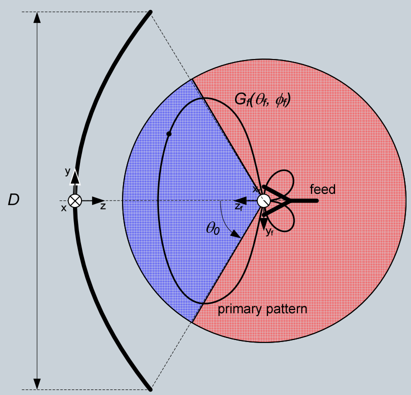
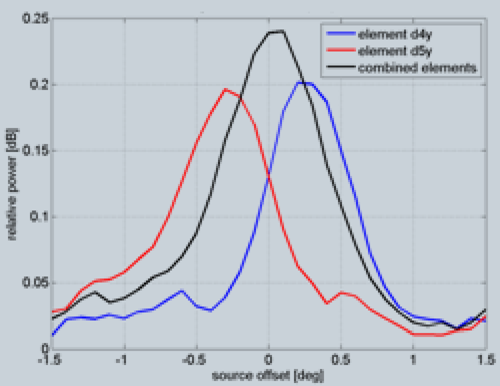
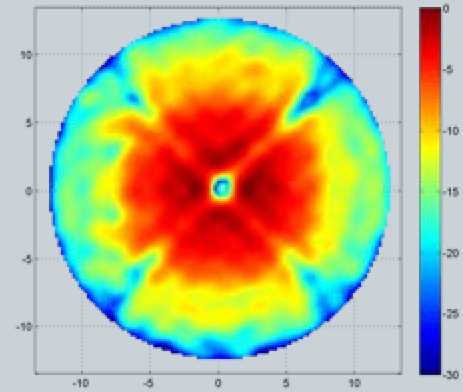
Efficiency and sensitivity definitions for reflector antennas in radio-astronomy

