ALMA Correlator Enhancement

Study Project Status

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

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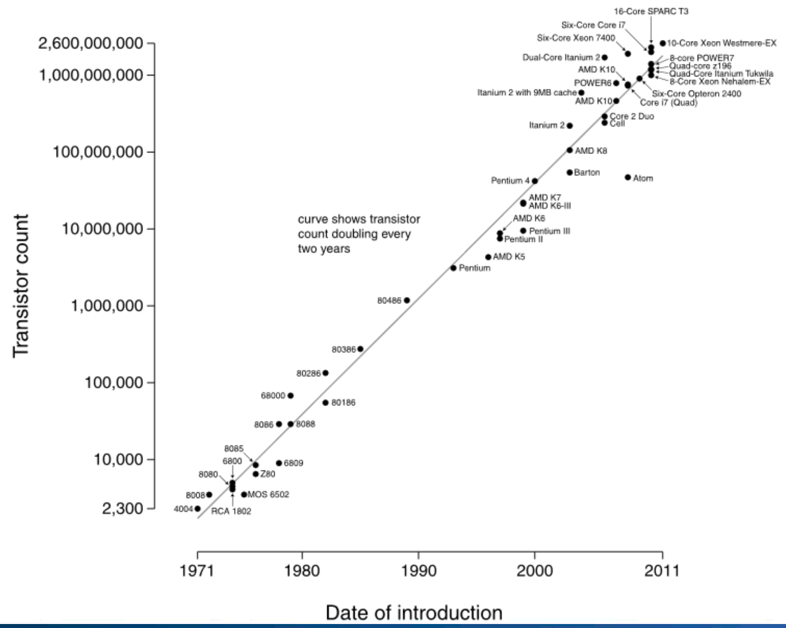
Outline

- Motivation
- Short technical description
- Summary of performance gains
- Cost/schedule guesstimates

Motivation

- Improve ALMA's science productivity
- Technology has evolved
  - Over a decade since hardware was designed
  - Order of magnitude improvement possible without major disruption??
  - Moore's Law

