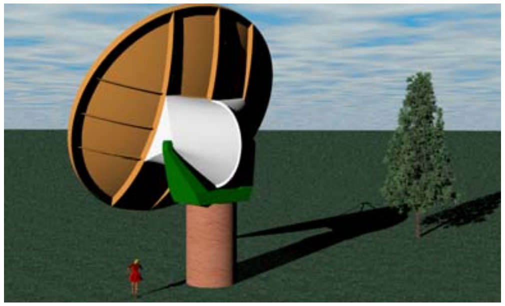
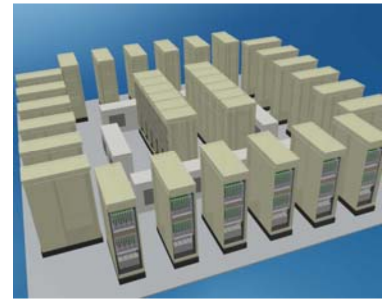
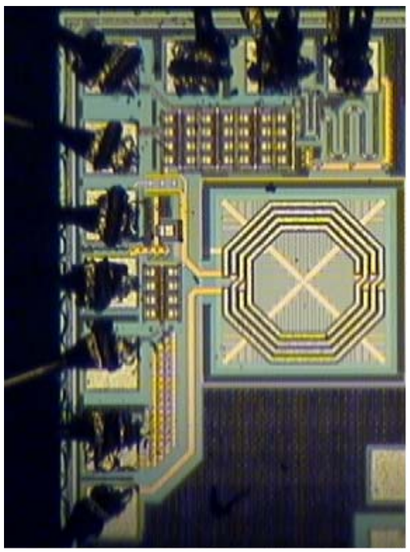




Instrument Requirements and Options for Meeting the Science Opportunities 300-3000 MHz



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National Research Council Canada

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Outline

1. Look at primary influences on survey speed.
   - Are we concentrating on the key technical issues?
2. Costs and prospects for Phased Focal Plane Arrays (PFPA's) to enhance Field of View.
3. A quick look at an HI-line Survey using a variation on the SKA Reference Design.
4. What design to choose if we were allowed to go ahead "now"?
5. Sensible de-scoping thoughts and how to go ahead.

Introductory Remarks

- In this frequency range the US community should be thinking “SKA”.
  - Lower frequencies need a site protected from RFI.
- Important to start soon on SKA or a decade of momentum will be lost.
- Probably need a reassessment of affordability.
  - “Descoping” is likely to be necessary from original SKA specs.
  - This frequency range is likely to yield the best science for $$’s.
- Science in the 300-3000 MHz range:
  - Key science “targets” that can be addressed in this frequency range:
    - Origin and evolution of cosmic magnetism (high dynamic range continuum polarimetry).
    - Galaxy evolution, cosmology, and dark energy (redshifted HI survey).
    - Strong field tests of gravity using pulsars and black holes.
  - Focus on a representative science area for this talk (example HI survey).
- Four critical parameters (A, Tsys, Ω, freq. range)
  - Best frequency range is 300-15GHz, emphasizing reflector infrastructure.

Survey Speed

$$ss = 0.211\left(\frac{4}{\pi}\right)^2\left(\frac{A_{tot}}{T_{sys}}\right)^2 BS_{\min}^2\Omega_{FOV}\left[\frac{\deg^2}{s}\right]$$

$$ss = 161\left(\frac{4}{\pi}\right)^2\left(\frac{A_{tot}}{T_{sys}}\right)^2 BS_{\min}^2\Omega_{FOV}\left[\frac{fractional sky}{year}\right]$$

- A_{tot} in m^2; T_{sys} in K; B in GHz; S_{min} in mJy; Ω_{FOV} in ster.
- This form of equ'n has no dependence on antenna size or λ.
- A, T_{sys} & Ω_{FOV}
  - expensive instrumental parameters.
  - B also an instrumental parameter for continuum observations.
- S_{min}
  - determined by "science".
  - B determined by science for line observations.
- At DRAO our strategy is to concentrate on technology to improve T_{sys}, A_{tot}, and Ω_{FOV}. Others are doing this as well.

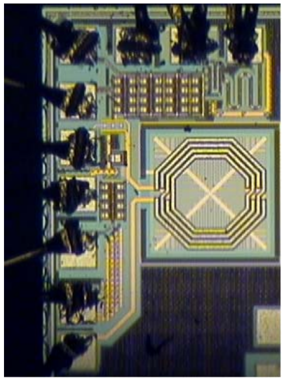
T_{sys}

- Improving room temperature T_{rcvr} is the most cost effective method to improve T_{sys}.
  - High f_T transistors available now in CMOS and SiGe (soon will be widely available).
  - Uncooled LNA's require different design skills from cooled LNA's.
  - LNA cost becomes negligible.
- Uncooled CMOS LNA's can still be improved, SiGe will be better.
  - Underpins assumption of 25K for T_{sys} (T_{rcvr} = 15 K, $T_{spillover}$ = 10K).
- Innovative cooling techniques should continue to be an area of radio astronomy development effort (e.g. ATA work).
- For PFPA's, cooling must be distributed over a wide area or delivered in many "compact cooling packages".

