ngVLA Workshop

Signal organization for long-distance transfer with wide-band front ends

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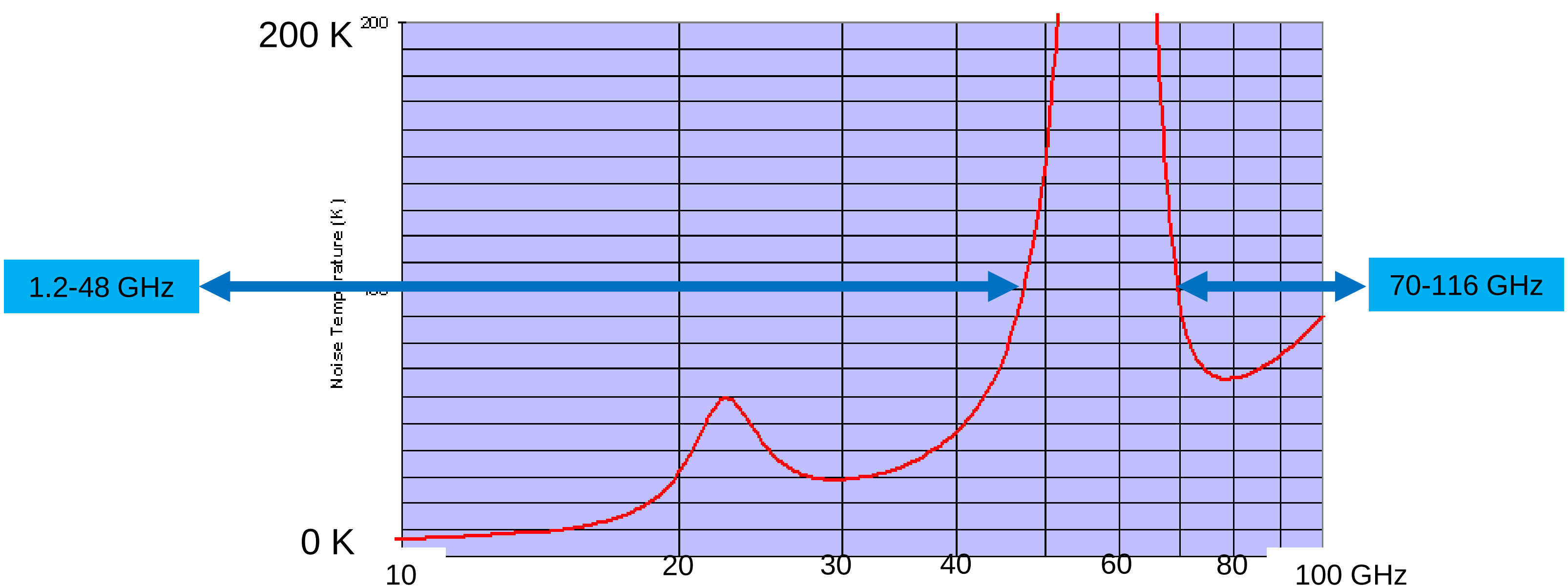
Outline

- This is a short talk, giving a high-level, somewhat tutorial view.
- Illustrates principles and methodology, not final choices
- Topics:
  - Top-level assumed requirements
  - Partitioning into front-end bands
  - Digitization methods: direct vs. downconverted
  - Instantaneous bandwidth vs. frequency coverage
  - Quantization (bits per sample): dynamic range requirement
  - A strawman scheme

