MadMax: Optics considerations

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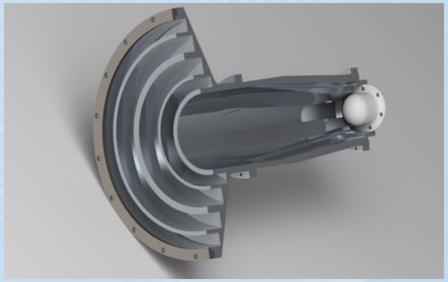
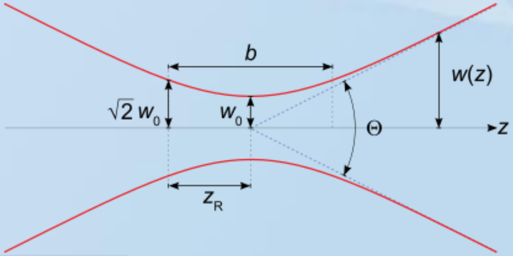
Outline

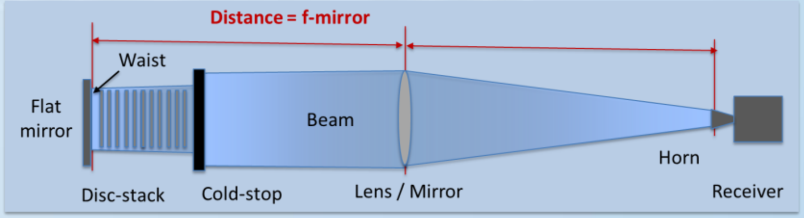
- Introduction
  - Who am I
  - What are we doing ?



- MadMax from an optical point of view
  - Horn antennas
  - Gaussian optics (Diffraction limited optics)
  - Sketch of a possible MadMAX optics layout
  - Possibilities to optimize the system



- Conclusions



Who am I?

- PhD from Cologne University in 2003
- since early 2003: employee at the MPIfR in the “Submillimeter division”
- since 2011: head of the “Incoherent receivers” group
- Feb. 2015 to June 2018: head of the “APEX receiver systems” group
- since April 2018: head of the “Project group” in the “Electronics division”

GREAT: a heterodyne receiver for SOFIA

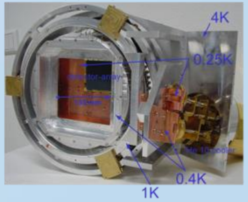
- Boeing 747sp as telescope basis with a 2.5m Infrared-telescope
- joint Program between the US (80%) and Germany (20%)

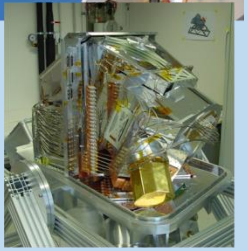
German REceiver for Astronomy at Terahertz frequencies

- modular heterodyne spectrometer
  - 0.5 to 4.7 THz
- developed by a consortium of four German science institutes:
  MPIfR (PI-institute), University of Cologne, DLR-PF, MPS

A-MKID a large camera for APEX

- dual color APEX direct detection camera
  - LFA: 347 GHz
  - HFA: 850 GHz
- squared field of view: > 15 x 15 arcmin2
- number of pixels (pixel spacing 1 Fλ)
  - ➔ 3520 pixel in LFA
  - ➔ 21600 pixel in HFA
- detectors operating with sensitivities dominated by the sky background
- good system stability that allows mapping of extended structures
- cooling:
  - two 4K pulse-tubes
  - He 10 sorption cooler





APEX

Location	Llano de Chajnantor 50 Km east of San Pedro de Atacama, Northem Chile
Coordinates	Latitude : 23º00'20.8" South Longitude :67º45'33.0" West Altitude : 5105 m
Diameter	12 m
Mass	125000 kg
Main reflector	264 aluminium panels
Secondary reflector	Hyperboloidal Aluminium; Diameter 0.75m
Mounting	Alt-Az
Surface accuracy (r.m.s.)	17 micron
Pointing accuracy (r.m.s.)	2" rms over sky Pointing accuracy on track 0.6"
Manufacturer	Vertex Antennentechnik
f/D	8
Beam width (FWHM)	7.8" * (800 / f [GHz])

The Effelsberg 100-m telescope

You may know:

Europe's largest dish (only second to 103-m GBT)

Aperture : 7850 m^2,

Gain : 1.5 K/Jy (<20 GHz)

Gregorian design : prime & secondary focus

Surface accuracy : < 0.5 mm - track < 0.3mm

Weight : 3200 t,

slewing speed : 30/16 deg/min

Frequency cov. : 400 MHz – 90 GHz

Resolution : 9' @ 1.4 GHz, 10" at 87 GHz,

Pointing acc. : ~3"

Observing modes: continuum, spectroscopy, pulsars & transients, VLBI (EVN, global, mm)