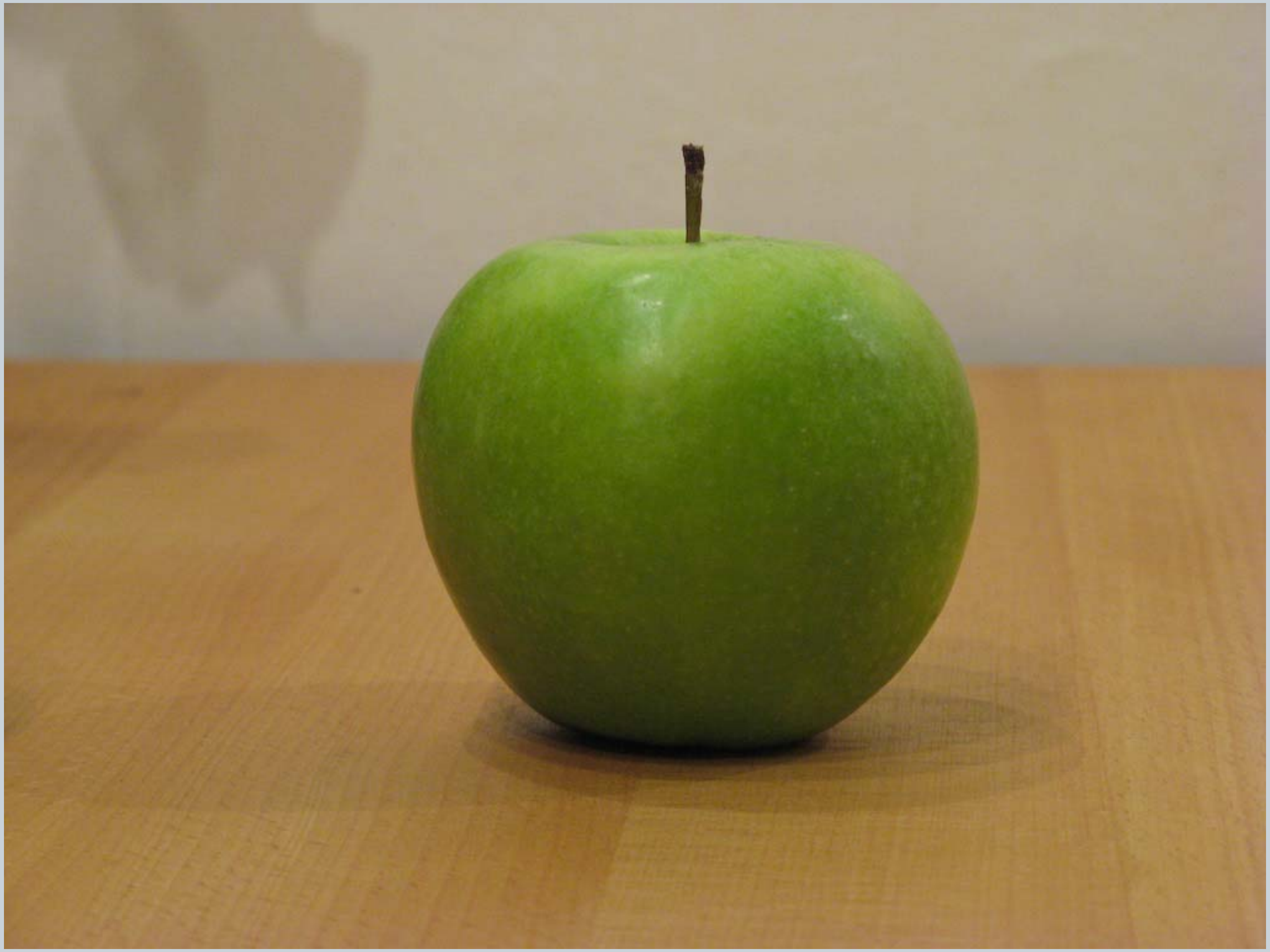
Wim van Cappellen







What is this?



and this?

and this??

Regarding efficiencies,
we have exactly the same problem!

Introduction

- Sensitivity is defined by the smallest flux ΔS that a radio telescope can detect

$$\Delta S \propto \frac{T_{sys}}{A_e \sqrt{B\tau}}$$

where B is the considered bandwidth and τ is the integration time.

- Let's consider the effective area A_e and the system temperature T_{sys} in more detail

- There turns out to be a lot of confusion!

Introduction

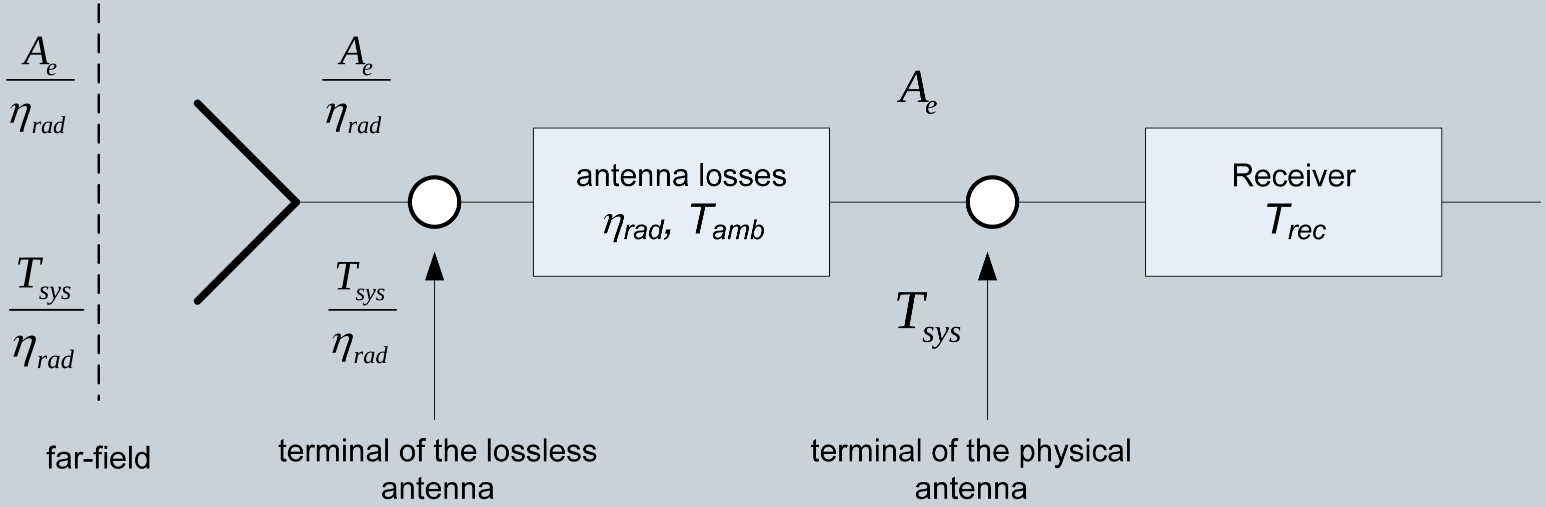
- In this study, the following books/authors were considered:
  - IEEE Standard Definitions of Terms for Antennas
  - C.A. Balanis
  - R.E. Collin
  - G. Cortés Medellín
  - M.V. Ivashina
  - P-S. Kildal
  - J.D. Kraus
  - Y.T. Lo & S.W. Lee
  - K. Rohlfs
  - A.W. Rudge
  - M.I. Skolnik
- If you stay with your favorite author, it is mostly fine. But don't mix them up.

