Introduction to radio astronomy
Lectures 3 & 4

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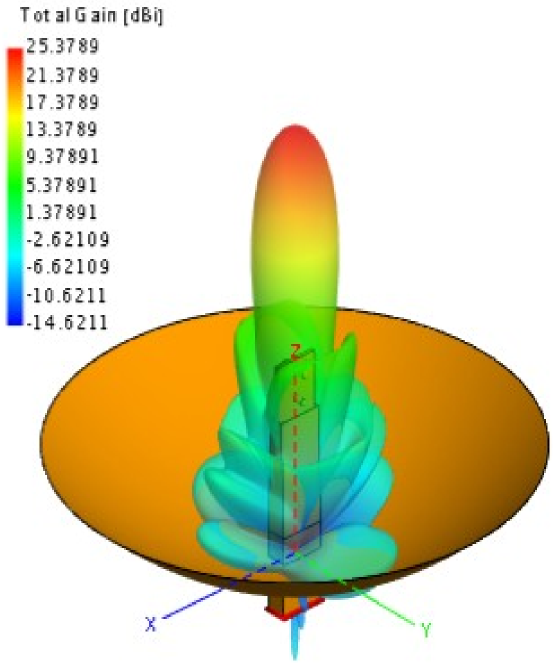
Outline – Lectures 3 and 4

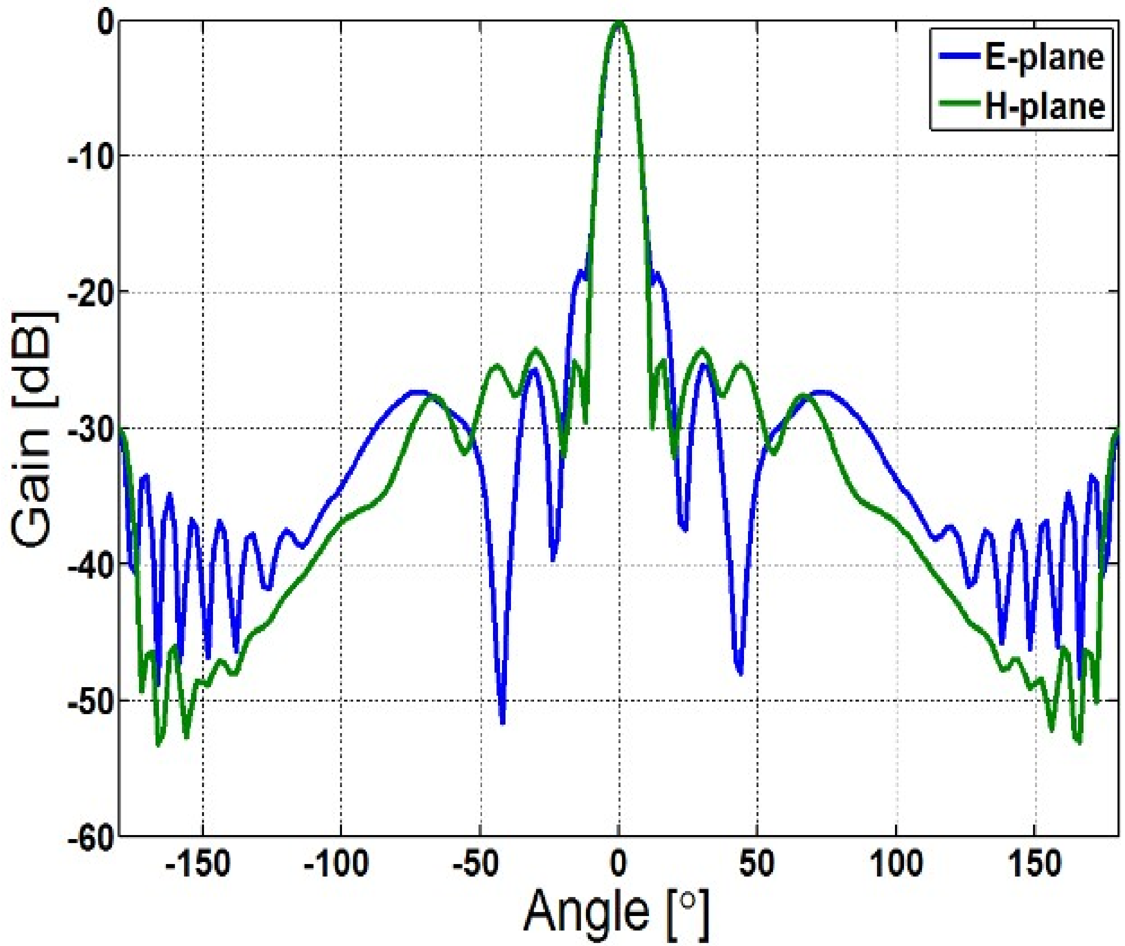
- Antennas, antenna arrays & detectors
  - Antenna gain & radiation patterns
  - Antenna arrays: Sparse phased arrays vs. modern interferometers
  - Detectors & correlators
- Non-ideal effects in radio measurements
  - Noise & noise temperature
  - Amplitude and phase errors
  - Corrections/calibrations

All lectures to be found at: http://wave.asu.cas.cz/barta/lectures/radioastronomy

Antennas, antenna arrays and detectors

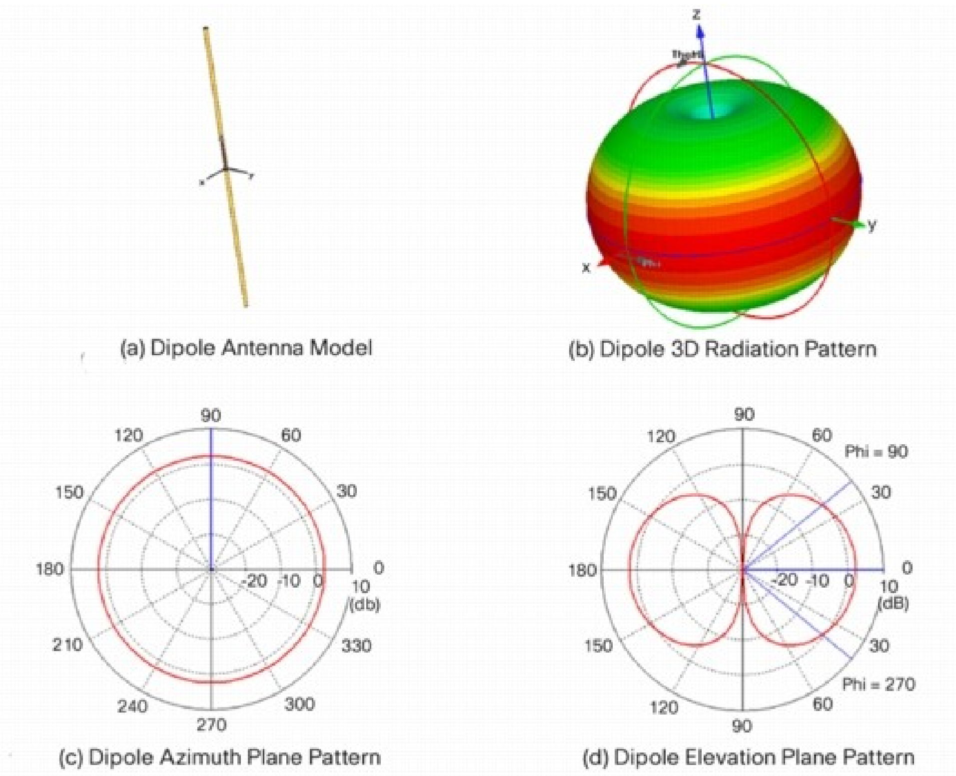
Radio astronomy: Why is everything so big?



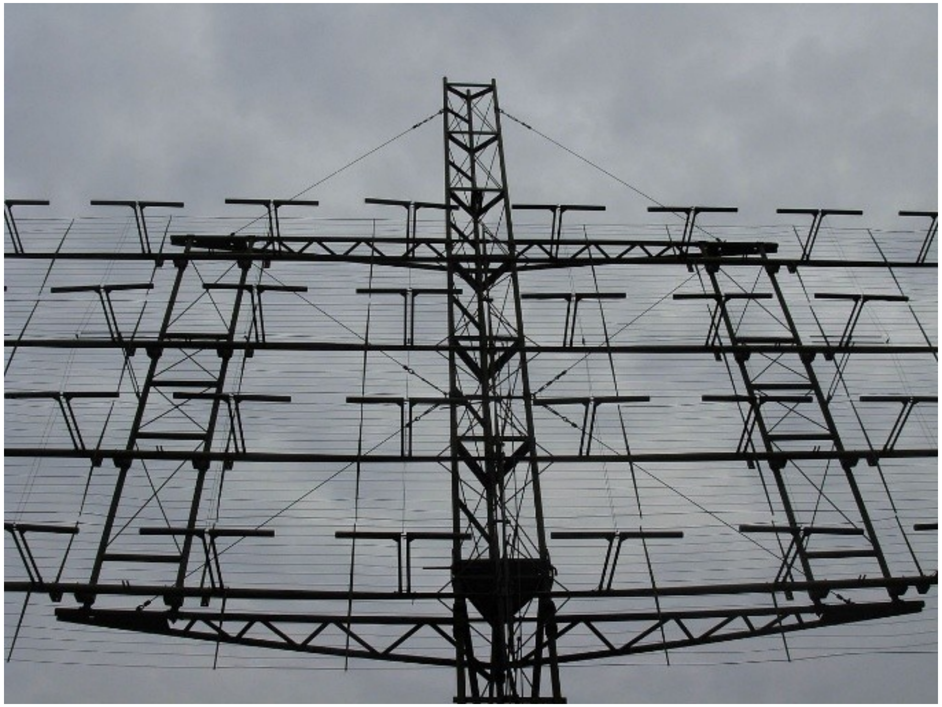


Antenna aperture / antenna gain: ***Sensitivity***
Antenna primary/main beam & side lobes: ***Spatial resolution***

Antennas & detectors

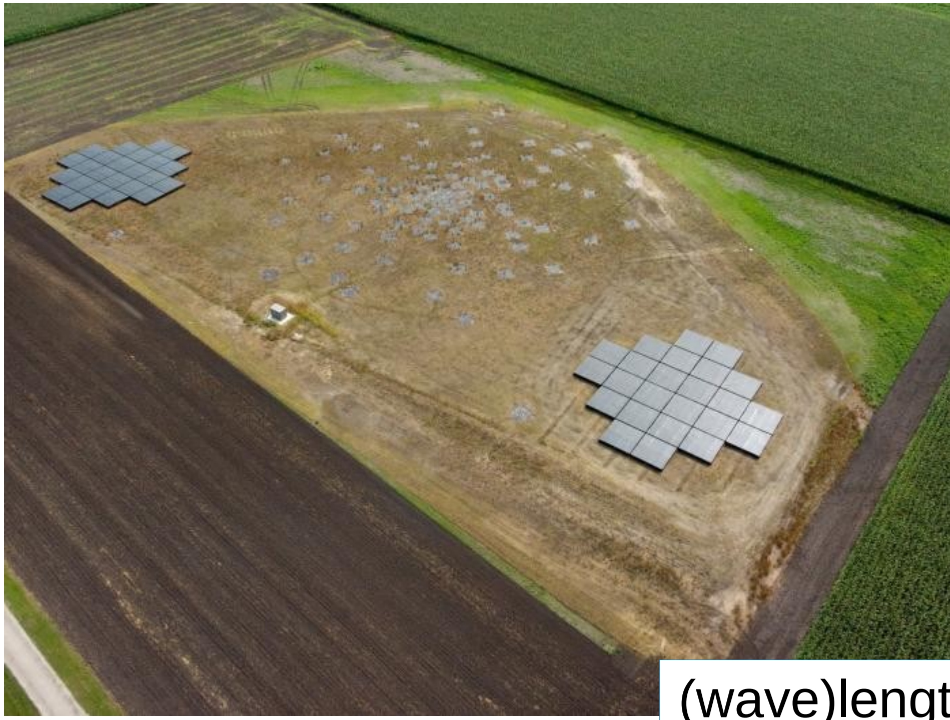


(a) Dipole Antenna Model
(b) Dipole 3D Radiation Pattern
(c) Dipole Azimuth Plane Pattern
(d) Dipole Elevation Plane Pattern

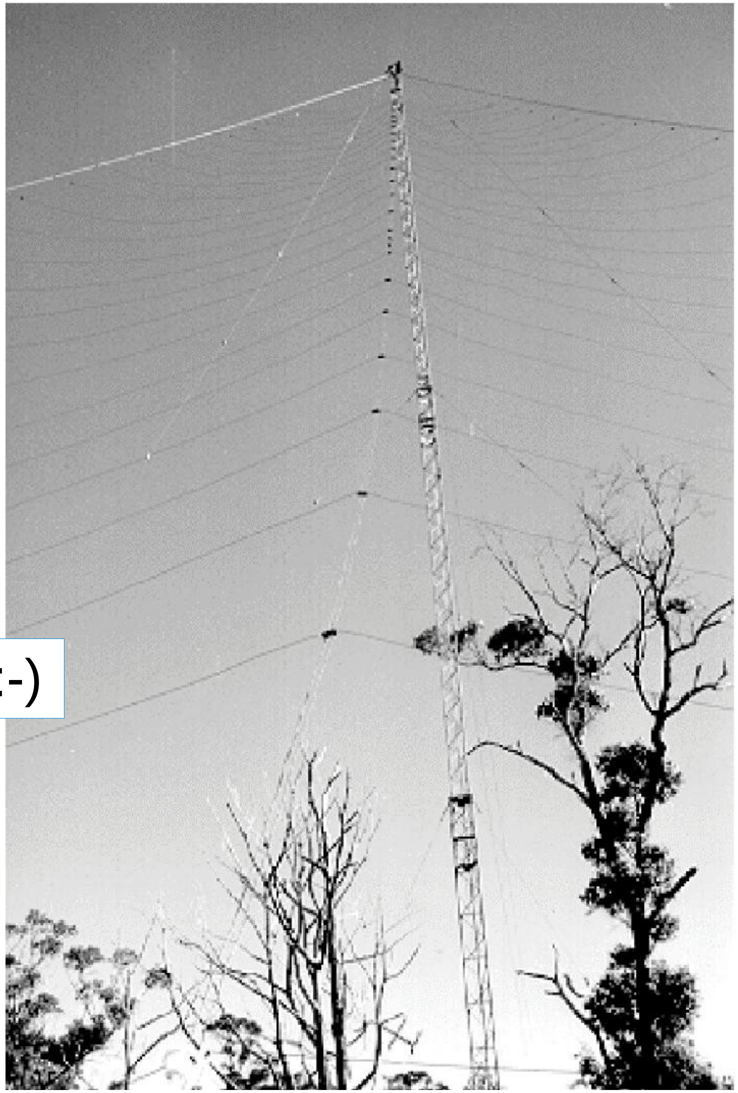


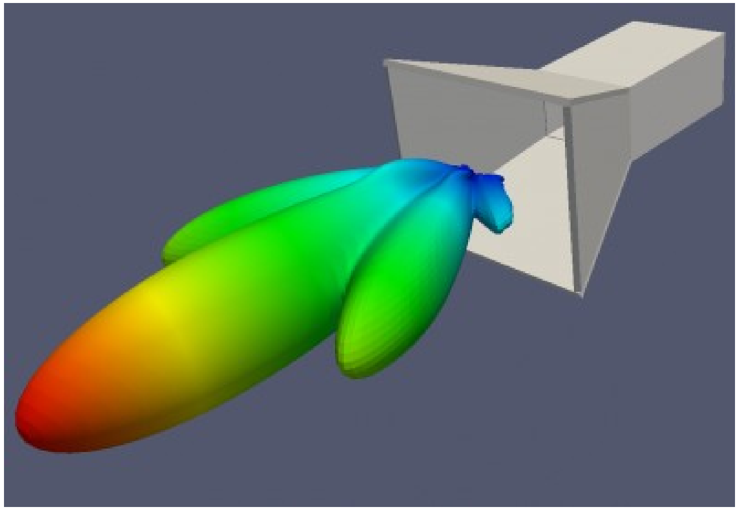
Simplest antennas: dipoles / dipole arrays