Microprocessor Transistor Counts 1971-2011 & Moore's Law



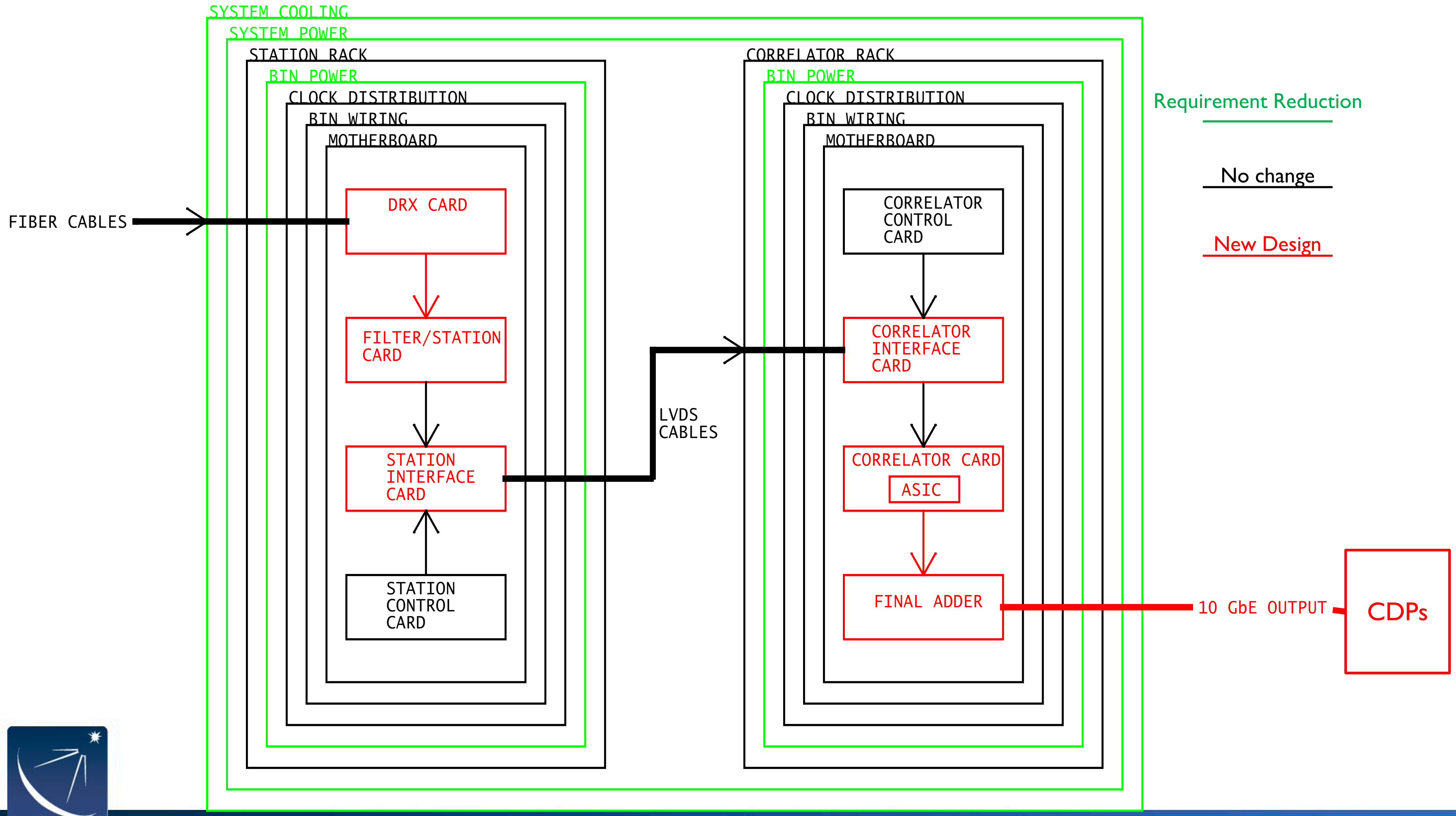
Purpose of the Study Project

See if the following is possible and, if so, at what cost:

- **Bandwidth** can be doubled by doubling the data rate
- **Resolution** can be enhanced by replacing custom correlator Application Specific Integrated Circuit (ASIC)
- Both of these improvements imply a redesign of the circuit boards in the data path but no change in infrastructure.

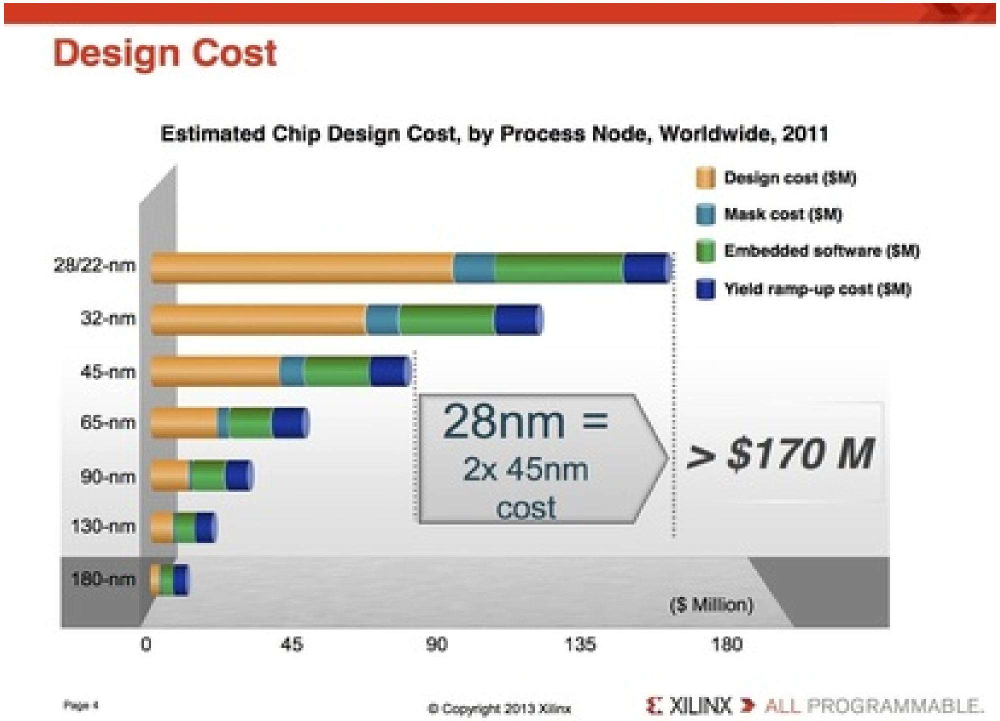
Design Approach:

