The OOF Holography Technique: Correcting the Effects of Gravity and Thermal Gradients on Large Filled-Aperture Telescopes

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September 2010
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Outline

1. Introduction
2. The OOF Holography Technique
3. Simulations
4. Application to the GBT
5. Conclusions
Requirements for telescope surface

Ruze law:

\[
\text{Efficiency } \propto \exp \left[ - \left( \frac{4\pi \sigma}{\lambda} \right)^2 \right]
\]  \hspace{1cm} (1)

- \(\sigma\): Root-mean-square wavefront error
- \(\lambda\): Observing wavelength

Note: this is surface efficiency, not aperture efficiency
Requirements for telescope surface

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Factors affecting telescope surface accuracy

Sources of inaccuracy:

- Manufacturing accuracy of panels and subsequent deformation
- Setting error: static
  → Setting requires $1:10^6$ measurement accuracy
- Residual gravitation deformation: repeatable
  (Major gravity deformations are compensated by homology)
- Thermal deformation: $\approx 60$ minute timescale
- Wind: short timescale
- Ageing effects

Characteristic length scale or errors:

- Gravity, thermal effects, tend to cause large-scale errors
- Wind is likely to be large-scale
- Setting error can be both large- and small-scale
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Telescope natural limits

von Hoerner (1967), 1967AJ.....72...35V
Telescope natural limits
Gravity & thermal effects and the homology principle

[Data partially from Radford & Woody, 2009, NA URSI meeting, Boulder]
Introduction

Causes of deformation

“Active” radio-telescopes

Key concept

Compensate rather than prevent surface error

1. Homology
2. Active surface
Telescope measurement techniques

Almost all telescopes end up using some combination of these – no single technique can satisfy all requirements:

- Conventional surveying
- Photogrammetry
- Interferometric holography using astronomical sources
- Transmitter with-phase holography
- Transmitter phase-retrieval holography
- Out-Of-Focus (OOF) holography (or, phase-retrieval holography with astronomical sources)
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Simulated Out-Of-Focus Beams, Perfect Telescope
or “point-spread-functions”

- In-Focus
- -ve De-Focus
- +ve De-Focus

- $\approx -12 \text{ dB of taper}$
- De-focus: $\approx \lambda$ of path across the aperture
A surface with random large-scale errors

Receiver Response (Taper/Apodisation/...)

Surface Errors (Projected to an imaginary surface)
Simulated Out-Of-Focus Beams

- In-Focus
- -ve De-Focus
- +ve De-Focus

≈ −12 dB of taper
Random large-scale surface error added to the surface
Simulated Out-Of-Focus Beams, with noise

- In-Focus
- -ve De-Focus
- +ve De-Focus

- $\approx -12\, \text{dB of taper}$
- Signal-To-Noise: 100:1 per pixel
Aims of the OOF technique

- Measure the complete optical aberrations in a telescope
  - Surface errors + mis-collimation + receiver optics...
- Rapidly
  - I.e., under \( \approx \frac{1}{2} \) hour
  - Currently at the GBT, measurements take < 5 minutes
- As a function of elevation, time of day, etc
  - Measure the effect of gravity
  - Measure the thermal deformation
- Without extra equipment
  - Makes it easy to interleave with science observations
  - (Zero materials cost)
Technique overview

- **How:** Use beam power maps
  - Astronomical receivers
  - Astronomical sources

- **Trick I:** Obtain the beam-maps relatively far out-of-focus
  - Breaks degeneracies
  - Reduces the required signal to noise

- **Trick II:** Appropriate parametrisation of errors
  - We use Zernike Polynomials
  - Trades required signal to noise with resolution
  - Low-orders correspond to classical/common aberrations

- **Relatively low-resolution**
  - Usually not be high-enough resolution for panel-to-panel errors
Basics: Fourier relationship between aperture and far-field

Aperture

Far-field amplitude & phase

FFT
Basics: Beam maps (power-only)

Aperture

FFT + \| \|^2

Power only
The OOF Holography Technique

The OOF Holography Algorithm

A classic non-linear inverse problem:

- The forward model
  - Conceptually relatively simple: only requires an FFT
  - Beam switching, non-point like sources, atmospheric effects, off-axis pixels, etc., make it complex
- Parametrisation of surface errors
  - Zernike polynomials
- Likelihood of data given model
  - Take normally distributed errors
  - Pointing errors, residual atmospheric emission, gain fluctuation can also be important
- Solver algorithm
  - Levenberg-Marquardt maximum-likelihood
  - MCMC
The OOF Holography Algorithm

