

The Digital Signal Processing Trade Space for Space-based Radio Telescopes

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The data bottleneck

Terrestrial examples:

- OVRO-LWA:
 - ~1 Tb/s raw ADC rate
- VLA:
 - correlator output up to 60MB/s = 40 Tb/day.
 - Only 27 antennas.

Space mission examples:

- Roman:
 - 11Tb per day,
 - Highest data rate NASA astrophysics mission, flagship
- PRIMA concept – probe class
 - 1.8Tb per day



Ways to downlink more data

- More sensitive receiver → \$\$\$
- More ground station time → \$\$\$
- More downlink power → increase mission size, weight, & power
- Less distance from Earth
 - Note that lunar far side needs a relay system
- Free-space laser communications
 - Under active development
 - See Lazio Megawave talk



DSN control room: credit NASA/JPL-Caltech

Ways to downlink less data

- Interferometer data rate out of correlator:

$$= (\text{duty cycle}) \times N_f \times 0.5 N_a (N_a - 1) \times N_p \times N_b / t$$

Frequency channels Antennas Polarization products Bit depth Integration time

Bandwidth & Time smearing

- Bandwidth smearing:
 $(\Delta v/v) \times (\theta/\Delta\theta) < \sim 0.7$
- Time smearing: maximum integration time depends on how fast source moves through fringe pattern
 - Slower relative velocities at Lagrange points than LEO
 - Moon has a long sidereal day



Image: Yifei Pei, Dark Sky association photo contest 2nd place winner

Correlator architecture: FX

Resource use:

- **FFT:** scales as $N_f \log(N_f) \times N_a$
- **X-engine:** Scales as number of baselines, $(N_a \times (N_a - 1))/2 \sim N_a^2/2$
- Repeat for every channel:
total X-engine $N_f \times N_a^2/2$
- Resource use scales with precision:
 - require lots of bits in FFT to prevent overflow
 - Can “re-quantize” to lower precision after FFT, before X engine

Advantage of FX:

- Better spectral response, use with PFB

$$\langle x_a(\nu) x_b^*(\nu) \rangle = \langle \mathcal{F}(x_a(t)) \mathcal{F}(x_b(t))^* \rangle$$

