NRAO ALMA Correlator Enhancement Proposal

Rich Lacasse and many collaborators

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

Collaborators

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Outline

- Scientific Motivation
  - Observing Efficiency
  - Higher time resolution
- Technical Approach
  - Upgrade as opposed to replace
  - Good "bang for the buck"
- Ripple effects and status

Scientific Motivation

- A ROAD MAP FOR DEVELOPING ALMA, ASAC Recommendations for ALMA 2030, Bolatto et. al. states:

  *"The ability to provide and process **wider instantaneous bandwidths**, together with continuous improvements in receiver sensitivity, can bring **scientifically significant increases in observation speed**. The ultimate goal is to **correlate an entire receiver band in one go**, with no loss of sensitivity. This requires improvements not just to the receivers themselves, but also to the digitizers, the IF transport, **the correlator**, and the archive." …**Doubling the bandwidths of the** digitizers, fiber-optics transmission, **correlator**,*

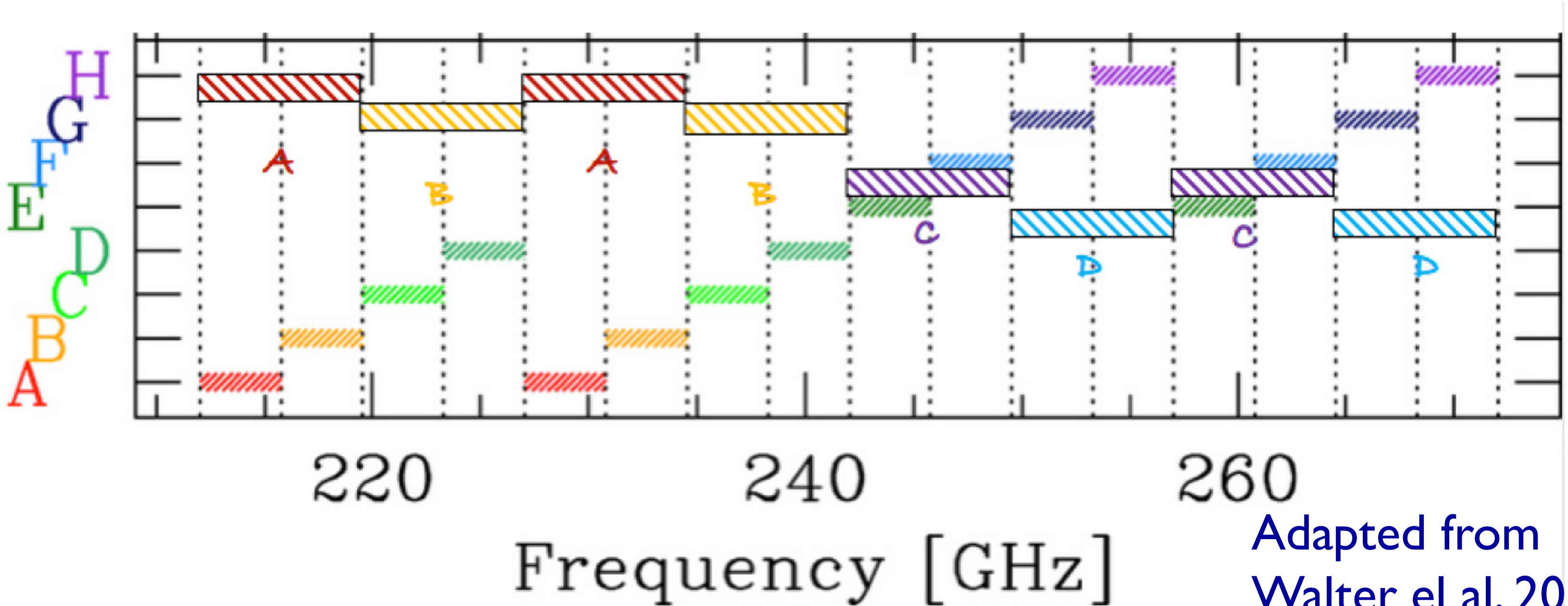
  and archive seem, likewise, eminently possible with current technology.
- Efficiency improvement gained by 4-bit correlation
- There is some interest in higher time resolution (FRBs, pulsars, solar)

Proposal in a Nutshell

- Double the current bandwidth, providing instantaneous coverage of the entire IF band.
- Increase the spectral resolution by a factor of 8
- Increase the time resolution, at least in hardware, by a factor of 16.