Change as little as possible (hardware and software)



ASIC Design Tradeoffs
(Application Specific Integrated Circuit)

- The ASIC cost dominates the project
- Finer geometry results in smaller die size, lower power but higher cost.
- Cost versus design node:

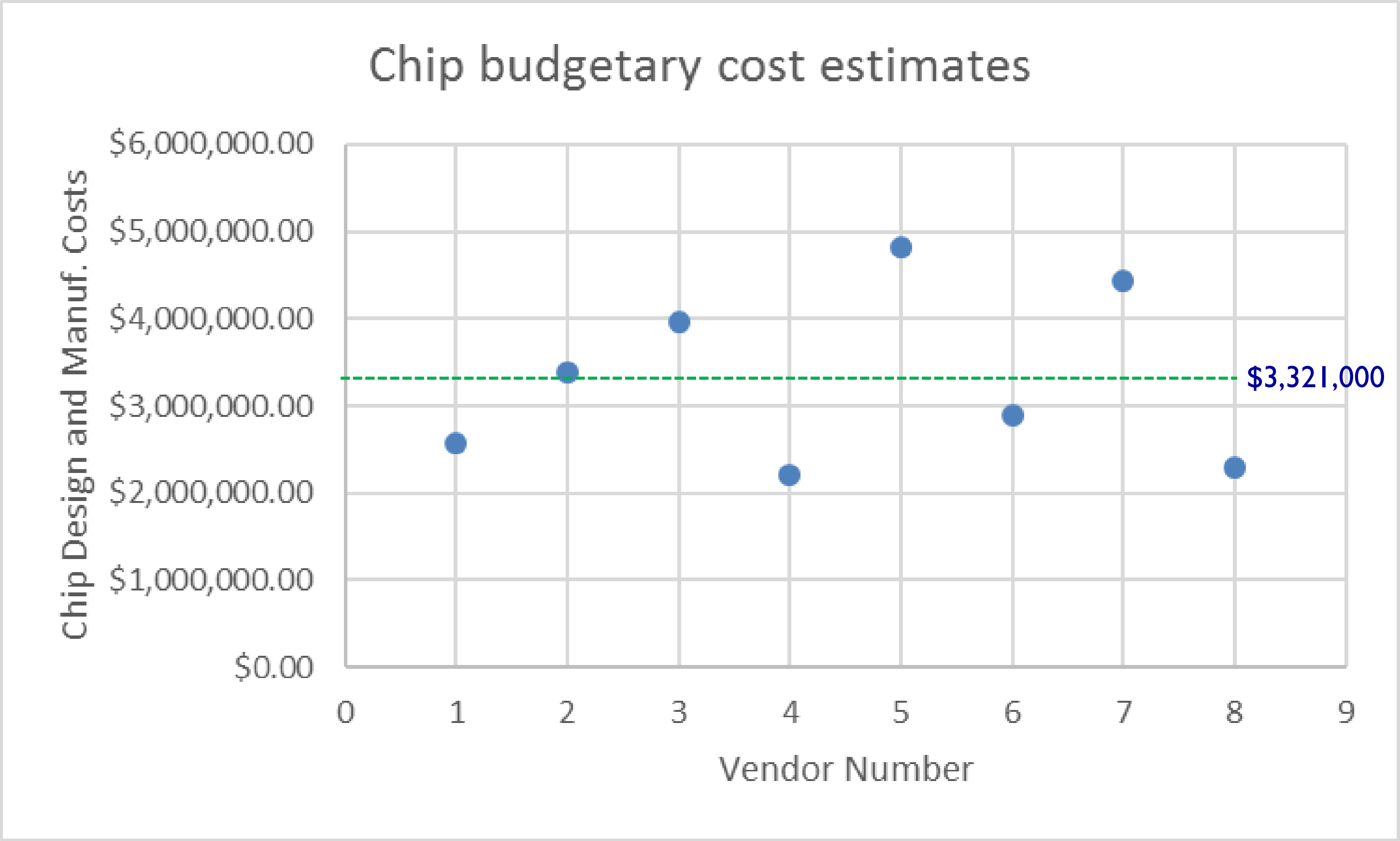


(source: EE Times web blog, FPGA as ASIC alternative, April 21, 2014)

Some Technical Details - finding the ASIC "sweet spot"

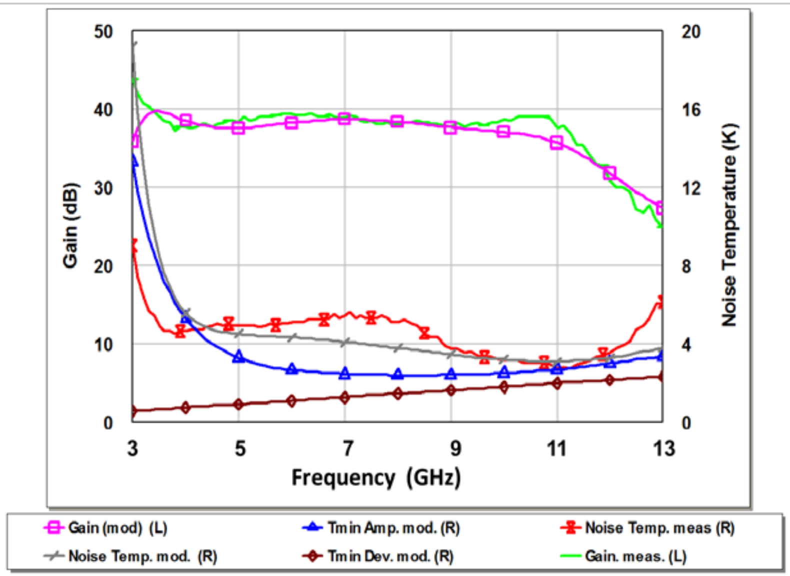
- We have investigated the use of Field Programmable Gate Arrays (FPGAs), commercial off-the-shelf products, for this application and found that they are too power-hungry and very costly. Our design is "flip-flop" intensive and most FPGAs do no have enough flip-flops.