Outline

- Reference planes
- Efficiency definitions
- Sub-efficiencies
- Temperature
- Conclusions

Reference planes

- Although the ratio of A_e to T_{sys} remains constant, the individual values of A_e and T_{sys} depend on where they are considered

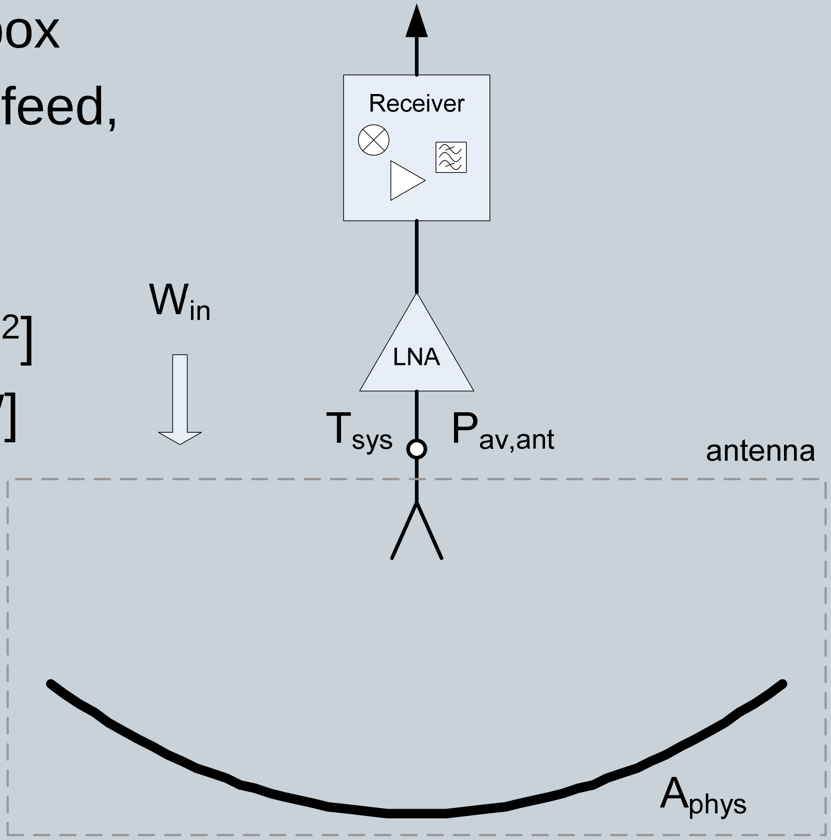


- We refer them to the terminals of the physical antenna

Receiving (reflector) antenna system

- Consider the antenna as black box with single output port (includes feed, reflector and all interactions)

- Incident power density W_{in} [W/m^2]
- Available output power $P_{av,ant}$ [W] at the antenna terminals



Effective area

- IEEE definition
  - Effective Area $$A_e = \frac{P_{av,ant}}{W_{in}}$$
- Everyone agrees on this one