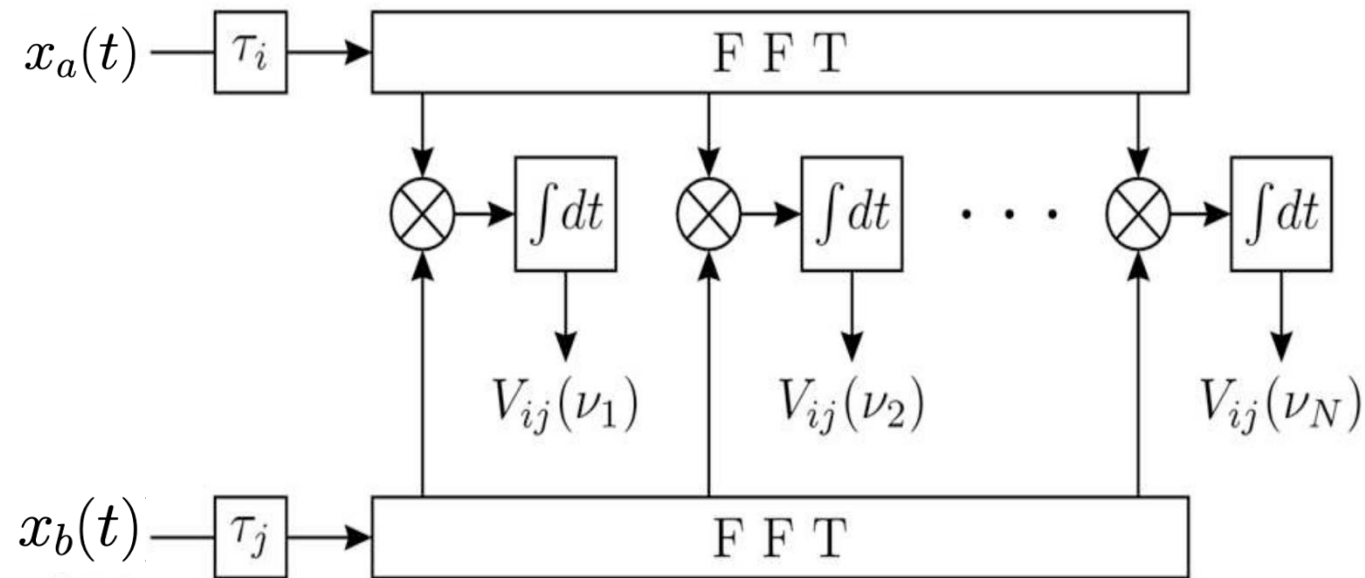


Figure from Walter Briskin's 2004 SIW lecture

Correlator Architecture: XF

Resource use

- X engine: Still scales as number of baselines, $\sim N_a^2/2$
- Repeat this for every lag $\sim N_f \times 2$
- FFT still $N_f \log(N_f)$, but now we need one FFT per *baseline*
- F engine total goes as $N_f \log(N_f) \times N_a^2/2$
- However, only one FFT per time integration
- Can use lower precision multipliers up front for the X engine

