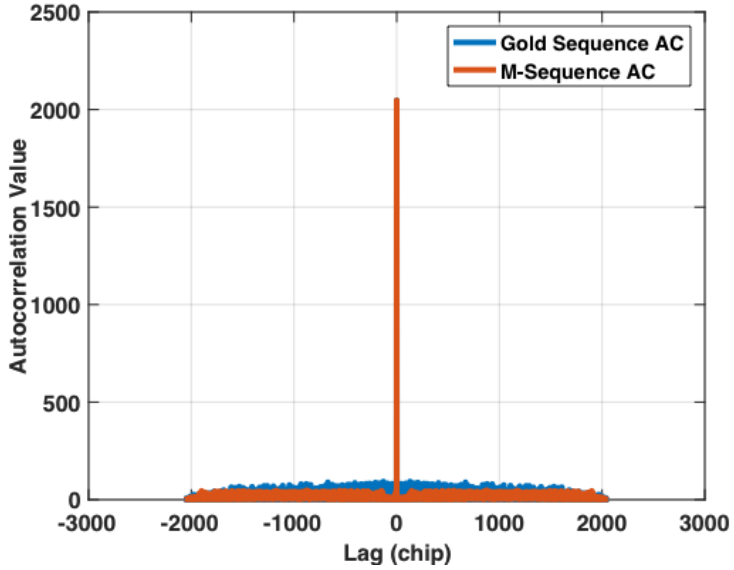
Code Determination

- Typical codes used for spread-spectrum waveforms include:
  - M-Sequences
  - Gold Codes
- Gold codes tend to have better cross-correlation performance at the expense of slight degradation in auto-correlation performance.
  - This is a useful property in the case of direct sequence spread spectrum multi-user applications such as when multiple spacecraft share the same downlink radio-frequency channel.



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Generation of Gold Codes

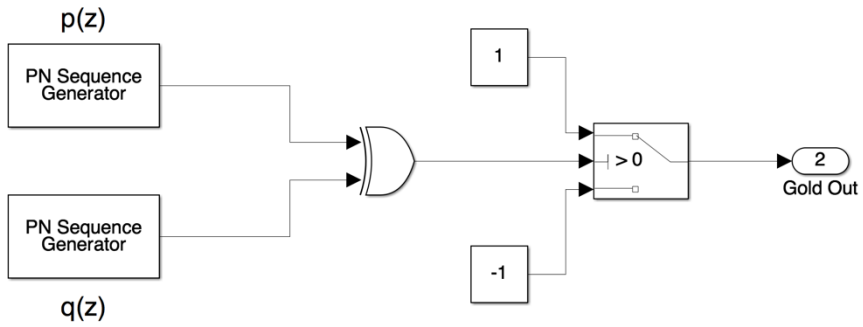
- Gold codes are generated by multiplication of two specially selected M-sequences. These two sequences are chosen using the following theorem:

Theorem from [3]

Let f_1 and f_t be a preferred pair of primitive polynomials of degree N whose corresponding shift registers generate maximal linear sequences of period $2^N - 1$ and whose cross-correlation function θ satisfies the inequality.

$$|\theta| \leq \begin{cases} 2^{(N+1)/2} + 1 & \text{for } N \text{ odd} \\ 2^{(N+2)/2} + 1 & \text{for } N \text{ even } N \neq mod\ 4 \end{cases}$$

Then the shift register corresponding to the product polynomial $f_1 \cdot f_t$ will generate $2^N + 1$ different sequences each period $2^N - 1$ and such that the cross-correlation function θ of any pair of such sequences satisfies the above inequality.



Gold Sequence Generator

[3] R. Gold, "Optimal binary sequences for spread spectrum multiplexing (Corresp.)," in IEEE Transactions on Information Theory, vol. 13, no. 4, pp. 619-621, October 1967.

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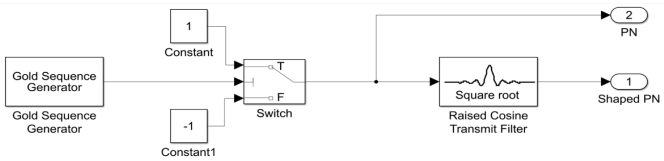
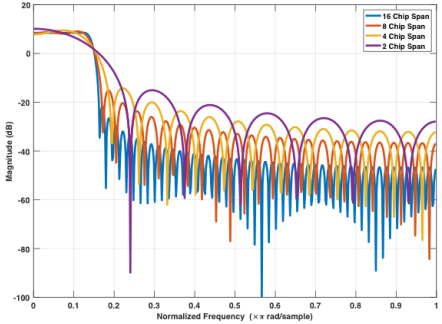
Implementation of the PN Delta-DOR Waveform

- Implementation of the firmware module was done with Mathworks Simulink®:



- Longer chip spans in the pulse-shaping filter helps sharpen the pass-band, at the expense of implementation complexity (longer filter):



Category	Increase in FPGA Utilization Relative to Baseline Design (PN DDOR Module Only)	Increase in FPGA Utilization Relative to Baseline Design (PN DDOR and Pre-distortion Filter)
Slice Registers	1.38%	13.93%
Slice LUTs	1.10%	8.01%
Logic LUTs	0.99%	7.90%
DSP48E	0.00%	77.66%

