National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

The Electric Field Conjugation

Controlling Amplitude and Phase

Amir Give'on
Jet Propulsion Laboratory
California Institute of Technology, Pasadena CA

Acknowledgments: Brian Kern, Laurent Pueyo, Stuart Shaklan

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Are there other Earth-like planets?

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

Solutions

Nulling interferometer

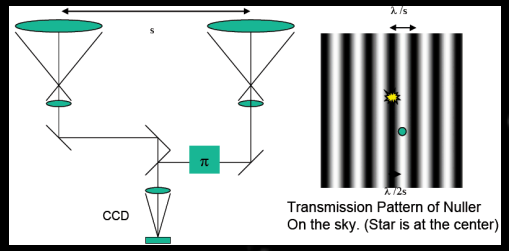
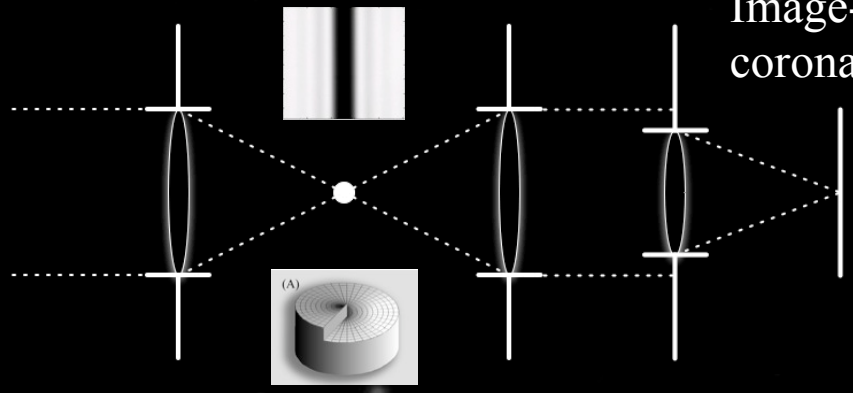
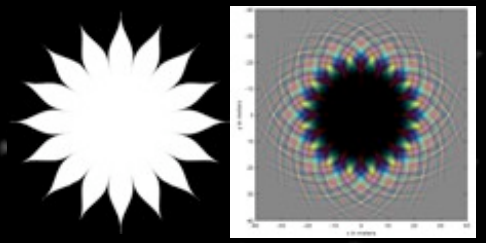


