Some Reflector and Feed Antenna Technologies that Made a Difference: Fundamentals and examples from radio telescopes, satellite communications and radio links

Presentation given as Distinguished Lecturer of IEEE APS Society.
There exist a corresponding 3 page text in:
P.-S. Kildal, “Some Reflector and Feed Antenna Inventions that Made a Difference”, Africon 2013, Mauritius

Per-Simon Kildal
Distinguished lecturer of IEEE Antennas and Propagation Society
Abstract

• The presentation reviews some inventions within reflector antennas and feeds that represented a large step forward when they were introduced, in terms of both performance and industrial or scientific usefulness. The fundamental design principles as well as the actual solutions will be overviewed in a simple manner. The overview covers dipole-disk with ring for ship Earth stations, corrugated horns, hat-fed antennas for radio links, and wideband log-periodic “eleven” feed for SKA and VLBI 2010 radio telescopes. The inventions can in all cases be associated with simple fundamental EM principles, and an improvement of a fundamental sub-efficiency.

• Keywords: Reflectors, feeds, wire grid, PEC/PMC strip grid.
About Per-Simon Kildal

• Per-Simon Kildal (IEEE M’82-SM’84-F’95) has MSEE and PhD from The Norwegian Institute of Technology in Tronheim, Norway. Since 1989 he has been Professor at Chalmers University of Technology, Gothenburg. He is now heading the Division of Antenna Systems at Department of Signals and Systems at Chalmers.

• Prof Kildal received two best paper awards for articles published in the IEEE Transactions on Antennas and Propagation, and he was the recipient of the 2011 Distinguished Achievements Award of the IEEE Antennas and Propagation Society.

• Kildal has authored an antenna textbook, and more than 150 journal articles and letters, most of them in IEEE or IET journals. He has designed two very large antennas, including the Gregorian dual-reflector feed of the Arecibo radiotelescope. He has invented several reflector antenna feeds, the latest being the so-called eleven antenna.

• Kildal is the originator of the concept of soft and hard surfaces, recently resulting in the gap waveguide, a new low-loss metamaterial-based transmission line advantageous in particular above 30 GHz. Kildal has received large individual grants from the Swedish research council VR and from the European Research Council ERC for research on gap waveguides.

• His research group has pioneered the reverberation chamber into an accurate Over-The-Air (OTA) measurement tool for antennas and wireless terminals subject to Rayleigh fading. This has been successfully commercialized in Bluetest AB.
Some Reflector and Feed Antenna Technologies that Made an Industrial Difference Originating from Radio Telescopes

A personnel history with Keys to Success:
Very basic EM principles, Characterization, Protection & Commercialization

Per-Simon Kildal
Distinguished lecturer of IEEE Antennas and Propagation Society
Purpose and content

- Show how basic science can give successful industrial spin-offs
  - Three personal examples
- Reason: Innovations in industry requires also
  - Out of box thinking
  - Think different
  - the Crazy Ones cause the big breakthroughs

- I hope that this talk can inspire young engineers/scientists to work with SKA and to commercialize ideas originating from SKA
Apple’s “Think different” campaign/slogan in year 2000

• .......

• Because the people **who are crazy enough** to think they can change the world, are the ones who do.

• Steve Jobs
Background of this talk

• Worked with Tor Hagfors, Cornell Univ. (died 2007)
  – 1977-82: PhD on EISCAT ionospheric radar
  – 1982-94: Projects on Arecibo radio telescope

• Several industrial projects
  – 1982-89: With companies in Norway
  – Since 1989: With Ericsson, and own start-ups in Sweden

• Collaboration with Sander Weinreb, Caltech

• Collaboration with Arnold van Ardenne & Co ar Astron in NL
  – Since 2005: on efficiencies in focal plane arrays
  – 2006: Arnold became Adjunct Professor at Chalmers
  – 2007 SKADS Workshop: Contributions
  – 2011: Marianna Ivashina and Rob Maaskant joined my research group.
Content

• Keys to success with inventions in my case
  – Basic principles (wire grid, PEC/PMC grid)
  – Characterization: Subefficiencies

• EISCAT VHF antenna (wire grid, two rods)
  – Wire grid ➔ ring for INMARSAT Ship Earth station antenna

• Gregorian feed of Arecibo radio telescope
  – Corrugated horns ➔ soft & hard surfaces ➔ PEC/PMC strip grids
  – Mathematical model of line feeds ➔ successful hat feed for radio links

• SKA
  – decade bandwidth ➔ logperiodic antennas ➔ eleven feed
  – Focal-plane arrays & MIMO arrays ➔ decoupling efficiency
Keys to success with inventions in my case

- Projects with scientific instruments and interaction with their users
- Very basic EM principles
  - Polarization-dependent PEC wire grid
  - Polarization-independent PEC/PMC wire grid
  - Rethinking of the logperiodic antenna
  - BOR antennas
- Characterization
  - We need to quantify good and bad
  - Related to physical phenomena
- Protection
  - Patent protection defines ownership
  - Makes it easier to defend most places in the world
- Commercialization
  - The ultimate proof of usefulness
Subefficiencies of Paraboloids and Cassegrain Antennas

Similar formulas apply to general multi-reflector systems.