0.35dB (24.5 K) Noise Figure Wideband Room temperature CMOS LNA

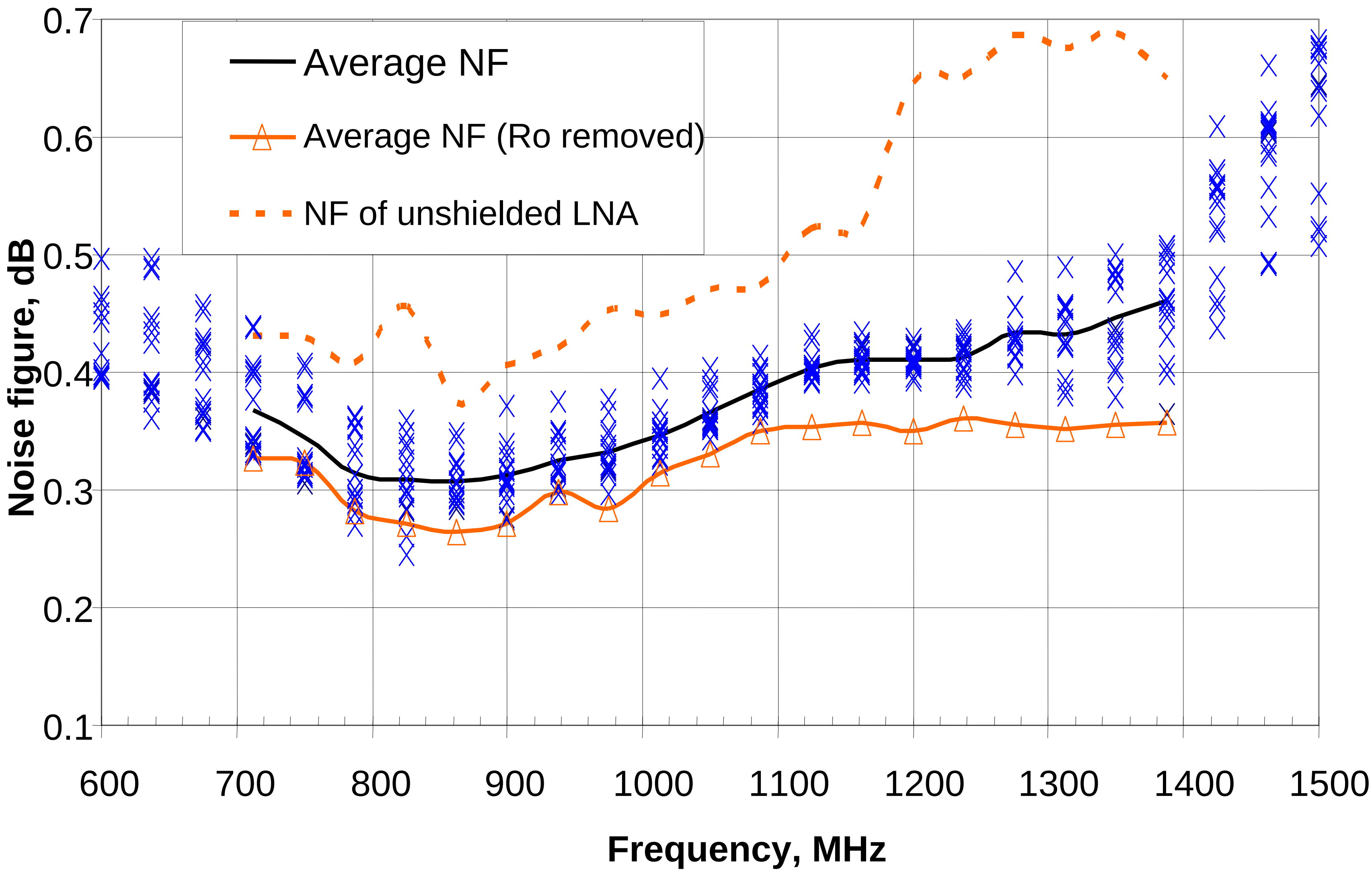
- Frequency: 700MHz-1400MHz
- DC Power: 45mW
- Noise Figure <0.35dB (when noise from output matching network, ie Ro is removed)
- Gain (S21): 20dB to 16dB
- Return Loss: > 15dB
- OIP3: 7.5dBm (1GHz)
- OP1dB: -5.3dBm (1GHz)

- LNA topology was introduced in [1].
- LNA was designed in bulk 90nm CMOS.
- LNA noise figure optimization was performed based on [2].



[1] L. Belostotski, J. W. Haslett, and B. Veidt, "Wide-band CMOS low noise amplifier for applications in radio astronomy," in *IEEE International Symposium on Circuits and Systems*, pp. 1347–1350, May 21-24 2006.
[2] L. Belostotski and J. W. Haslett, "Noise figure optimization of inductively-degenerated CMOS LNA's with integrated gate inductors," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 53, pp. 1409–1422, July 2006.

Noise figure



Collecting Area (A_{tot})

- Antennas are the likely most expensive component of a large parabolic reflector-based array.
  - Exceptions may exist, such as cylinders, for which the cost of data processing might explode to exceed the cost of the antennas.
  - Aperture Arrays are likely to be even more expensive in the 300-3000 MHz freq. range.
- Not much improvement in the cost of parabolic reflectors is gained by “designing” for an arbitrary upper frequency cut-off (e.g. 3 GHz).
  - Important to understand “natural thresholds” of performance as a function of frequency.
  - Wind performance is a key cost driver.
  - Currently 10-15 GHz looks like a natural threshold.
  - 10-m diameter is the smallest “safe” diameter for 300 MHz ($\lambda = 1$ m).
    - Slightly larger diameters should be considered, depending on $/m^2.

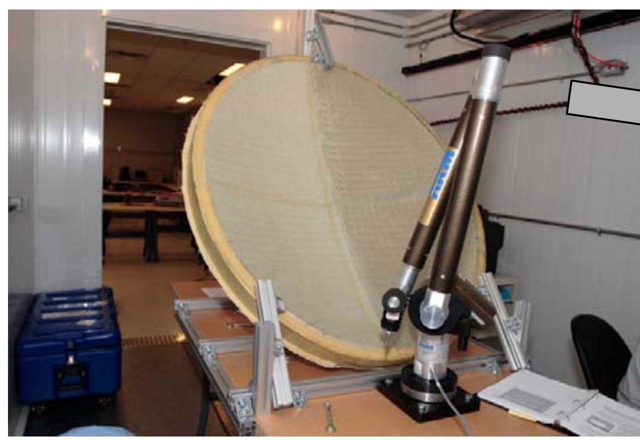
Collecting Area (A_{tot}) (cont'd)

- Design the antenna to fit the manufacturing process, not the other way around.
  - Probably not a good idea to depend on “cheap labour”.
  - Better to perfect the manufacturing process.
- ATA, Patriot Systems, and DRAO developing optimized antenna designs.
  - Could squeeze costs to <1000 $/m^2$ for 10-15 m antennas that operate f < 15 GHz.
  - Rule of thumb – total antenna cost is 3 x reflector cost.