Antenna efficiency

- IEEE definition (of an aperture type antenna)

$$\eta_{ant} = \frac{A_e}{A_{phys}}$$

- Many authors (at least 5 from my list) use the term ‘aperture efficiency’ for what the IEEE defines as antenna efficiency

- It is proposed to adopt the IEEE definition

Aperture efficiency

- IEEE definition

$$\eta_{ap} = \frac{D_0}{D_{\max}} \quad \text{where (mostly)} \quad D_{\max} = \frac{4\pi}{\lambda^2} A_{phys}$$

- In the IEEE version, both the co and cross-pol components are included.
- Many authors (at least 5 from my list) use the term ‘aperture efficiency’ for what the IEEE defines as antenna efficiency
- One excludes the spillover part
- One considers only the co-pol contribution.

- It is proposed to adopt the IEEE definition

Radiation efficiency

- The radiation efficiency is a measure of the losses in the antenna
- IEEE: The ratio of the total power radiated by an antenna to the net power P_{acc} accepted by the antenna

$$\eta_{\text{rad}} = \frac{P_{rad}}{P_{acc}}$$

- Also $G(\theta,\varphi) = \eta_{rad} D(\theta,\varphi)$ and $\eta_{ant} = \eta_{ap}\eta_{rad}$

- Some authors also include mismatch, the IEEE does not

- It is proposed to adopt the IEEE definition

Polarisation efficiency

- IEEE: The ratio of the power received by an antenna from a given plane wave of arbitrary polarisation to the power that would be received by the same antenna from a plane wave of the same power flux density and direction of propagation, whose state of polarisation has been adjusted for a maximum received power.

- However:
  - A high polarisation purity requirement for the end result (usually maps) does not automatically imply a low cross-polarisation of the antenna
  - Two sufficiently orthogonal components of the field are sampled by a telescope
  - The final purity depends on the antenna properties, coupling in the receiving chain and the system calibration.