24/7 Operation fully funded via core budget of institute

Comprehensive renewal of receiver/backend systems nearly complete

New-technology driver and test-bed: state of the art with direct access

Horn antennas

Horn antennas can be

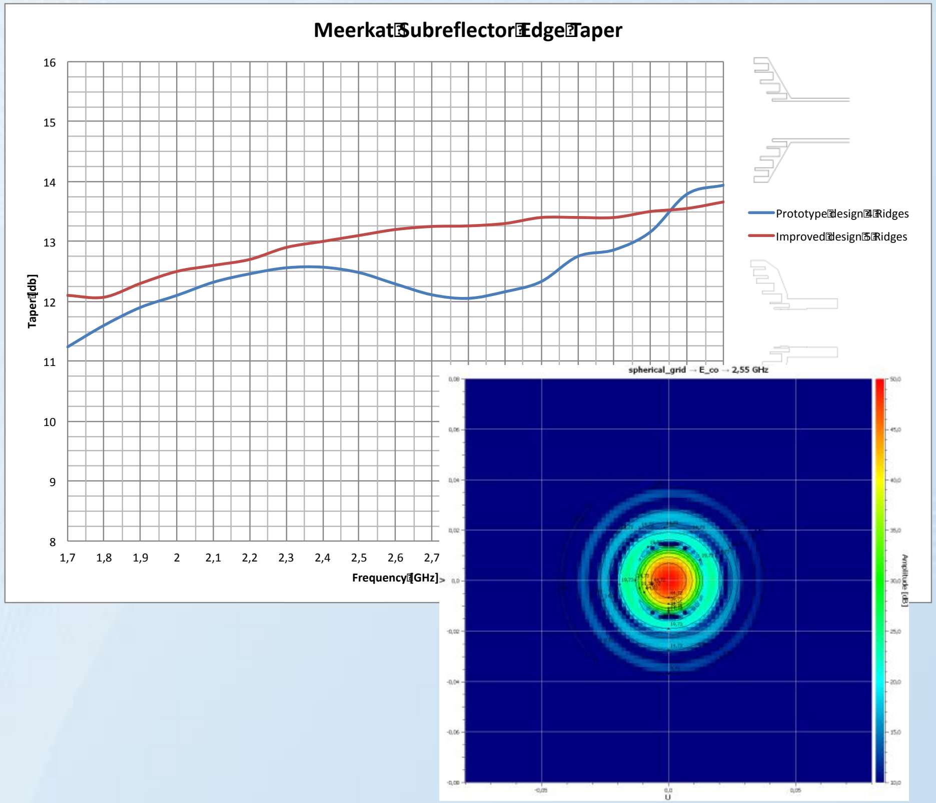
- optimized to couple nearly perfect to a Gaussian beam,
- adapted to a wide range of opening angles (~ 7° to ~ 60°),
  - small angles result in long horns
- designed for a huge relative bandwidth (e.g.0.5 to 3 GHz)
  - huge bandwidth means focus position is changing with frequency

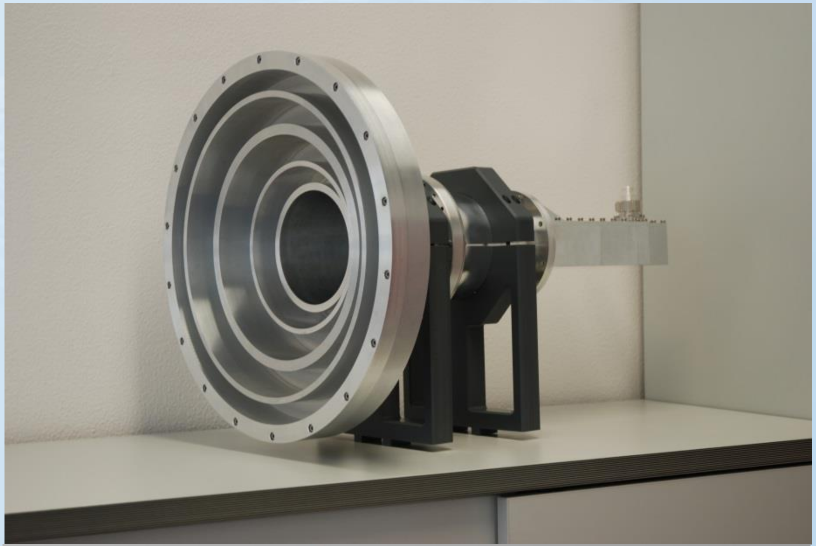
They give access to both polarizations and their “output port” can be matched to a waveguide or to a coaxial line.

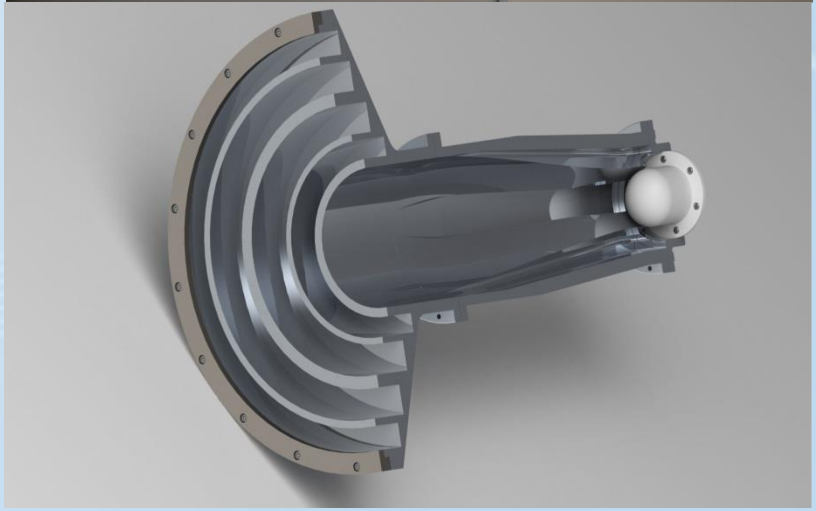
Optics and Horn antenna should be optimized together