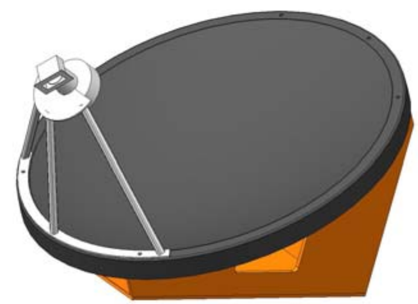
DRAO Composite Ant. Program Phase 1: 1-m Composite Antenna

Mold

“Plug”

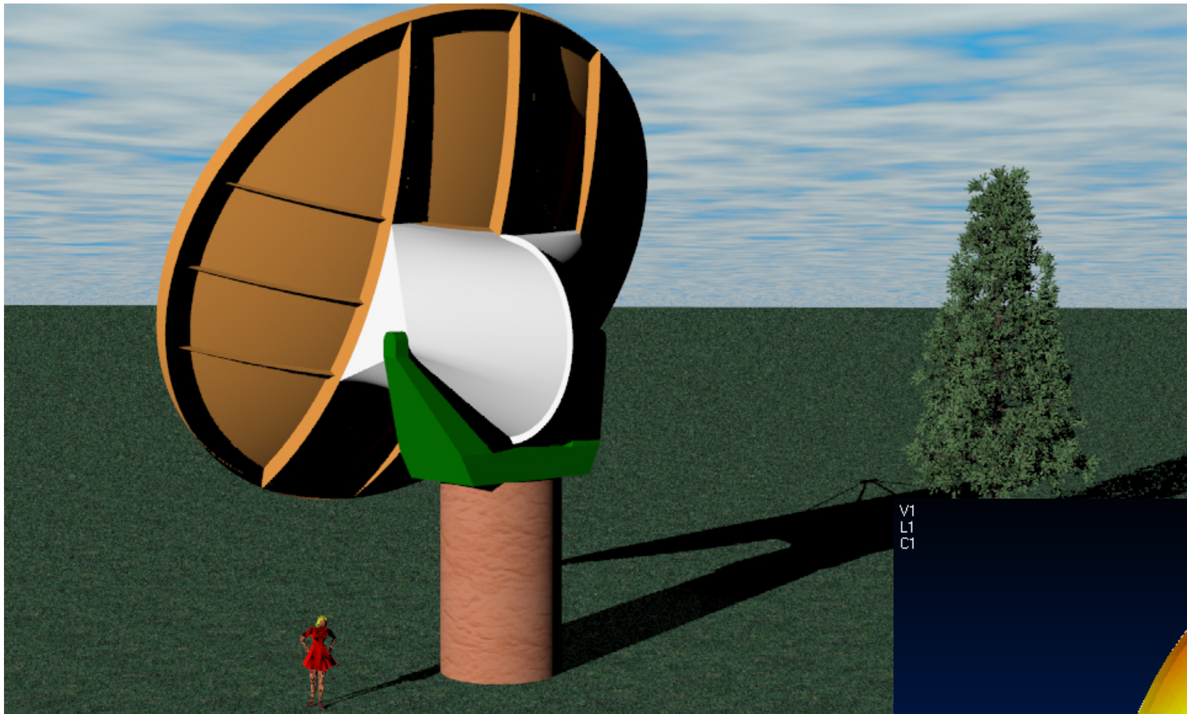


Reflector (<0.3 mm rms)

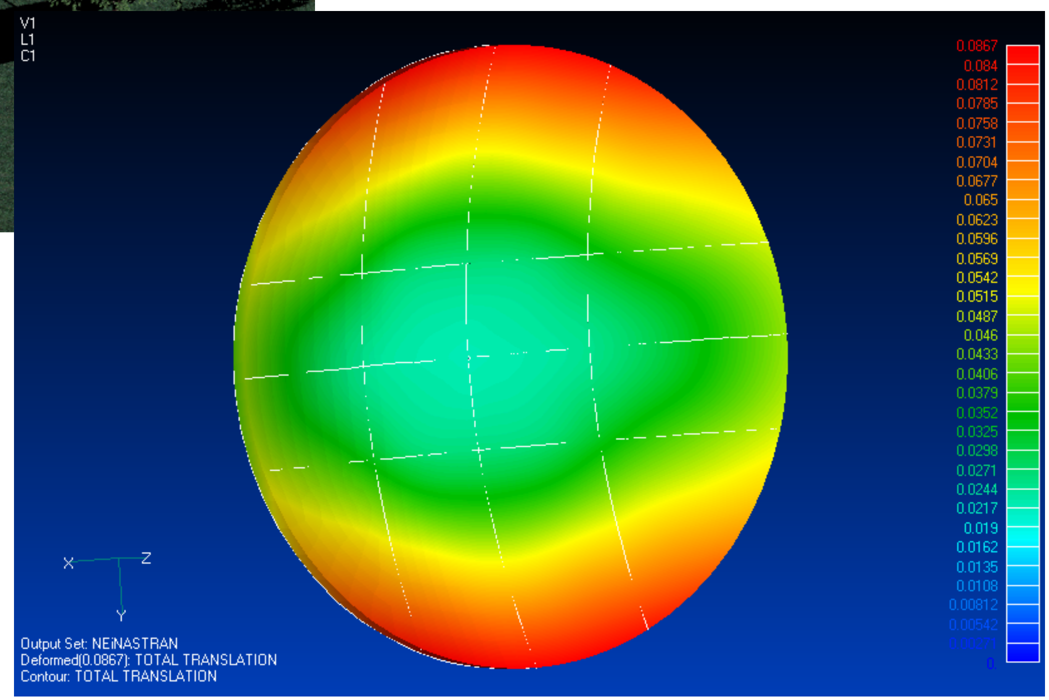


Antenna

Phase 2: Demonstration Operational Composite Dish



- 12-m Reflector.
- Actual design (not just a graphic).