Antennas & detectors



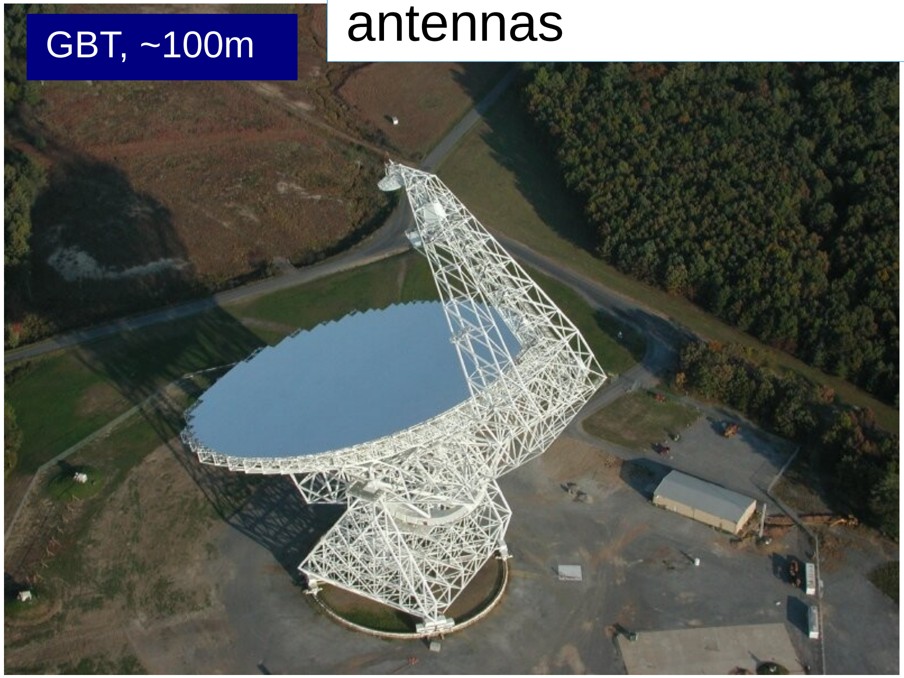
(wave)length matters :-)



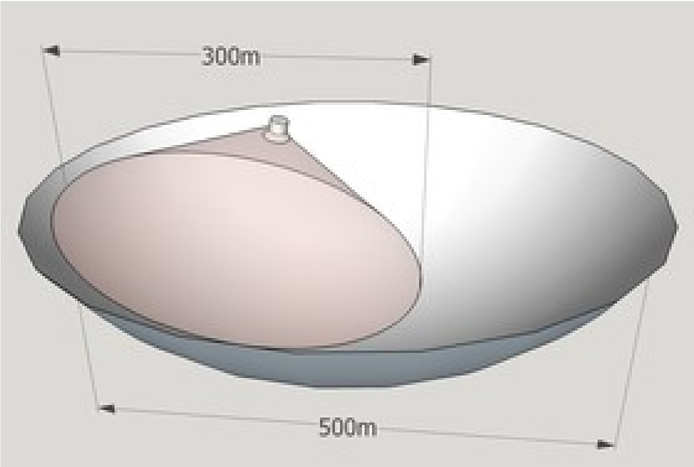


Antennas & detectors

(partly) movable parabolic dishes - ‘universal’ antennas



Velké mísy – *single-dish* přijímače



FAST, ~500m

(FAST webpage)

- Operating frequencies: 70 – 3000MHz
- Science: Neutral hydrogen maps, pulsars, VLBI, chemistry, FRBs, exoplanets, SETI,…
- 2016 – 2019: Commissioning & Science Verification; Oct 2019+: Science operation

Beyond the SD technical limitations: Antenna arrays

Náhrada jedné obří antény soustavou mnoha antén:

Radiová interferometrie

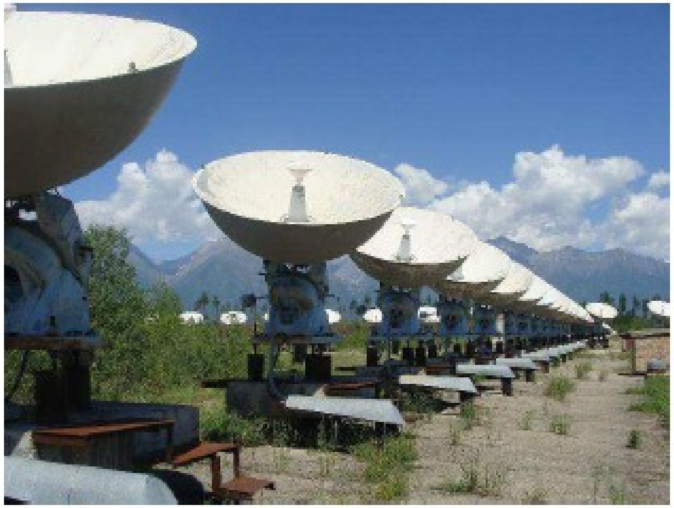
Fázované anténní řady
+ přímé scanování úzkým svazkem soustavy
(historický přístup)

Fourierovské zobrazování / Aperturní syntéza
(moderní metoda)

Antennas & detectors

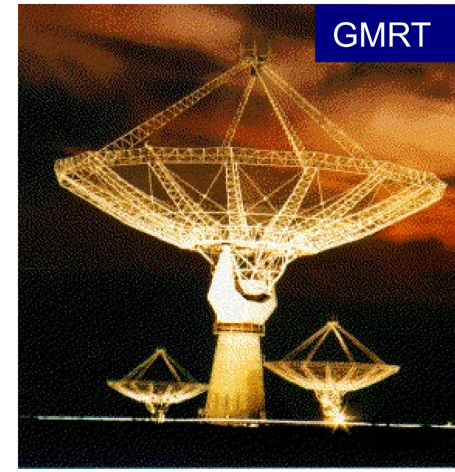
Interferometric arrays

Příklady moderních AS systémů



SSRT

MUSER



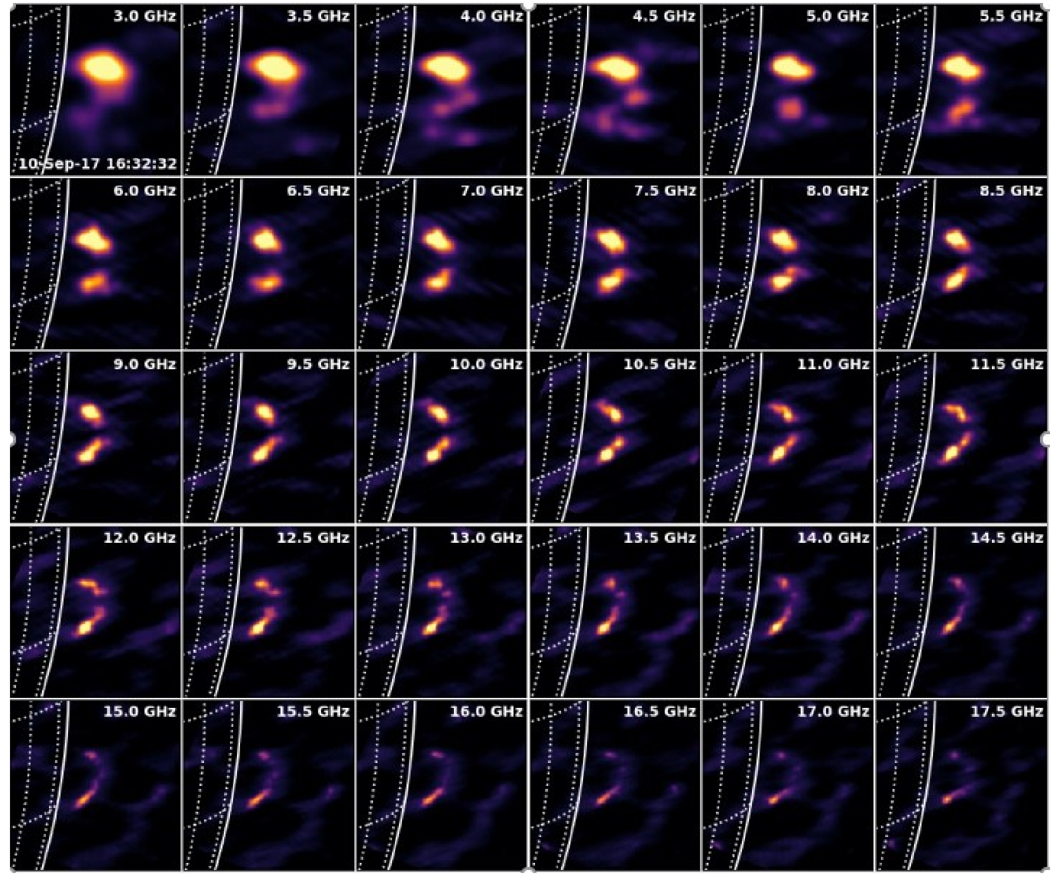
LOFAR

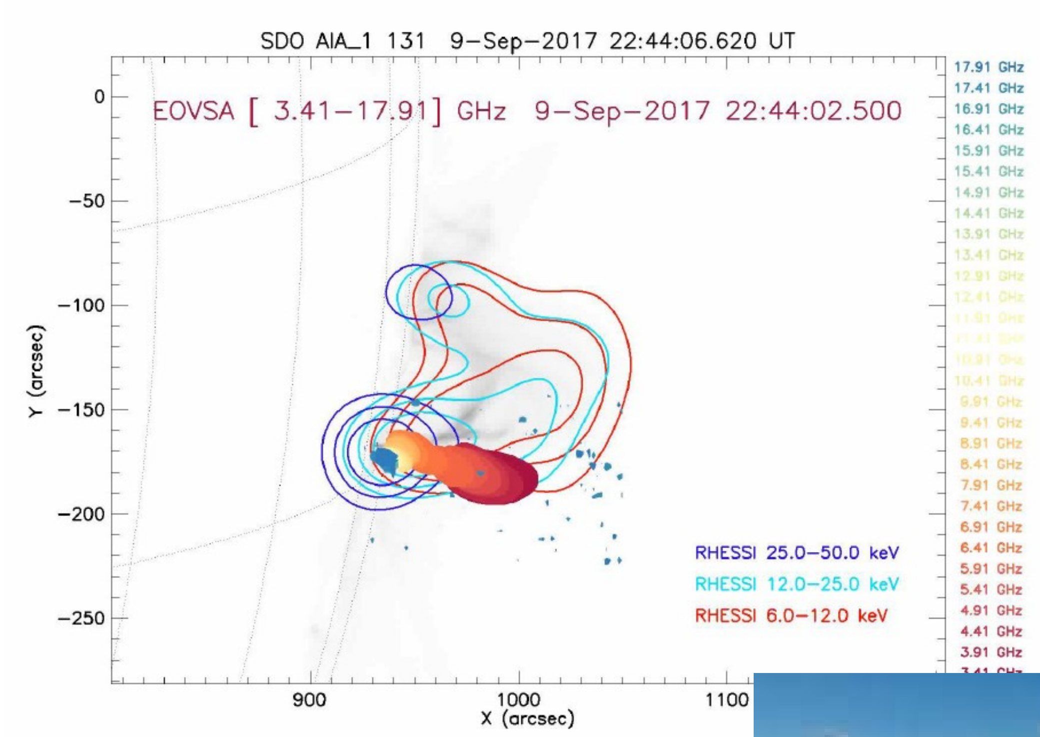
ALMA

SKA

Modern AS systems – Multi-frequency imaging / spectral cubes

- **E-OVSA [US]**





D. Garry, G. Nitta: E-OVSA
CESRA 2019 presentations

Antennas & detectors

VertexRSI: 264 panels spanning 8 rings with 12 (rings 1 and 2), 24 (rings 3 and 4), and 48 (rings 5 through 8) individual panels which are roughly a half-meter-square in area.

AEM: 120 panels spanning 5 rings with 8 (ring 1), 16 (ring 2), and 32 (rings 3 through 5) individual panels which are roughly one-meter-square in area.

Melco 12 m: 205 panels spanning 7 rings with 5 (ring 1), 20 (rings 2 and 3), and 40 (rings 4 through 7) individual panels which are roughly one-meter-square in area.

Melco 7 m: 88 panels spanning 5 rings with 4 (ring 1), 12 (ring 2), and 24 (rings 3 through 5) panels which are each roughly one-meter-square in area.

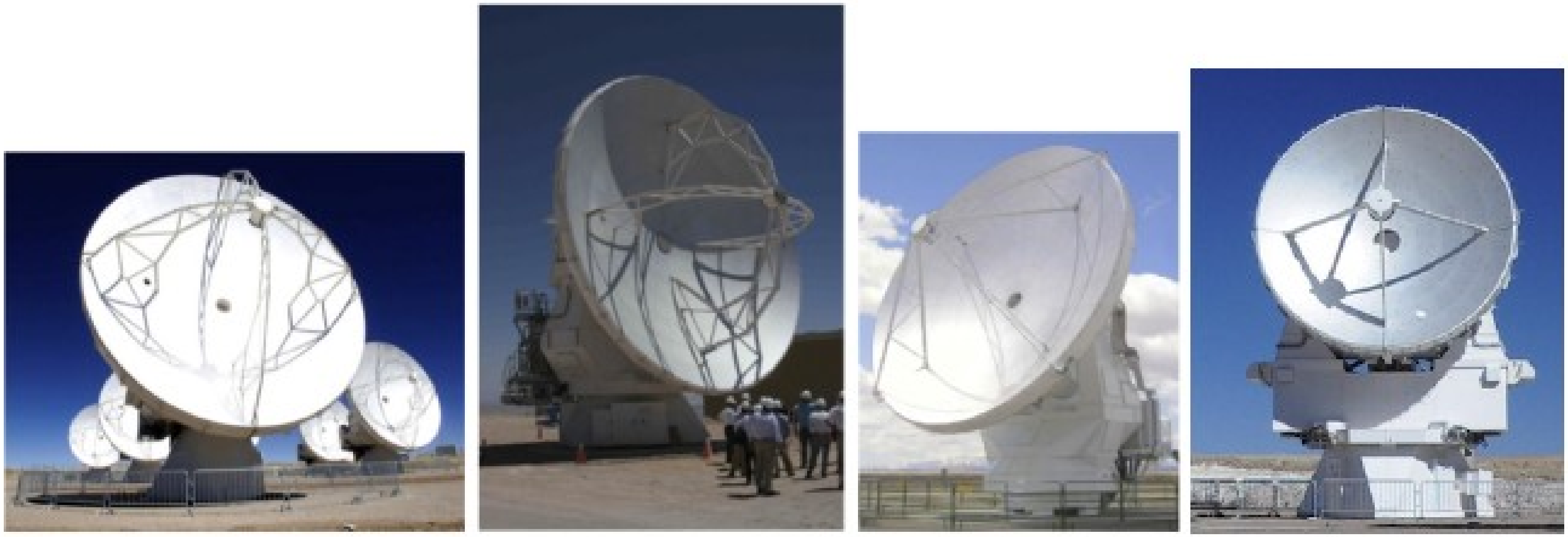
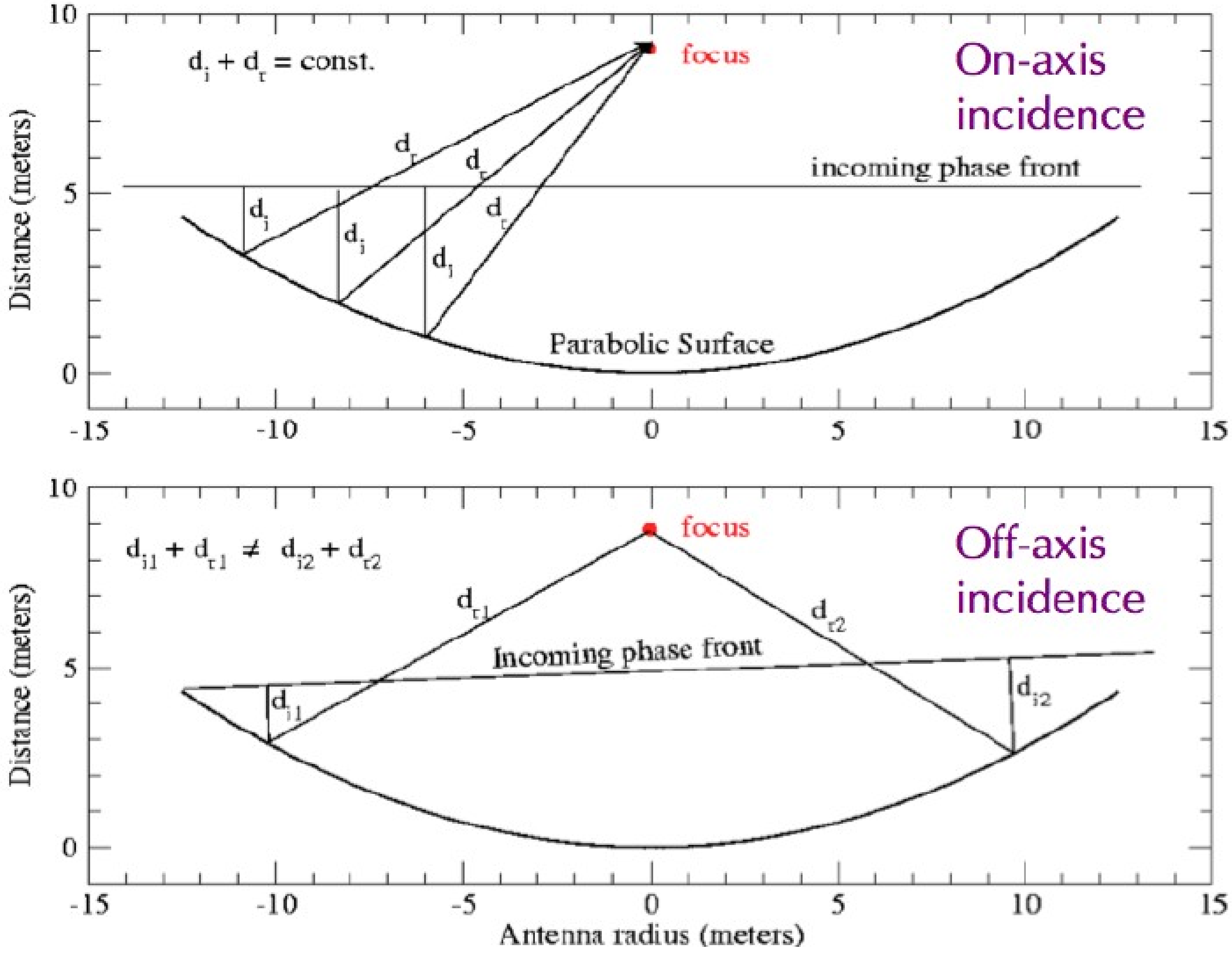
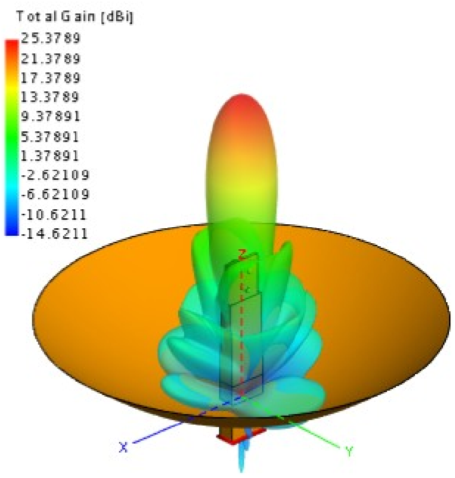