Feed Design

- Octave feed and OMT
- 1.75 -3.5 GHz bandwidth
- Improved design finalized
- Design by C. Kasemann



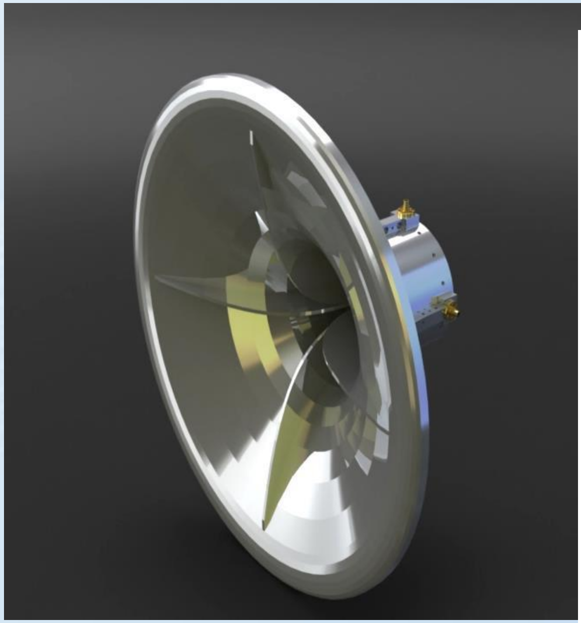


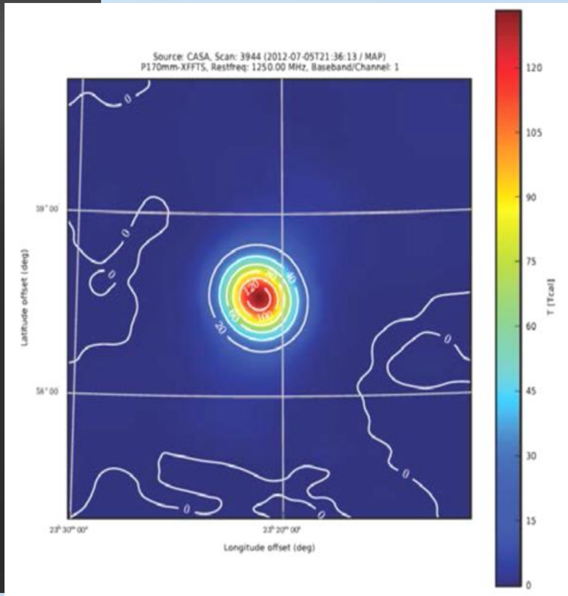


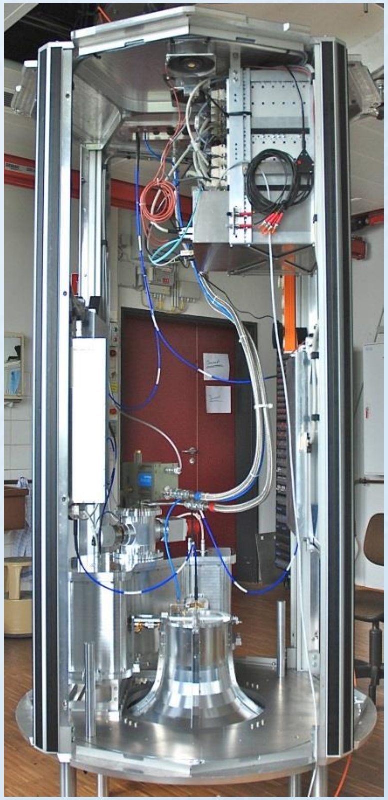
Ultra-Broad-Band Receiver

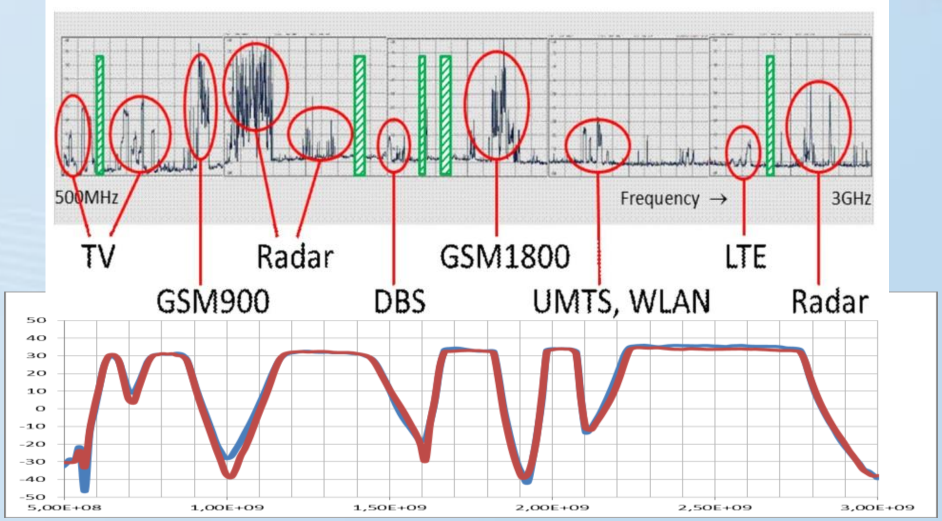
Designed for Pulsar observations

- increase in bandwidth -> sensitivity
- covers 0.6GHz – 2.5Ghz (3.0GHz)
- RFI requires filtering
- $T_{rec} < 20K$
- Baseband detection

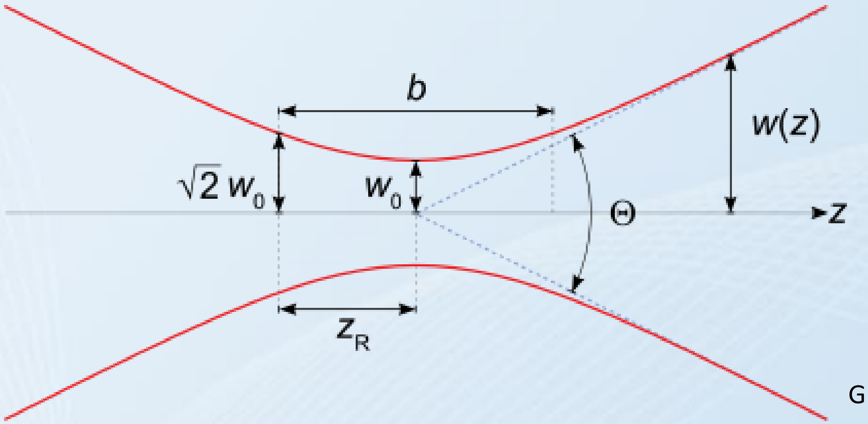








Gaussian optics



A standard horn antenna couples with > 95% to the Gaussian fundamental mode!

Graphics taken from Wikipedia

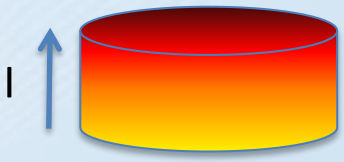
- Paraxial approximation applied to formalism of Maxwell
- Using Gaussian beams (monochromatic beam with Gaussian amplitude profile)
  - for simplification only fundamental transverse mode (TEM_{00}) is used