- Example design (not SKA optimized).
  - Total Deflection in maximum operational wind (30 mph).
  - Good in 30 mph wind.
  - Weighted rms = 0.6 mm for 10 dB edge illumination.

Obtaining Large Fields of View (FoV)

1. Small reflecting antennas with “single-pixel” feeds (2 receivers).
   – Lower frequency limit determined by the antenna diameter.
   – Traditional design; bandwidth can be very large (e.g. ATA feed).
   – Obvious fall-back scheme for a large reflector array.
2. Arrays of small (~λ-sized) antennas (Aperture Arrays).
   – Electronic beam-forming can produce very large FoV’s.
   – Huge numbers of antennas needed to obtain collecting area at decimeter λ’s.
   – Never been demonstrated to radio astronomy standards at decimeter λ’s.
   – If technical issues are overcome, costs will be a major impediment at short λ’s.

Obtaining Large Fields of View (FoV) (cont'd)

3. Large reflectors with Phased Focal Plane Arrays (PFPA's).
   - Focal plane contains array of small antennas (e.g. dipoles, Vivaldi's).
   - Beams are formed electronically to match the size of reflector focal spots.
   - Never been demonstrated to competitive radio astronomy standards at decimeter λ's.
   - Array size is much smaller than for AA's.
   - A number of technical issues must be solved, although far fewer than for the superficially similar problems of AA's.
4. Large reflectors with off-axis traditional feeds (similar to 1.)
   - Contiguous FoV not possible.
   - Feed rotator or equatorially mounted antennas required.
   - For many astronomy projects, contiguous field coverage is not required.

My Opinions on “Which Approach?” to Large FoV

- All options are being pursued by SKA groups.
- See potential implications of Option 1 on HI galaxy surveys.
  - could underpin an early version of SKA.
- AA’s will not be practical in the foreseeable future (except at long λ’s).
- PFPA’s have enough potential to be worth research effort, which may take 5-7 years.
- Traditional focal plane feed-arrays (e.g. horn arrays) may be a useful stop-gap, but have negative implications for antenna costs (e.g. feed rotators or equatorial mounts).

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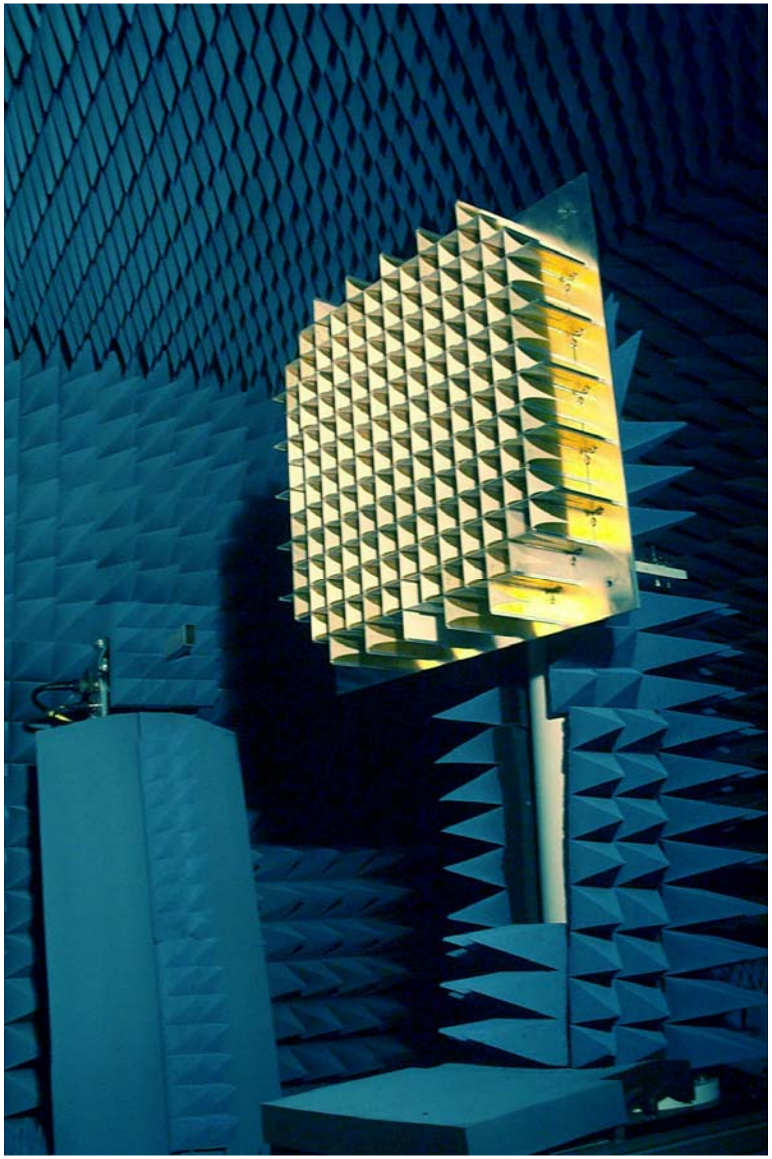
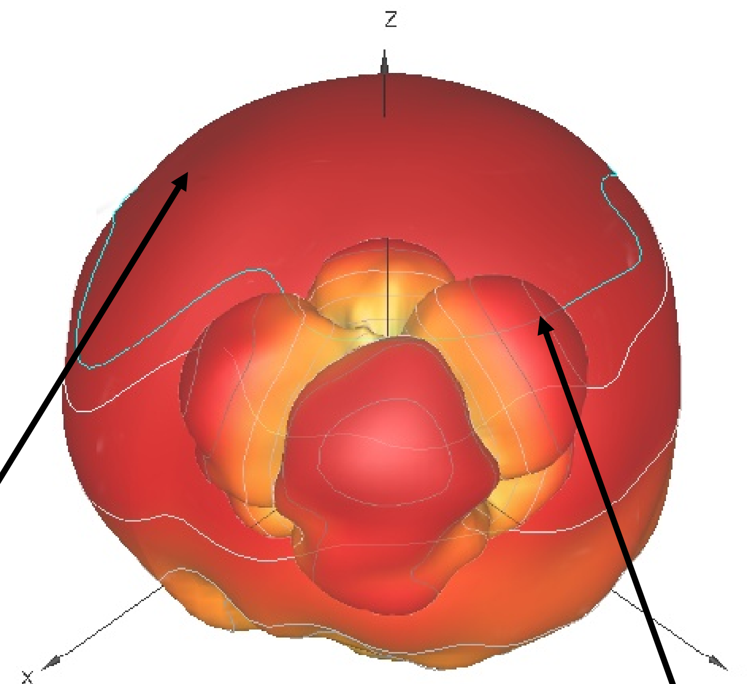
Spherical Near-field Scanner



Measuring Vivaldi Array at DRAO

e.g. Single Vivaldi in array with all others terminated.