Assumed Requirements

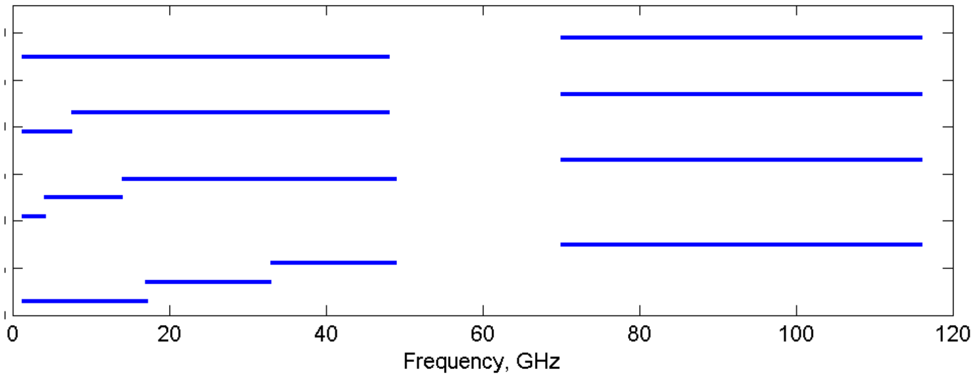
1. Cover the range 1.2 to 116 GHz continuously, except for ~50 GHz to ~70 GHz (oxygen absorption).
2. To control cost, minimize the number of feed+LNA assemblies.
3. [Cool as much as possible of the feed+LNA assemblies to ~20K using a single cryocooler.]
4. Consistent with the above, obtain the best possible A_e / T_{sys} at all frequencies.

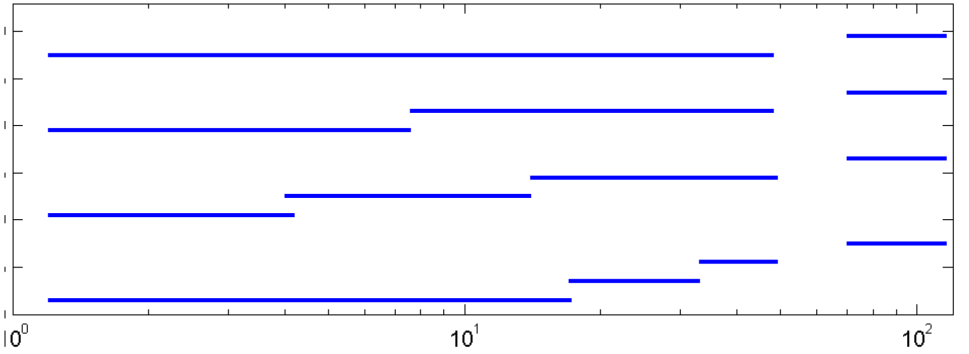
Noise temperature at zenith from sea level due to absorption by atmospheric gasses



Band Partitioning

- *High bandwidth ratio* is challenging for feed/LNA. Up to 7.0 might be practical, but could compromise A_e / T_{sys}.
- *High absolute bandwidth* is challenging for digitization. Up to 20 GHz might be practical in one channel.