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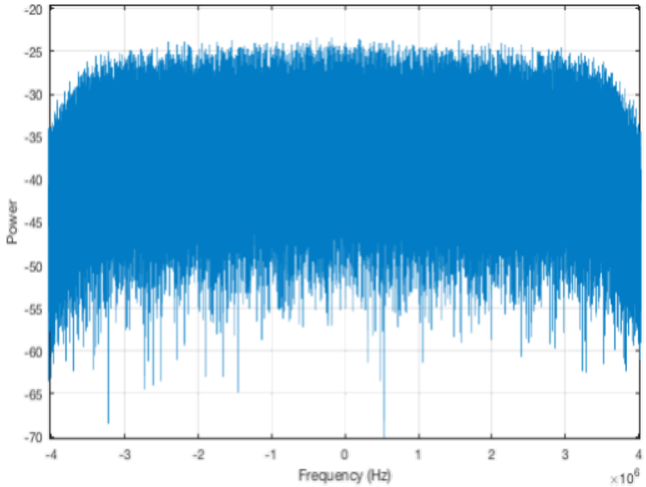
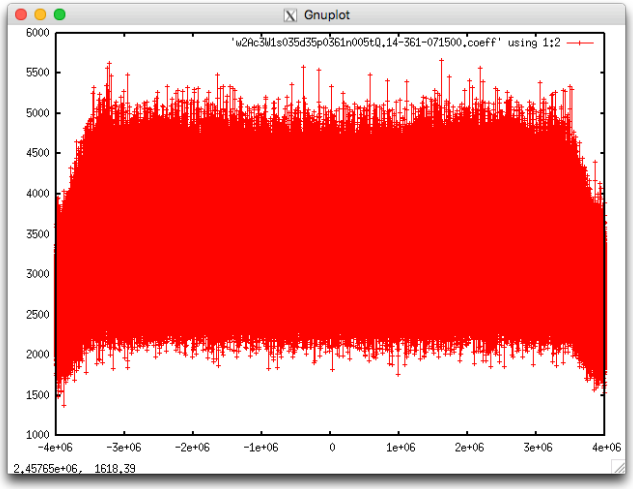
Output Pseudo-Noise (PN) DOR Signal

- JPL's Iris cubesat radio is now capable of transmitting spread spectrum PN code Delta-DOR signals.
- Recorded spectrum closely matches quasar spectrum.
- Instrumental dispersive phase (previously a leading error source) contribution to Delta-DOR measurement error is reduced from 0.03ns down to <0.005ns (**83% reduction**).

Iris PN Delta-DOR



8 MHz Quasar



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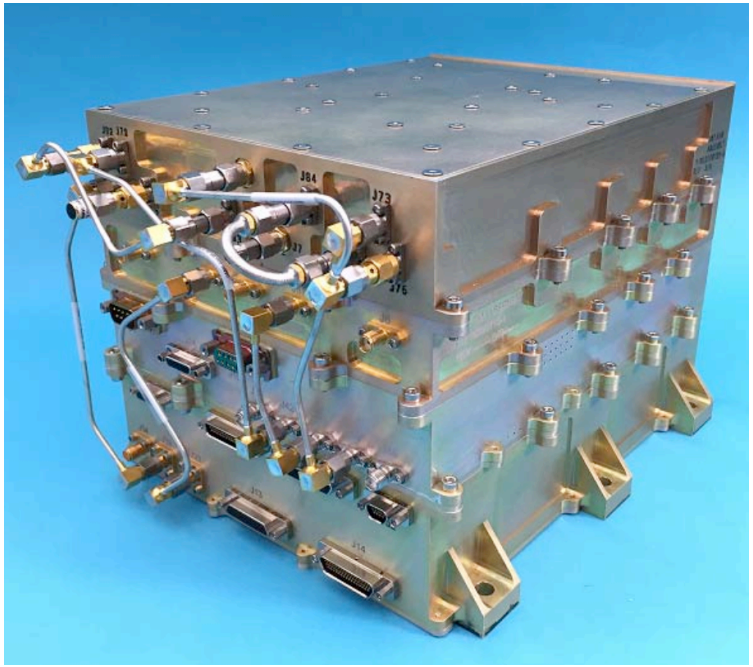
Conclusions

- Now that PN Delta-DOR has been successfully implemented on an Iris radio flight unit, we hope to infuse the X-band PN Delta-DOR mode onto one or two of the Iris EM-1 radios flight software and demonstrated in flight.
- We plan on extending the X-band design into the Ka-band. Requirements and implementation details are being prepared for the Ka-band version of the PN Delta-DOR mode, perhaps using the JPL Universal Space Transponder (UST) radio [4].
    - Much larger improvements in PN Delta-DOR accuracy are expected at Ka-band due to the abundant bandwidth.

The Universal Space Transponder



[4] M. Pugh et al., "The Universal Space Transponder: A next generation software defined radio," 2017 IEEE Aerospace Conference, Big Sky, MT, 2017, pp. 1-14.

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