Surface Errors \rightarrow Defocus \rightarrow Aperture phase \rightarrow Aperture Amplitude \rightarrow Telescope Beam \rightarrow FFT \rightarrow Model \rightarrow Minimise \rightarrow Residual

Observing Strategy \rightarrow Observation

Minimise \rightarrow Residual

Model \rightarrow Observation
Zernike Polynomials: $n = 1$
Zernike Polynomials: $n = 2$
Zernike Polynomials: $n = 3$

Trefoil

Coma
Zernike Polynomials: $n = 4$

Spherical
Zernike Polynomials: $n = 5$

2nd Order Coma
Suitable astronomical sources

- Ideal sources are strong and point-like $\Rightarrow$ at longer mm-wavelengths quasars usually ideal targets
- At short millimetre and sub-mm wavelengths quasars may be weak $\Rightarrow$ can use planets:
  - Extended sources not a problem, sharp edges most important
  - Need to model the extended source and any substructure (limb darkening; rings!)
- Spectral line observations also possible:
  - High S/N with masers
  - Excellent atmospheric rejection
  - Can be problems reading out fast enough
  - Fewer sources than quasars
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Simulations Overview

Topics:
- Required signal-to-noise
- Effects of pointing errors
- Optimum size of defocus
- Maximum resolution that can be achieved


http://adsabs.harvard.edu/abs/2007A%26A...465..679N

Also other talks on the OOF technique:

http://www.mrao.cam.ac.uk/~bn204/publications/publicationlist.html
Simulations: Error on the retrieved surface Vs S/N
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Why GBT?

- A fully active, continuously adjusted, primary surface $\implies$ instant application of corrections
- The GBT is *not* exactly homologous
  - Non-homologous deformation is corrected by the active surface
  - This correction initially calculated using a finite-element model
  - Not quite accurate enough – needed a refinement
- Exposed, all-steel, construction is susceptible to thermal deformation
- Large collecting area $\implies$ high signal to noise
- 2209 actuators $\implies$ OOF holography *can not* be used for initial setting
Application at the GBT

Modelling residual gravitational errors

- Measure surface errors over wide range of elevations
- During night-time to minimise thermal effects
- Construct a model for how telescope deforms as function of elevation

⇒ Equivalent of measuring the ‘focus-curve’ but for many more possible deformations

Near real-time measurement and correction of thermal error

- Measure surface using bright quasar
- Apply correct immediately
- Repeat every \( \sim 1 \) hour

⇒ Equivalent of a ‘peak and focus’ measurement, but again for many more deformation modes
Obtained 37 measurements over three sessions covering a range of elevations

Used the dual-beam Q-band receiver (42 GHz)

Fit $a \sin(\theta) + b \cos(\theta) + c$ to each Zernike coefficient individually
GBT Observation at Q-Band
Sample GBT Observation at Q-Band: The Retrieved Surface
Gravitational Model: Vertical Coma

\[ n = 3, l = -1 \]

\[ Elevation (\text{deg}) \]

\[ Phase (\text{rad}) \]

\[ n = 3, l = -1 \]

\[ Elevation (\text{deg}) \]

\[ Phase (\text{rad}) \]

\[ Elevation (\text{deg}) \]

\[ Phase (\text{rad}) \]
Gravitational Model: Horizontal Coma

\[ n = 3, \ l = 1 \]
Gravitational Model: Trefoil

\[ n = 3, l = -3 \]
Gravitational Model: Trefoil

\[ n = 3, \ l = 3 \]

\[ \begin{align*} 
\text{Phase (rad)} & \quad \text{Elevation (deg)} \\
\text{---} & \quad \text{---} \\
20 & \quad 0 \\
40 & \quad 0 \\
60 & \quad 0 \\
80 & \quad 0 \\
\end{align*} \]
Gravitational Model: Astigmatism

Phase (rad)

Elevation (deg)

$n = 2, l = -2$

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Gravitational Model: Astigmatism

\( n = 2, l = 2 \)
Gravitational Model

$n = 4, l = -4$

$n = 4, l = -2$

$n = 4, l = 0$

$n = 4, l = 2$

$n = 4, l = 4$

$n = 5, l = -5$

$n = 5, l = -3$

$n = 5, l = -1$

$n = 5, l = 1$
Gravitational Model: Efficiency

Measured total aperture efficiencies at Q-band (42 GHz)
GBT Observation at 90 GHz with MUSTANG
Night-time thermal deformation from MUSTANG
Performance in extreme conditions: in-focus beam