Waist radius	ω_0
Rayleigh length	$z_R = \frac{\pi {\omega_0}^2}{\lambda}$
Spot size parameter	$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$
Wave-front curvature	$R(z) = z \left[1 + \left(\frac{z_R}{z}\right)^2\right]$
Beam divergence	$\theta = 2\,\varphi = 2\frac{\lambda}{\pi\omega_0}$

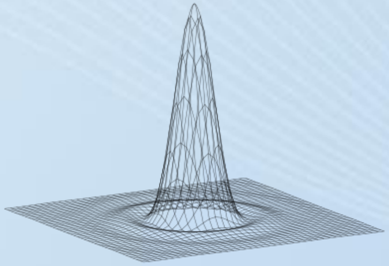
MadMax from an optical perspective

- Stack of n 1m diameter radiators each having a
  - uniform filling factor
  - planar wave-front
  - beam opening angle
    $\lambda/D = (30\text{mm} > \lambda > 3\text{mm})/\ 1\text{m} = (1.7° > \text{FWHM} > 0.17°)$

Uniform circular intensity distribution



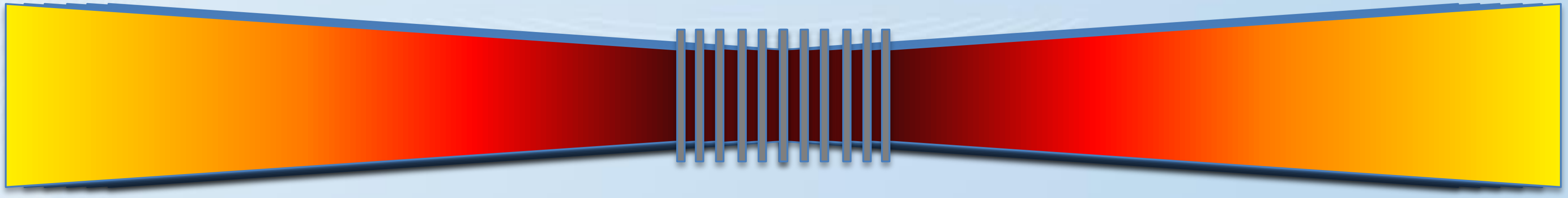
Fourier-Transform →



3d-plot from Wikipedia

Airy-pattern in far field

➔ Superposition of n individual (interacting?) signal-beams



Beam

Disc-stack (Booster)