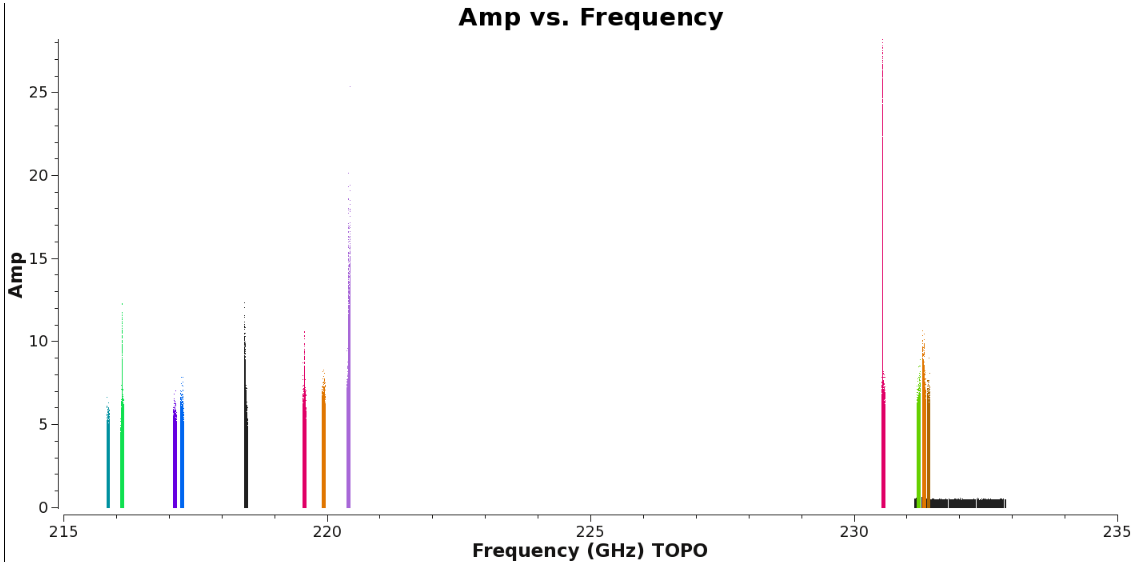
Obvious Advantages

- Root-2 increase in continuum sensitivity
- Factor of 2 increase in spectral survey speed (e.g., Band 6 below)