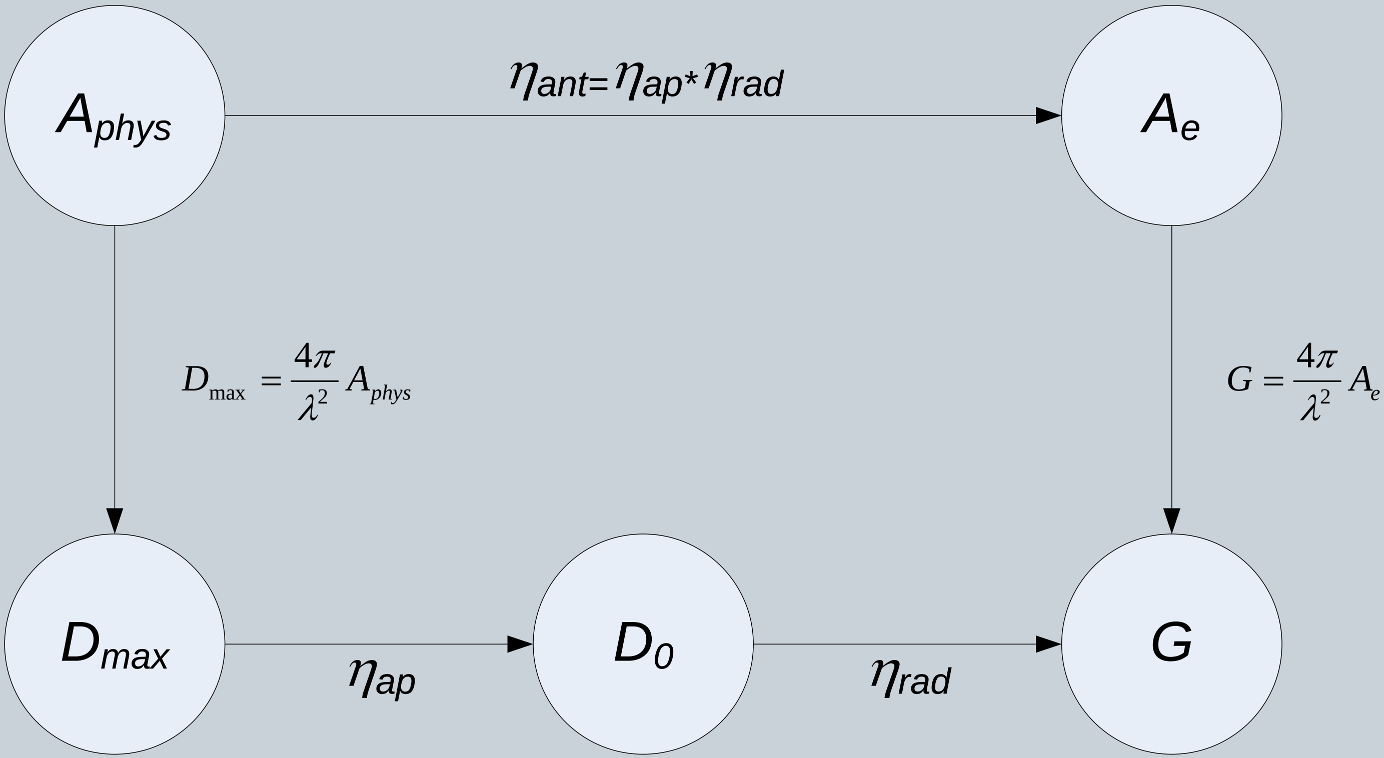
Polarisation efficiency

- Low cross-polarisation of the antenna eases the calibration
- But as long as the degree of cross-polarisation is accurately known (and preferably stable) the measured signals can be corrected for this instrumental polarisation

- In astronomy, the polarisation efficiency itself is of minor importance and does not contribute to the antenna efficiency.

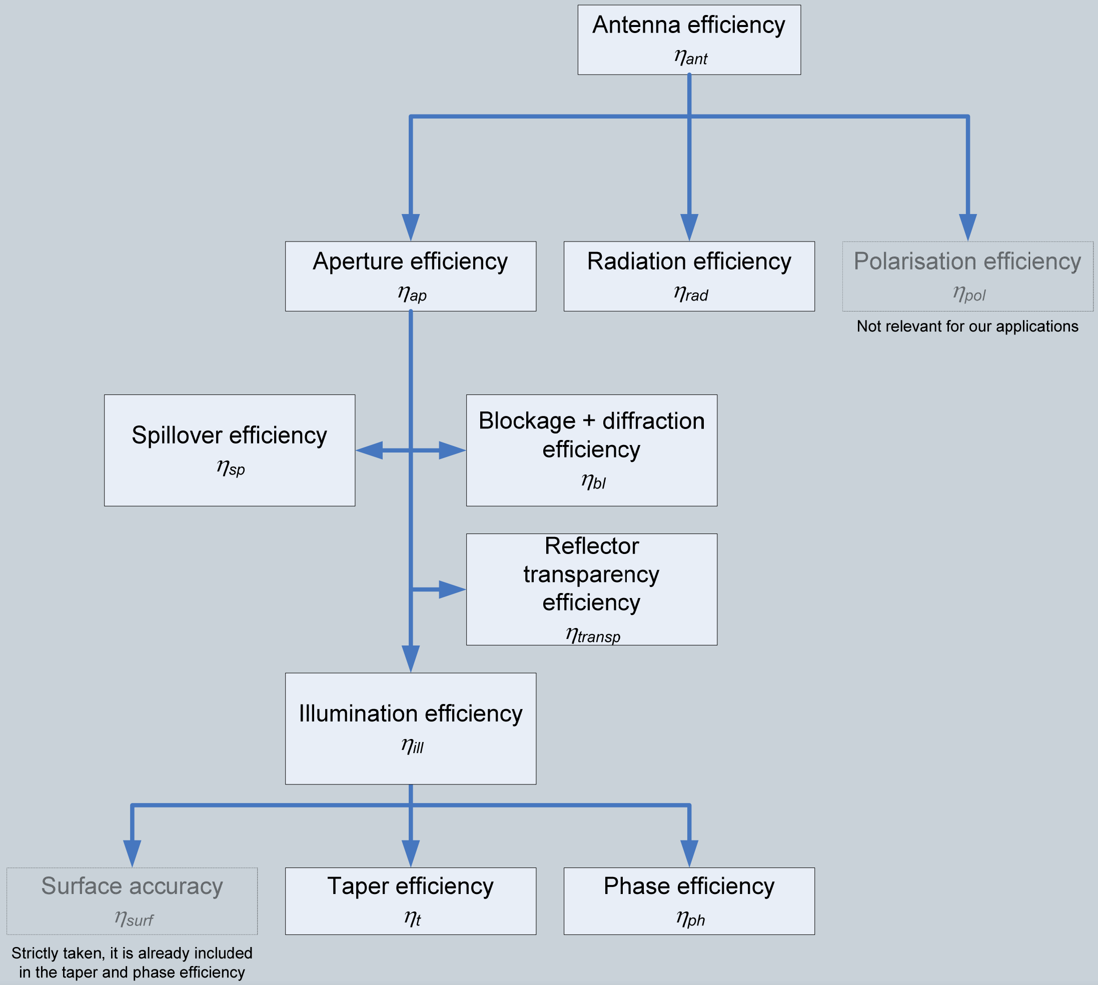
- It is proposed to adopt the IEEE definition