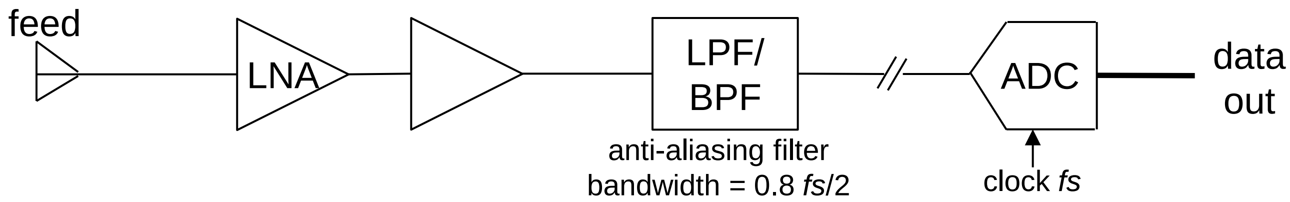


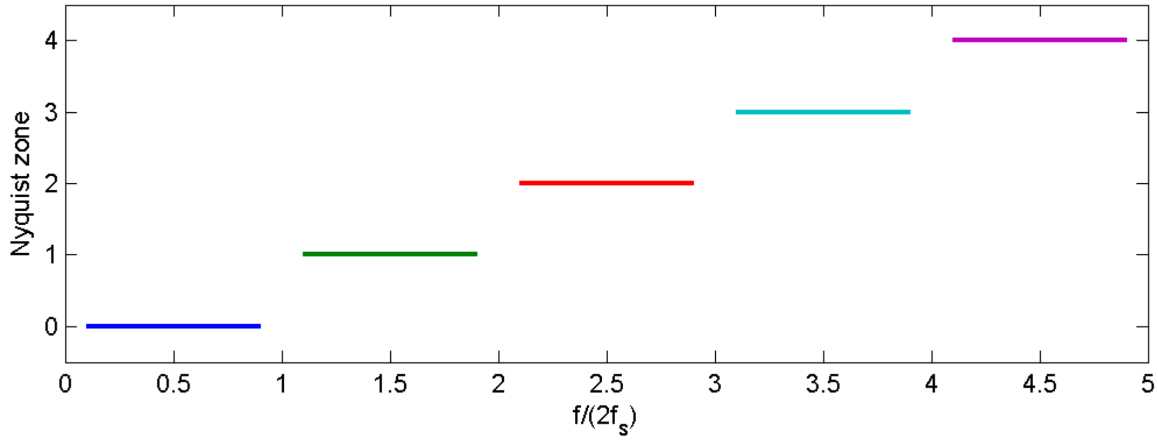
Number of bands	Range, GHz	Ratio (feed, LNA)	BW (digitization)
2	1.2-48	40.0	46.6 GHz
	70-116	1.66	46.0 GHz
3	1.2-7.58	6.32	6.4 GHz
	7.58-48	6.32	40.4 GHz
	70-116	1.66	46.0 GHz
4	1.2-4.2	3.5	3.0 GHz
	4-14	3.5	10.0 GHz
	14-49	3.5	35.0 GHz
	70-116	1.66	46.0 GHz
4	1.2-16.8	14.0	15.6 GHz
	16.8-32.4	1.93	15.6 GHz
	33-48	1.45	15.6 GHz
	70-116	1.66	46.0 GHz

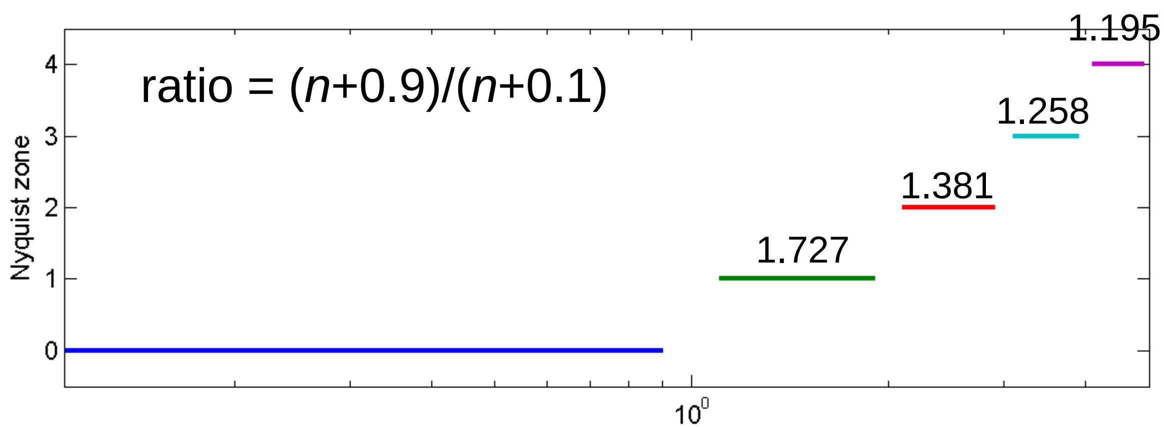
Digitization Schemes

- Directly at RF (popular when feasible)
  - Only one LO needed (sampling clock)
  - Digitized bandwidth = (sampling rate)/2
  - Nyquist zone $n > 1$ possible only when bandwidth ratio $< (n + 1)/n$.
  - Precludes phase switching
- Single-sideband down-conversion
  - Very messy when RF bandwidth ratio > 1
  - May require multiple conversion stages
  - Two (or more) LOs needed
  - Digitized bandwidth = (sampling rate)/2
- Double-sideband down-conversion to baseband
  - Can usually be done in one stage
  - Two LOs needed.
  - Requires two ADCs (I and Q)
  - Digitized bandwidth = sampling rate.