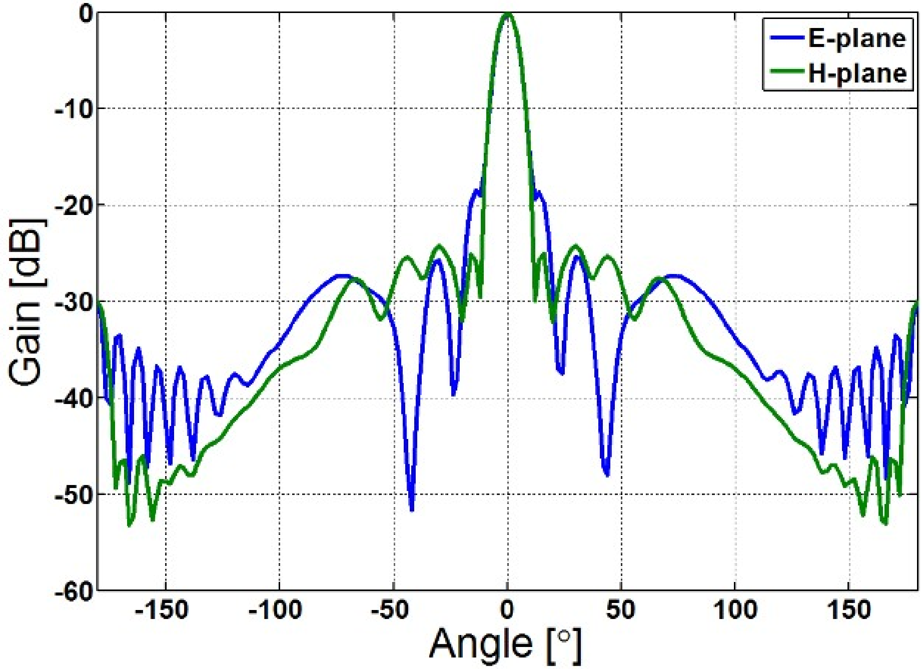
Figure A.1: The four different ALMA Antenna designs: Vertex 12 m, MELCO 12 m, AEM 12 m, and MELCO 7 m (from left to right).

Parabolic dish: Primary beam forming



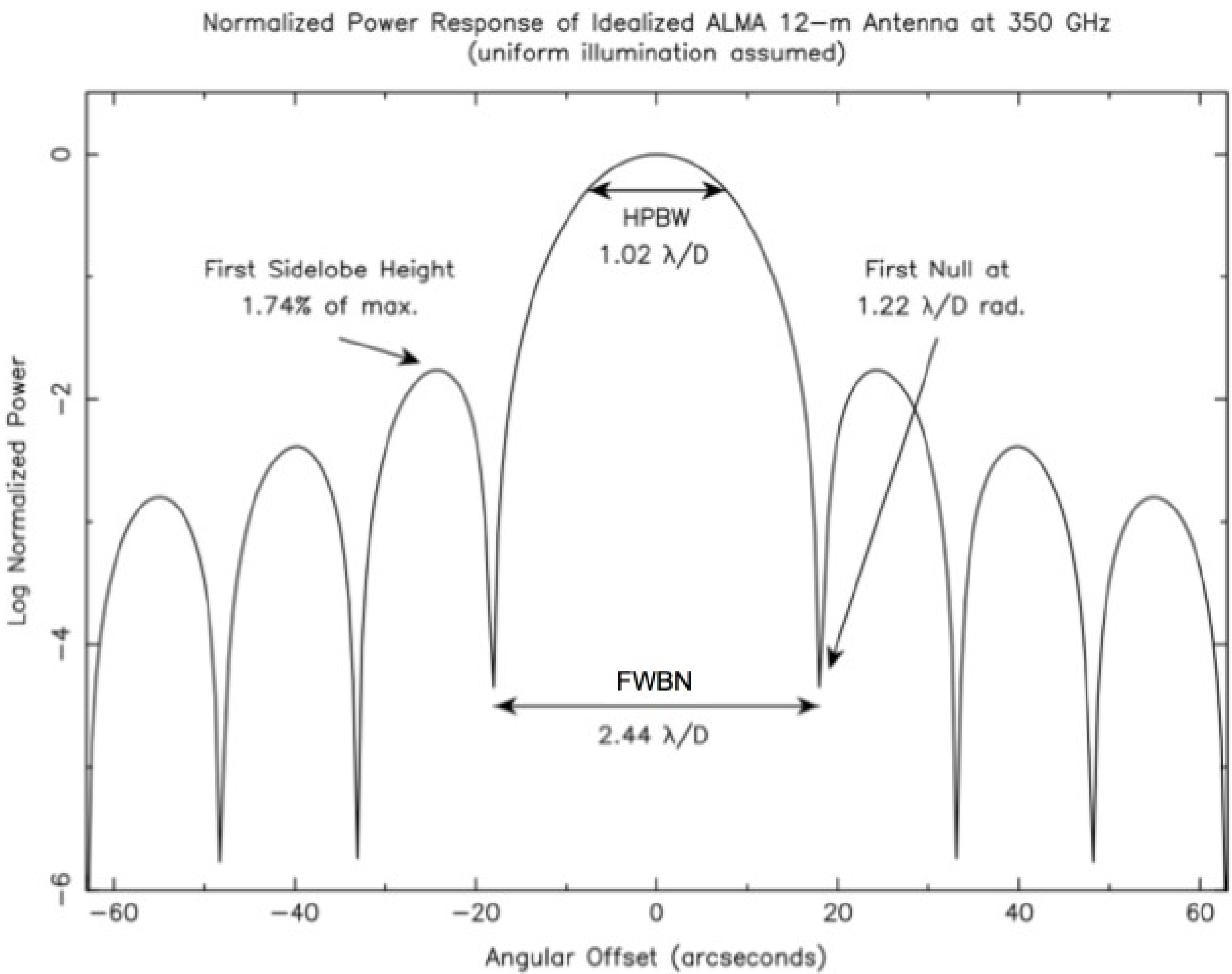
Antennas & detectors





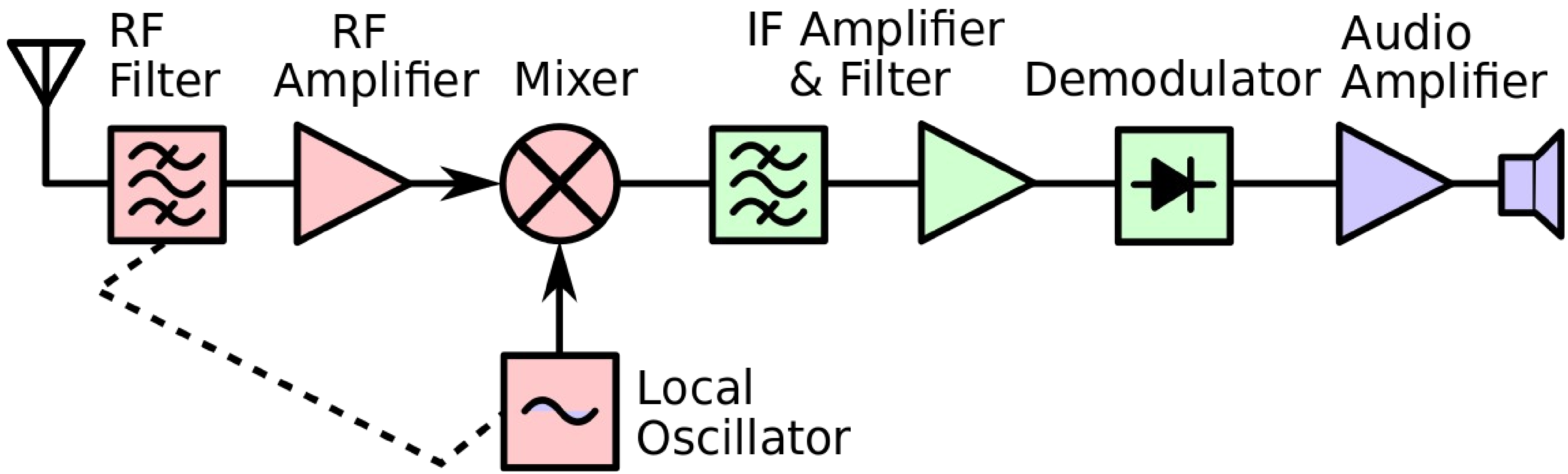
Antenna gain
Antenna aperture
Antenna primary/main beam & side lobes

Antennas & detectors

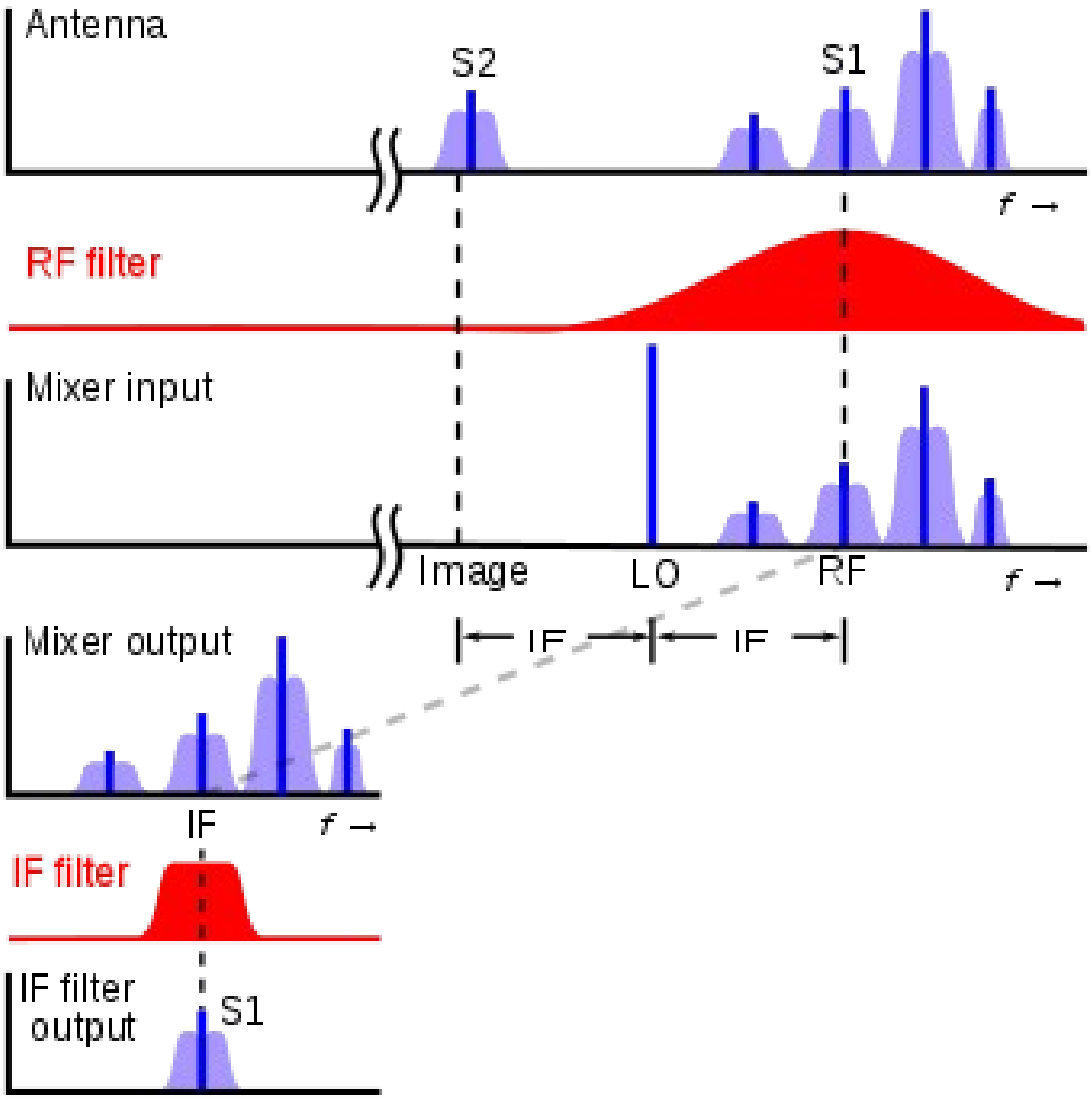


Antennas & detectors

Heterodyne – Block scheme

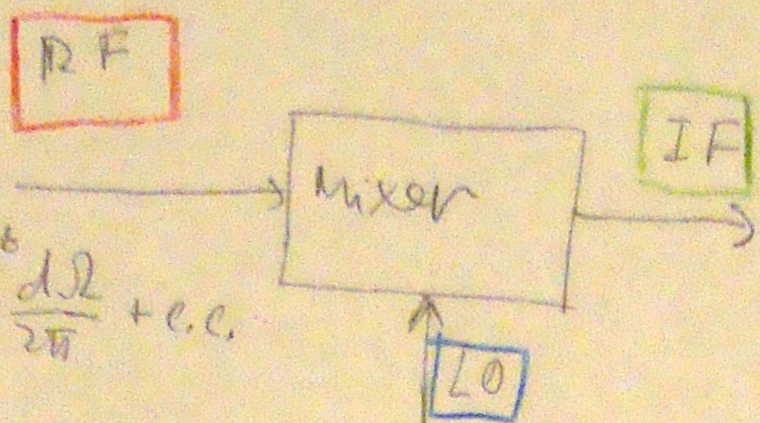


Antennas & detectors: Mixers & down-conversion



Heterodyne – working principle

Frequency down-conversion



$$E_{RF}(t) = \int E(\Omega)\cdot e^{i\Omega t}\,\frac{d\Omega}{2\pi} + c.c.$$

$$E_{LO}(t) = E_{LO}\cdot\cos\omega_0 t$$

$$E_M(t) = g(E(t)), \quad E = E_{RF} + E_{LO}$$

$$E_M = g_0 + g_1 E + g_2 E^2 + \dots$$

$$E_M(t) = g_0 + g_1\left(\left[\frac{E_0}{2}\cdot e^{i\omega_0 t} + c.c.\right] + \left[\int E(\Omega)\cdot e^{i\Omega t}\,\frac{d\Omega}{2\pi} + c.c.\right]\right) +$$

$$+ g_2\left(\frac{E_0^2}{4}\cdot\left(e^{i\omega_0 t} + e^{-i\omega_0 t}\right)^2 + 2\cdot\frac{E_0}{2}\left[\int E(\Omega)\cdot e^{i(\omega_0+\Omega)t} + E(\Omega)\cdot e^{i(\Omega-\omega_0)t} + \bar{E}(\Omega)\cdot e^{-i(\Omega-\omega_0)t} + \bar{E}(\Omega)\cdot e^{-i(\Omega+\omega_0)t}\,\frac{d\Omega}{2\pi}\right] + \left[\int E(\Omega)\cdot e^{i\Omega t} + \bar{E}(\Omega)\cdot e^{-i\Omega t}\,\frac{d\Omega}{2\pi}\right]^2\right.$$