- We have designed and simulated the ASIC using the language VHDL.
- We have provided this design to and discussed it with several chip design companies
- Eight ASIC design companies have provided budgetary estimates for the design and manufacture of 10,000 packaged chips.

Some Technical Details
- finding the ASIC "sweet spot", cont'd

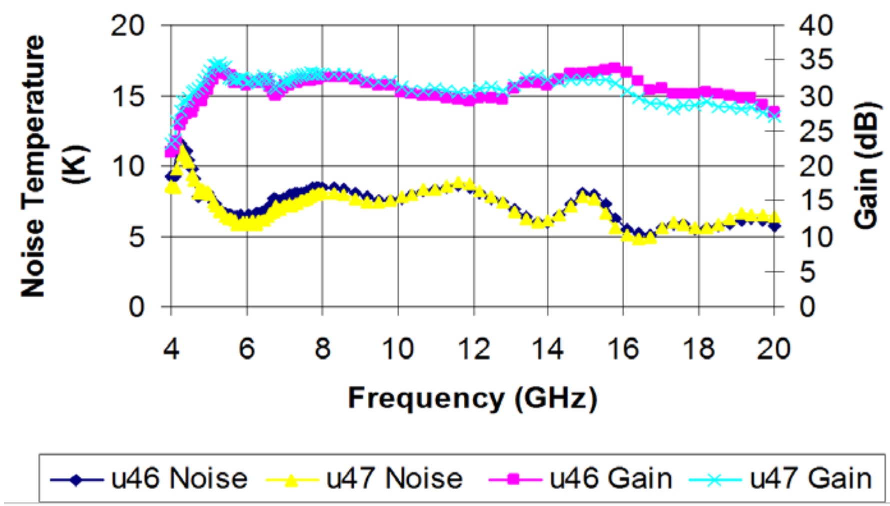


The Bandwidth Sweet-Spot

- Our goal is to match the existing ALMA IF bandwidth, 8 GHz USB and LSB, dual polarization (32 GHz processed bandwidth total)
- For many applications this bandwidth is optimal because wider bandwidth raises the noise floor.