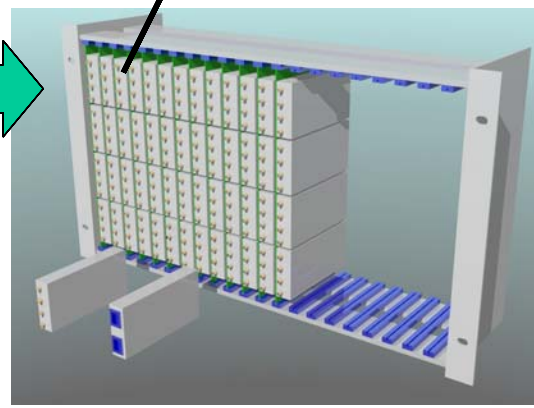
Co-pol response

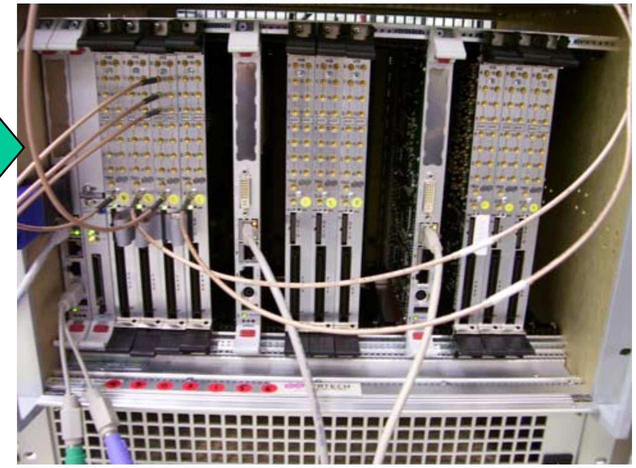
Cross-pol response

Cross-pol/co-pol = -10dB

Prototyping at DRAO

Receiver module





Antennas

- 192 Vivaldi’s
- 2 polarizations

RF section

- 192 receivers
- Four banks of 12 modules
- 4 Receivers per module
- Agilent LNA; Maxum Rx (COTS)
- Outputs: RJ-45 and Cat-7 Cable

COTS Digital Back End

- Made by Lyrtech
- 192 Channels, 16 boards
- 100 MS/s ADCs (14-bit)
- V3000 Xilinx FPGA
- 128 MB RAM per board
- Programmed using Simulink-System Generator

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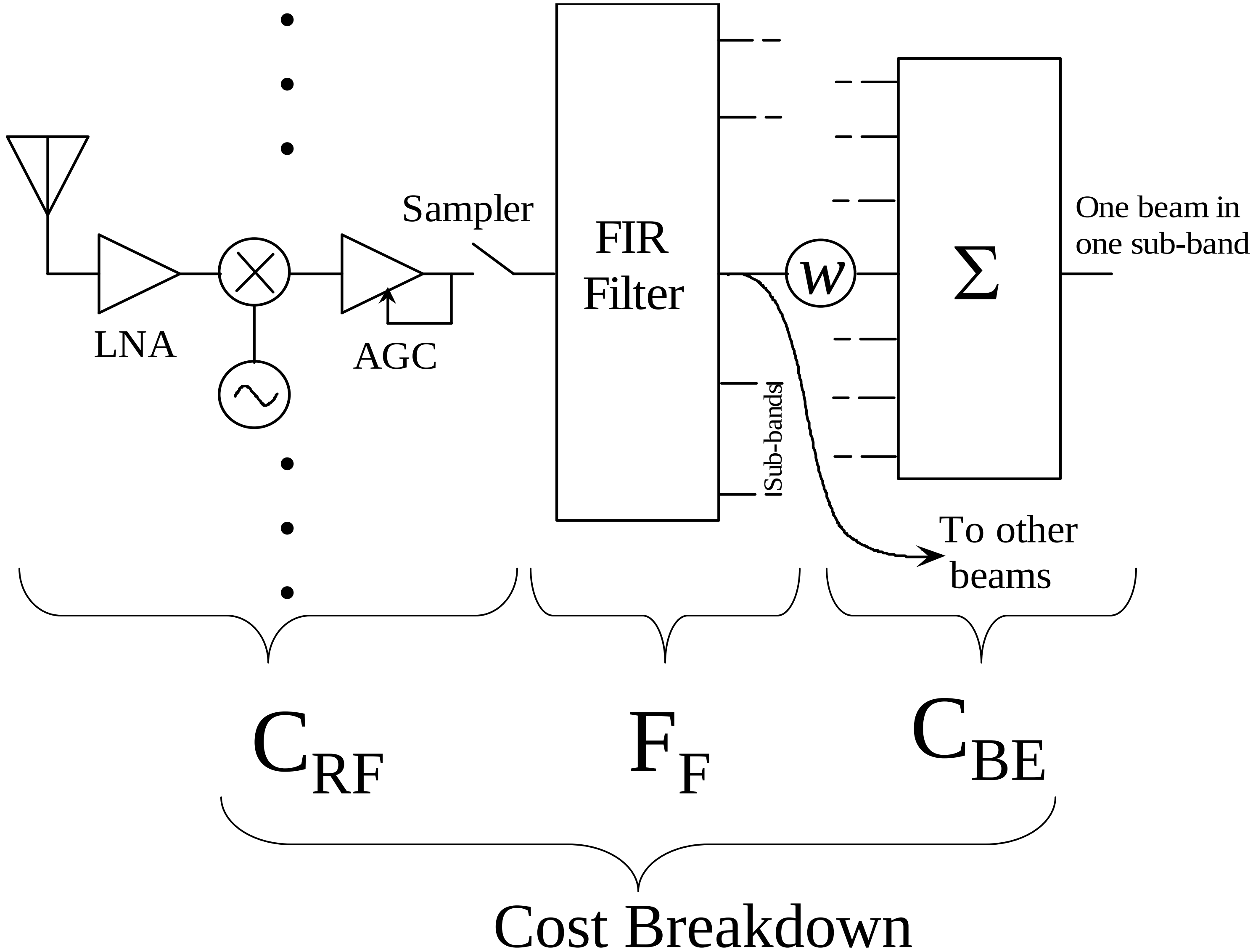
Weinreb* on Costs ($US)