Antennas & detectors: Mixers & down-conversion

$$\iint \left(E(\Omega)\cdot e^{i\Omega t} + \bar{E}(\Omega)\cdot e^{-i\Omega t}\right)\cdot\left(E(\Omega')\cdot e^{i\Omega' t} + \bar{E}(\Omega')\cdot e^{-i\Omega' t}\right)\frac{d\Omega}{2\pi}\frac{d\Omega'}{2\pi} =$$

$$= \iint \Big[E(\Omega)\cdot E(\Omega')\cdot e^{i(\Omega+\Omega')t} + \bar{E}(\Omega)\cdot\bar{E}(\Omega')\cdot e^{-i(\Omega+\Omega')t} +$$

$$+ E(\Omega)\cdot\bar{E}(\Omega')\cdot e^{i(\Omega-\Omega')t} + \bar{E}(\Omega)\cdot E(\Omega')\cdot e^{-i(\Omega-\Omega')t}\Big]\frac{d\Omega}{2\pi}\frac{d\Omega'}{2\pi}$$

$$= \iint E(\Omega)\cdot E(\Omega')\cdot e^{i(\Omega+\Omega')t}\frac{d\Omega}{2\pi}\frac{d\Omega'}{2\pi} + \iint E(\Omega)\bar{E}(\Omega')\cdot e^{i(\Omega-\Omega')t}\frac{d\Omega}{2\pi}\frac{d\Omega'}{2\pi}$$

$$+ \text{c.c.}$$

$$\Omega + \Omega' = \omega$$

$$\Omega' = \omega - \Omega$$

$$d\Omega' = d\omega$$

Antennas & detectors: Mixers & down-conversion

$$\Omega + \Omega' = \omega$$

$$\Omega' = \omega - \Omega$$

$$d\Omega' = d\omega$$

$$\iint E(\Omega)\cdot E(\omega-\Omega)\cdot e^{i\omega t}\,\frac{d\Omega}{2\pi}\,\frac{d\omega}{2\pi} = \int\left(\int E(\Omega)\cdot E(\omega-\Omega)\cdot\frac{d\Omega}{2\pi}\right)\cdot e^{i\omega t}\,\frac{d\omega}{2\pi}$$

$$\Omega - \Omega' = \omega$$

$$\Omega' = \Omega - \omega$$

$$d\Omega' = -d\omega$$

$$-\iint E(\Omega)\,\bar{E}(\Omega-\omega)\cdot e^{i\omega t}\,\frac{d\omega}{2\pi}\,\frac{d\Omega}{2\pi} = \int\left(-\int E(\Omega)\cdot\bar{E}(\Omega-\omega)\,\frac{d\Omega}{2\pi}\right)\cdot e^{i\omega t}\,\frac{d\omega}{2\pi}$$

$$+ g_2 \left(\frac{E_0^2}{4} \cdot \left(e^{i\omega_0 t} + e^{-i\omega_0 t}\right)^2 + 2 \cdot \frac{E_0}{2} \left[\int E(\Omega) \cdot e^{i(\omega_0+\Omega)t} + E(\Omega)\cdot e^{i(\Omega-\omega_0)t} + \right.\right.$$

$$\left.\left. + \bar{E}(\Omega) \cdot e^{-i(\Omega-\omega_0)t} + \bar{E}(\Omega)\cdot e^{-i(\Omega+\omega_0)t} \frac{d\Omega}{2\pi} + \left[\int E(\Omega) \cdot e^{i\Omega t} + \bar{E}(\Omega) \cdot e^{-i\Omega t} \frac{d\Omega}{2\pi}\right]^2 \right]\right) =$$

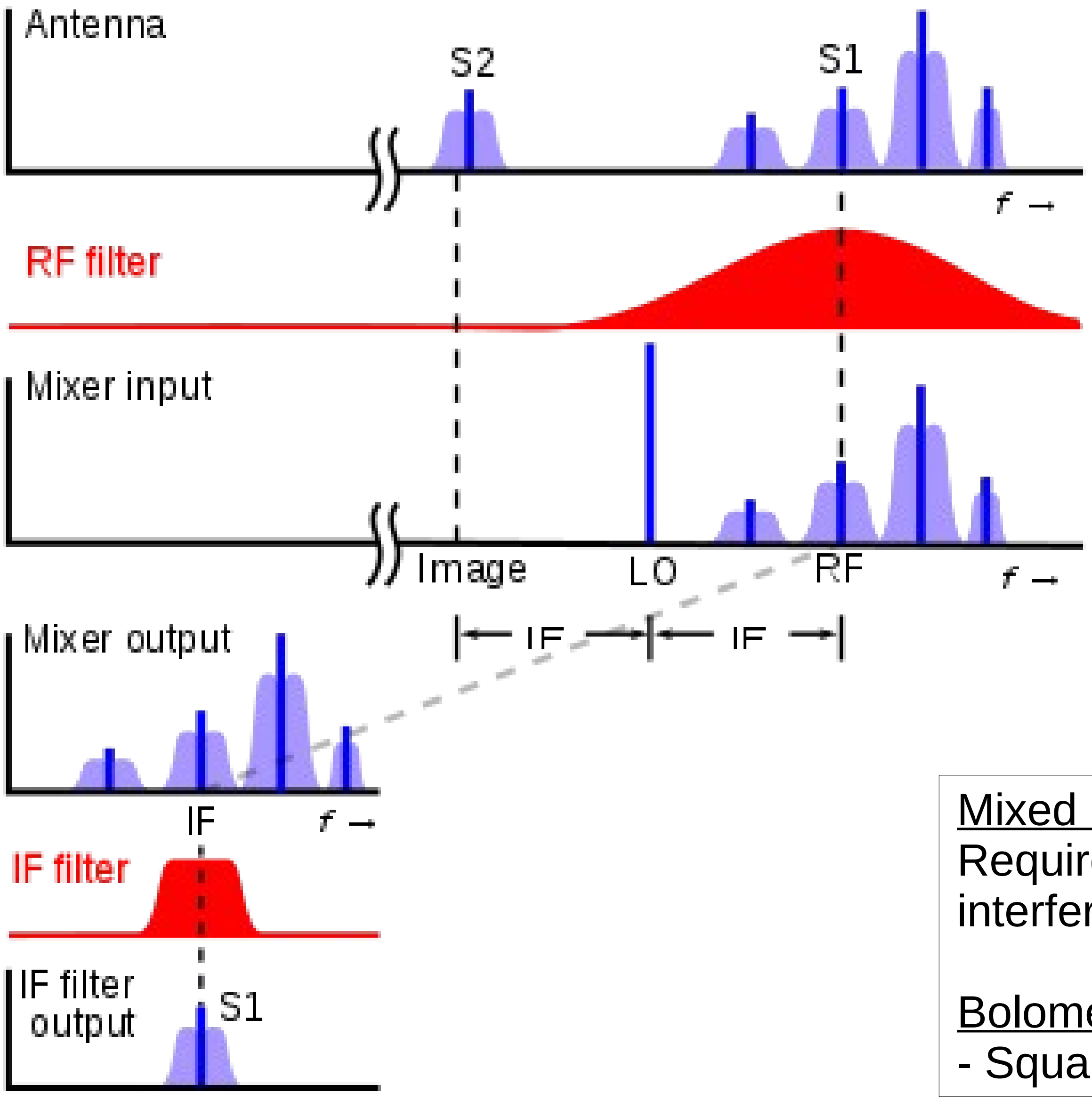
$$g_0 + g_1 \left[\left(\frac{E_0}{2} e^{i\omega_0 t} + \int E(\Omega) \cdot e^{i\Omega t} \frac{d\Omega}{2\pi} \right) + c.c. + g_2 \cdot \left[\frac{E_0^2}{2} + \frac{E_0^2}{4} \left(e^{i\omega_0 t} + c.c.\right) + \right.\right.$$

$$+ E_0 \int E(\Omega) \cdot e^{i(\Omega+\omega_0)t} \frac{d\Omega}{2\pi} + \boxed{\int E(\Omega) \cdot e^{i(\Omega-\omega_0)t}\frac{d\Omega}{2\pi} + c.c.}$$

$$+ \int \left(E(\Omega) \cdot E(\omega-\Omega) \frac{d\Omega}{2\pi}\right) e^{i\omega t}\frac{d\omega}{2\pi} + \boxed{\int\left(\int E(\Omega) \cdot \bar{E}(\Omega-\omega)\frac{d\Omega}{2\pi}\right) \cdot e^{i\omega t}\frac{d\omega}{2\pi}}$$

$$\left.\left. + c.c. \right]\right] + \ldots$$

Antennas & detectors: Mixers & down-conversion



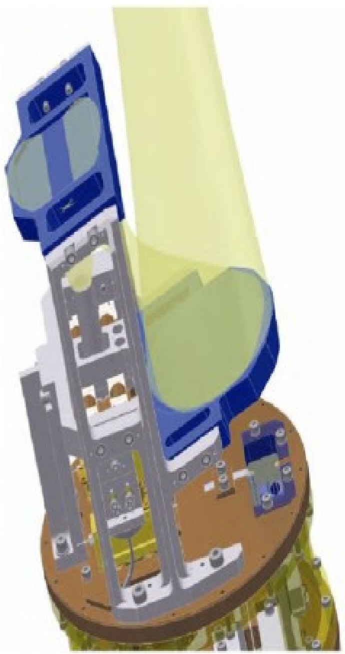
Heterodyne – working principle

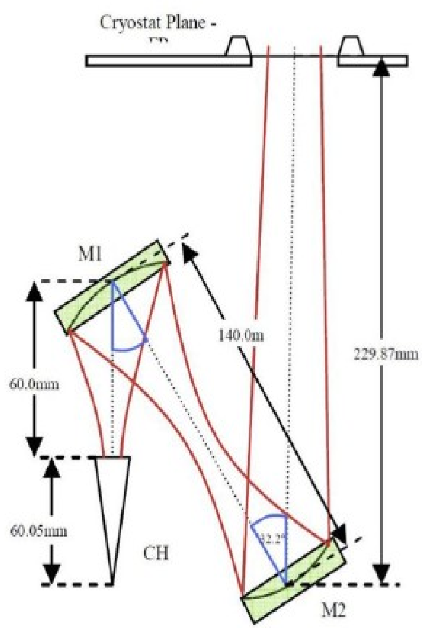
Frequency down-conversion

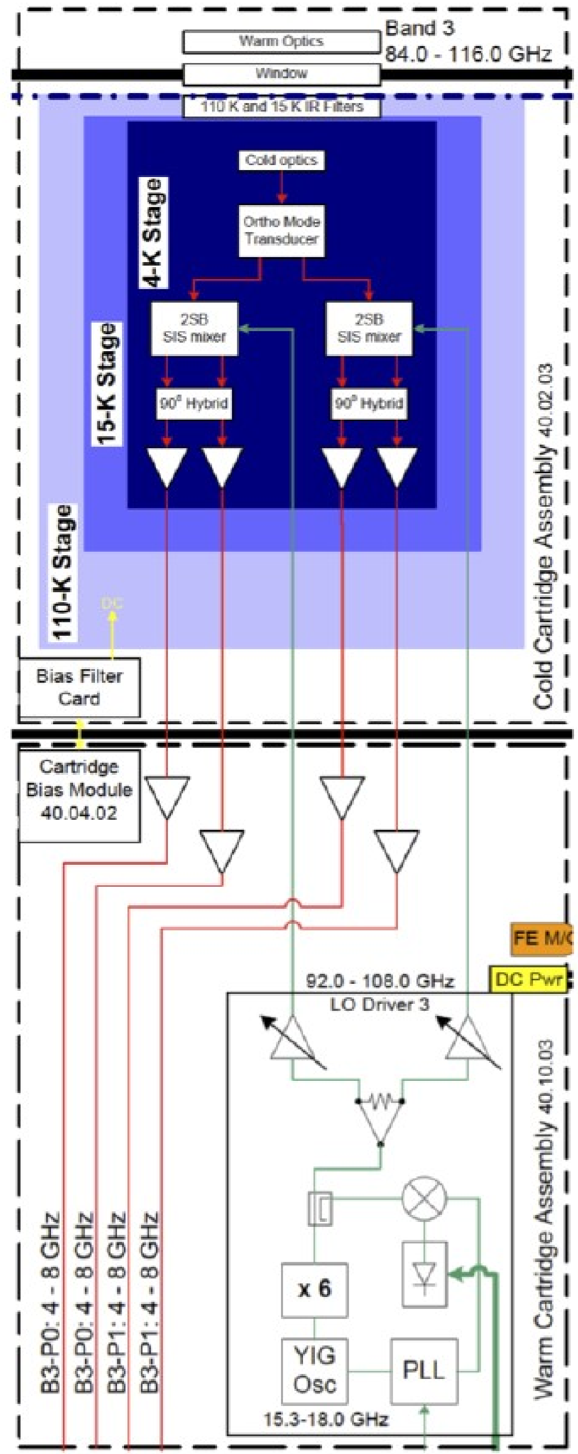
<u>Mixed (down-converted/IF) signals:</u>
Required for DSP – digital spectroscopy, interferometry

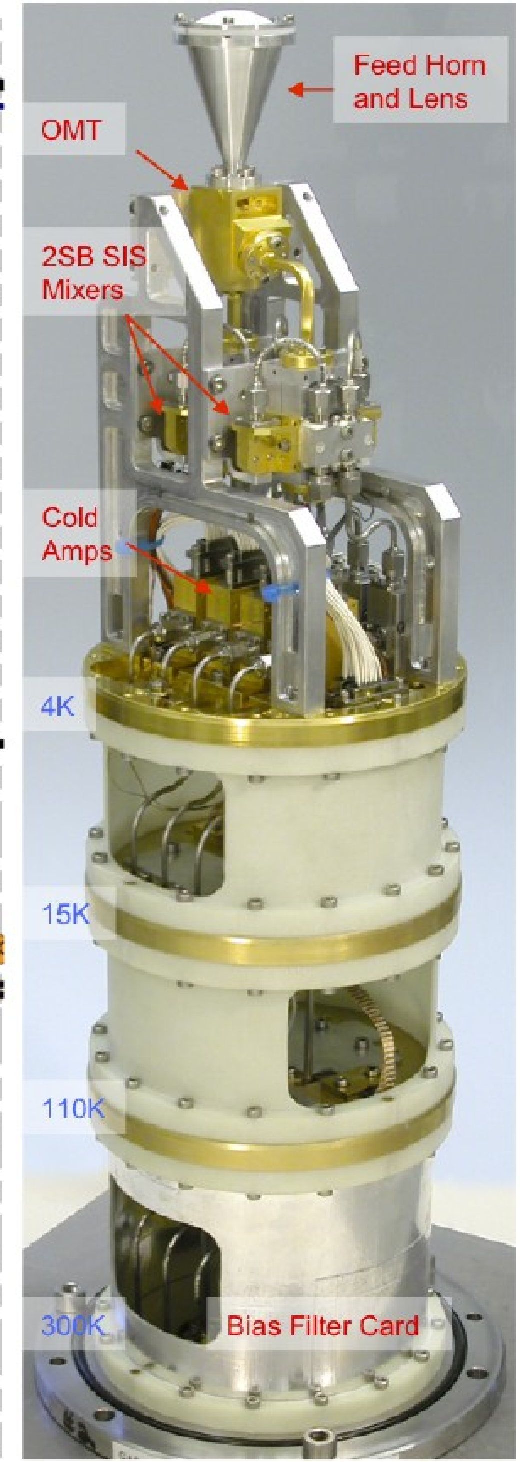
<u>Bolometry/radiometry</u>: P~E^2 over some band
- Square-Law Detector (SQLD)