4 – 12 GHz



5 – 20 GHz

The Extra Noise is Amplified!

Longer observation times for typical projects

- Typical SIS mixer conversion losses range from factors of 3 to 10 depending on the band.
- A 3°K increase in an IF amplifier following the mixer results in a receiver temperature increase of 9 to 30 K.
- We believe the "sweet spot" is matching the current ALMA IF bandwidth (8GHz).
- Continuum observations and spectral line searches benefit from wider bandwidth.
- Fixed bandwidth spectral line observations (very typical of ALMA case), however, take *longer* with a wider band receiver.
- So, it's a trade-off: what bandwidth provides the greatest amount of science, integrated over all types of projects?

Astronomical Benefits to ALMA

- Increased spectral grasp at any given resolution (8x # points)
- Improved efficiency and coverage for spectral surveys (2X BW)
- Improved high spectral resolution (7.6 KHz to 1.9 KHz @ 62.5 MHz BW)
- Increased sensitivity through improved availability of higher-bit modes (4x4 versus 2x2, discussed in next slide)
- Improved temporal resolution (to 1 msec on cross correlation as compared to 16 msec currently)

Mode Table Changes

Table 3: Mode chart with two baseband channels per quadrant processed with no polarization cross products.

Mode #	Number of filters	Total Bandwidth Per IF input Current/Proposed	Number of Spectral Points Current/Proposed	Spectral Resolution Current/Proposed	Correlation	Sample Factor	Sensitivity (/0.96)
7	32	2/4 GHz	4096/32768	488/122 kHz	2-bit x 2-bit	Nyquist	0.88
8	16	1/2 GHz	4096/32768	244/61 kHz	2-bit x 2-bit	Nyquist	0.88
26	16	1/2 GHz	2048/16384	488/122 kHz	2-bit x 2-bit	Twice Nyquist	0.94
44	16	1/2 GHz	1024/8192	976/244 kHz	4-bit x 4-bit	Nyquist	0.99
9	8	0.5/1 GHz	4096/32768	122/30.5 kHz	2-bit x 2-bit	Nyquist	0.88
27	8	0.5/1 GHz	2048/16384	244/61 kHz	2-bit x 2-bit	Twice Nyquist	0.94
45	8	0.5/1 GHz	1024/8192	488/122 kHz	4-bit x 4-bit	Nyquist	0.99
59	8	0.5/1 GHz	512/4096	976/244 kHz	4-bit x 4-bit	Twice Nyquist	0.99
10	4	250/500 MHz	4096/32768	61/15.3 kHz	2-bit x 2-bit	Nyquist	0.88
28	4	250/500 MHz	2048/16384	122/30.5 kHz	2-bit x 2-bit	Twice Nyquist	0.94
46	4	250/500 MHz	1024/8192	244/61 kHz	4-bit x 4-bit	Nyquist	0.99
60	4	250/500 MHz	512/4096	488/122 kHz	4-bit x 4-bit	Twice Nyquist	0.99
11	2	125/250 MHz	4096/32768	30/7.5 kHz	2-bit x 2-bit	Nyquist	0.88
29	2	125/250 MHz	2048/16384	61/15.3 kHz	2-bit x 2-bit	Twice Nyquist	0.94
47	2	125/250 MHz	1024/8192	122/30.5 kHz	4-bit x 4-bit	Nyquist	0.99
61	2	125/250 MHz	512/4096	244/61 kHz	4-bit x 4-bit	Twice Nyquist	0.99
12	1	62.5/125 MHz	4096/32768	15/3.8 kHz	2-bit x 2-bit	Nyquist	0.88
30	1	62.5/125 MHz	2048/16384	30/7.5 kHz	2-bit x 2-bit	Twice Nyquist	0.94
48	1	62.5/125 MHz	1024/8192	61/15.3 kHz	4-bit x 4-bit	Nyquist	0.99
62	1	62.5/125 MHz	512/4096	122/30.5 kHz	4-bit x 4-bit	Twice Nyquist	0.99
31	1	31.25/62.5 MHz	4096/32768	7.6/1.9 kHz	2-bit x 2-bit	Twice Nyquist	0.94
63	1	31.25/62.5 MHz	2048/16384	30/7.5 kHz	4-bit x 4-bit	Twice Nyquist	0.99
69	Time Division Mode	2/4 GHz	128/1024	15.6/3.9 MHz	2-bit x 2-bit	Nyquist	0.88