Adapted from Walter el al, 2016 and Wootten, 2017

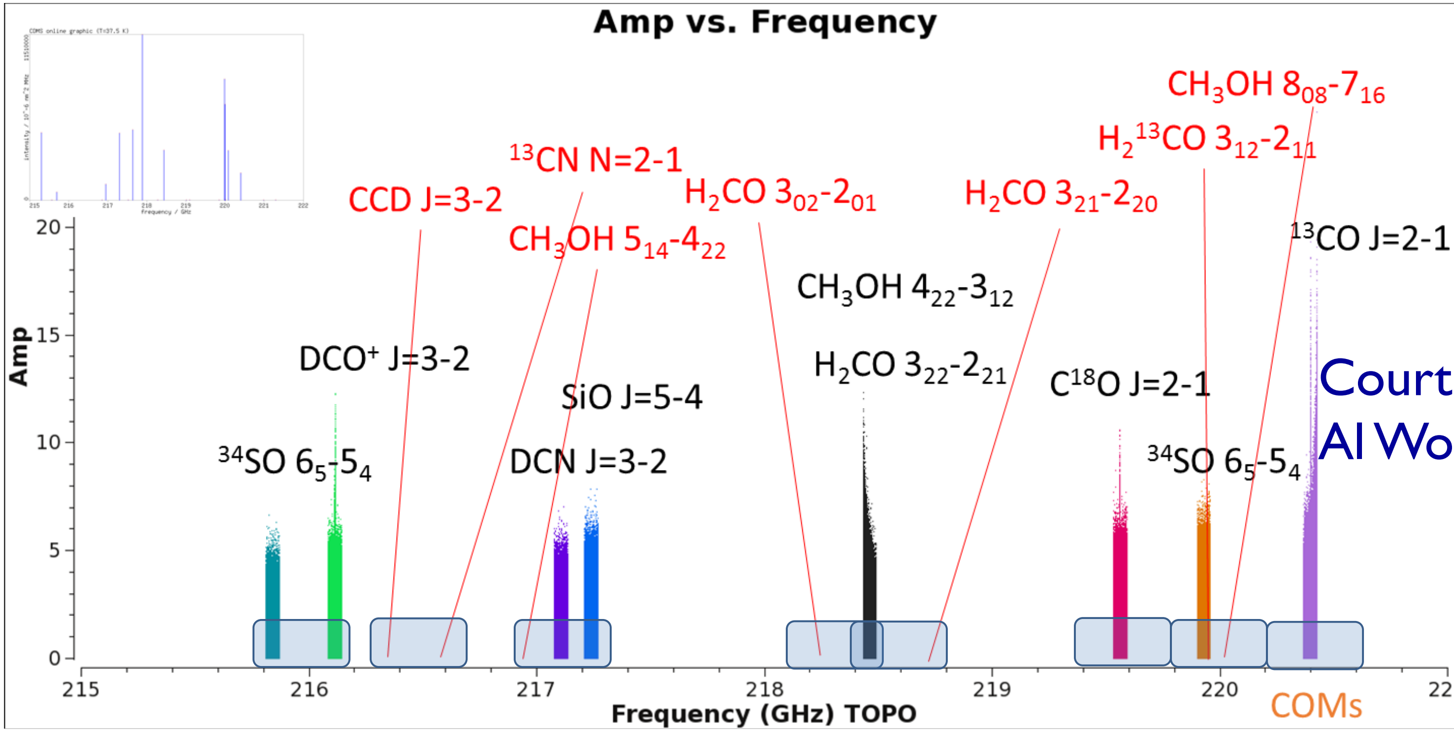
Scientific Motivation – less obvious



Courtesy of Al Wootten

- Typical Correlator Setup, Starved for BW at high resolution
- 12 high resolution 58 MHz windows available (need one low res window for continuum)
- Many ***lines cannot be covered***
- Upgraded correlator provides broader windows at high resolution, in addition to higher resolution across them

Less Obvious Advantage I



Courtesy of Al Wootten

- In Red are important lines that are missed with current correlator
- Upgraded correlator accesses all the missed lines at the current resolution, using wider filters, shown in blue.

Less Obvious Advantage 2

Total Bandwidth	Number of Spectral Points	Spectral Resolution	Correlation	Sample Factor	Minimum dump time[1]	Sensitivity[2]
2 GHz	32768	61 kHz	2-bit x 2-bit	Nyquist	512 msec	0.88
2 GHz	16384	122 kHz	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
2 GHz	8192	244 kHz	4-bit x 4-bit	Nyquist	128 msec	0.99

- At narrower bandwidths, trade-offs to improve sensitivity are possible
- Software for twice-nyquist and 4x4-bit correlation is currently unavailable, but will be developed in parallel with the upgrade.