Overview



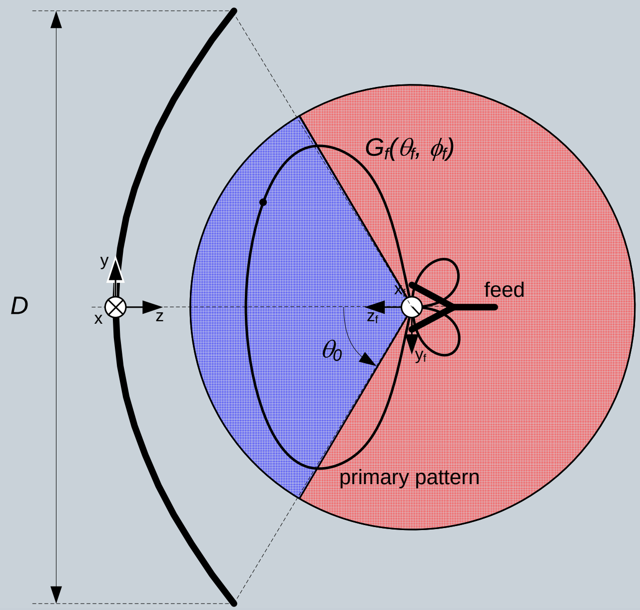
A_{phys}
$\eta_{ant}=\eta_{ap}*\eta_{rad}$
A_e
$D_{\max} = \frac{4\pi}{\lambda^2} A_{phys}$
$G = \frac{4\pi}{\lambda^2} A_e$
D_{max}
η_{ap}
D_0
η_{rad}
G

Overview of sub-efficiencies



Spillover efficiency

- Spillover is usually considered in transmit mode
- Spillover is the ratio of the power intercepted by the reflecting elements to the total power.



$$\eta_{sp} = \frac{\int_{\Omega_R} G_f(\theta_f, \phi_f) d\Omega}{\int_{4\pi} G_f(\theta_f, \phi_f) d\Omega}$$

The *total* power is considered (in co and cross polarisations)

Spillover efficiency

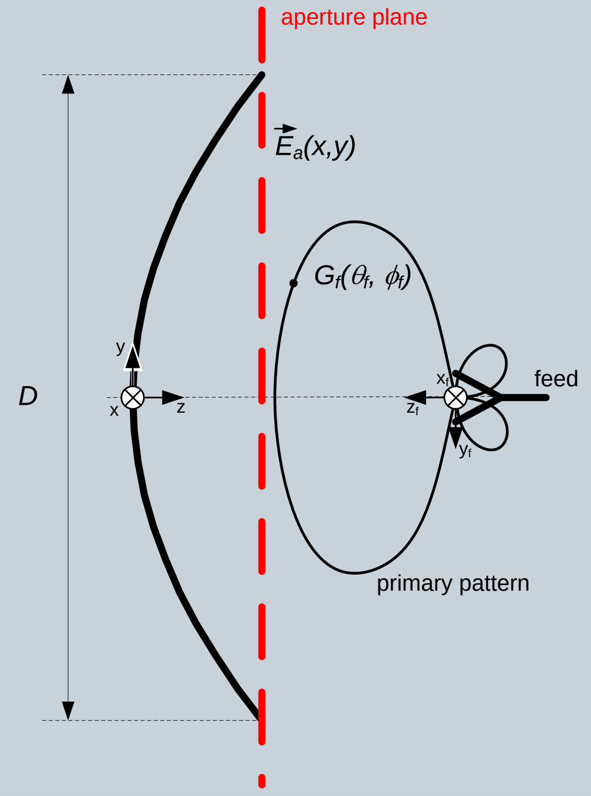
- Almost everyone agrees on this one, but one author names this quantity ‘feed efficiency’.
- It is proposed to adopt the IEEE definition