Factorization of feed efficiency: \[ e_{ap} = e_{sp} e_{pol} e_{ill} e_{f} \]

Spillover, polarization, illumination and phase eff.

Spillover efficiency \( e_{sp} \)
Relative spillover power is given by \( 1 - e_{sp} \)
Typically between -0.05 dB and -0.5 dB.
Major contributor to the antenna noise temperature.
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EISCAT VHF antenna
EISCAT line feed
Reflection and transmission properties of wire grids (non-grazing incidence)

<table>
<thead>
<tr>
<th>E-field polarization</th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canonical surface</td>
<td>STOP (reflects)</td>
<td>STOP (reflects)</td>
</tr>
<tr>
<td>Perfect Electric Conductor (PEC)</td>
<td>STOP (reflects)</td>
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</tr>
<tr>
<td>Horizontal PEC</td>
<td>GO (passes)</td>
<td>STOP (reflects)</td>
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</tr>
</tbody>
</table>

The lines in the table shows the direction of the wires in the grid.
Radiation pattern of line feed in transverse plane (1980):

longitudinal and transverse polarization

The longitudinal rods work as a wire grid, shaping the far field of the longitudinal polarization, and not the transverse one.
Aperture efficiencies from transverse element patterns

<table>
<thead>
<tr>
<th></th>
<th>Transv. pol.</th>
<th>Long. pol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spillover ( \eta_{sp} )</td>
<td>0.9273</td>
<td>0.9339</td>
</tr>
<tr>
<td>Illumination ( \eta_{till} )</td>
<td>0.9414</td>
<td>0.9429</td>
</tr>
<tr>
<td>Polarization ( \eta_{pol} )</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>Transverse phase errors ( \eta_{t\phi} )</td>
<td>0.9998</td>
<td>0.9995</td>
</tr>
<tr>
<td>( \eta_t )</td>
<td>0.8728</td>
<td>0.8807</td>
</tr>
</tbody>
</table>
Ca 1980: Small efficient resonant reflector antenna with dipole-disk feed

The ring makes the E- and H-plane patterns equal

(works as a conical surface of rings)
Resonant reflectors can be very efficient and influence system design strongly.

Radome with standard small reflector

With optimum resonant reflector of same gain
In small primary-fed reflectors multiple reflections between feed and reflector can be used to increase gain.

The encircled resonance was used.
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Radiotelescope in Arecibo
Platform with old 300 MHz line feed (left) and enclosure with dual-reflector feed inside (right)
1982-88: Methods for design and analysis of Gregorian dual-reflector feed
Broadband SOFT corrugated primary feed (Ying, A. Kishk and P-S. Kildal, 1995)
Constant beamwidth over 0.9-1.7 GHz

Aperture-field when used in Arecibo three-reflector system
Realization of soft and hard surfaces with corrugations (1988) (metamaterials)

Soft STOP surface (left)    Hard GO surface (right)

Transverse air-filled corrugations    Longitudinal dielectric-filled corrugations
PEC/PMC strip model of ideal soft and hard surfaces (2003)

- Ideal soft surface = polarization-independent STOP surface
- Ideal hard surface = polarization-independent GO surface

strip period $\rightarrow 0$
2005: Table for comparing surfaces with respect to propagation along surfaces. ERC funded GAP WAVEGUIDES are results of this table.

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<tr>
<th>Canonical Surface</th>
<th>E-field Polarization</th>
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<tr>
<td></td>
<td>VER or TM</td>
</tr>
<tr>
<td>PEC</td>
<td></td>
</tr>
<tr>
<td>PMC</td>
<td></td>
</tr>
<tr>
<td>PEC/PMC Strip grid</td>
<td>SOFT</td>
</tr>
<tr>
<td></td>
<td>HARD</td>
</tr>
<tr>
<td>PMC-type EBG</td>
<td>grazing</td>
</tr>
<tr>
<td></td>
<td>close to normal</td>
</tr>
</tbody>
</table>

The lines in the table show the direction of the PEC/PMC wires in the grid. The EBG surface contains mushrooms (patches w/vias), illustrated as yellow squares.
### Canonical surface (non-gracing incidence)