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Performance enhancements

Time resolution

- The current implementation has time resolution of 1 msec for auto products and 16 msec for cross-products.
- The addition of RAM to the correlator chip makes it possible to trade time resolution for spectral resolution on auto and cross-products, a new feature (**is this useful??**):

Time Resolution (msec)	Spectral Points (per baseband)
1	512
2	1024
4	1024
8	2048
16	4096
32	8192
64	16384
128	32768
256	65536
512	65536
1024	65536

Astronomical Benefits to ALMA, e.g.

(3) Since a larger swath of spectrum may be observed in this example spectral scan, the calibration overhead is cut, thus further improving efficiency—only one bandpass calibration need be made per spectral setting, rather than several.

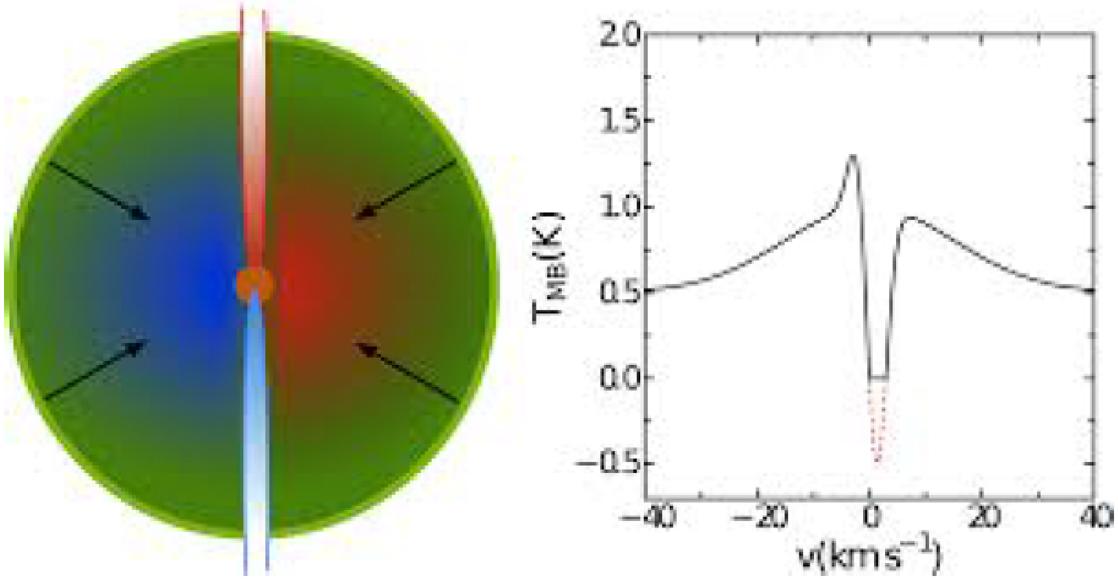

Figure 1 Schematic of a cold molecular core collapsing to form a star. As seen against the core, material falling onto the core, moving away along the line of sight, absorbs radiation from the core itself, resulting in a suppressed redshifted wing on the line.