* SKA Memo #77, May 2006.

- Antenna: $\$5 + 0.2D^{2.7}$ k in large quantities.
  - $105k for 10 m; $169k for 12 m; $304k for 15 m.
  - 1300 - 1700 $\$/m^2$.
  - Much lower than current prices.
- Tsys = 18K, uncooled at F < 1.4 GHz.
- Cooled high freq. receivers at $30k each f > 1 GHz.
- PFPA's at $1K "per beam".

PFPA Concept Diagram



Cost Equation for PFPA's

$$C_{FPA} = C_{RF} + C_{BE} = 4\left[n_p \left(\frac{f}{D} \right)^2 C_{chan} + \frac{F_O F_F}{\pi} C_{BF} \right] \left(\frac{D}{\lambda_{\min}} \right)^2 FoV$$

- C_{RF}, C_{BE} – see previous slide.
- n_p is number of polarizations.
- f/D is the focal ratio of the reflector.
- C_{chan} is the cost of a single channel, LNA through to FIR filter.
- F_O is a sampling factor for beam overlap (~4-6).
- F_F is a factor to control spillover noise for wide band FPA's (~4-6) (ie. weights are a function of frequency).
- C_{BF} is the cost of a single beamformer (digital summer).
- λ_{min} is the shortest wavelength in the band.
- FoV is the field of view (steradians).

Cost Limit for PFPA's

$$C_{FPA} = C_{RF} + C_{BE} = 4\left[n_p\left(\frac{f}{D}\right)^2 C_{chan} + \frac{F_O F_F}{\pi} C_{BF}\right]\left(\frac{D}{\lambda_{\min}}\right)^2 FoV$$

Representative values for an L-band PFPA on a 10-m antenna

$n_p = 2$; $f/D = 0.4$; $F_O = 6$; $F_F = 8$; $\lambda_{min} = 0.2$ m; $D = 10$ m; FoV = 50 deg^2.

$$C_{FPA} = 49C_{chan} + 2300C_{BF}$$

- We can only guess at C_{chan} and C_{BF} right now! C_{chan} technology is RF, A/D, data transmission and some digital (FIR's). C_{BF} technology is entirely "compact" digital.
- C_{chan} is inherently larger (more expensive) than C_{BF}.
- We could look at it the other way around – "How far must we push these costs down to make it affordable?"
  - Threshold of pain: If C_{chan} = \$1000 & C_{BF} = \$20, then C_{FPA} = \$95k, about the cost of an antenna. We must do much better than this!

Other Technical Issues

- Calibration of PFPA's will be critical.
  - Electronic field de-rotation may be possible if calibration accuracy is sufficient.
- Data Transmission is likely to be more expensive than we expect, especially because of the cost of optical modulators (esp. for PFPA's) and for trenching on longer runs.
- The real cost of imaging needs further study.
  - Optimization for surveying (more special purpose software).
- If we plan construction starting in this decade, Moore's Law should be discounted compared with the prominent role it has played so far in "mind" of the SKA community.

SKA (Reference Design Specs)

- Specifications over 300-3000 MHz.
  - A_{tot}/T_{sys} = 20000 m^2/K.
  - Ω_{FOV} = 50 deg^2 (f < 1 GHz); 1-10 deg^2 (f > 1 GHz).
- T_{sys} = 25 K (my guarded assumption, uncooled).
- Implications for astronomy e.g. HI-line galaxy survey:
  - To observe all M^* galaxies (7 x 10^9 M_{solar}) at z = 0.3 requires ~0.1 mJy sensitivity (5σ).
    - ss = 320 halfsky / yr.
  - At z = 1, ss = 12.8 halfsky / yr.
  - At z = 3, ss = 0.13 halfsky / yr.