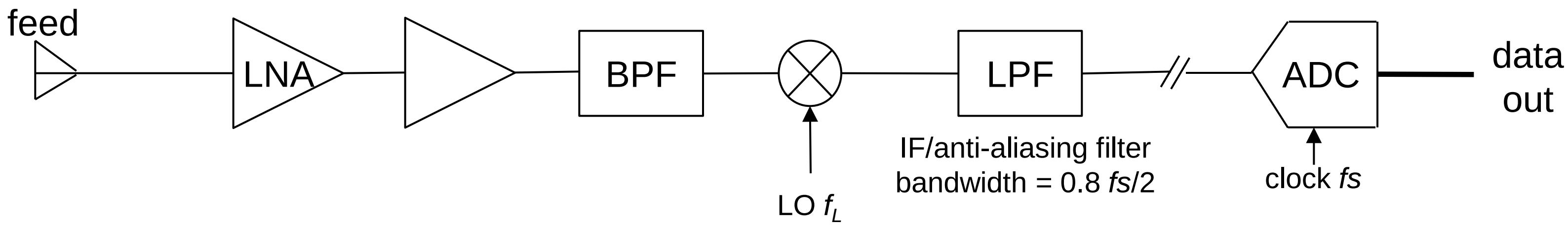
Direct Digitization (no down-conversion)