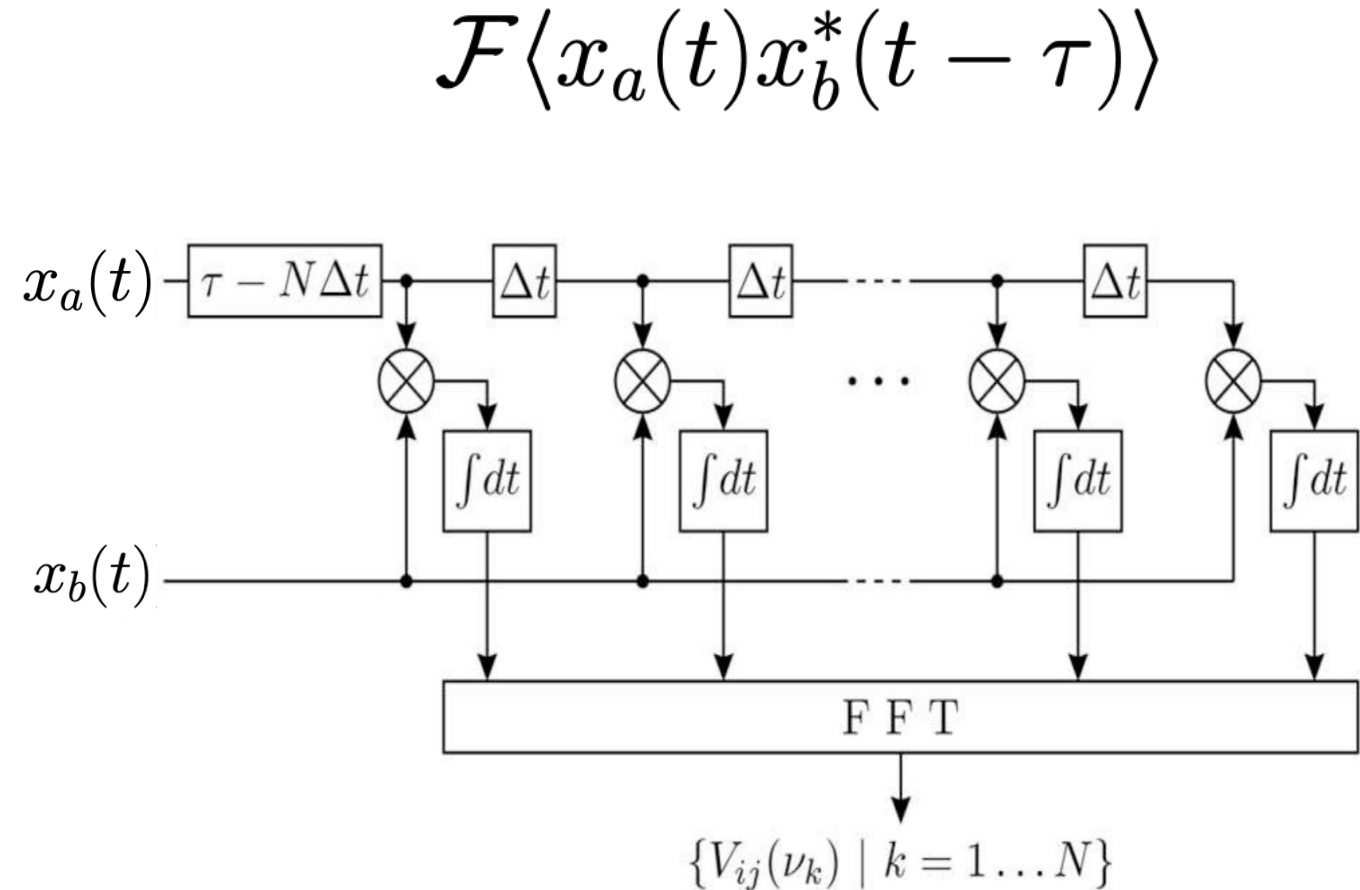