Probably significant ice/snow in the dish

In-Focus beam at 90 GHz
Performance in extreme conditions

In-Focus  +ve De-Focus  -ve De-Focus

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Performance in extreme conditions: Fitting $n = 2$

In-Focus  

+ve De-Focus

-ve De-Focus

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OOF Holography  

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Performance in extreme conditions: Fitting $n = 3$

In-Focus

+ve De-Focus

-ve De-Focus
Performance in extreme conditions: Fitting $n = 4$
Performance in extreme conditions: Fitting $n = 5$

![In-Focus](image1)

![+ve De-Focus](image2)

![-ve De-Focus](image3)
Performance in extreme conditions: Fitting $n = 6$
Performance in extreme conditions: Fitting $n = 7$

In-Focus

+ve De-Focus

-ve De-Focus
Performance in extreme conditions: Fitting $n = 8$
Inferred surface errors $n = 2$
Inferred surface errors $n = 3$
Inferred surface errors $n = 4$
Inferred surface errors $n = 5$
Inferred surface errors $n = 6$
Inferred surface errors $n = 7$
Inferred surface errors $n = 8$
Detailed comparison of beams

In-focus

Observed beam

Best-fit beam with $n = 8$
Detailed comparison of beams
+ve defocus

Observed beam

Best-fit beam with $n = 8$
Detailed comparison of beams
-pre defocus

Observed beam

Best-fit beam with $n = 8$
Performance in extreme conditions: High-res \((n = 12)\)
High-res surface map
Zernike polynomials used in the high-res map I
Zernike polynomials used in the high-res map II
Zernike polynomials used in the high-res map III
Zernike polynomials used in the high-res map IV
Zernike polynomials used in the high-res map V
Basic results

- OOF technique eliminated non-panel gravitational error
- Can be used very effectively to measure thermal deformation
- Used to also correct thermal deformation
Recent highlights

- Use of the 64-pixel MUSTANG 90 GHz camera to greatly accelerate acquisition and accuracy of measurements
- "AutoOOF": Automatised acquisition, processing and application of corrections with minimum intervention
- Routine application of thermal corrections during scientific observations
- Calculating the pointing and focus from OOF observations
OOF in action at the GBT
Correcting the thermal deformations of the telescope
In perspective at the GBT

- During the night-time, surface errors are dominated by small scale errors
  - Greatly reduced using traditional holography from 1.5 years ago
  - Dominated by gravity+thermal deformation of individual panels
- The OOF-derived gravitational model in use for all observations $\nu > 26$ GHz
  - Makes 20%-30% improvement at 90 GHz around rigging angle
  - Significantly greater improvement at other elevations
- During daytime, thermal errors can become comparable to small-scale setting error
  - ‘Auto-OOF’ mode commissioned to acquire and correct for errors
  - Used during night-time and day-time for observing $\nu > 40$ GHz
  - Corrections tend to apply $\sim 90$ minutes
  - Important requirement to fully opening daytime to high-frequency observing
- Obviously, significant benefits in terms of absolute calibration
Conclusions

- Can measure wavefront errors to about $\lambda/70$ if beam-maps are made with reasonable S/N (about 100:1)
- Array receivers (bolometer or heterodyne) greatly accelerate measurement: a couple of minutes is achievable now
- Flattened the gain-elevation curve of the GBT
- Demonstrated significant improved efficiency at 90 GHz
- Demonstrated removal of thermal effects
- Opened the possibility of daytime observing with GBT at 3 mm (and more routinely at 7 mm)
- In everyday use now at NRAO/GBT
Potential future uses

- Commissioning/troubleshooting (sub-)mm telescopes with array receivers
- Large single-dish cm/mm/sub-mm telescopes (CCAT?)
  - Thermal effects very difficult to control
  - OOF is a proven, low-cost solution
  - Also, surface setting, residual gravitational correction
- Space telescopes
  - *Have* to rely on phase-retrieval
  - Characterisation of telescopes (e.g., for CMB missions?)
  - Adjustment of deployable space telescopes
    (e.g., JSWT, which currently will use a simpler but related technique)
More information

- A&A papers (Nikolic et al, 2007)
- [http://www.mrao.cam.ac.uk/~bn204/oof/](http://www.mrao.cam.ac.uk/~bn204/oof/)
- All the software is available under GPL
- NRAO-Green Bank wiki:
  - [http://wiki.gb.nrao.edu/bin/view/PTCS/OOFHolography](http://wiki.gb.nrao.edu/bin/view/PTCS/OOFHolography)