Modeling Antenna Beams

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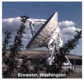
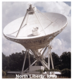
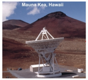






What to learn from this talk

EM simulations of antennas can be complicated

* *Many* people have spent careers on the subject
* No single solution exists
* There are several levels of approximation valid in different regimes

Ability to describe antennas is a limitation

* Antennas are not perfect (manufacturing tolerances, . . .)
    - e.g., ALMA feeds
* Detailed geometry is time dependent (gravity, wind, weathering, . . .)
* Beam-solving may need to become standard calibration practice

But, sophisticated modeling is already pretty good . . .

* . . . and many tools are available

Why model beams at all?

Engineering

* Trade-off between $T_{\rm sys}$ and gain
  - Answer depends on $T_{\rm rec}$, focal plane size, and other specs
* Understand and/or minimize instrumental polarization
* Determine key antenna parameters
* Understand observed antenna defects

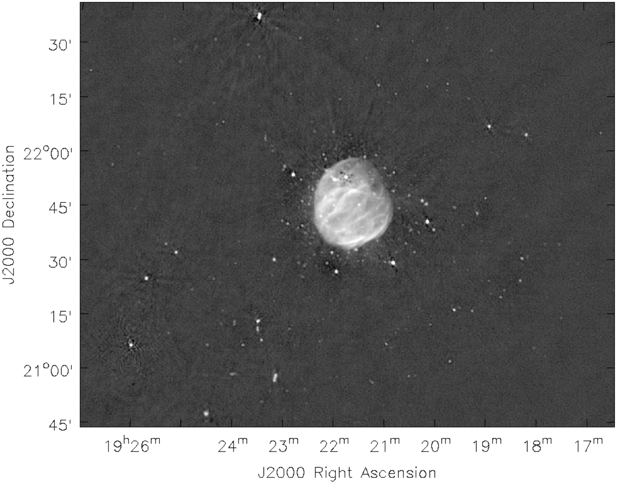
Deconvolution & imaging

* Changing parallactic angle
* Different primary elements (e.g., ALMA & VLBI)
* Wide fields of view (e.g., EVLA)

RFI cancellation

* Not really subject of this meeting
* Nulling of RFI from known directions

Imaging



See Sanjay Bhatnagar's slides . . .

Why is primary beam modeling hard?

Some important dimensions $\sim \lambda$

* Wires, gaps between panels, nuts & bolts
* Small structures are effective scatterers $\propto \lambda^2$

Some important dimensions $\gg \lambda$

* $\longrightarrow$ large computational problem

Difficult to fully describe an antenna

* Unmodeled scatterers
* Manufacturing defects
* Limited rigidity & pointing errors
* Electronic gain drifts and atmosphere hinder measurement

Lots of special cases

* Self-shadowing of curved surfaces
* Resonant structures

Why is primary beam modeling hard (2)

Images courtesy Alvy Ray Smith;
`http://alvyray.com/Photography/PhotoVLA.htm`

Levels of electromagnetic beam modeling

0. No model (complexity is $\mathcal{O}1$)

* Assume unit gain in all directions
* This is the default assumption usually used!

1. FT of aperture pattern ($\mathcal{O}N \log N$)

* Predicts general beam shape (e.g., Airy disk) with nulls, side lobes

2. Geometrical optics (ray tracing; $\mathcal{O}\mathrm{large} \times N$)

* Better beam shape
* Polarization can be computed
* Cannot handle caustics or electrically small features
* E.g., my software (cassbeam)

Levels of electromagnetic beam modeling (2)

3. Physical optics (complexity is $\mathcal{O}N^2$)

* Computes currents on surfaces and wires
* Uniform Theory of Diffraction (UTD) integrated (`http://www.cvel.clemson.edu/modeling/tutorials/techniques/gtd-utd/gtd-utd.html`)
* E.g., GRASP 9

4. Method of Moments ($\mathcal{O}N^2 \log N$)

* Best for small structures
* Multi-path and resonance structures fully solvable
* Very slow for large problems
* E.g., NEC2 and its variants

5. Quantum Optics? ($\mathcal{O}e^N$)

Model elements

What is N?