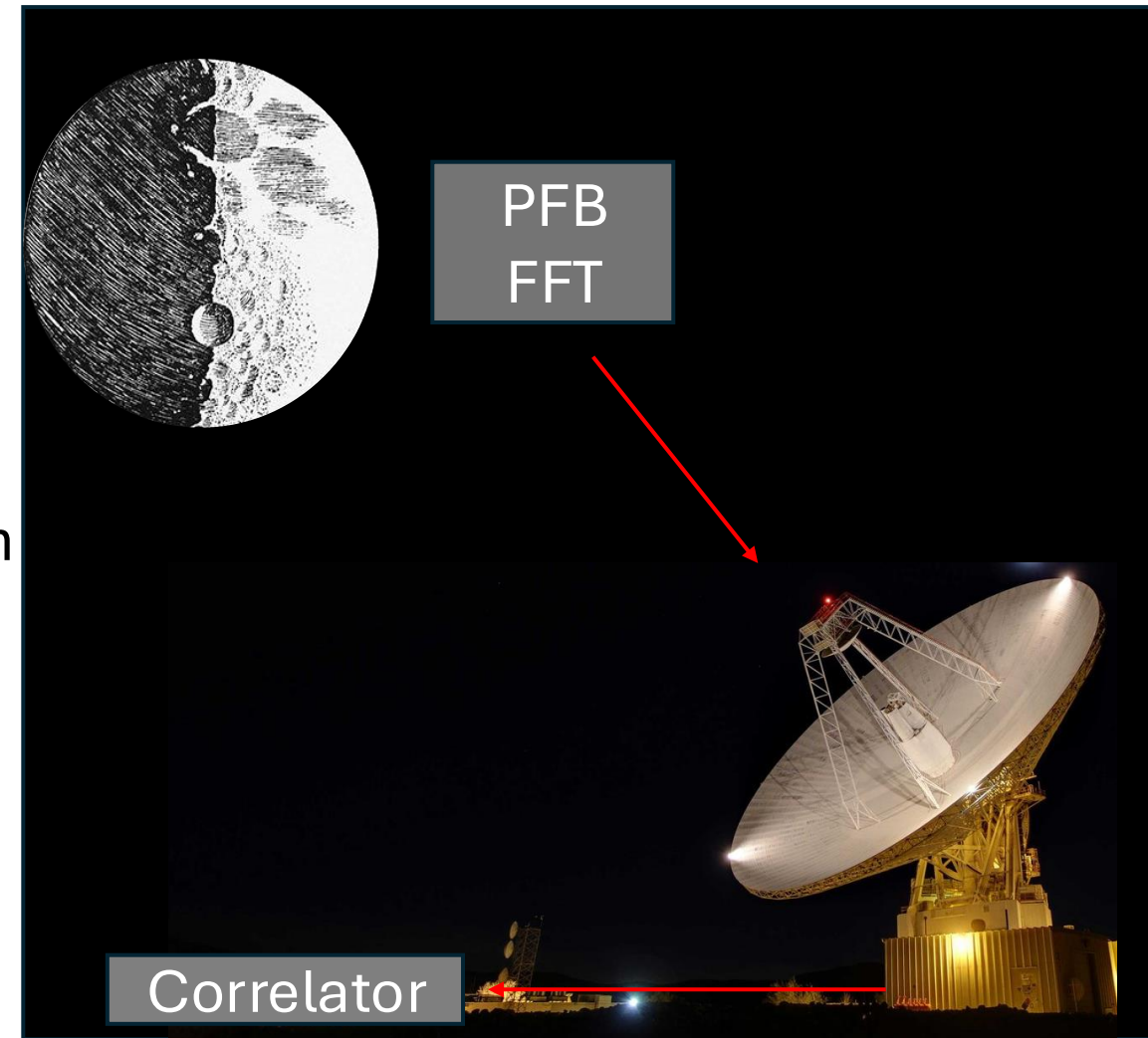