Impact on ALMA Operations

- From the hardware and facilities points of view, this upgrade would not be a major perturbation to ALMA operations…
  - There are significant challenges in chip, firmware, and software design and test, but these can mostly be done off-line.
  - No racks to rip out
  - No change in power and clock distribution
  - No change in cooling requirements
  - No change in CLO or patch panel
  - From the hardware point of view, it's mostly a matter of swapping cards and adding some cables.
- The tough issue is dealing with the normal system testing environment
  - Very hard to design a system that looks both like the old correlator and the new correlator.
  - Can we make a clean break by rigorous and thorough testing using a "fifth quadrant?"

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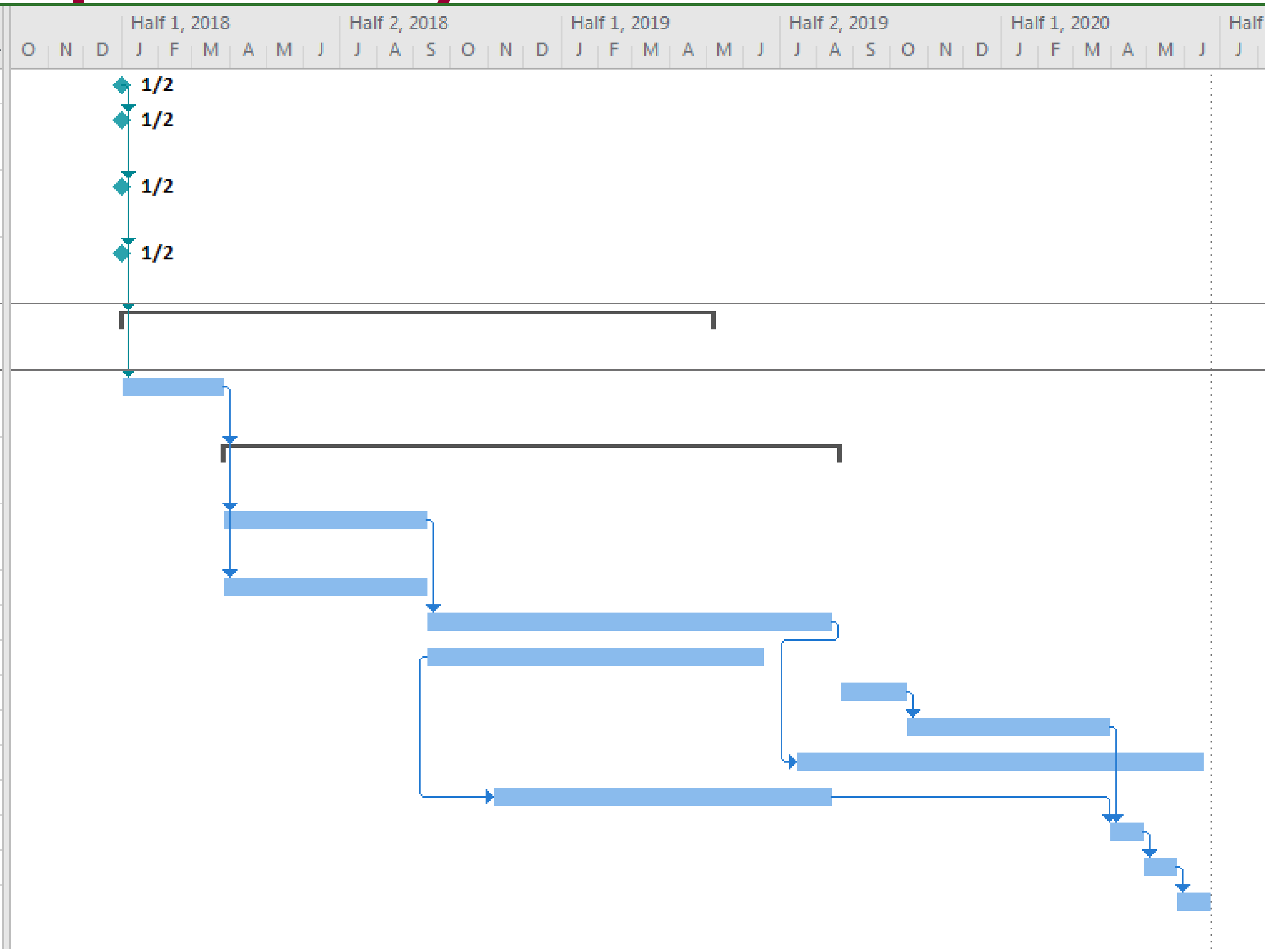
Costs, *preliminary…*