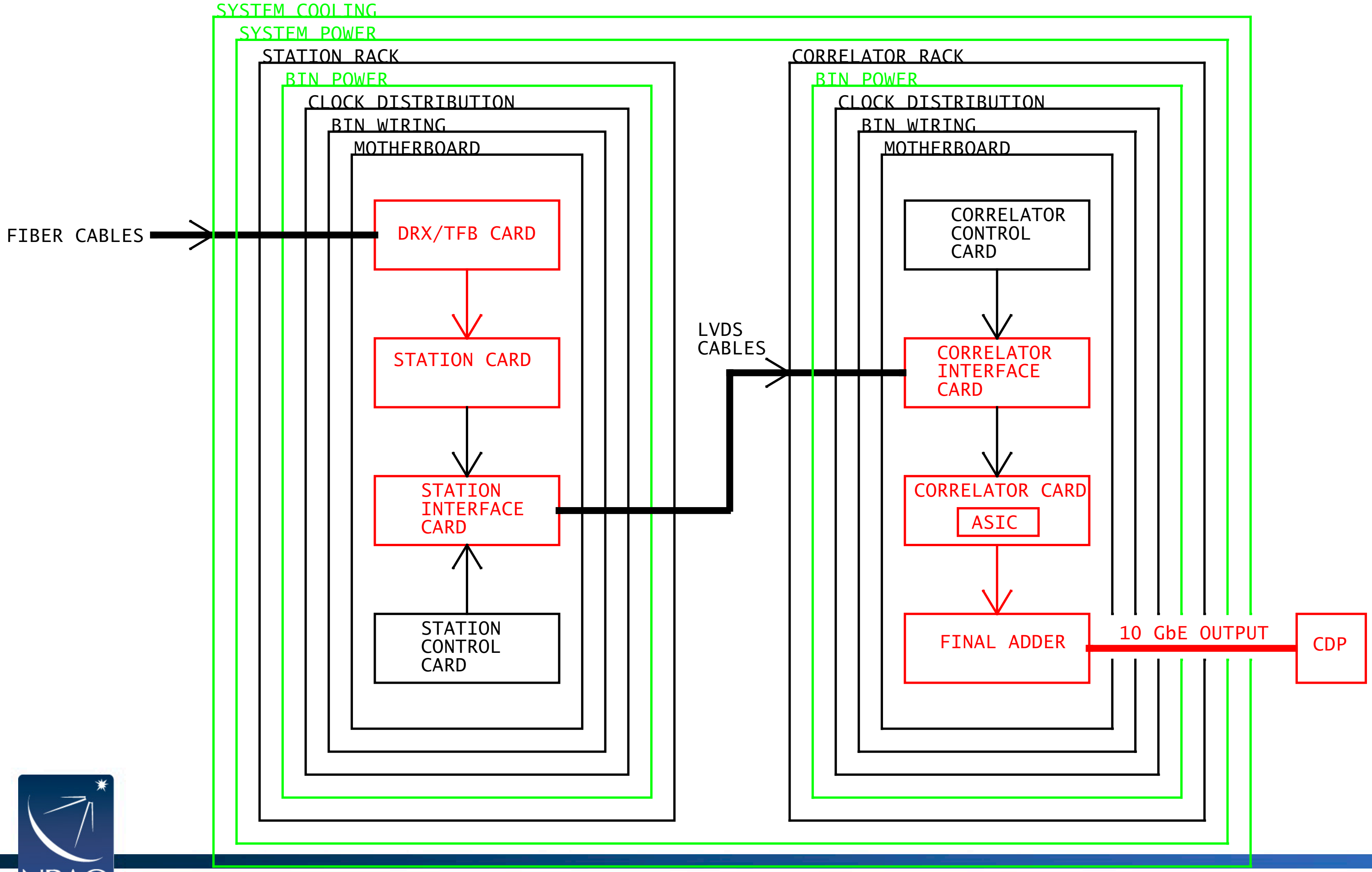
Technical Approach

- The ALMA Correlator design was begun around the year 2000.
- In the intervening years, technology has progressed significantly (surprise!)
- A group in North America and Europe recently completed a study project focused on upgrading the correlator
  - Approach: upgrade the ***existing*** infrastructure
  - Conclusion: It is a doable project
- The study project has led to an ALMA development proposal
  - Still being evaluated
  - Will concentrate on the technical approach and interfaces, which is what is of interest here