Figure from Walter Briskin's 2004 SIW lecture

Heterogenous architectures: F & X in different places

- F-engine on spacecraft/lander, X engine on ground
 - E.g. Sunrise
- F-engine at dipole station, X engine in central hub
- Only a subset of channels go to X engine
 - FFT size driven by channel bandwidth – which may be driven by bandwidth smearing requirements or the need to excise narrow-band RFI, rather than directly by science spectral requirement
- Proposed mission concepts have huge fractional bandwidth:
 - Process different subbands at different frequency or time resolution



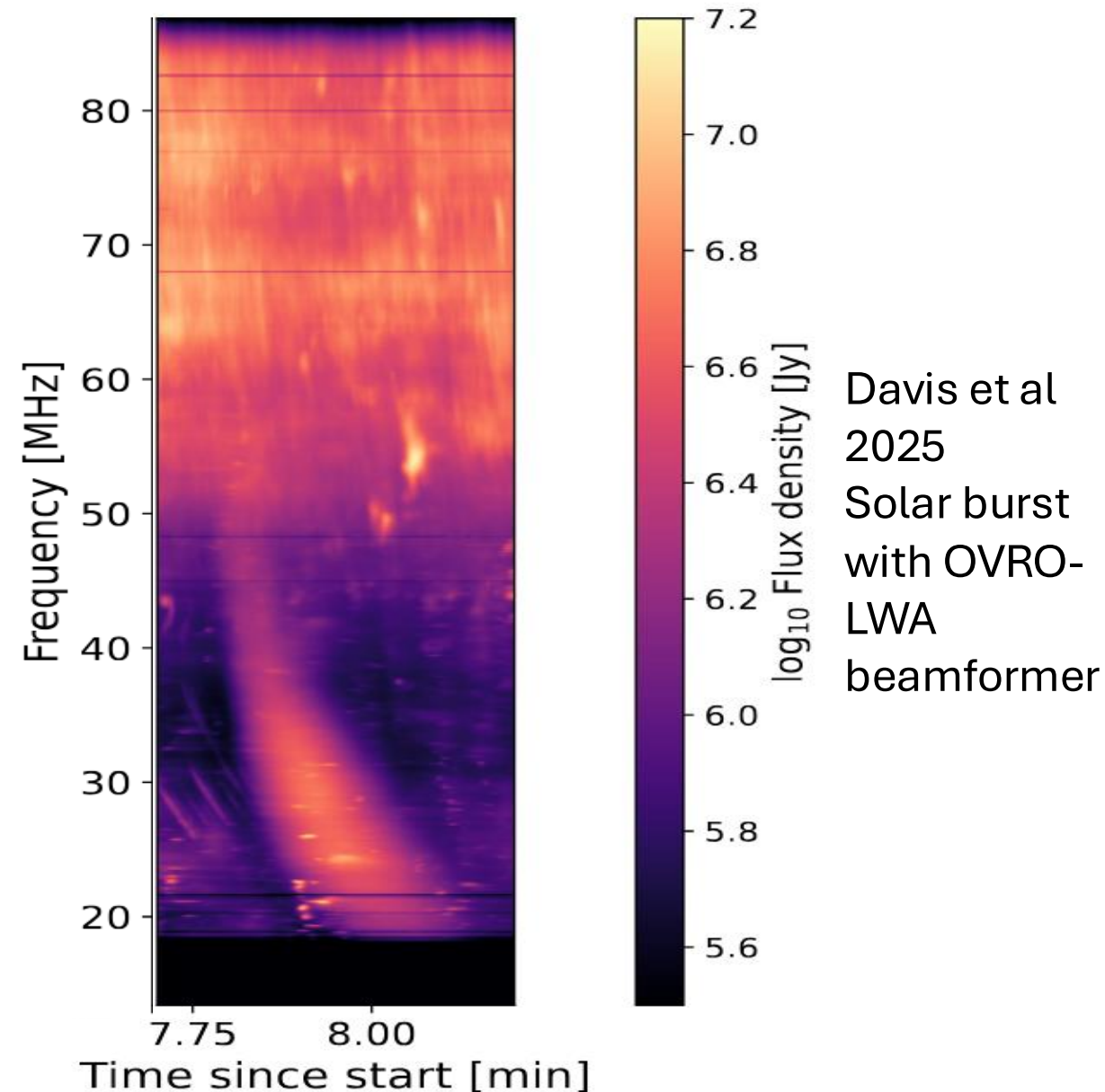
DSN adapted from NASA image

Downlink higher level data products?

- Must include a test mode that preserves access to raw data
- Additional computational resource use
→ size, weight, and power
- Intermediate step: Apply frequency and/or visibility based flagging on spacecraft/lander

Lowering data rate by limiting duty cycle

- Buffer+trigger mode for transients
- Sequential subband observations for non-transients
- Sub-array observing modes?



Data transfer *among* mission elements

Cabled connections:

- Coaxial cable: limited to short distances
- Digital fiber optic: long distances, requires digitizer (& more power) at each dipole
- RFoF: long distances, can digitize centrally, highly temperature-dependent gain
- All require deployment robotics



OVRO-LWA

Data transfer *among* mission elements

Relay from dipoles to hubs:

- Required by free-flying arrays, optional in a lunar surface context
- Requires digitizer and comms transceiver (more power) at each dipole element
- Requires additional communications spectrum



Alvarez-Muniz+2026

Conclusions

- Ultra-low-frequency radio interferometers are data-intensive
- Signal processing & communications technology exists, but demands tradeoffs in DSP strategy
- New technologies that may enable greater capabilities include free-space laser communications, and radio frequency over fiber within array
- Main takeaway: We have a lot of options and must make tradeoffs

Extra slides

X engine on spacecraft/lander, F engine on ground

- Spectral response heavily favors FX correlators, so this would only be appealing if good analog + digital filter can be performed at high precision before requantizing to low precision at lag correlator input
- Appealing if $N_f > N_{\text{baseline}}$
- Downlink data rate goes as: $N_f \times N_{\text{baseline}} \times N_b \times N_p / t$
 - Still goes as N_f because of Nyquist-Shannon theorem
 - But t can be larger