Half-sky, 5-year HI Galaxy Survey Simulation

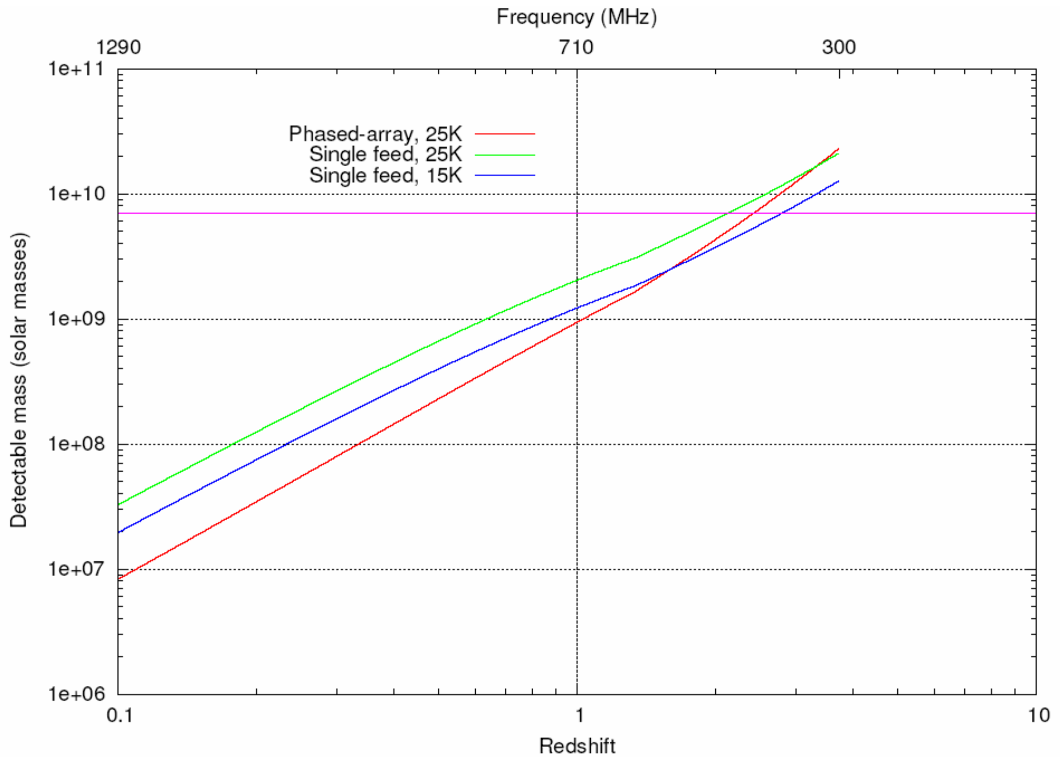
$$ss = 0.211\left(\frac{4}{\pi}\right)^2\left(\frac{A_{tot}}{T_{sys}}\right)^2 BS(z)^2_{\min}\,\Omega_{sp}\left[\frac{\deg^2}{s}\right]$$

PFPA feeds – fixed FoV.

$$ss = 0.211\left(\frac{4}{\pi}\right)\left(\frac{A_{tot}}{T_{sys}}\right)^2 BS(z)^2_{\min}\,\frac{\lambda^2}{D^2_{ant}}\left[\frac{\deg^2}{s}\right]$$

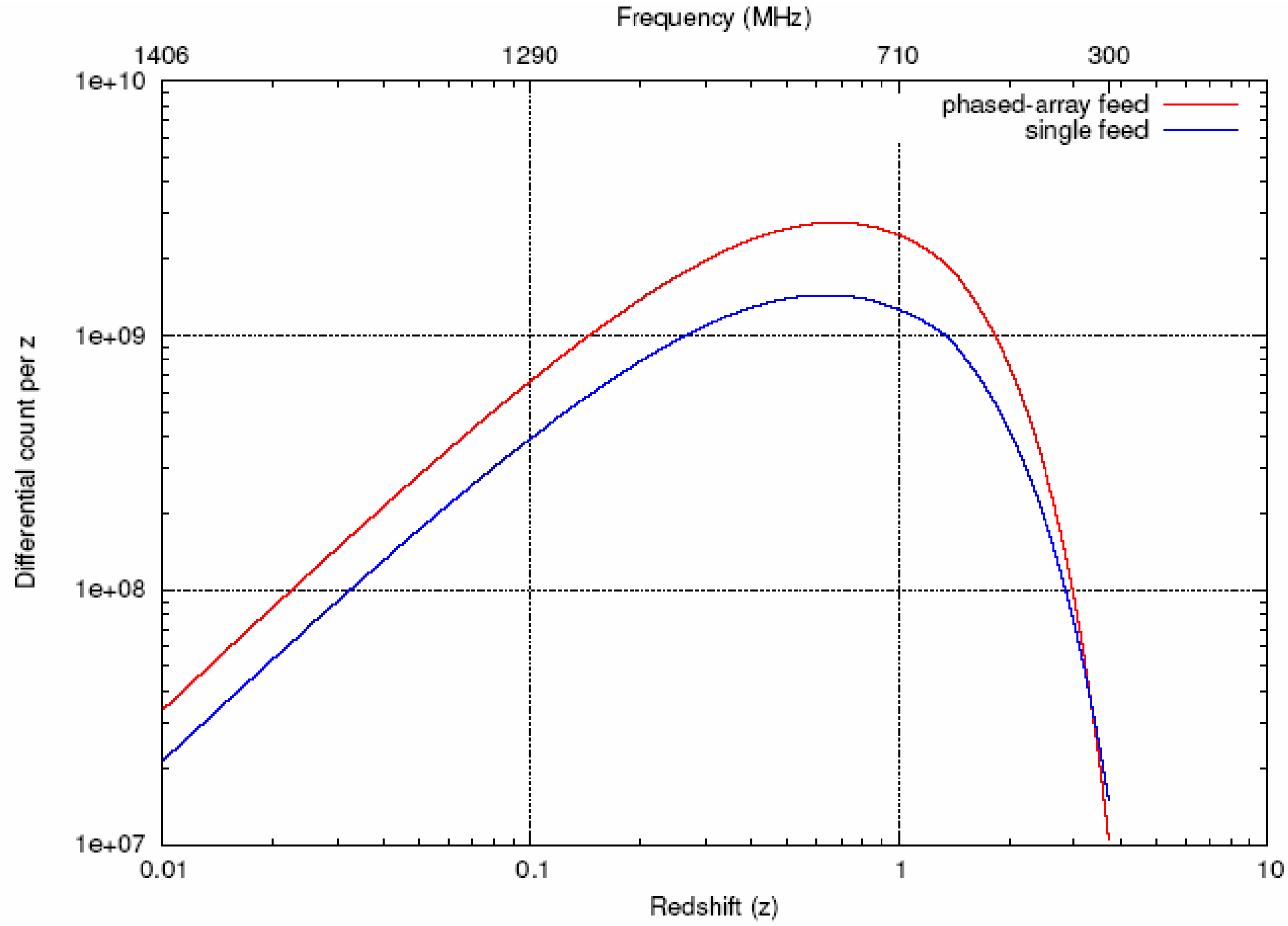
"Single-pixel" feeds for 10-m dia. Antennas.

- All galaxies more massive than the curve will be detected.
- Survey coverage at z = 0 determines the time scale.
- Purple horizontal line is the mass of an M^* Galaxy.
- For single-pixel feeds, more observing time is provided to high-z objects (FoV overlap).
- "Cosmology" introduces slight curvature at high z.
- Single-pixel feed
    - green line: uncooled.
    - blue line: cooled.