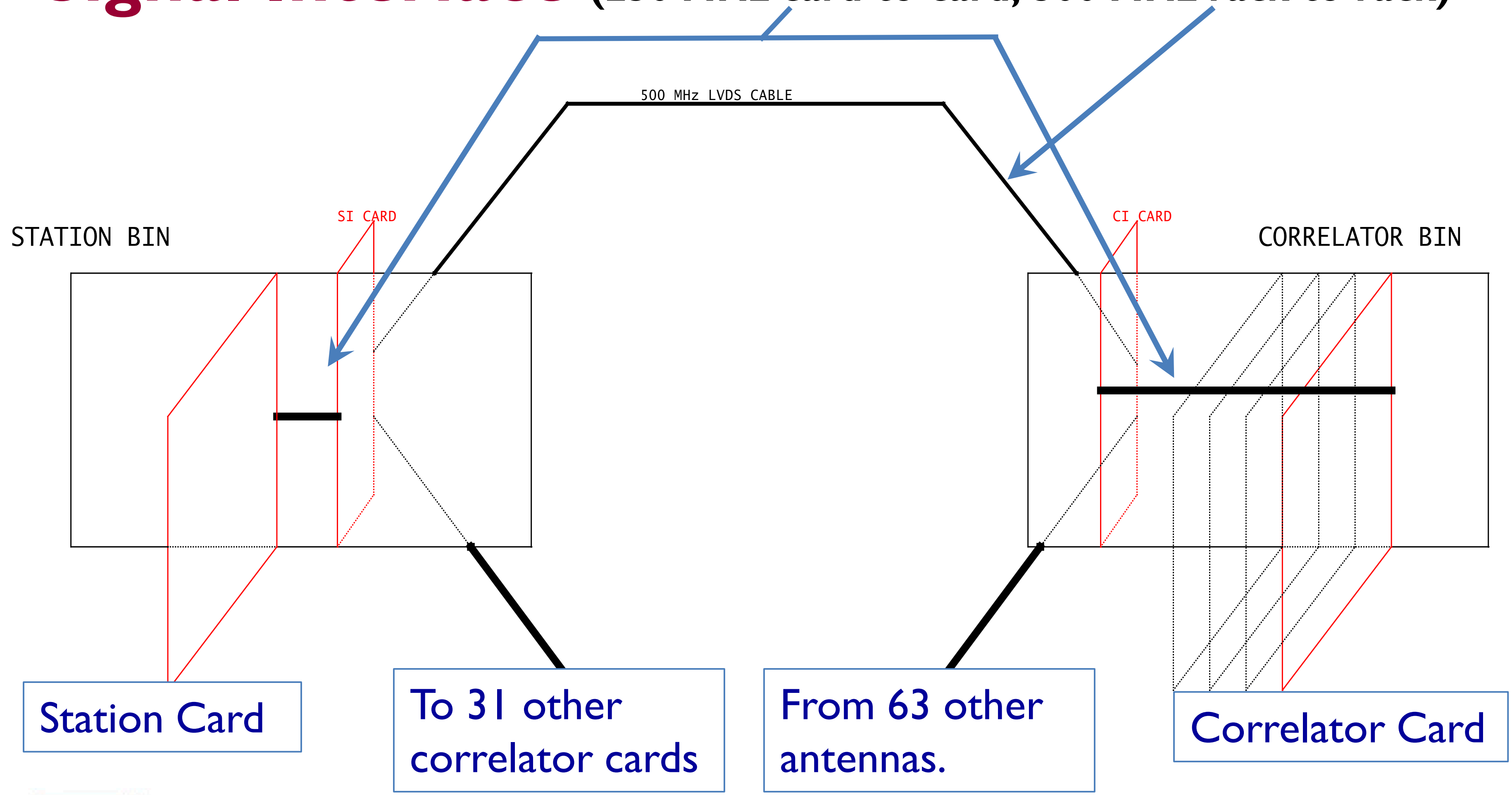
Correlator Configuration:

Station Bins, Correlator Bins, Computers

Block Diagram (black existing, red new, green reduction)



Signal Interface (250 MHz card-to-card, 500 MHz rack-to-rack)



Key External Interface Requirements

Sample Rate

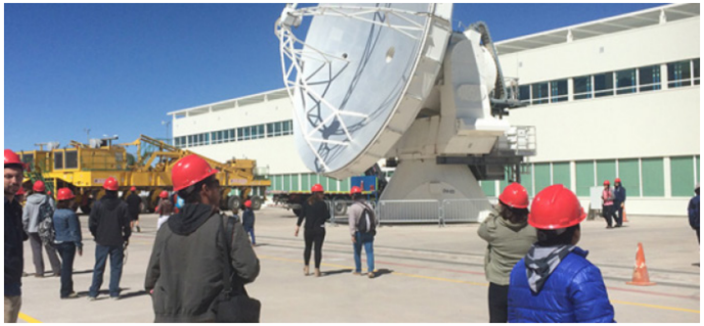
- Currently 4 Gs/s, 3-bit
- **Improve to 8 Gs/s, 3 or 4-bit**
  - Note that correlator design has 2, 3 and 4 bit modes
  - The new 4-bit modes will have better spectral resolution than the current 2-bit modes (not available for all bandwidths)

Output Data Rate

- Flexible: data can be time or spectral averaged to accommodate required data rates.
- Currently <= 60 MB/s peak, 6 MB/s average
- **500 MB/s average or more is possible.**

System Test Approach

- Goal is to minimize disruption to a very busy observatory
- System Test in Charlottesville using
  - "5th Quadrant"
  - Pseudo-random data sources
  - Production software with very few modifications
- System Test at the OSF
  - "5th Quadrant
  - Real-world signal chain
  - Production software



Ripple Effects

Anti-Aliasing Filter

- Filter in front of the sampler and associated electronics

Samplers and Data Transmission

- Discussed later in this session!