Antennas & detectors

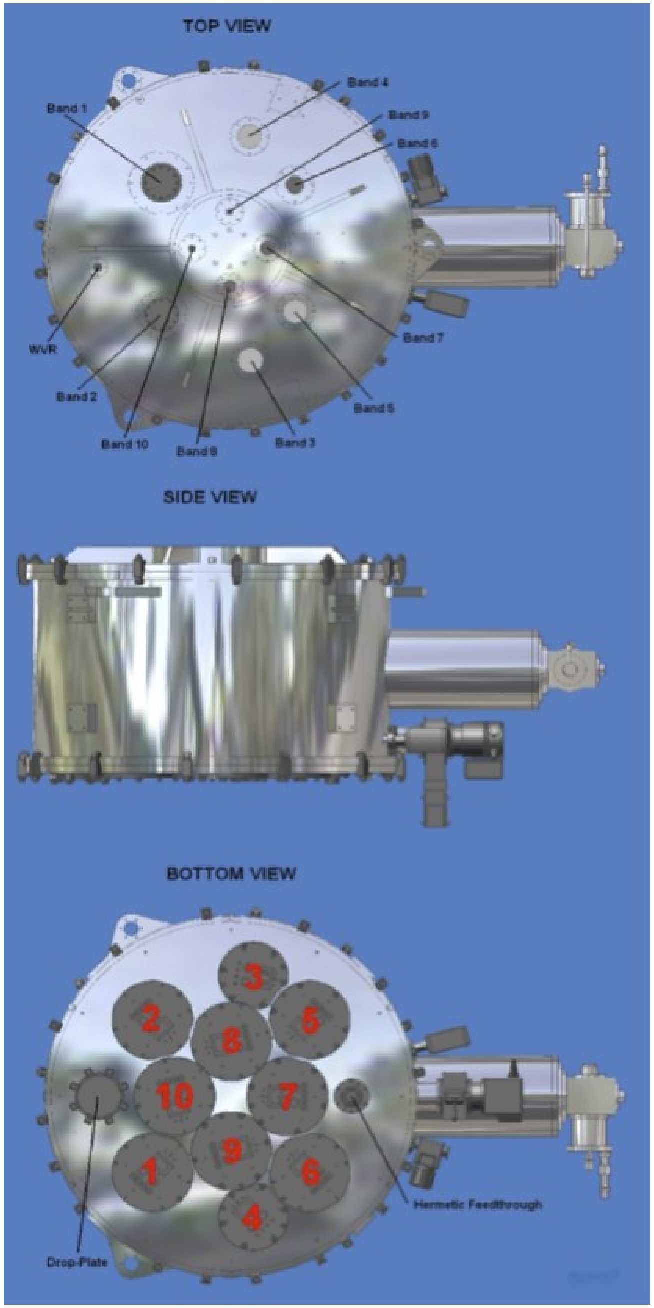


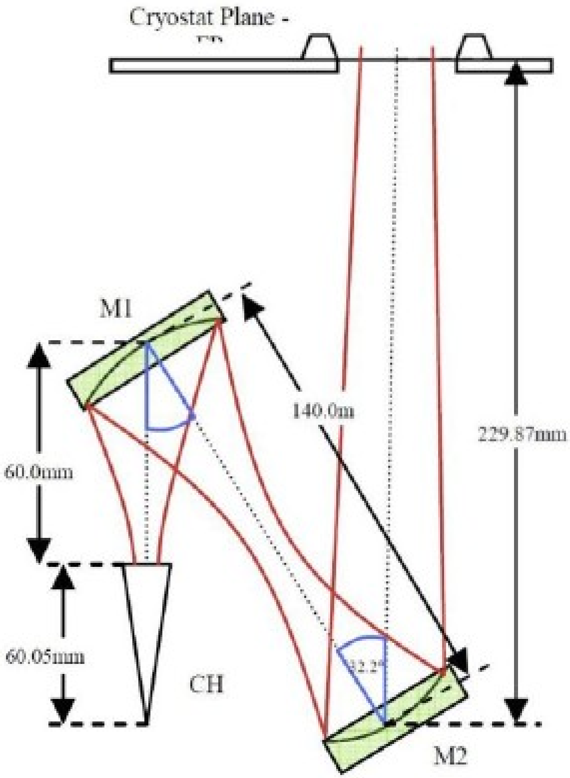




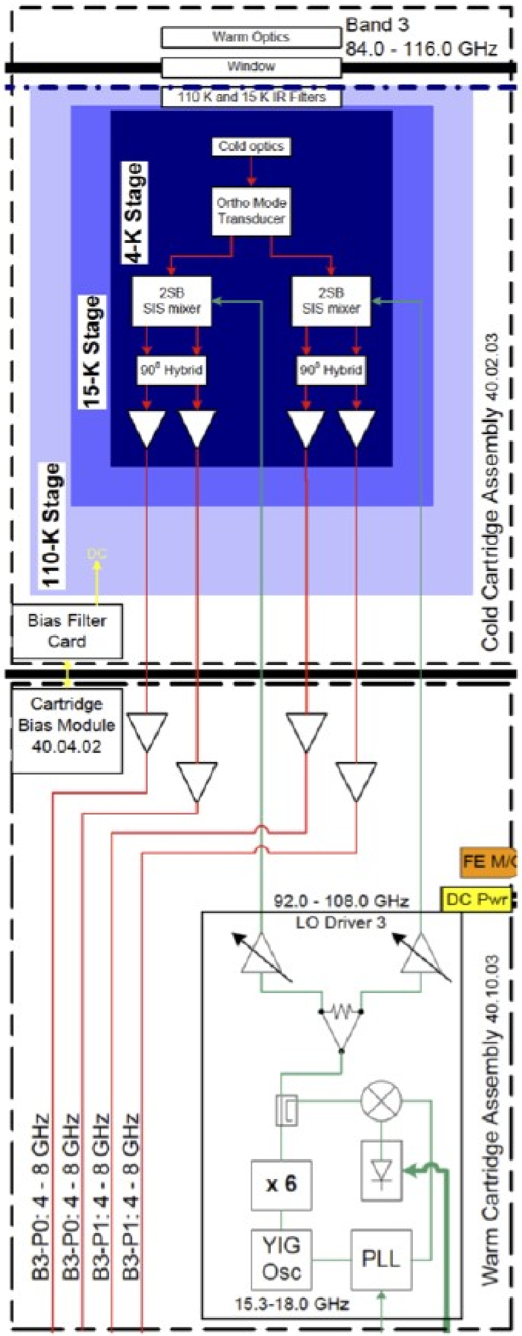


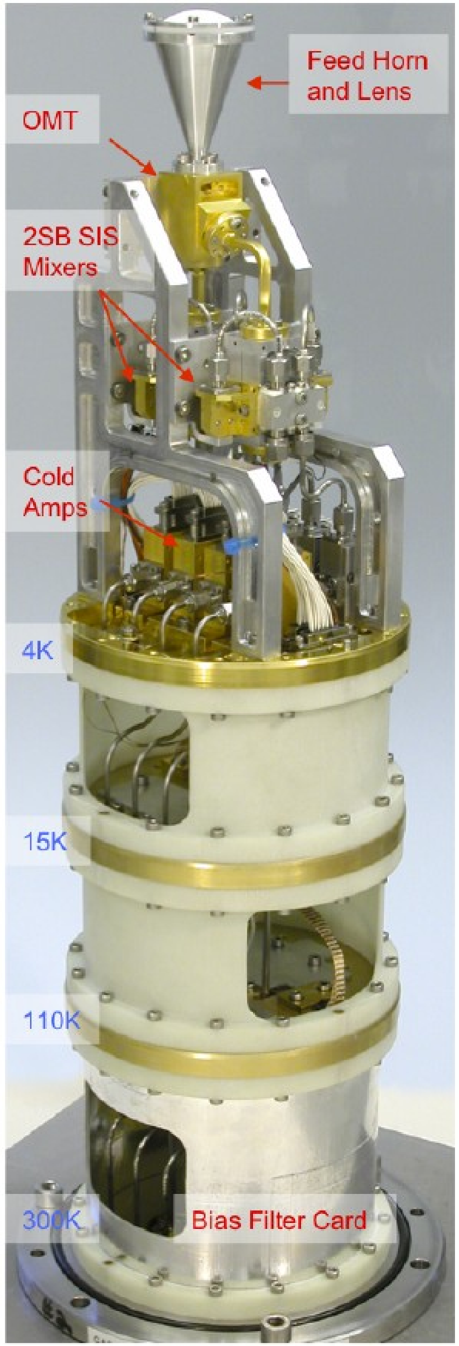
Antennas & detectors

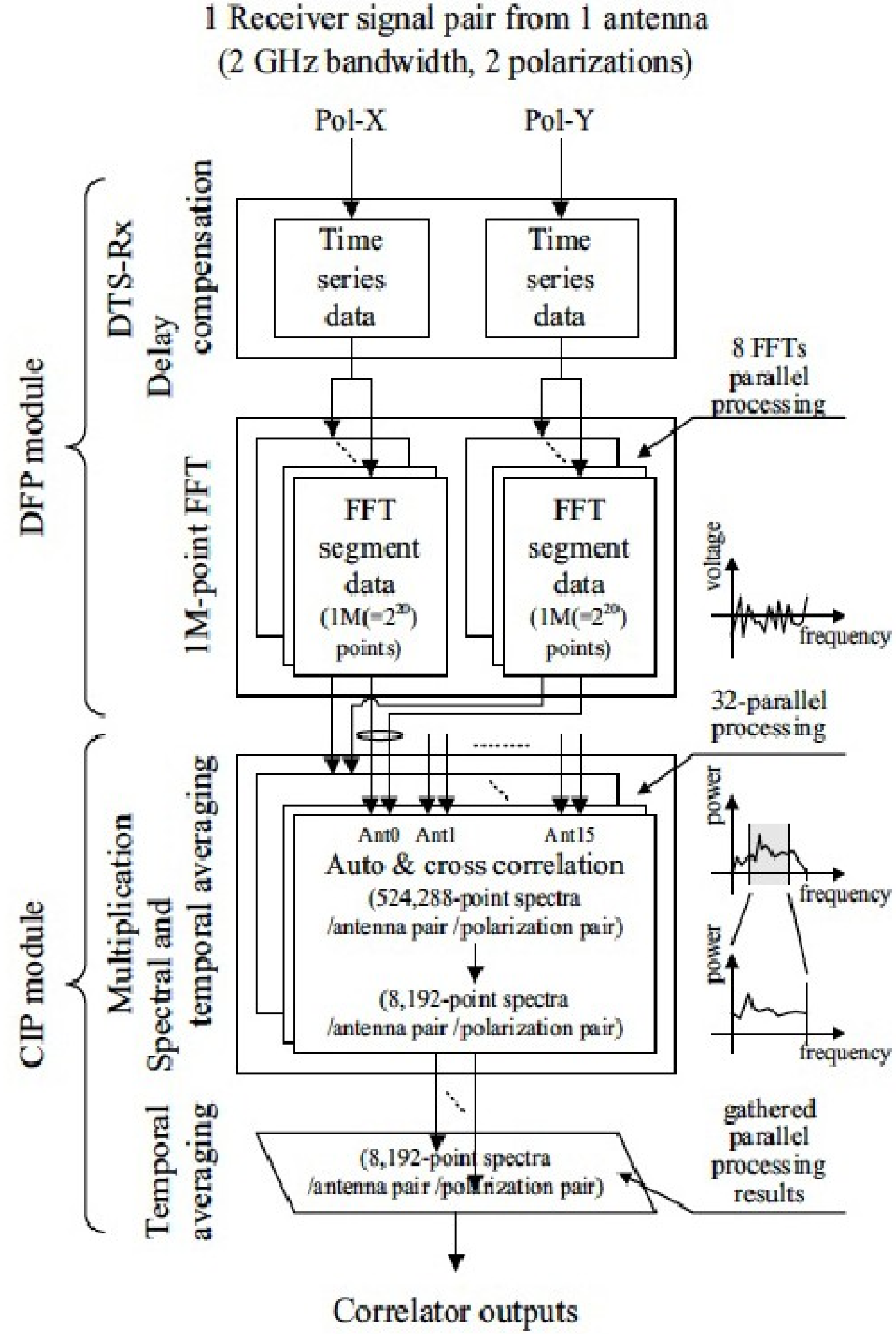




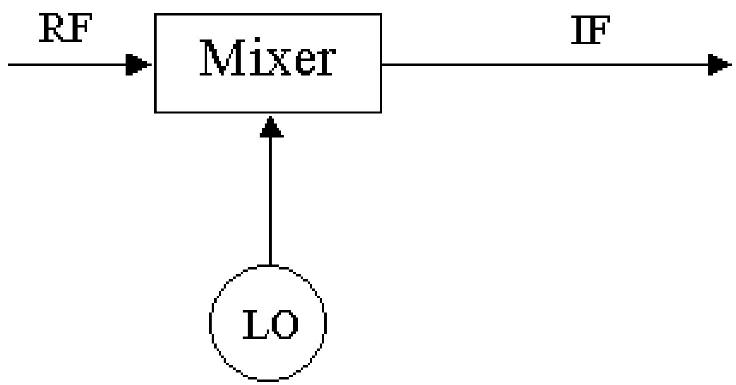
Příklad: ALMA – cesta signálu



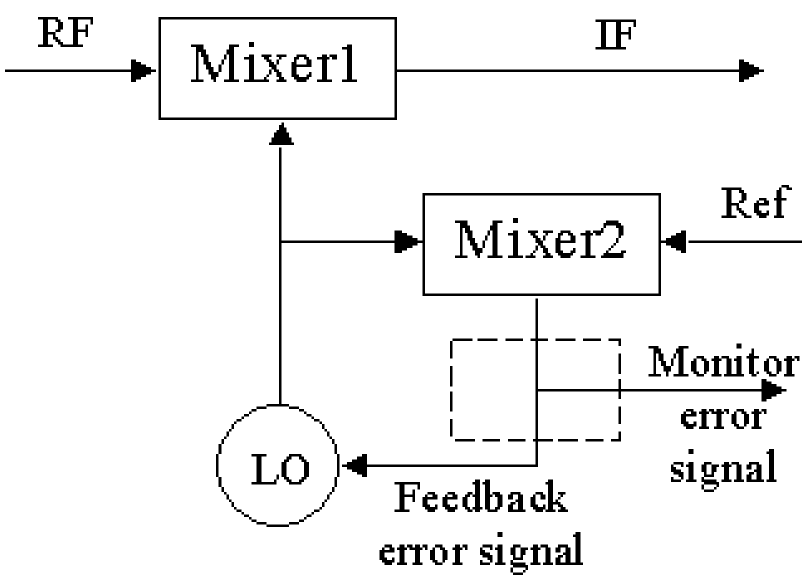




Antennas & detectors



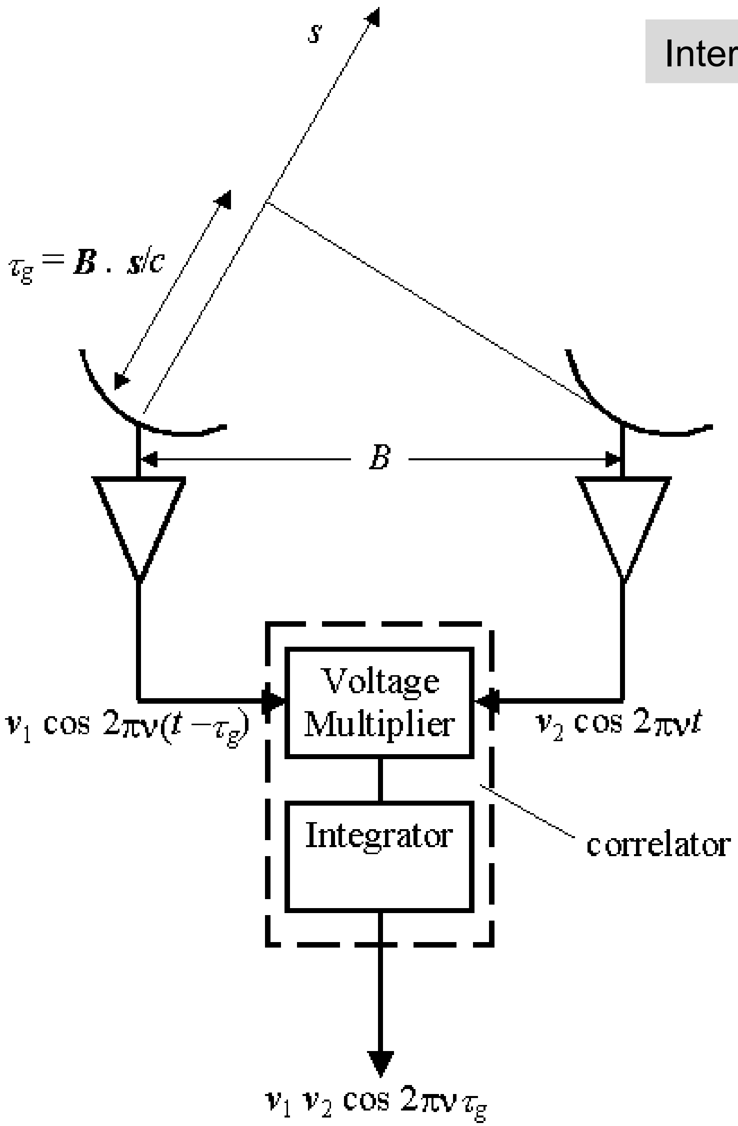
SD heterodyne

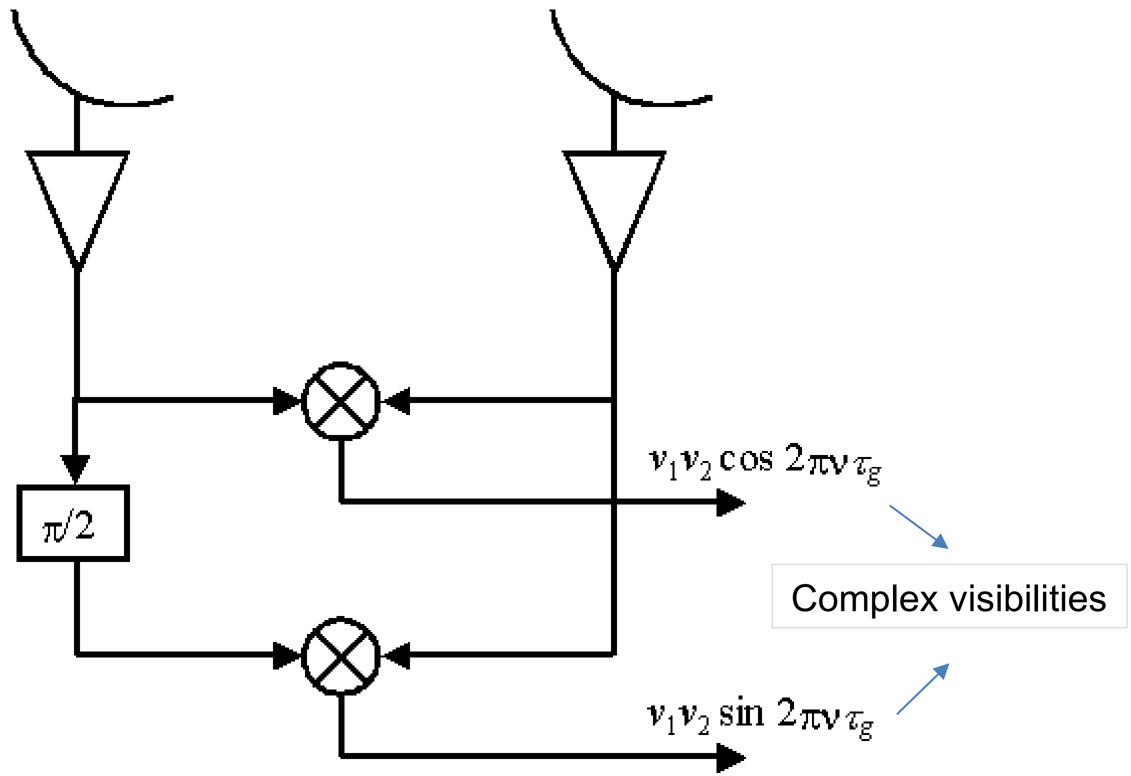


Interferometric heterodyne

Antennas & detectors

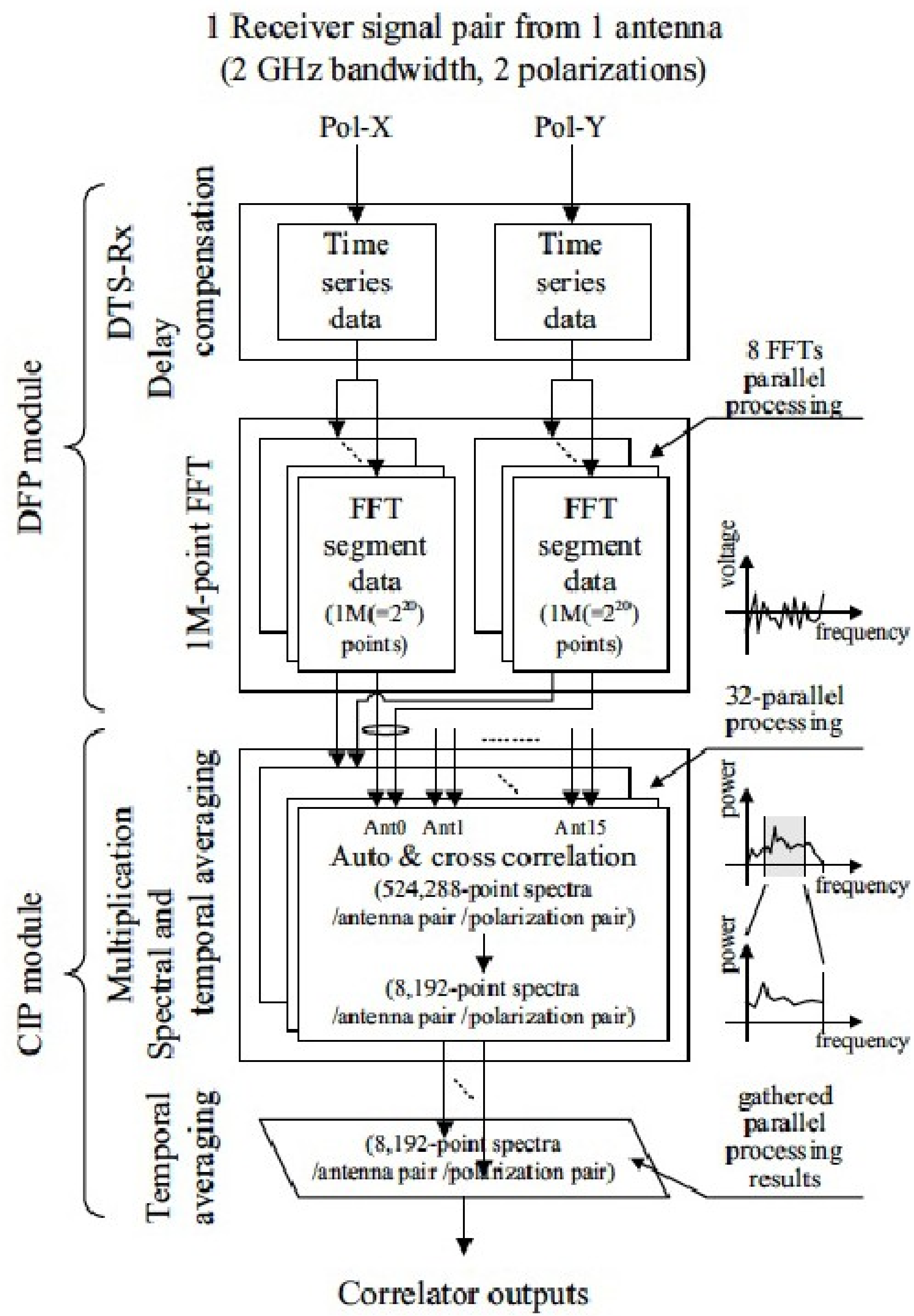
Interferometric correlator





Antennas & detectors

More on detectors/correlators shall come specifically for each radioastronomical method (e.g., spectro-polarimetry, aperture synthesis,...).



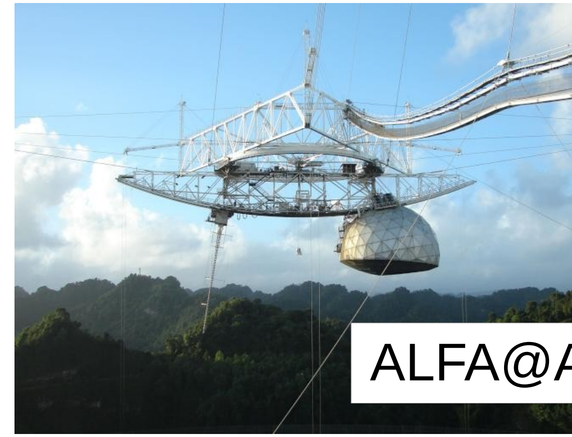