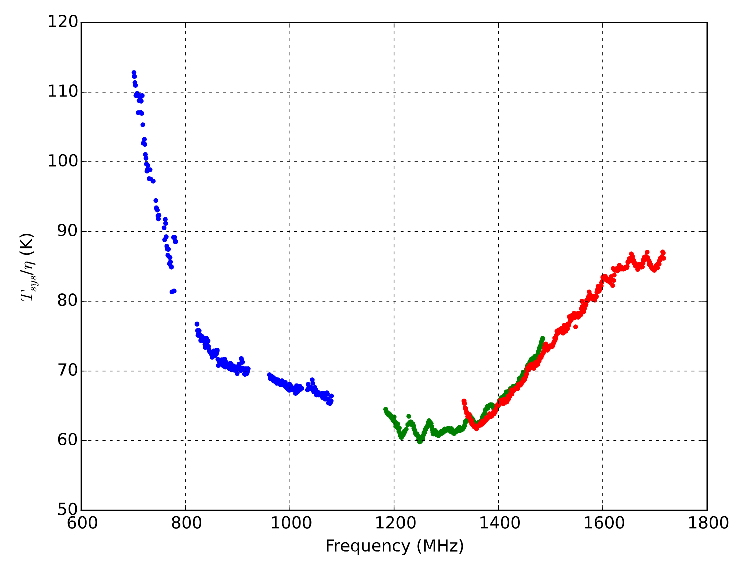
Beam

Phased Array Feed (PAF) for Effelsberg

- Modified ASKAP PAF
- 188 patch antennas
  (94 per polarization)
- Frequency range 0.7GHz – 1.8GHz
- 300 MHz instantaneous bandwidth
- 36x2 independent beams
- Science commissioning Dec 2017

A multi-element receiver can to some extend access the power in the side lobes.

But on (very) high cost!



Disk as transmitter

Diffraction tells us FWHM ≥ λ/D

FWHM to beam-waist (correct FWHM(z) to w(z); but both are linear to z…) :

- FWHM is the half power width of the intensity distribution,
  waist is 1/e width of the field distribution ➔

  $0.5 = e^{-2\frac{x^2}{\varphi^2}}$ with x = FWHM/2 = $\frac{\lambda}{2D}$ ↔ $\varphi = \frac{\lambda}{2D}\frac{\sqrt{2}}{\sqrt{-\ln(0.5)}}$ (opening angle)

- from Gaussian optics: $\varphi = \frac{\lambda}{\pi\omega_0}$

  $\rightarrow \frac{\lambda}{\pi\omega_0} = \frac{\lambda}{2D}\frac{\sqrt{2}}{\sqrt{-\ln(0.5)}}$ ↔ $\omega_0 = \frac{\sqrt{-2\ln(0.5)}}{\pi} D \approx 0.375\ \mathrm{D}$ (in the MadMax case 375mm)

In far field the beam transmitted by the disk is equivalent to a Gaussian beam with a waist of 375mm at location of the disk

This waist-size is frequency independent!!

Coupling disk-beam to a receiver

Coupling the Receiver to exactly the far-field disk-beam:

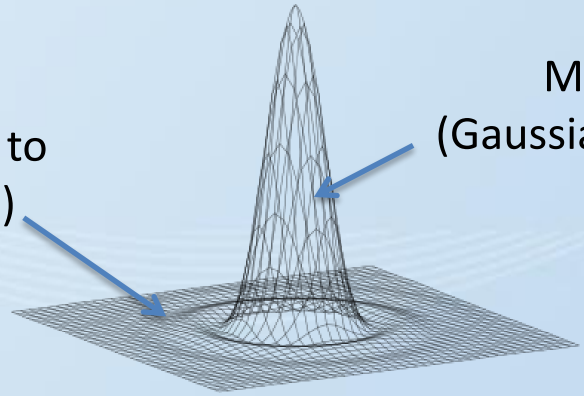
Part of the receiver beam power which is coupled to the disk:

$$\frac{P(r)}{P_0} = 1 - e^{-2\left(\frac{r}{\omega_0}\right)^2} = 97.2\% \text{ for r = 500mm, } \omega_0 \text{ = 375mm}$$

This means ~3% of the receiver beam are dumped in the mounting structure!

➔ without cooling, the system noise temperature will be increased by ~9K!

➔ this does not mean we are receiving 97.1% of the radiated power!