Software in other systems:

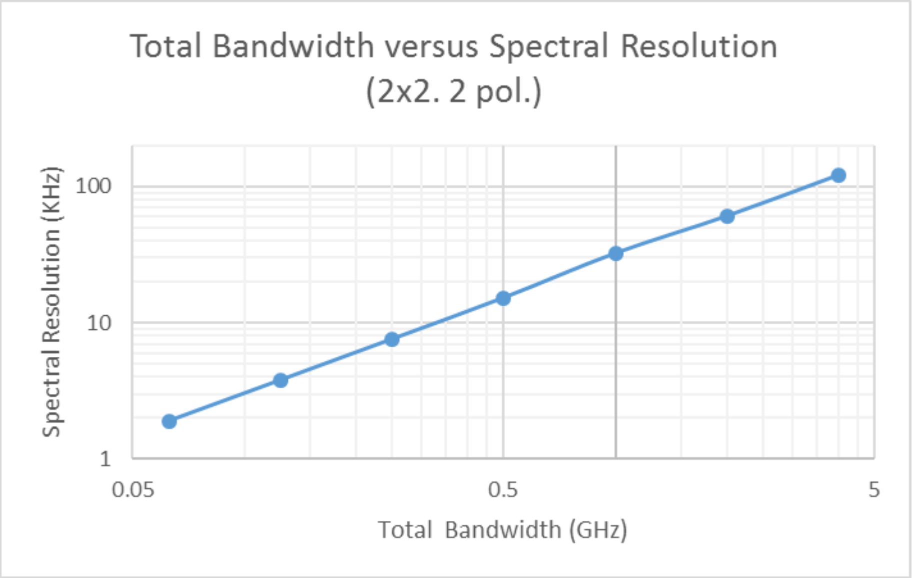
- M&C for Front End and Back End (bandwidth)
- Telescope Calibration (TELCAL, 8X # points)
- Observing Tool (all new capabilities)
- Data transmission between systems (hardware and software)
- Data analysis (CASA, calibration, 8X # points, BW)

What It Does Not Do

Correlation Resolution Limitations

- Widest bandwidths are still 2-bit x 2-bit resolution
- 4x4-bit correlation is possible only at narrower bandwidths
- Does not quite get to 1 KHz resolution in dual-pol modes

Correlator still trades spectral resolution for bandwidth.



Summary

- ALMA2030 vision calls for doubling the bandwidth
- Our proposed design does this and improves spectral and time resolution.
- We feel that our design accomplishes that with
  - Minimum disruption
  - Minimum effort
  - Minimum cost -
  - Minimum risk
  - Fast time to operation
- Awaiting approval…

Thanks… and Questions?

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Backup slides

Single-pol modes

Mode #	Number of sub-channel filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity resolution at 230 GHz	Correlation	Sample Factor	Minimum dump time[1]	Sensitivity[2]
1	32	4 GHz	65536	61 kHz	0.08 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
19	32	4 GHz	32768	122 kHz	0.16 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
38	32	4 GHz	16384	244 kHz	0.64 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
2	16	2 GHz	65536	30.5 kHz	0.04 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
20	16	2 GHz	32768	61 kHz	0.08 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
39	16	2 GHz	16384	122 kHz	0.16 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
53	16	2 GHz	8192	244 kHz	0.64 km/s	4-bit x 4-bit	Twice Nyquist	64msec	0.99
3	8	1 GHz	65536	15.3 kHz	0.02 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
21	8	1 GHz	32768	30.5 kHz	0.04 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
40	8	1 GHz	16384	61 kHz	0.08 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
54	8	1 GHz	8192	122 kHz	0.16 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
4	4	500 MHz	65536	7.5 kHz	0.01 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
22	4	500 MHz	32768	15.3 kHz	0.02 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
41	4	500 MHz	16384	30.5 kHz	0.04 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
55	4	500 MHz	8192	61 kHz	0.08 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
5	2	250 MHz	65536	3.75 kHz	0.005 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
23	2	250 MHz	32768	7.5 kHz	0.01 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
42	2	250 MHz	16384	15.3 kHz	0.02 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
56	2	250 MHz	8192	30.5 kHz	0.04 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
6	1	125 MHz	65536	1.9 kHz	0.0025 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
24	1	125 MHz	32768	3.75 kHz	0.005 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
43	1	125 MHz	16384	7.5 kHz	0.01 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
57	1	125 MHz	8192	15.3 kHz	0.02 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
25	1	62.5 MHz	65536	0.95 kHz	0.00125 km/s	2-bit x 2-bit	Twice Nyquist	512 msec	0.94
58	1	62.5 MHz	16384	3.75 kHz	0.005 km/s	4-bit x 4-bit	Twice Nyquist	128 msec	0.99
68	Time Division Mode	4 GHz	512	7.8125 MHz	10.2 km/s	3-bit x 3-bit	Nyquist	16 msec	1.00
71	Time Division Mode	4 GHz	512[3]	7.8125 MHz	10.2 km/s	2-bit x 2-bit	Nyquist	16 msec	0.88