Part	Quantity	Unit cost	Total	Comments
ALMA2 ASIC	11,200	302	3380000	
Correlator Cards	160	1734	277360	
Correlator power card	170	1494	253930	
Station Card	160	2413	386000	
DRX/TFB	150	0	0	ESO deliverable
Stn Interface Cards	160	700	112000	
Corr Interface Cards	610	700	427000	
Final Adder	7	3143	22000	
Cables			10000	
Computers	20	5000	100000	
Test Fixture	1	250000	250000	JAO Collaboration
Misc	1	50000	50000	
Total Parts			**$5,268,290.00**	
Shipping			**$20,000.00**	
Travel			**$50,000.00**	
Labor			**$850,000.00**	
Total			**$6,188,290.00**	
Total with Contingency (15%)			**$7,116,533.50**	
Total with Overhead costs			**TBD**	

Schedule, *preliminary…*

Task Name	Duration
Project start	0 days
Card Designs Complete	0 days
FPA Designs Simulated	0 days
ASIC Simulation Complete	0 days
ALMA2 ASIC Dev. And Prod.	**350 days**
Electronics Bids & Orders	3 mons
Electronics Construction	**365 days**
Test System Construction	6 mons
Low-level software	6 mons
High Level Software	12 mons
Card Test, phase 1	200 days
Card Test, phase 2	40 days
Contingency	6 mons
System Integration	12 mons
System Test, CV	10 mons
System Test, OSF	1 mon
Slack	1 mon
Installation and Test, AOS	1 mon



Issues

- How to make such a big change to ALMA without long downtime?
  - Needs dialog with ALMA
  - One idea:
    - Make use of identical test fixtures in CV and OSF
    - Fixture at OSF is connected to live antennas
    - Rigorous hardware/software testing at both locations
    - ~ 1 month shutdown to transition to new equipment (including samplers) and to commission a few highly used modes.
    - Then interleave commissioning and observing
  - Funding profile (how many dollars, when…) needs work!
  - Use of existing cables (to be tested)

Summary

- We are quite certain that an upgrade of the ALMA correlator is possible using the existing infrastructure (2X bandwidth and 8X resolution).
- We feel that the proposed upgrade hits the sweet spot in terms of cost of the chip at the heart of the design
- We feel that the design's processed bandwidth is optimal
- Good "bridge" to a future software correlator in the mid to late 2020s.
- Further reading:
  - Enhancing the Performance of the 64-antenna ALMA Correlator (Escoffier, Lacasse, Saez, John Webber, Rodrigo Amestica, Alain Baudry) http://library.nrao.edu/public/memos/naasc/NAASC_114.pdf

Backup slides

How does this affect observing time?

Continuum observation case

- What the astronomer cares about is system temperature because this affects how long she has to observe to get a desired SNR.
- $\Delta T/T \sim 1/\text{sqrt}(BW * \tau)$
- => $\Delta T \sim T/\text{sqrt}(BW*\tau)$
- => If you double the bandwidth and the system temperature T increases by less than the square-root of 2 then ΔT is smaller in the double-bandwidth case than the single bandwidth case.
- =>For continuum observations, you are better off observing a given band in 2 pieces if a wider band increases the system temperature by more than 1.4 (continuum sensitivity)

How does this affect observing time?

Continuum case, cont'd

ALMA Band	Bandpass GHz	T_{sys} Now	T_{sys} 16 GHz	Tsys now/ Tsys 16 GHz
3	92-108	70	75?	1.07
4	133-155	80	90	1.13
6	221-265	90	100	1.11
7	283-365	140	155	1.11
8	393-492	500	520	1.04
9	610-712	900	930	1.03

So there is an advantage to wider bandwidth for continuum observations