Illumination efficiency

- Efficiency loss due to non-uniform amplitude *and* phase illumination of the aperture plane
- Defined at aperture plane

$$\eta_{ill} = \frac{1}{A}\frac{\left|\int_A \vec{E}_a(x,y)dA\right|^2}{\int_A \left|\vec{E}_a(x,y)\right|^2 dA}$$

- There is no IEEE standard



Taper and phase efficiency

$$\eta_{ill} = \frac{1}{A}\frac{\left|\int_A \vec{E}_a(x,y)dA\right|^2}{\int_A \left|\vec{E}_a(x,y)\right|^2 dA}$$

$$\eta_t = \frac{1}{A}\frac{\left[\int_A \left|\vec{E}_a(x,y)\right| dA\right]^2}{\int_A \left|\vec{E}_a(x,y)\right|^2 dA}$$

Taper efficiency

$$\eta_{ph} = \frac{\left|\int_A \vec{E}_a(x,y)dA\right|^2}{\left[\int_A \left|\vec{E}_a(x,y)\right| dA\right]^2}$$

Phase efficiency

- The phase efficiency is not independent of the taper efficiency!

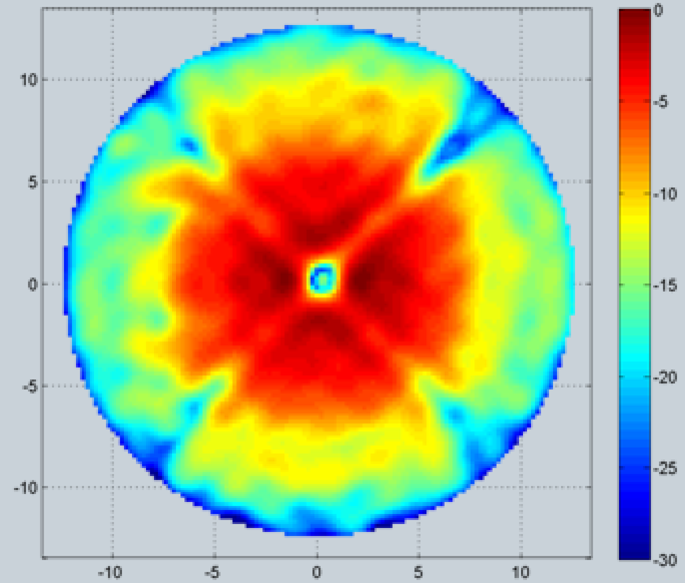
Illumination, taper & phase efficiency

- The above illumination efficiency includes amplitude AND phase errors
- Some authors only consider amplitude errors in the illumination efficiency
- One author integrates only over the co-polar power. He introduces a separate term for the power-loss in the orthogonal polarisation (‘polarisation sidelobe efficiency’)

- It is proposed to adopt the efficiencies on the previous slide

Blockage and diffraction

- Reduction of efficiency due to blockage by for example the support struts and the feedbox



Example of feed box and struts blockage

Blockage and diffraction

- IEEE: Condition resulting from object lying in the path of rays arriving at or departing from the aperture of an antenna.

- The blockage and diffraction efficiency is the efficiency factor related to these losses

$$\eta_{b+d} = \left|1 - \Delta_{cb} - \Delta_d\right|^2$$

- It is proposed to adopt this definition

Reflector surface

- Random deviations of the reflector profile from the ideal parabolic shape will cause the radiation pattern to deteriorate, primarily by a decrease in the antenna's aperture efficiency, and an increase in its sidelobe levels.