Dual-pol modes

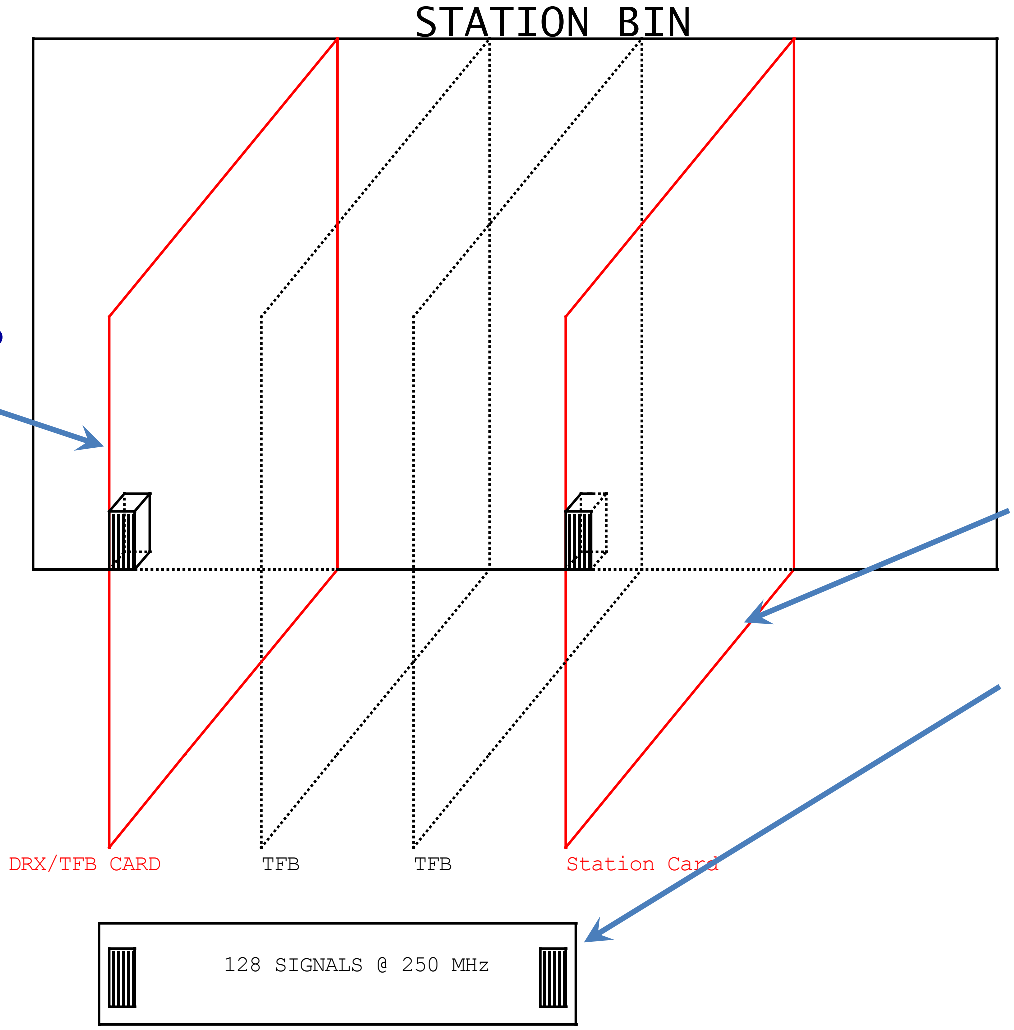
Mode #	Number of sub-channel filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity resolution at 230 GHz	Correlation	Sample Factor	Minimum dump time[1]	Sensitivity[2]
7	32	4 GHz	32768	122 kHz	0.16 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
8	16	2 GHz	32768	61 kHz	0.08 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
26	16	2 GHz	16384	122 kHz	0.16 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
44	16	2 GHz	8192	244 kHz	0.32 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
9	8	1 GHz	32768	61 kHz	0.04 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
27	8	1 GHz	16384	122 kHz	0.08 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
45	8	1 GHz	8192	244 kHz	0.16 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
59	8	1 GHz	4096	244 kHz	0.32 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
10	4	500 MHz	32768	15.3 kHz	0.02 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
28	4	500 MHz	16384	30.5 kHz	0.04 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
46	4	500 MHz	8192	61 kHz	0.08 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
60	4	500 MHz	4096	122 kHz	0.16 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
11	2	250 MHz	32768	7.6 kHz	0.01 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
29	2	250 MHz	16384	15.3 kHz	0.02 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
47	2	250 MHz	8192	30.5 kHz	0.04 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
61	2	250 MHz	4096	61 kHz	0.08 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
12	1	125 MHz	32768	3.8 kHz	0.005 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
30	1	125 MHz	16384	7.6 kHz	0.01 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
48	1	125 MHz	8192	15.3 kHz	0.02 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
62	1	125 MHz	4096	30.5 kHz	0.04 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
31	1	62.5 MHz	32768	1.9 kHz	0.0025 km/s	2-bit x 2-bit	Twice Nyquist	512 msec	0.94
63	1	62.5 MHz	8192	7.6 kHz	0.01 km/s	4-bit x 4-bit	Twice Nyquist	128 msec	0.99
69	Time Division Mode	4 GHz	512[3]	7.8 MHz	10.2 km/s	2-bit x 2-bit	Nyquist	16 msec	0.88