Side lobes (not coupled to main mode)

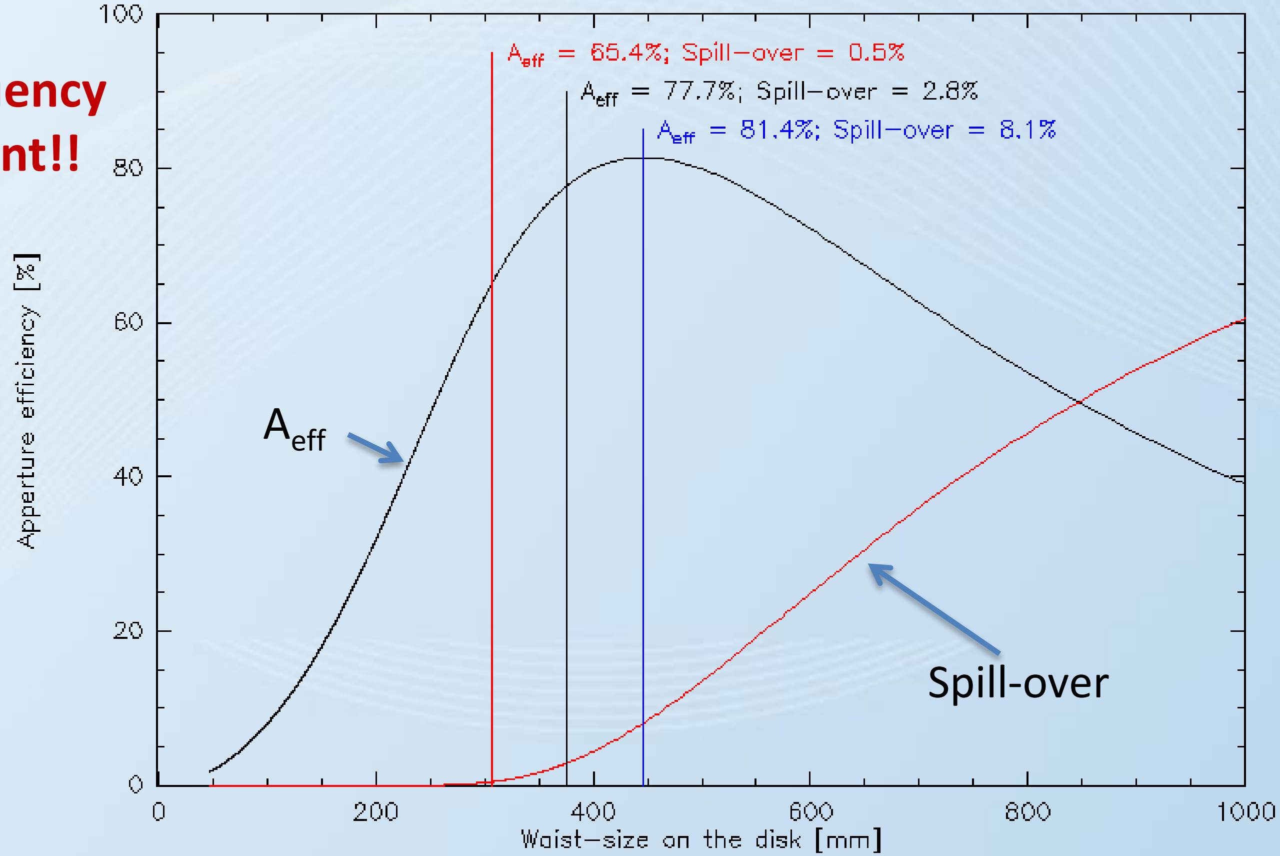
Main beam (Gaussian main mode)

Is this the best we can do?

Aperture efficiency

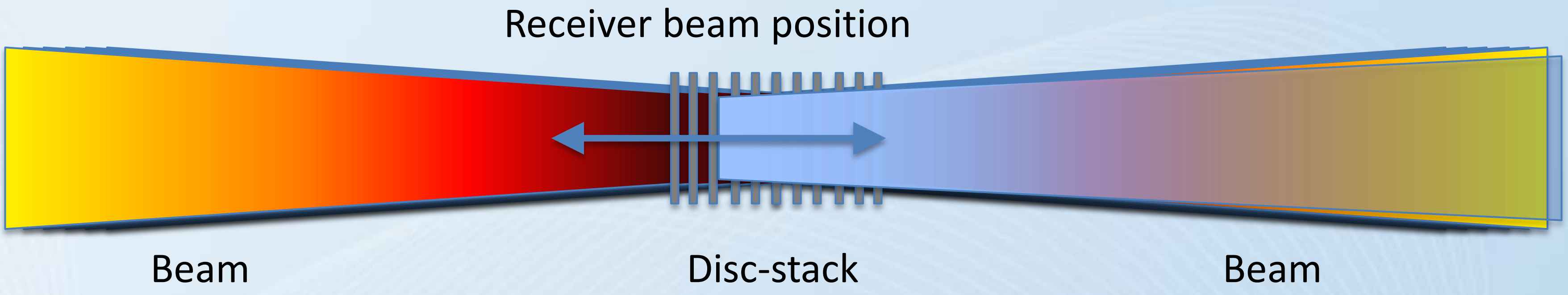
- How efficient couples a Gaussian beam to an equally illuminated 1m diameter field?
- Same problem as in Radio Astronomy:
  Main dish is illuminated by a point source equally

This is frequency independent!!



Maximizing the Aperture efficiency means adding spill-over!