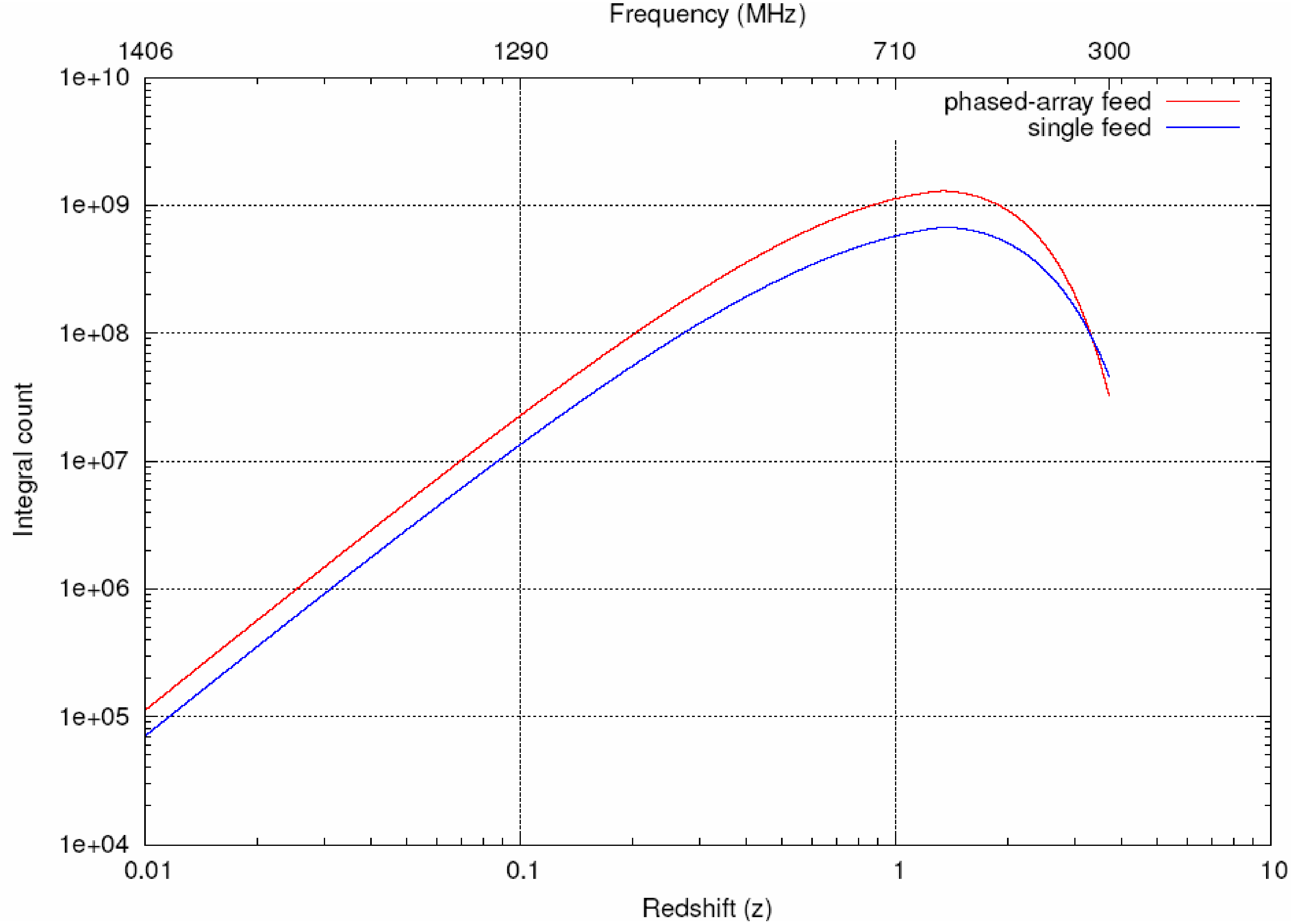
Note: Sky-noise included at low freq.

Differential Galaxy Counts



Counts for unity redshift bin (ie for counts in a redshift bin of 0.01, then multiply the counts by 0.01.).

Integral Galaxy Counts



Remarks on an HI Galaxy Survey

- Survey assumes frequency coverage from 0.3 to 1.4 GHz.
  - May be difficult with 1st generation PFPA's.
- Not sure whether this survey will detect a dark energy signature – needs specialist advice.
- Excellent survey to study evolution of galaxies over a huge fraction of the age of the Universe.

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If I had to decide on what to design now for a construction start in 5 years …

- Build collecting area out to 50 km (~300,000 m^2; 3800 10-m antennas).
- Do one of the following at the prime focus:
  - Equip with cooled, single-pixel, wide-band feeds to cover 300 MHz – 10 GHz (if possible) to get T_{sys} = ~15K (A/T_{sys} = 20000).
  - Carry out an aggressive PFPA program in parallel with early construction and if PFPA's can outperform single pixel feeds, equip with PFPA's (Tsys = 25K; A/T_{sys} = 12000).
- Carry out a sequence of surveys, beginning with small survey programs (high-z HI/OH, continuum, pulsar) and a some open proposal time.
- After 3-4 years, carry out major all-sky surveys over next decade.
- Cost guess: antennas ($350M), receivers ($100M), data transmission ($100M??), correlation ($50M??), image processing ($50M??), infrastructure($100M??). Total =$750M.
  - There is hope that this could be built for less than one billion $.

Sensibly Decoping the SKA

- Modify the approach to science
  - Consider a “program” approach: less distinction between capital and operating $.
  - Consider a particle physics model.
    - Build infrastructure
      - antenna array, signal transmission
    - Modify periodically to optimize for large experiments.
      - E.g. feeds, signal processing, software.
    - Continue to operate general purpose telescopes (EVLA, etc).
- Frequency range
  - Let antenna technology dictate …
- Field of View
  - Examine PFPA’s closely. Continue development but don’t depend on them.
- Long Baselines
  - Build out gradually.
- Sensitivity
  - Don’t sacrifice this!

End