Cross-pol modes

Mode #	Number of sub-channel filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity resolution at 230 GHz	Correlation	Sample Factor	Minimum dump time[1]	Sensitivity[2]
13	32	4 GHz	16384	244 kHz	0.32 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
72[3]	32	2 GHz[3]	16384	122 KHz	0.16 km/s	2-bit x 2-bit	Twice Nyquist	512 msec	0.94
14	16	2 GHz	16384	122 kHz	0.16 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
32	16	2 GHz	8192	244 kHz	0.32 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
15	8	1 GHz	16384	61 kHz	0.08 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
33	8	1 GHz	8192	122 kHz	0.16 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
16	4	500 MHz	16384	30.5 kHz	0.04 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
34	4	500 MHz	8192	61 kHz	0.08 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
17	2	250 MHz	16384	15.3 kHz	0.02 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
35	2	250 MHz	8192	30.5 kHz	0.04 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
51	2	250 MHz	4096	61 kHz	0.08 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
18	1	125 MHz	16384	7.6 kHz	0.01 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
36	1	125 MHz	8192	15.3 kHz	0.02 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
52	1	125 MHz	4096	30.5 kHz	0.04 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
66	1	125 MHz	2048	61 kHz	0.08 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
37	1	62.5 MHz	16385	3.8 kHz	0.005 km/s	2-bit x 2-bit	Twice Nyquist	512 msec	0.94
67	1	62.5 MHz	4096	15.3 kHz	0.02 km/s	4-bit x 4-bit	Twice Nyquist	128 msec	0.99
70	Time Division Mode	4 GHz	512	7.8 MHz	10.2 km/s	2-bit x 2-bit	Nyquist	32 msec	0.88

Implementation Details – Station Bin

DRX and TFB functions absorbed into one card



DRX/TFB to Station Card interconnect via rigid-flex board.

Major concerns, minor concerns (in my opinion, anyway)

- ASIC cost (especially if we need to re-spin the chip)
- Non-correlator upgrades to ALMA needed
- Amount of control card firmware required

- System installation/testing
- Rack-to-rack LVDS interface
- ASIC power dissipation