- Since the illumination and phase efficiency are defined in the aperture plane of the reflector, the effect of reflector surface errors is formally included in them.
- In practice the illumination and phase efficiencies are often calculated from the feed radiation pattern. In that situation one should include the reflector surface efficiency separately.

Reflector transparency

- The IEEE has no standard definition of reflector transparency efficiency.

- Reflectors with a mesh surface instead of solid metal plates will loose some efficiency due to the transparency of the mesh.
- It reduces the directivity of the main lobe and increases the sidelobe level.

- The reflector transparency efficiency is defined as the ratio of the directivity of the secondary pattern that is obtained with a mesh reflector surface and the directivity of the secondary pattern of a solid reflector.

Feed efficiency

- The IEEE has no standard definition
- At least 4 different definitions have been found in literature
  - Product of illumination, spillover and polarisation efficiencies
  - Efficiency describing the losses in the feed (=radiation efficiency)
  - Substitute for just the spillover efficiency
  - As the first, but including the radiation efficiency
  - Etc, etc.
- There is no need for a definition of feed efficiency. The use of the term ‘feed efficiency’ is strongly discouraged to avoid confusion.
- If one does use the term, then its definition must be clearly specified.

Beam efficiency

- Does not contribute to the antenna efficiency
- IEEE: The ratio of the power received over a specified solid angle when an antenna is illuminated isotropic by uncorrelated and unpolarised waves to the total power received by the antenna.

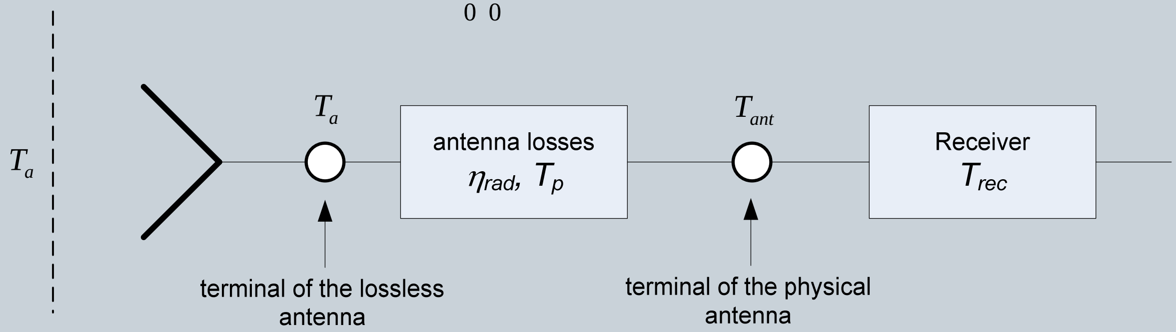
$$\eta_{beam} = \frac{\Omega_M}{\Omega_A} = \frac{\iint\limits_{\text{main lobe}} U(\theta,\varphi)d\Omega}{\iint\limits_{4\pi} U(\theta,\varphi)d\Omega}$$

- One author only includes the co-polar contributions
- As we will see later, it can be a practical quantity in noise calculations
- It is proposed to adopt the IEEE definition

System Temperature

$$T_{sys} = \eta_{rad} T_a + (1 - \eta_{rad}) T_p + T_{rec}$$

$$T_a = \frac{\int_0^{2\pi}\int_0^{\pi} T_B(\theta,\phi) G(\theta,\phi) d\Omega}{\int_0^{2\pi}\int_0^{\pi} G(\theta,\phi) d\Omega}$$



- For more info about T_a see SKA Memo 95 by Germán Cortés Medellín at http://www.skatelescope.org

Temperature

$$T_a = T_{main}\eta_{beam} + (1-\eta_{beam})\frac{\iint\limits_{sidelobes} T_B(\theta,\phi)D(\theta,\phi)d\Omega}{\iint\limits_{sidelobes} D(\theta,\phi)d\Omega}$$

- T_{main} contributions
  - Cosmic and galactic background
  - Atmpspheric contributions
  - Source under study
- T_B is brightness temperature distribution

Conclusions

- If we cannot even distinguish apples from apples, how can we ever distinguish efficiencies?
- So beware: not everyone means the same although they use the same name
- A set of consistent definitions is proposed, but most importantly:

Define (or refer to) the definitions that you use!

Conclusions