Waist position



Each disk has its own beam,

but we only can place one receiver waist within the stack

➔ waist will be off by 0.5 times stack-length in best case

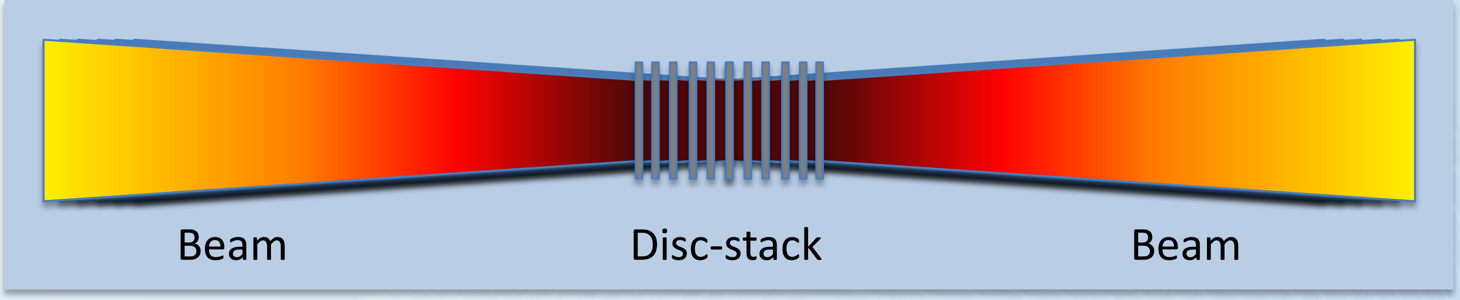
- So where to put the receiver focal plane (= waist position) ?

Waist-position for a waist of 375mm at 10 GHz is uncritical

  - lowest frequency is the worst case
  - changes in coupling integral are negligible

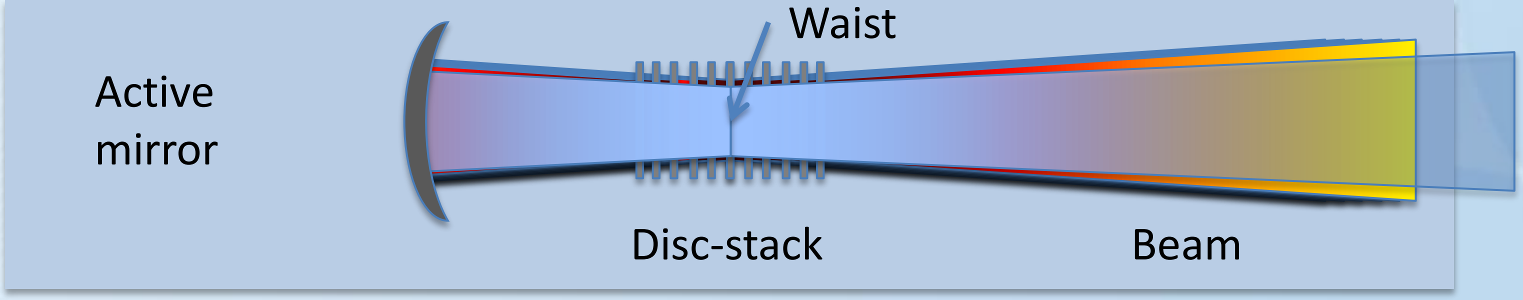
➔ we can assume equal coupling for all disks in the stack

Optics (1)

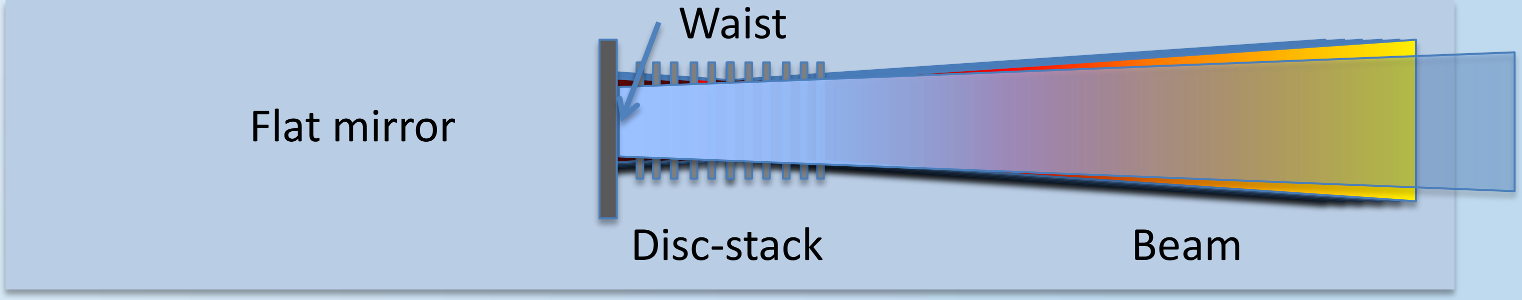


- Disk stack radiates in two directions
  ➔ we need a cavity like system to be able to receive all signals
  (assumption here: no absorption by disks, which is obviously wrong)