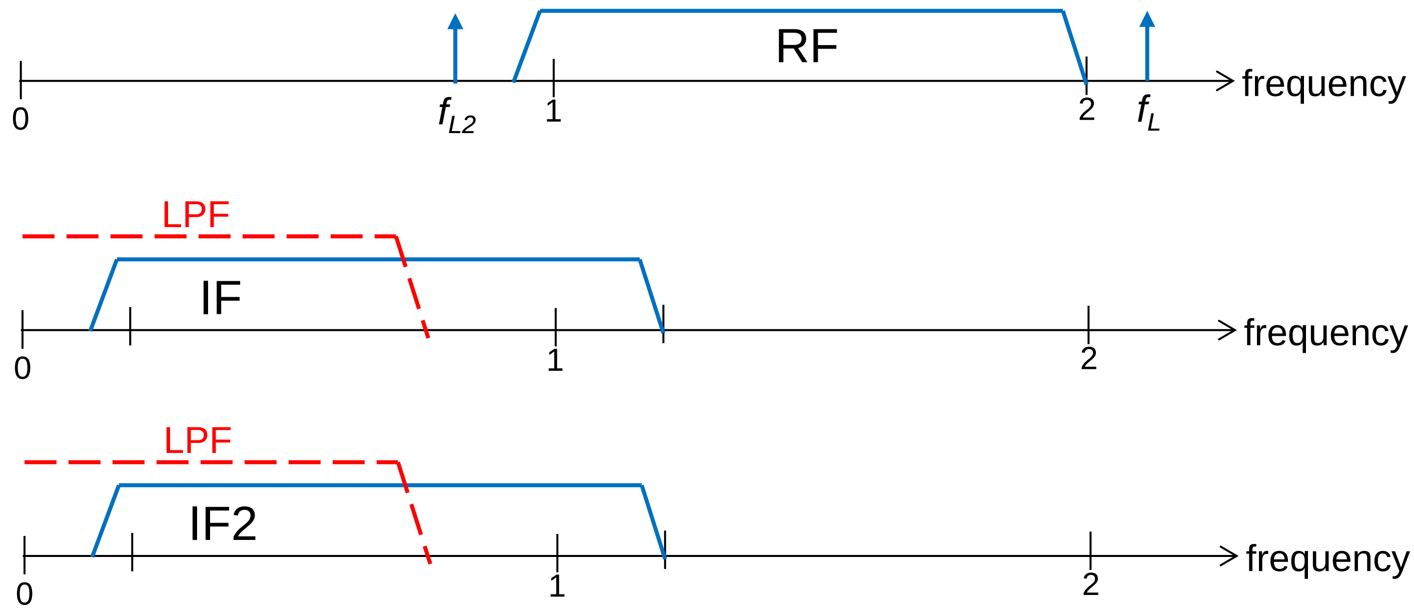




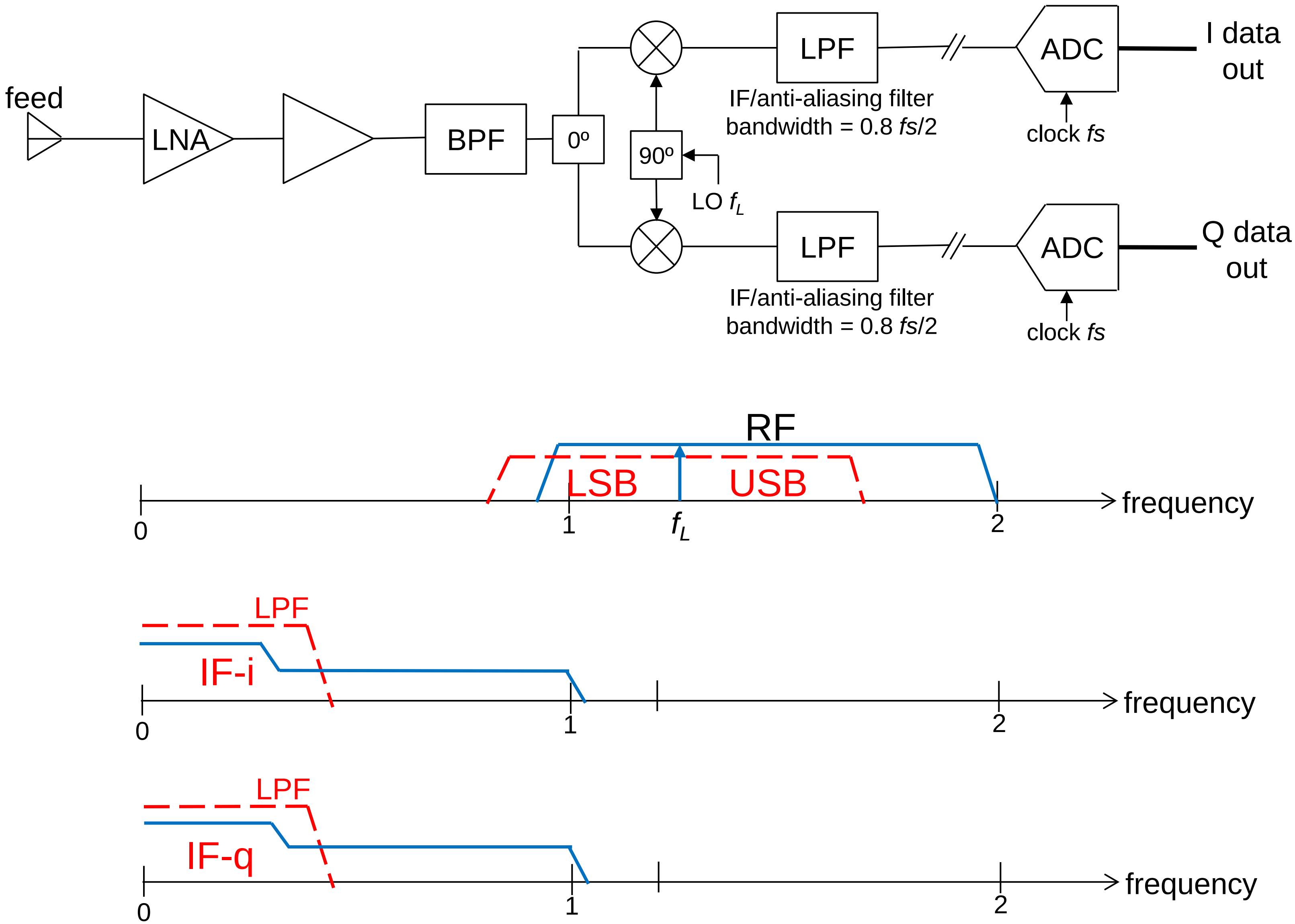
Single Sideband Down-Conversion



If the RF bandwidth ratio is >2 (1 octave)...