Interferometers & correlators: heavy HPC business...

(malá) část korelátoru ALMA @AOS

Trends: Multi-feed arrays – „CCDs“ for radio astronomy

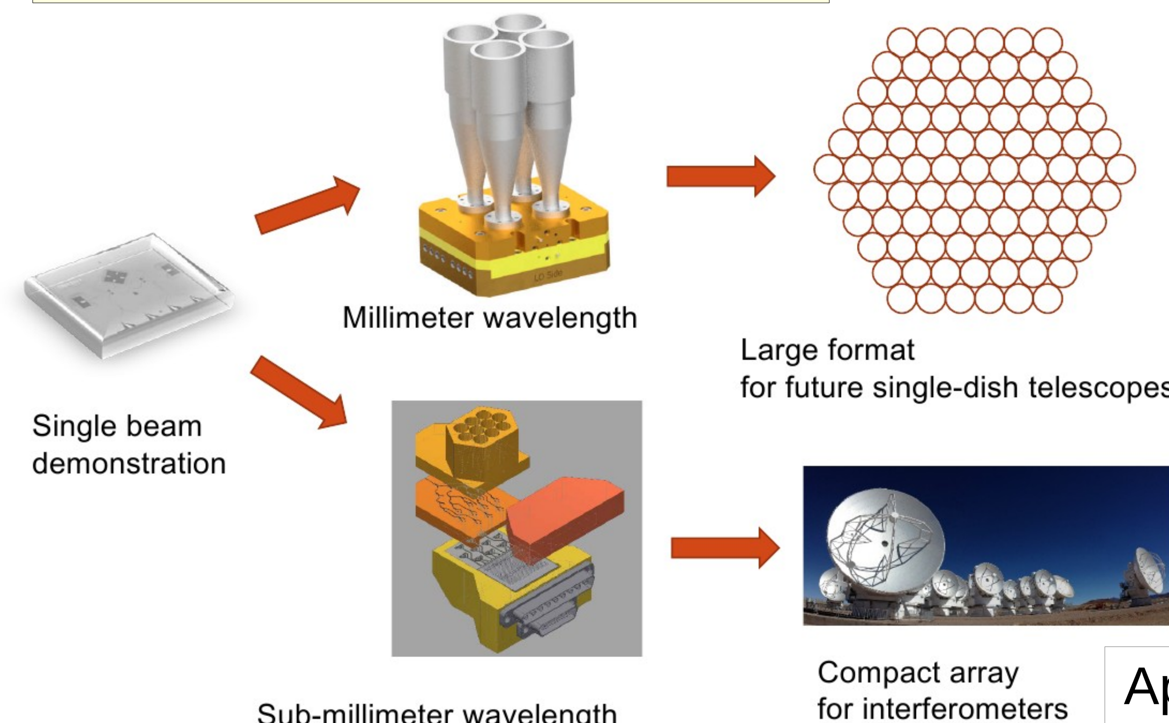
Sigle-feed:
FoV je dáno šířkou svazku jedné antény (ALMA 12m: ~ 1'@100GHz). Větší pole se mosaikují.

Multi-feed:
Zvětšení FoV, zrychlení mosaikování



ALFA@Arecibo

(see ALMA Development Workshop 2019 on-line proceedings)

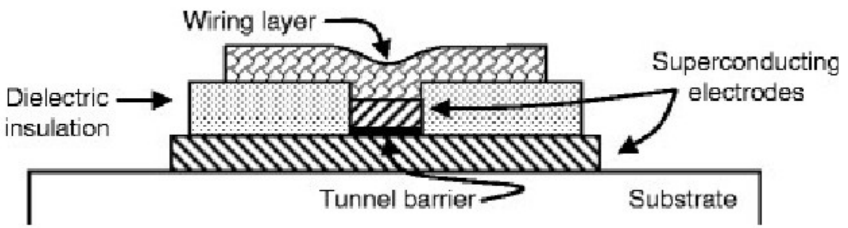


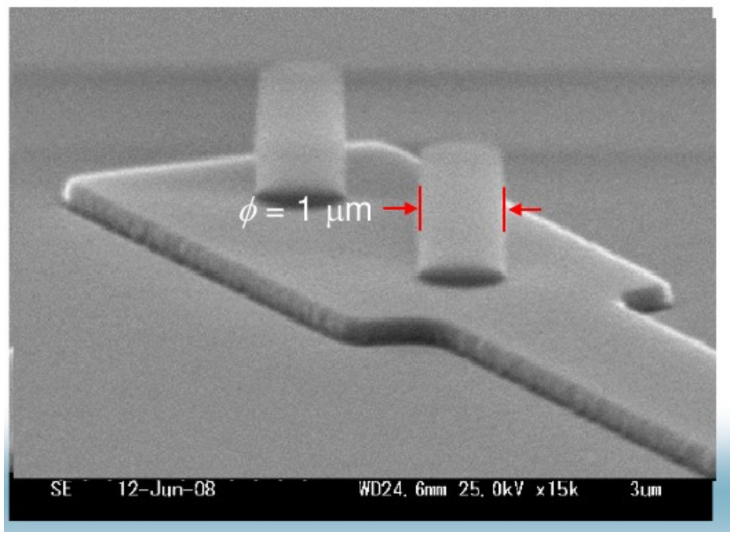
Phased multi-array@ASKAP

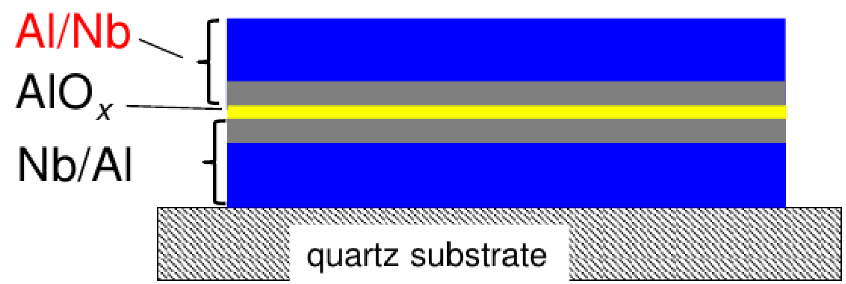
Aplikace i v mm/sub-mm oblasti

Trends 2: Increasing sensitivity & resolution

(see ALMA Development Workshop 2019 on-line proceedings)







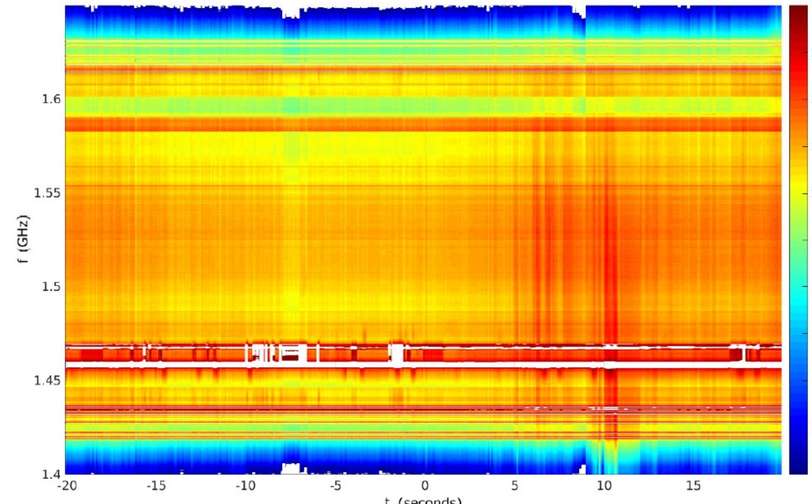
SKA1_Mid 350 MHz – 14 GHz
64 MeerKAT dishes
133 SKA1 dishes.