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>E-field Polarization</th>
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<tbody>
<tr>
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<tr>
<td>Gracing incidence</td>
<td>GO (passes)</td>
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### Canonical Surface Gracing incidence

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<td>PMC</td>
<td>STOP</td>
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<tr>
<td>PEC/PMC Strip grid</td>
<td>STOP</td>
</tr>
<tr>
<td>PEC/PMC Strip grid</td>
<td>STOP</td>
</tr>
<tr>
<td>PEC/PMC Strip grid</td>
<td>GO</td>
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</table>

### E-field Polarization

- **VER**tical: GO
- **HOR**izontal: STOP
Hat feed is a result of Kildal’s theoretical modeling of the Arecibo line feeds.
Hat feed in ring-focus paraboloid (new phase efficiency)

Low sidelobes
Good efficiency

The initial idea of the hat feed was based on the theoretical formulas in the paper on the previous page.
1987-88: 15 GHz military link project for EB NERA (low volume)
Hat fed reflectors have been in production since 2000

The below photos are from an improvement done in 2006.
More than 930,000 hat antennas has been produced. Started Comhat AB in 1997. Now these products are in LEAX Arkivator Telecom AB.
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Allan telescope Array
a forerunner for SKA, 2003

Feed developed at UC Berkley
Idea behind Eleven feed new invention

- Two parallel dipoles over ground (Eleven configuration)
  - from book by Christiansen and Högbom Radio Telescopes
  - equal E- and H-plane patterns
  - Beamwidth constant with frequency
  - phase center is locked to the ground plane
  - low far-out sidelobes and backlobes.

- Decade bandwidth by
  - Logperiodic
  - Folded dipoles
Log-periodic feeds for reflector antennas, 2003

Example: Lowest frequency 500 MHz

Background:
UWB antennas = logperiodic

The Eleven antenna:
11 times smaller
……..and better
Breakthrough in wideband technology
Design of GMRT Eleven feed by Yogesh Karandikar on Master project Autumn 2006
Assembled hardware and drawing of 1-14 GHz Eleven feed
Directivity 11 dBi over more than a decade bandwidth

And $11 \geq$ decade
Co- and crosspolar patterns in 45 deg plane total and with removed higher order frequency variations.

A new subefficiency characterizes purity of feed pattern BOR1 efficiency.)
Sub-efficiencies from measured radiation patterns

Looks good, except for BOR1 efficiency below 2.5 GHz and above 9 GHz.

BOR1 efficiency is power lost in sidelobes due to higher order frequency variations.
Leightweight 400 – 2000 MHz
Eleven antenna version

Weight 8.5 kg

800 mm
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‘We are going to develop new technology for both antennas and receivers for the SKA’, says John Conway, deputy director for Onsala Space Observatory.

Science/Engineering management

- Electromagnetic design of wideband feeds for reflector antennas
- Modeling of antenna-receiver systems and calibration of radio telescopes

2 from SA:
Research efforts towards characterization of Mutual Coupling Effects in dense Focal Plane Arrays


2007  Invited lecture by Kildal on the characterization of reflector antennas feeds at the SKADS Marie Curie workshop, Dwingeloo

2007  Introduction of the unified decoupling efficiency for array feeds by the CHALMERS-ASTRON team (M. Kehn, M. Ivashina, P.-S. Kildal, and R. Maaskant)

Since that time:
- Several common journal and conference papers,
- FP7 MCA-VINNMER Fellowship (co-)funded by ASTRON and Chalmers,
- 2 PhD projects on FPAs (co-)funded by the Swedish and SA national research councils

Measurements of the FPA decoupling efficiency in the BlueTest reverberation chamber in Gothenburg
Characterization in rich isotropic multipath in reverberation chamber

Since 2010 Spin-off company Bluetest has success in market. Has now 35 employees and annual turnover of 90 Mkr
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<td>STOP</td>
</tr>
<tr>
<td>STOP</td>
<td>GO</td>
</tr>
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| PEC/PMC-Strip grid                        |                     |
| PEC                                      | GO                  |
| PMC                                      | STOP                |
| PEC/PMC-Strip grid                        | STOP                |

**Perfect Electric Conductor (PEC)**
- Horizontal PEC wire grid: GO (passes)
- Vertical PEC wire grid: STOP (reflects)

**PMC-type**
- EBG close to normal PMC grazing incidence: STOP (reflects)

**PEC**
- E-field polarization: STOP (reflects)

**PMC**
- E-field polarization: STOP (reflects)

**PEC/PMC**
- E-field polarization: STOP (reflects)
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