- N is the number of grid points in model
- Each usually represents a current or electric field
- 4 or 6 free parameters ($\mathcal{R}$ & $\mathcal{I}$ for 2 or 3 dimensions)
- Elements are not necessarily spatially compact (e.g., MoM)

How many elements are needed?

- Depends on field configuration and desired extent of calculation
- 0.1 to 50 per λ^2 for areas (typical)
- 0.3 to 5 per λ for wires and perimeters (typical)
- Ray-trace methods can often get away with far fewer
    - Aperture fields tend to be slowly varying

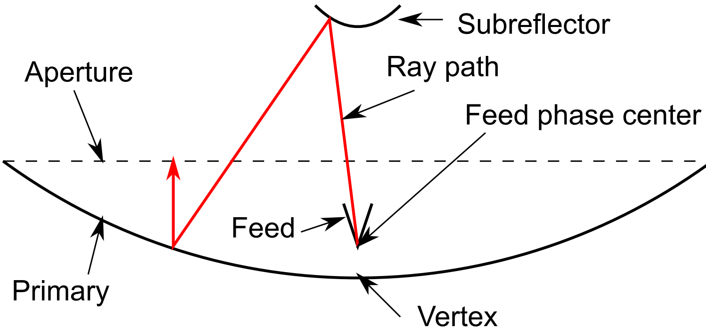
Hybrid modeling

* Often it is most effective to use different techniques for different aspects of a problem
* E.g., use MoM to simulate a feed pattern and PO to simulate full antenna beam

GRASP 8

See Bruce Veidt's slides ...

Cassegrain geometry



* Ray path (from feed phase center to aperture) is constant length for all rays
* Rays are normal to the aperture
* Subreflector shape can be uniquely determined by this length, the feed location, and the shape of the primary

What is it?

* Geometric optics simulator for Cassegrain systems
* Designed for analysis of VLA and VLBA primary beams
* Guts of it are in Sanjay Bhatnagar's A-projection (in CASA)

What does it produce?

* Beam shapes: Jones matrices as function of aperture or sky position
* Performance metrics: $T_{\rm sys}$, gain
* Efficiency analysis

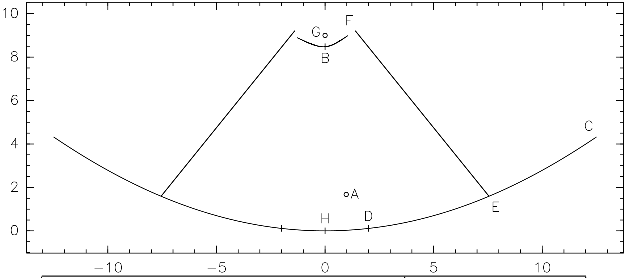
Getting started

* `cp -r /home/brisken/tutorial-cassbeam .` # *into your home directory*
* `cd tutorial-cassbeam`
* `. setup` # *set up $PATH and $LD_LIBRARY_PATH*
* `cassbeam vla.in` # *try it out!*
* `tigger vla.I.FITS` # *view the beam*

Documentation

* `gv cassbeam.ps`

The VLA



Point	Coordinates (meters)
A. Feed	0.975, 1.676
B. Intersection of subreflector and primary axis	0.0, 8.479
C. Edge of primary	12.5, 4.325
D. Inner edge of paneled primary	2.0, 0.112
E. Base of strut	7.550, 1.594
F. Top of strut	1.391, 9.217
G. Prime focus	0.0, 9.0
H. Vertex of primary	0.0, 0.0

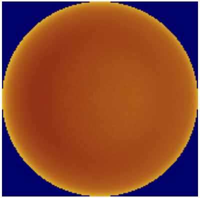
Sample input

```
name = VLA
sub_h = 8.47852    # meters from vertex to subreflector
feed_x = 0.97536   # meters from optic axis to feed ring
feed_y = 0.0
feed_z = 1.67640   # height of feed ring from vertex
geom = vla_geom    # file containing figure of primary
feedtaper = 13.0
feedthetamax = 9   # degrees
legwidth = 0.27    # meters; - for X shaped, + for + shaped
legthick = 0.36
legfoot = 7.55     # meters from optic axis at dish
legapex = 10.93876 # meters from vertex
hole_radius = 1.98 # meters
pol=1,0,0,0        # RCP
oversamp=1.0
roughness=0.0003   # 300 micron surface roughness
Trec=20.0          # receiver temperature
freq = 1.5         # GHz
```