SKA1_Low 50 – 350 MHz
131,000 aperture array dipole
512 stations of 256 antennas

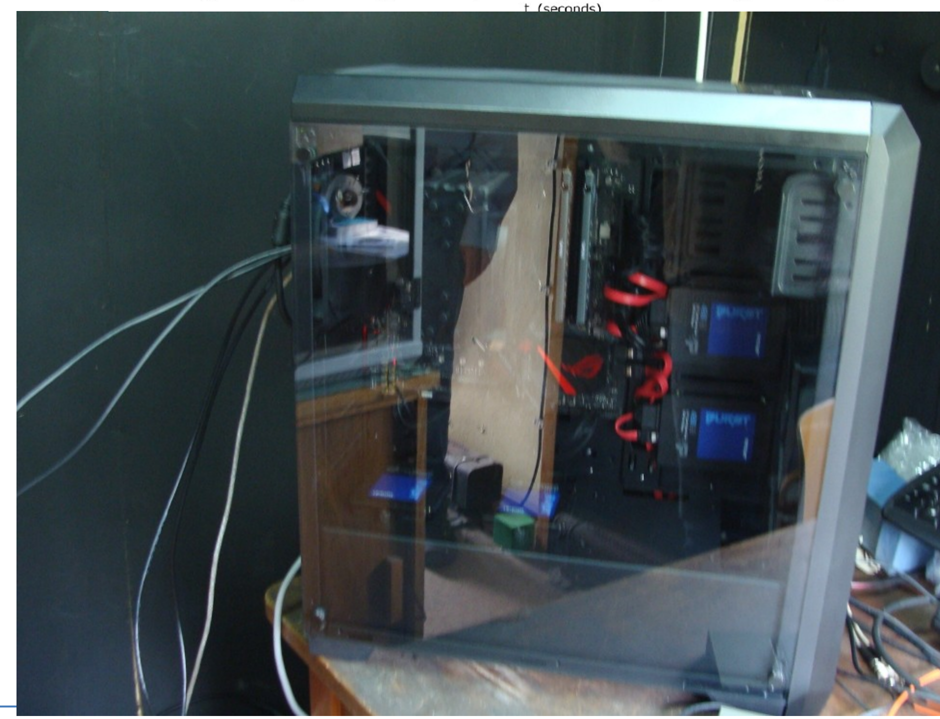
- Supravodivé detektory, nanotechnologie
- Vyšší frekvence (THz pásmo)
- Větší observatoře / VLBI sítě: Mezikontinentální, v budoucnu pravděpodobně i v kosmu

Trends 3: DSP technology now affordable for small & middle-size observatories

Spektrografy/spektro-polarimetry postavené jako Software-Defined Radio
Ondrejov **S**olar hi-**C**adence **A**utomated **R**adio **S**pectrograph(s) / OSCARS

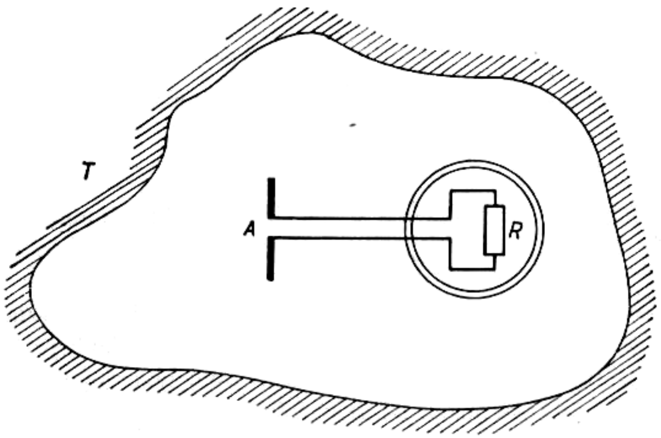


(Puričer, Kovář & Bárta, Electronics 2019)



No-ideal (d)effects and their mitigation: Basics of radio data calibration

Non-ideal effects - intro to calibration

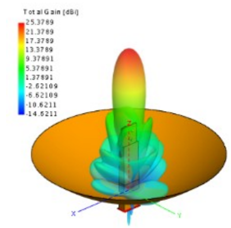


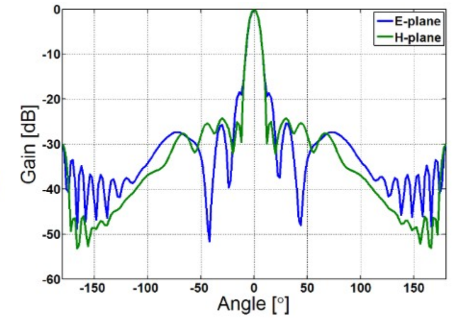
Concept of „antenna temperature“

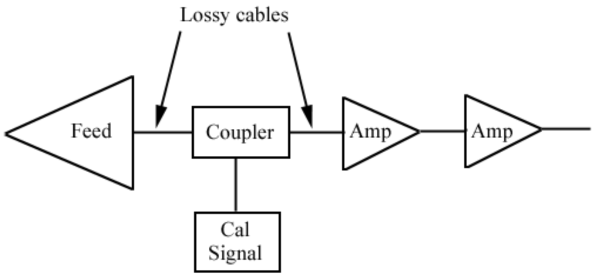
$$\Delta P_A = k_B T_A \, \Delta f$$

$$T_A = \int T_B(\vartheta,\varphi) G(\vartheta,\varphi) \frac{d\Omega}{4\pi}$$

gain





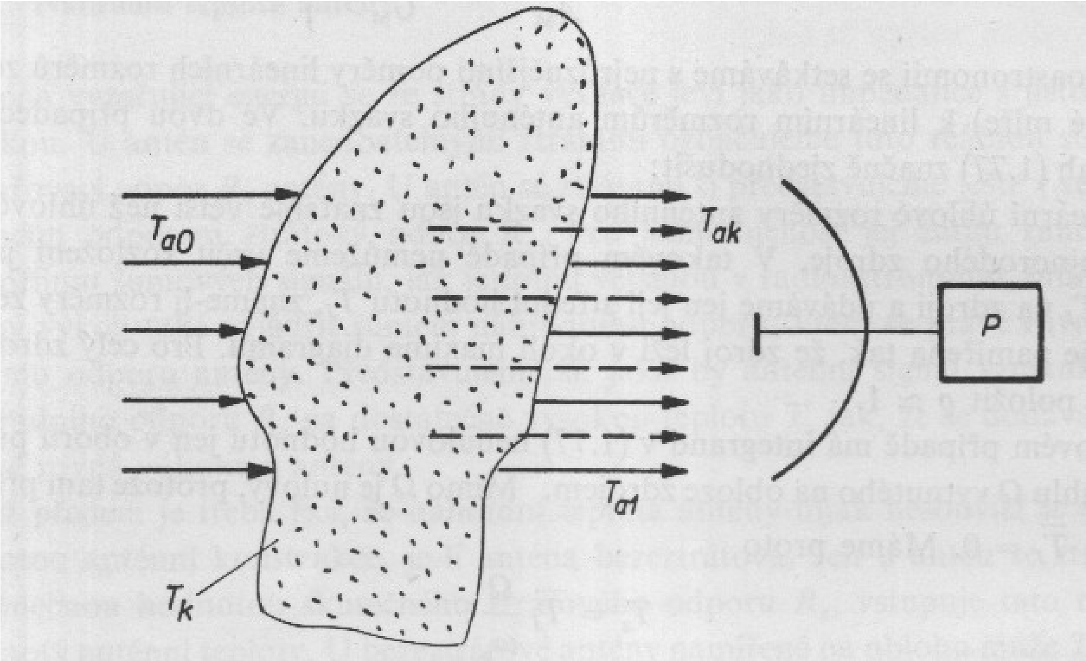


$P_{tot} = P_a + P_{sys} \Rightarrow T_{tot} = T_a + T_{sys}$ ← Non-ideal contribution: „System temperature“

$$T_{sys} = T_{bg} + T_{sky} + T_{spill} + T_{loss} + T_{cal} + T_{rx}$$

T_{bg} = noise contribution from microwave and galactic backgrounds
T_{sky} = noise contribution from atmospheric emission
T_{spill} = noise contribution due to ground radiation (spillover and scattering)
T_{loss} = noise contribution due to losses in feed
T_{cal} = noise contribution due to injected noise
T_{rx} = receiver noise temperature

Non-ideal effects - intro to calibration



$$T_{Jk} = T_k(1 - e^{-\tau_k})$$

$$T_{ak} = T_k(1 - \alpha)$$

$$T_a = T_{a1} + T_{ak}$$

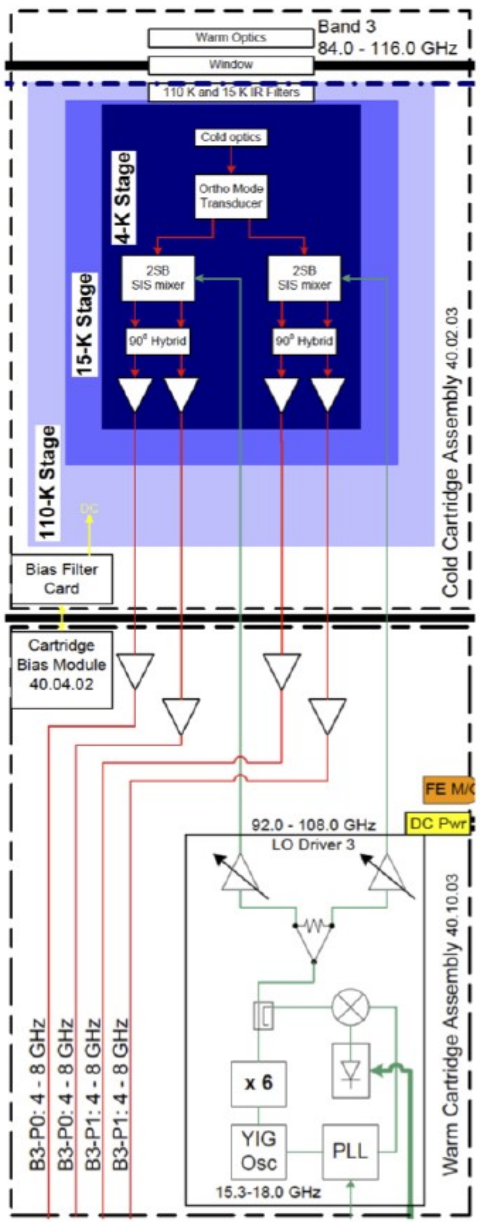
$$T_a = \alpha T_{a0} + (1 - \alpha)\, T_{ak}$$

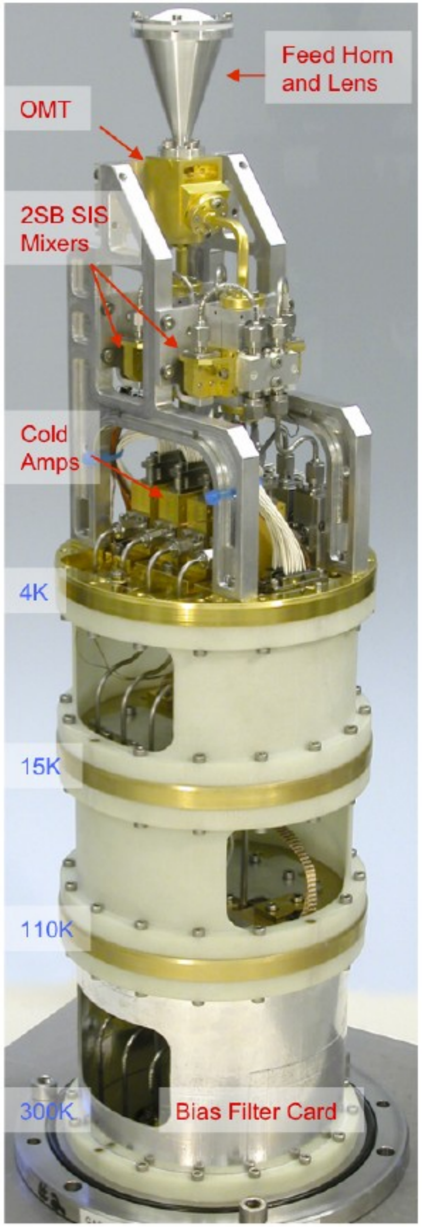
$$T_{\mathrm{sky}} = T_{\mathrm{atm}}(1 - e^{-\tau_0 \sec z})$$

$$T_{\mathrm{sky}}(z) = T_{\mathrm{sky}}(z=0)\frac{(1 - e^{-\tau_0 \sec z})}{(1 - e^{-\tau_0})}$$

$$T_{\mathrm{sys,ndsb}} = \frac{1}{\eta_{\mathrm{eff}} e^{-\tau_0 \sec z}}\left(T_{\mathrm{rx}} + \eta_{\mathrm{eff}} T_{\mathrm{sky,s}} + (1 - \eta_{\mathrm{eff}}) \times T_{\mathrm{amb,s}}\right)$$

Non-ideal effects - intro to calibration





$$T_{Jk} = T_k(1 - e^{-\tau_k})$$

$$T_{ak} = T_k(1 - \alpha)$$

$$T_a = T_{a1} + T_{ak}$$

$$T_a = \alpha T_{a0} + (1 - \alpha)\, T_{ak}$$

The most important is to suppress "noise" at the beginning of the amplification path!

Non-ideal effects - intro to calibration

Sensitivity: The minimum flux density (bright. temperature) we can detect above the noise (T_{sys})

$$\sigma_{\rm TP} = \frac{2\,k\,T_{\rm sys}}{\eta_{\rm q}\eta_{\rm c}A_{\rm eff}\sqrt{N\,n_{\rm p}\,\Delta\nu\,t_{\rm int}}}$$

N non-connected antennas

$$\sigma_{\rm S} = \frac{w_r\,2\,k\,T_{\rm sys}}{\eta_{\rm q}\eta_{\rm c}A_{\rm eff}(1-f_s)\sqrt{N(N-1)\,n_{\rm p}\,\Delta\nu\,t_{\rm int}}}$$

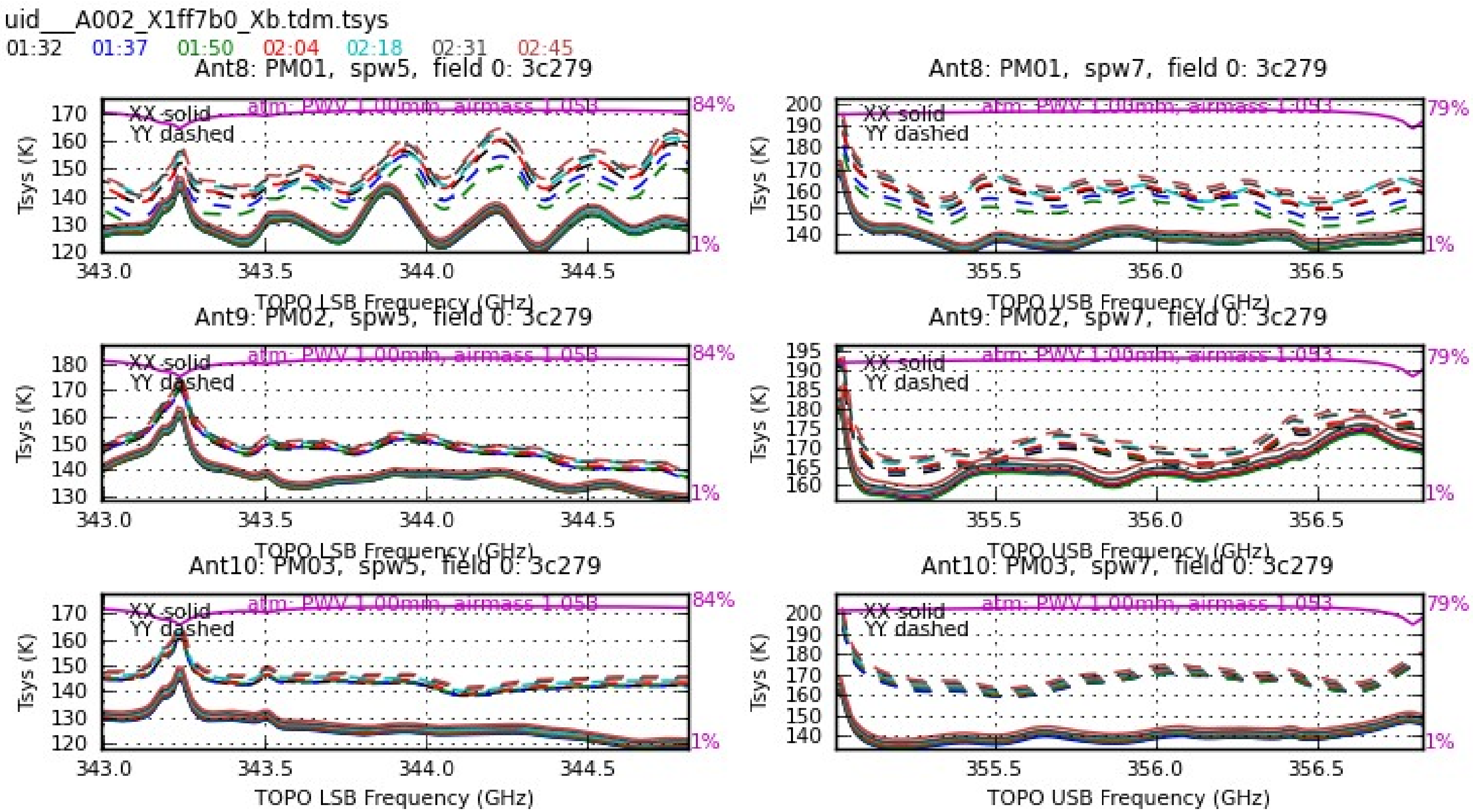
N antennas connected in interferometric correlator

$$\sigma_{\rm T} = \frac{\sigma_{\rm S}\lambda^2}{2k\;\Omega} \qquad \Omega = \frac{\pi\theta^2}{4\ln 2}$$