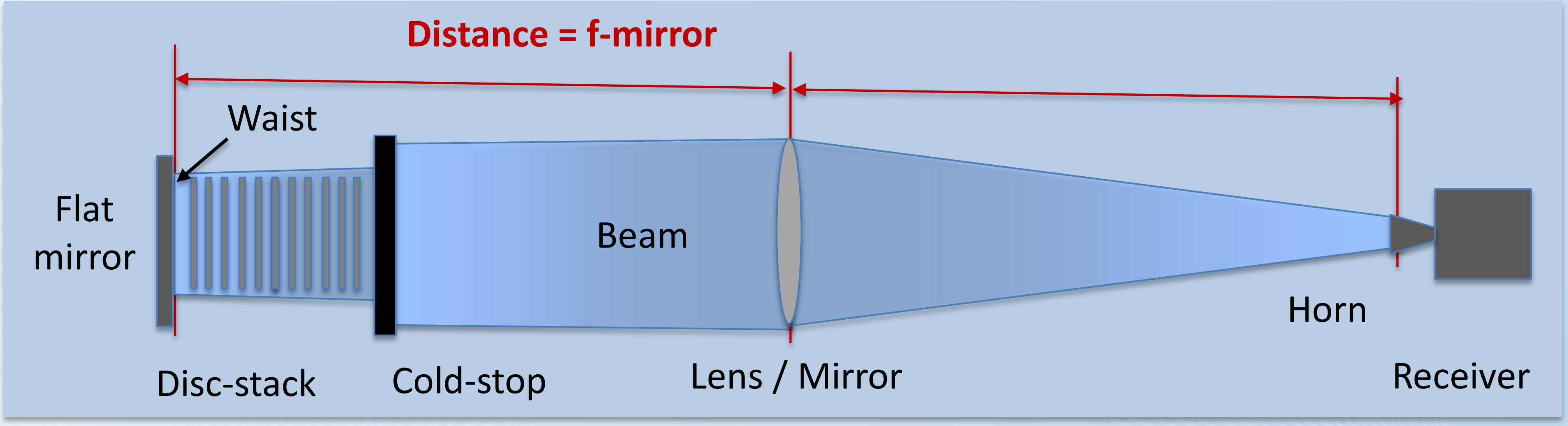
a)



b)



Optics (2)



- waist at the receiver stack is frequency independent
  - ➔ distance lens to waist must be equal to focal length of the lens
  - ➔ waist-size at the horn antenna scales linear with wavelength (opening angle is frequency independent)
- lens / mirror diameter should be much larger than disk-size (usually 5 w(z) ➔ ~2m !!)
- depending on Rx-bandwidth and focal length we may need
  - either an intermediate optics between lens and horn
  - or a z-focus adjuster

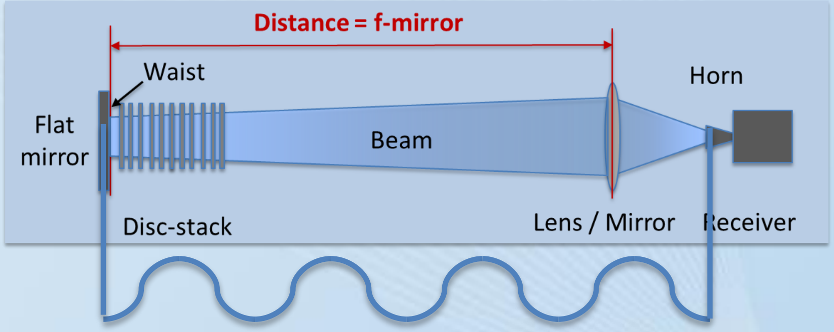
Standing waves

Even a receiver transmits usually, e.g.

- LNA noise
- mixing synthesizer signals
  (should not, but isolation often is not good enough)

- optical system forms a cavity
- reflection at the individual disks

➔ we will have massive standing-waves



This can make calibration and reproducibility of the measurements difficult, since system can react strongly on small changes

Only solution is a higher isolation

➔ we may even need an isolator between horn and LNA

What did I forget?

- Absorption by the disk material
  - will reduce throughput
  - depending on number of disks and disk-temperature:
    - do we need the flat mirror at all?
    - or is a cold dump better for the performance (more degrees of freedom in the optical design) ?
    - or can we even use two independent receivers, one from each side (without mirror in between)?

What else?

- …

Possible areas for optimization

Optimizing the optics by

- improving the coupling efficiency for the disk stack
  - balance between system temperature and aperture efficiency
- reducing spill-over noise (cold optics, baffle-structure)

➔ we need a detailed model of the optical system

- simultaneous operation of several receiver channels of your tuning accessing different harmonics of your booster tuning, e.g. by using:
  - dichroic mirrors
  - frequency splitters
  - special stacked horn antennas
  - using a wide band receiver to cover several harmonics in one shot
  - ….
- …..

Conclusions

- horn antenna design is not the main difficulty, can be adapted within a wide range to the needs of the optical system
- need a cavity-like system
  - the better the cavity the worse are standing wave problems
- optimization is mostly about
  - system temperature
    (optical throughput, spill-over loss, baffling, receiver design),
  - coupling efficiency,
  - multiplexing

Thank you