Double Sideband (IQ) Down-Conversion



How much *instantaneous* bandwidth?

- The maximum instantaneous bandwidth is that of the front end (feed/LNA assembly).
- The maximum bandwidth per digitized channel is set by ADC technology. Multiple channels are possible, but that increases complexity and cost.
- Cost of signal transmission and signal processing (correlation) are proportional to *total* instantaneous bandwidth (all channels)
- What is actually needed for science goals?
  - Do we need to process the full bandwidth of each front end (up to 46 GHz) all at once?
  - What science is lost if instantaneous bandwidth is limited to 10 GHz, but tunable to anywhere in the band?
  - How about 5 GHz instantaneous bandwidth? 2.5 GHz?
- Large processed bandwidth implies coarse spectral resolution
  - Otherwise the correlator output rate is too high

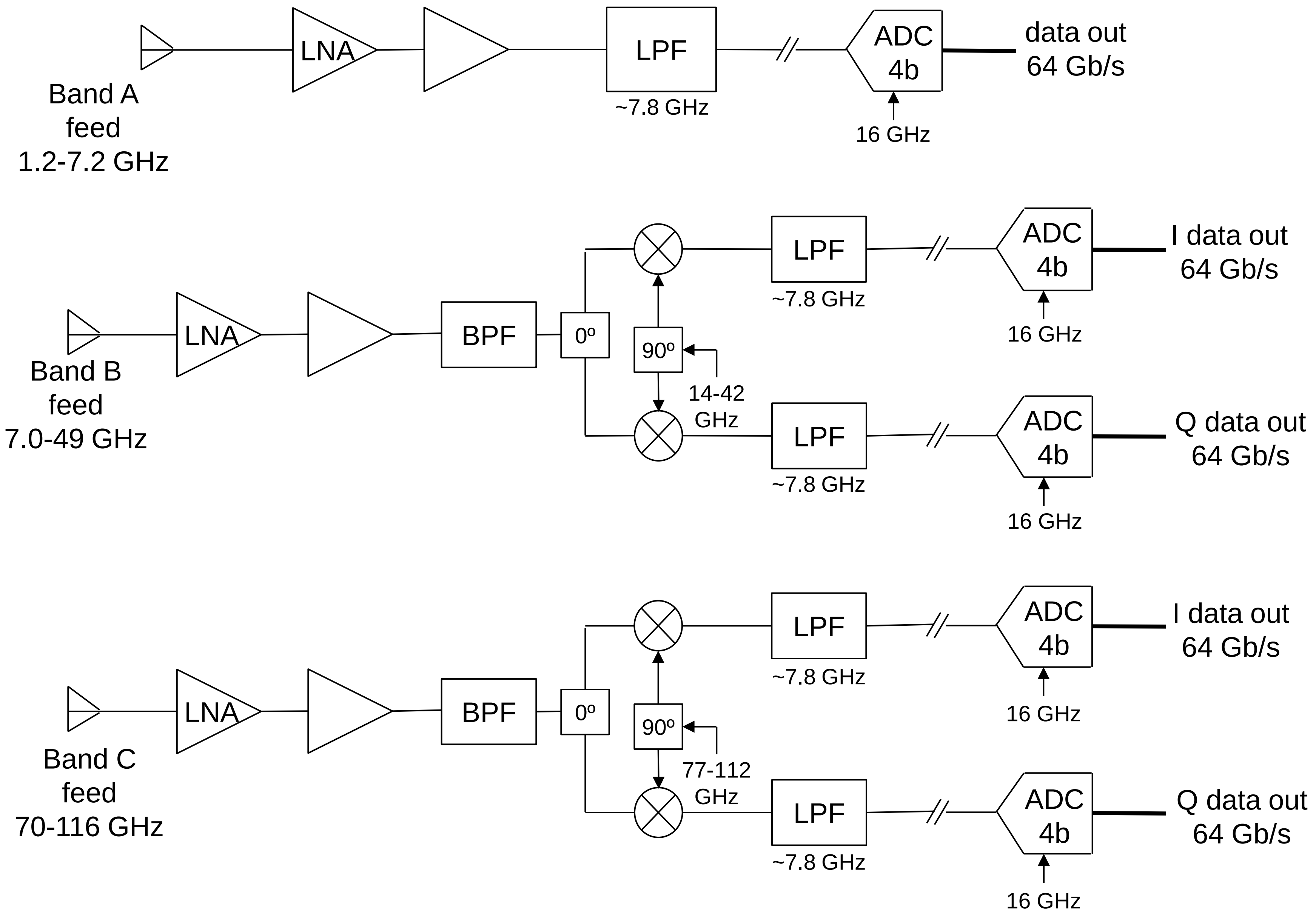
Proposed Arrangement

- Band A
  - 1.2 – 7.2 GHz, 6.0:1, 6.0 GHz useful bandwidth
  - Direct digitization at 16 GHz sampling rate (0 – 8 GHz Nyquist)
  - Single channel
- Band B
  - 7.0 – 49.0 GHz, 7.0:1, 42.0 GHz range
  - IQ downconverter, tunable over RF range, 0 – 7.2 GHz useful IF
  - Digitize each IF at 16 GHz sampling rate (0 – 8 GHz Nyquist)
  - Instantaneous bandwidth 14.4 GHz (USB + LSB)
- Band C
  - 70 – 116 GHz, 1.66:1, 46 GHz range
  - IQ downconverter, tunable over RF range, 0 – 7.2 GHz useful IF
  - Digitize each IF at 16 GHz sampling rate (0 – 8 GHz Nyquist)
  - Instantaneous bandwidth 14.4 GHz (USB + LSB)