Non-ideal effects - intro to calibration

Tsys decomposition @ VLA

l	T_{bg}	T_{sky}	T_{spill}	T_{loss}	T_{cal}	T_{rx}	T_{sys}
92 cm	25	3	15	7	5	70	125
20 cm	3	3	14	8	2	30	60
6 cm	3	3	7	5	2	30	50
3.6 cm	3	2	5	2	2	16	30
2 cm	3	8	6	13	6	80	116
1.3 cm	3	17	6	21	7	100	154



Tsys @ ALMA example

Non-ideal effects – intro to calibration

$$P_{rec} = G \cdot B + P_{sys}$$

Gain: complex number in general, including wave-phase shifts

Methods of calibration

- Absolute: Hot and ambient loads – noise generators (heated resistors noise diode, …)
- Relative: Scaled to an (celestial) object with known radio brightness – *calibrator*
  Typical radio flux calibrators: Quasars, solar system objects (planets & their moons)

More detailed description of calibration procedures shall come specifically for each radioastronomical method (e.g., spectroscopy, interferometry,...).

Non-ideal effects – intro to calibration

Methods of calibration

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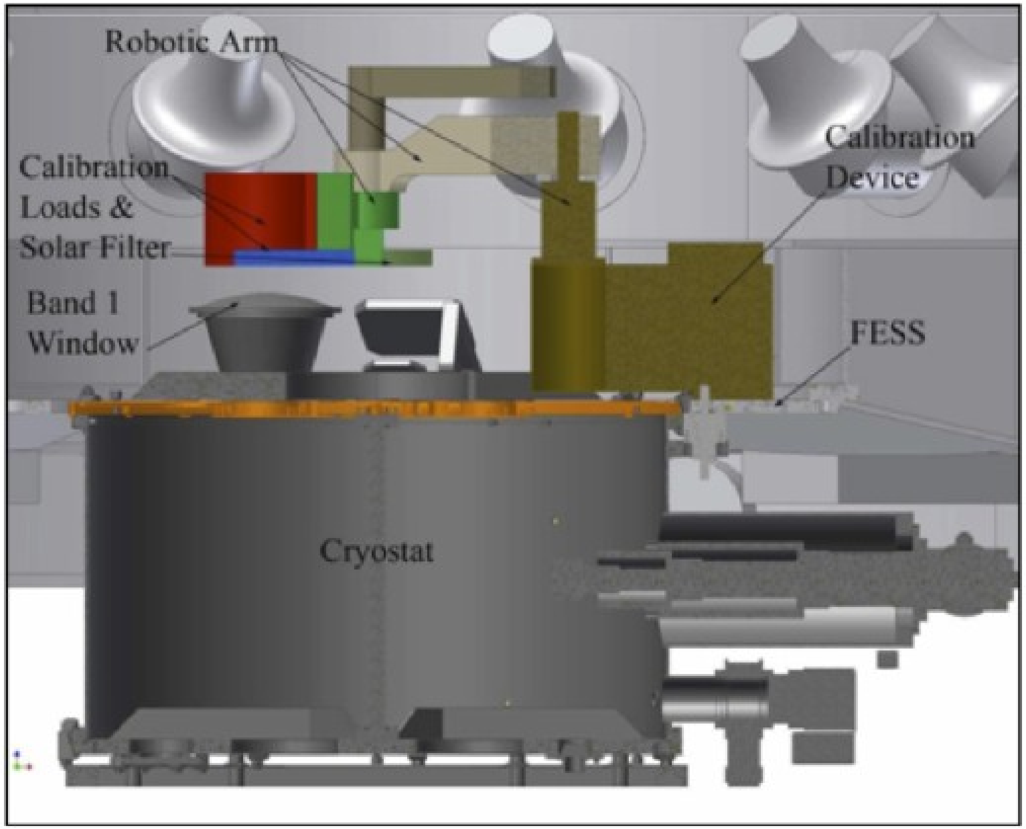
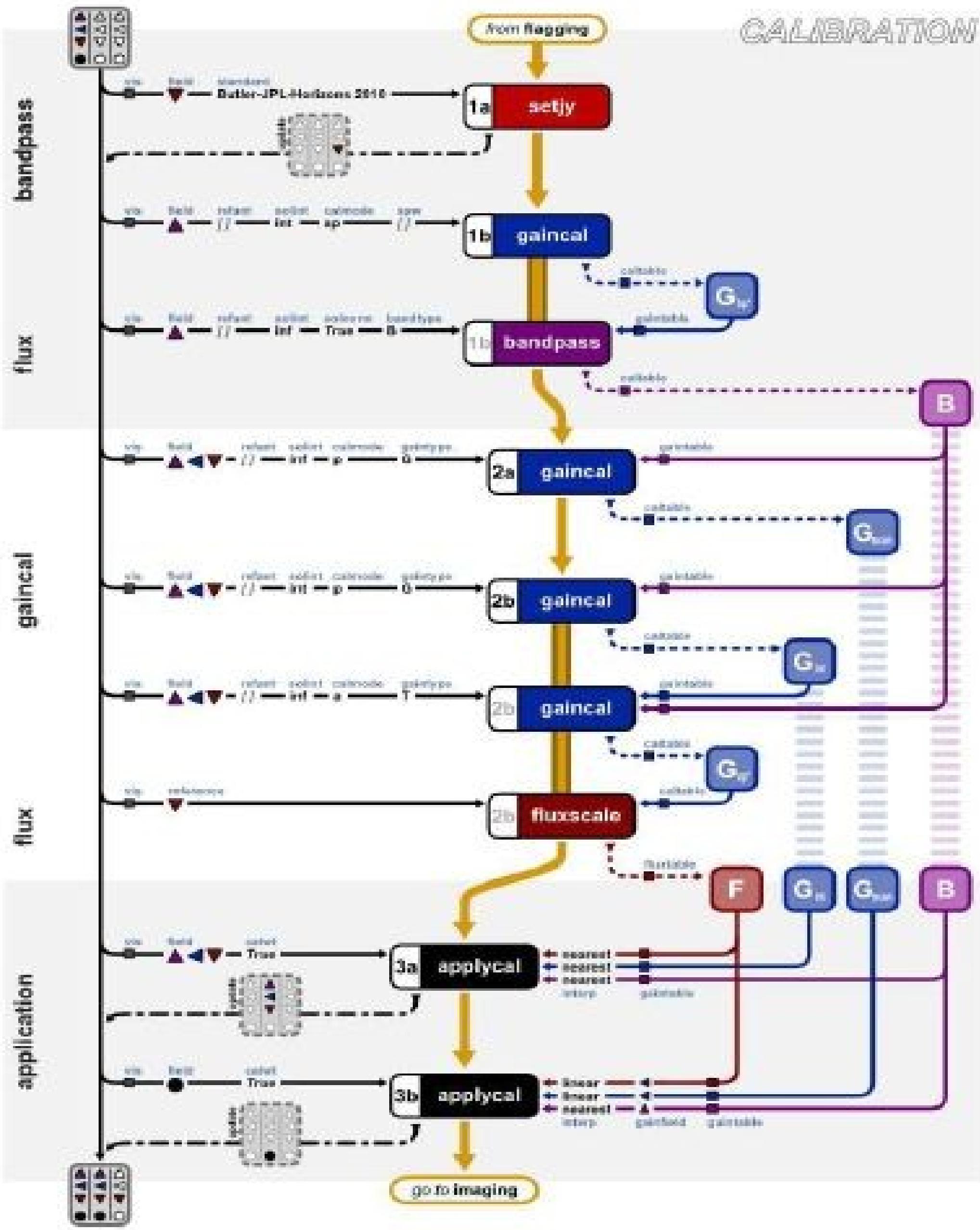
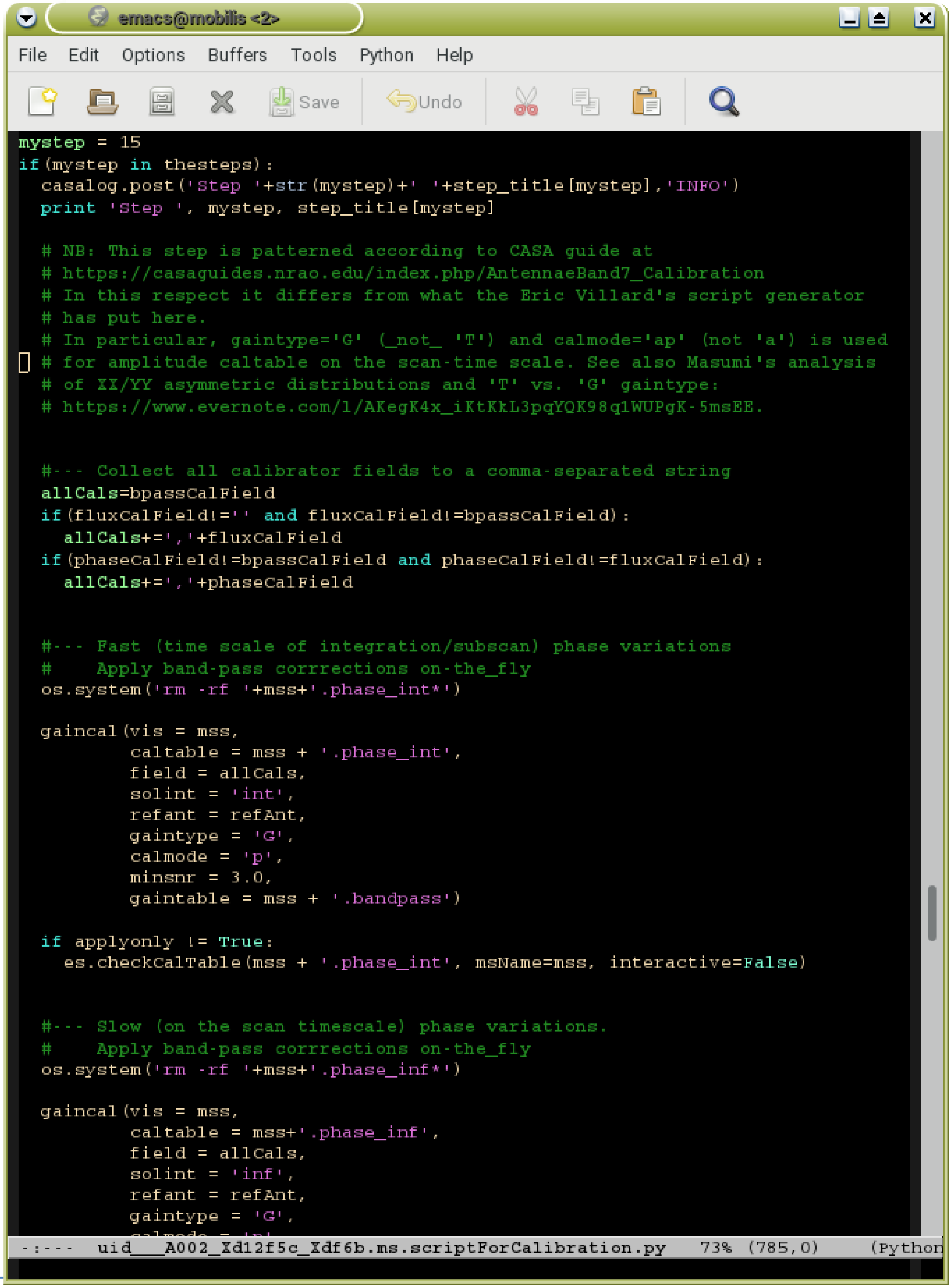


Example: ALMA calibration devices

More detailed description of calibration procedures shall come specifically for each radioastronomical method (e.g., spectroscopy, interferometry,...).

Illustration: Calibration in CASA





```
mystep = 15
if(mystep in thesteps):
  casalog.post('Step '+str(mystep)+' '+step_title[mystep],'INFO')
  print 'Step ', mystep, step_title[mystep]

  # NB: This step is patterned according to CASA guide at
  # https://casaguides.nrao.edu/index.php/AntennaeBand7_Calibration
  # In this respect it differs from what the Eric Villard's script generator
  # has put here.
  # In particular, gaintype='G' (_not_ 'T') and calmode='ap' (not 'a') is used
  # for amplitude caltable on the scan-time scale. See also Masumi's analysis
  # of XX/YY asymmetric distributions and 'T' vs. 'G' gaintype:
  # https://www.evernote.com/l/AKegK4x_iKtKkL3pqYQK98q1WUPgK-5msEE.


  #--- Collect all calibrator fields to a comma-separated string
  allCals=bpassCalField
  if(fluxCalField!='' and fluxCalField!=bpassCalField):
    allCals+=','+fluxCalField
  if(phaseCalField!=bpassCalField and phaseCalField!=fluxCalField):
    allCals+=','+phaseCalField


  #--- Fast (time scale of integration/subscan) phase variations
  #    Apply band-pass corrrections on-the_fly
  os.system('rm -rf '+mss+'.phase_int*')

  gaincal(vis = mss,
          caltable = mss + '.phase_int',
          field = allCals,
          solint = 'int',
          refant = refAnt,
          gaintype = 'G',
          calmode = 'p',
          minsnr = 3.0,
          gaintable = mss + '.bandpass')

  if applyonly != True:
    es.checkCalTable(mss + '.phase_int', msName=mss, interactive=False)


  #--- Slow (on the scan timescale) phase variations.
  #    Apply band-pass corrrections on-the_fly
  os.system('rm -rf '+mss+'.phase_inf*')

  gaincal(vis = mss,
          caltable = mss+'.phase_inf',
          field = allCals,
          solint = 'inf',
          refant = refAnt,
          gaintype = 'G',
```

Take-home message

- Radioastronomical systems are quite a large – the reasons are hunt for (1) higher SNR (needs big antenna area) and (2) resolution.
- The single-dish instruments have technical limit to antenna size, so far fully movable antennas are ~100m in diameter and lilely will not grow. The largest “stationary” aperture currently is FAST (~500m).
- Problem can be overcome by constructing antenna arrays: Interferometry / aperture synthesis. There are two ways how to combine the signals: (1) analog addition and (2) DSP + correlations.
- Working with high frequency signals is cumbersome: The solution is in mixing with the LO signals (mixer, downconversion, IF).
- Trends tend to the multi-feed arrays (even phased), cooled superconductor detectors, higher frequencies and longer baselines (VLBI).
- Instrument, atmosphere and man-made interference “pollute” the signal: In amplitude, phase, spectral characteristics and polarization. In order to mitigate those issues, a careful calibration of the data is necessary. I.e. comparison of the measured signal with that expected by observing the “source” (celestial or artificial inserted into the signal path) with known properties.