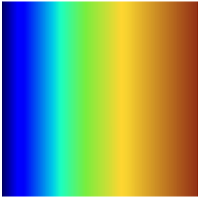
Sample output (performance metrics)

```
Spillover eff = 0.946406
  primary     = 0.998412
  subreflector= 0.947911
Blockage eff  = 0.855810
Surface eff   = 0.999644
Illum eff     = 0.996446
  phase eff   = 1.000000
  amp eff     = 0.996446
Diffract eff  = 0.849469
Misc eff      = 1.000000
Total eff     = 0.685333
Gain          = 105833.42  =  50.25 dBi
Tsys          = 26.075 K
  ground      =  3.108 K
  sky         =  2.968 K
  rec         = 20.000 K
Aeff          = 336.412286 m^2
Aeff/Tsys     = 12.901504 m^2/K
l beamshift   = 0.000001 deg
m beamshift   = -0.000000 deg
l beam FWHM   = 0.480216 deg
m beam FWHM   = 0.479970 deg
Peak sidelobe = 0.034835 = -14.579823 dB
```

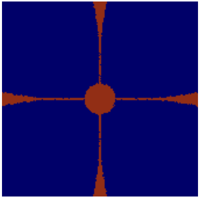
Sample output (images)



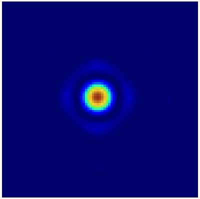
Amplitude



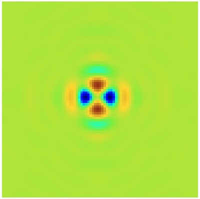
Phase



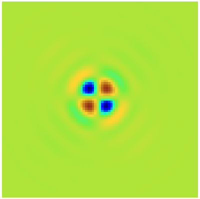
Blockage



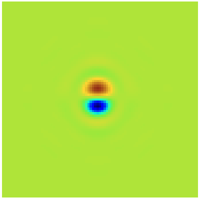
I



Q



U



V

Beam properties

1. Beam voltage patterns are smooth
2. Voltage patterns change sign across nulls
3. Beam squint from offset feed
4. Cloverleaf stokes Q and U (why?)

Algorithm

Choose one polarization state

For each grid point on aperture:

1. Trace ray into feed, calculating the subreflector point along the way
2. Calculate amplitude as product of feed pattern and $\frac{d\Omega}{dA}$
3. Propagate the polarization vector from the feed back to aperture
4. Multiply by phase factor $L\nu$ (a constant by design for unperturbed system)
5. Zero amplitudes of shadowed points

Fourier transform aperture field into far-field

Repeat for other orthogonal polarization state

Limitations

Diffraction not included

* Diffraction around subreflector and struts most severe
* Diffraction efficiency is estimated very crudely
* Low frequencies affected worst

Struts enter only as shadow

Feed pattern assumed to be Gaussian with perfect polarization

* This would be relatively simple to change

Very wide fields of view (~ 1 radian) poorly approximated

Antenna defects

Small scale defects

* Scatter power in all directions
* From surface roughness
* From small scatters within antenna
* Hard to model

Large scale defects

* $\rightarrow$ changes in small-scale beam structure (esp. first sidelobe)
* From optical misalignment (cassbeam *pathologies*)
* From misfigurement of surfaces
* From poorly modeled feed

Numerical Electromagnetics Code (LLNL)

* Version 2 (NEC2) in public domain
  - GPLed nec2++ variant and others available
  - http://www.si-list.net/swindex.html#nec2c
* Version 4 available with a license
  - But export restrictions apply
* A method of moments integral equation solver
* Structures are described as wires and surface patches
* Bridges the gap between a circuit and beam simulator
  - Calculates impedances and currents at feed points

Antenna design considerations

- For high dynamic range imaging, both a good beam *and* good knowledge of it are required
- RFI immunity and rejection will be stronger

Simplify optics

- Keep optical path free of scatterers
- Minimize unnecessary sharp angles
- Make use of shapes that are easy to model
- Antenna beam will scale more perfectly with frequency

Make use of symmetry

- Modeling is simpler
- Cancellation of some artifacts
- VLA is a bad example!