All digitizers and all channels identical at 16 GSa/s, regardless of band.

Correlator for 16 GHz bandwidth needed; half unused for band A.

Proposed Arrangement (each polarization)



Dynamic Range, or how many bits?

f1	f2	sqrt(f1*f2)	Tsys	kTB	Ae (0dBi)	Pi(10km)	Pi(1000km)
GHz	GHz	GHz	K	W	m^2	W	W
1.2	7.2	2.9394	12	9.936E-13	8.278E-04	3.017E+00	3.017E+04
7	21	12.1244	15	2.981E-12	4.865E-05	1.540E+02	1.540E+06
35	49	41.4126	30	5.962E-12	4.170E-06	3.593E+03	3.593E+07
70	84	76.6812	40	7.949E-12	1.216E-06	1.642E+04	1.642E+08
100	116	107.7033	50	9.936E-12	6.165E-07	4.050E+04	4.050E+08

+3dB

Pi is the EIRP needed at the given distance to produce 3 dB increase in total power over the system noise.

Conclusion: 3 to 5 bits of quantization are sufficient for all ngVLA bands.

Digitizers: Current and Future

Mfgr	PN	quant.	fs, max	BW	ENOB	@ fs	P	Notes
		bits	GSa/s	GHz	bits	GHz	W	
U Calgary		4	10	NS	3.84	10	0.104	IEEE VLSI Syst, 2014
Adsantek	ASNT7121	4	15	20	3.23	7.8	2.8	
Analog Dev	HMCAD5831	3	26	20	2.9	20	4.2	was Hittite
Micram	ADC30	6	30	20	NS	NS	NS	1 page DS only

In 2022...

- Will industry produce a 4b 20 GSa/s digitizer with good performance?

  -- What is the market for such a thing?

- If not, it is entirely reasonable for the radio astronomy community to develop a custom device. See U of Calgary paper.
  - Y. Xu, L. Belostotski and J.W. Haslett,"A 65nm CMOS 10GS/s 4-bit Background-Calibrated Non-Interleaved Flash ADC For Radio Astronomy," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* , vol. 22, no. 11, pp. 2316-2325, November 2014.

End

Happy Birthday

to

Sandy