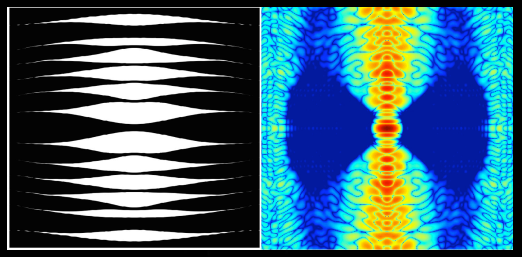
Image-plane occulter coronagraph



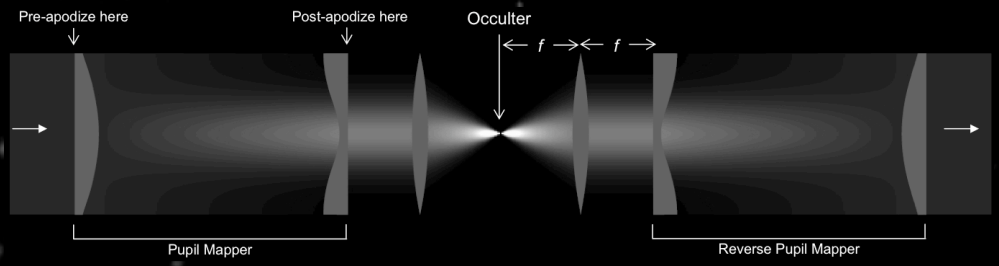
External occulter coronagraph



Shaped pupil coronagraph



Pupil mapping coronagraph

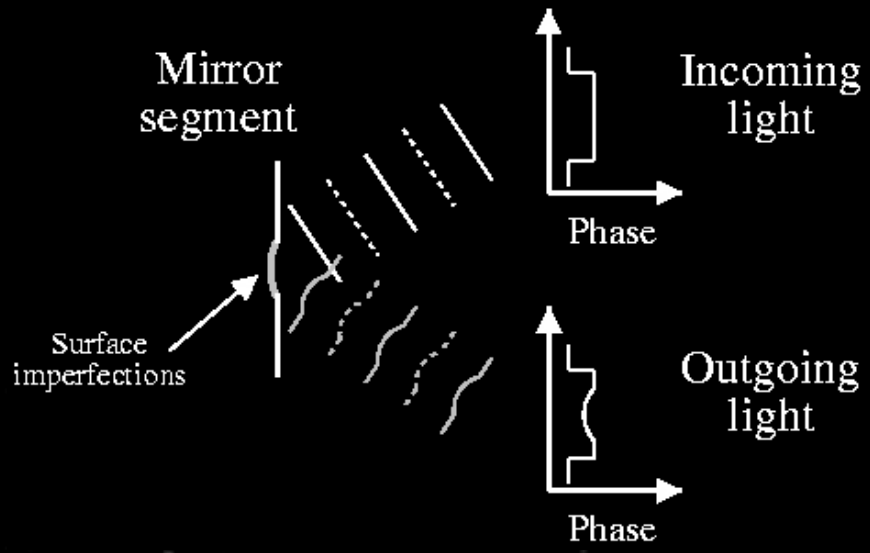


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

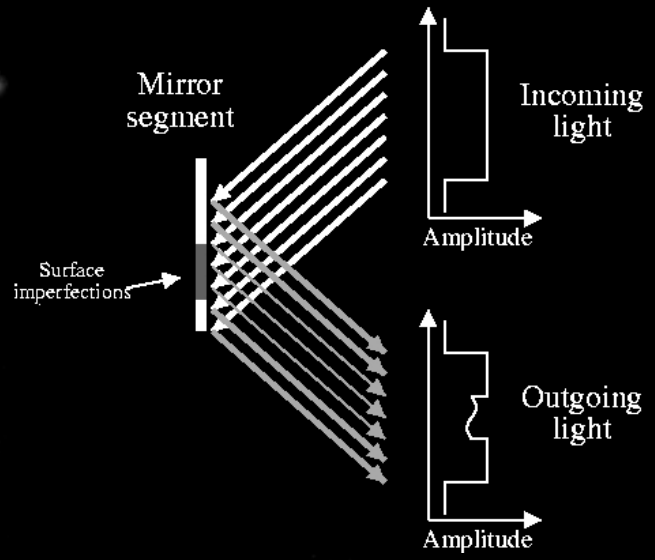
Problem: Wavefront aberrations!

Phase aberrations

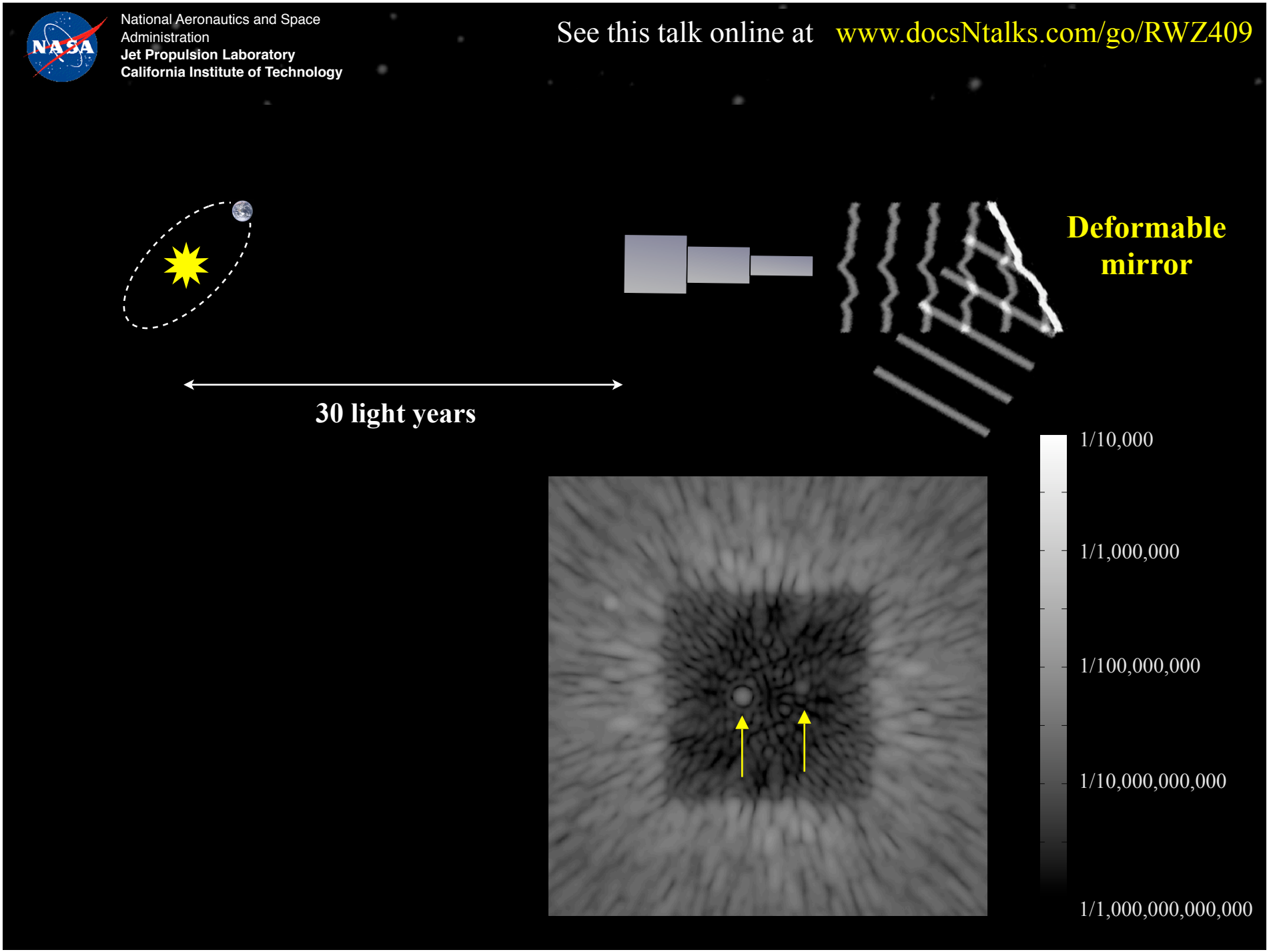


Requirement: ~λ/10,000

Amplitude aberrations



Requirement: ~1 / 1,000


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
See this talk online at www.docsNtalks.com/go/RWZ409
Deformable mirror
30 light years
1/10,000
1/1,000,000
1/100,000,000
1/10,000,000,000
1/1,000,000,000,000

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

What is EFC?

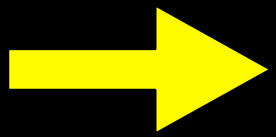
VS.

EFC is a formalism of the correction problem allowing us to use various tools to find the solution

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

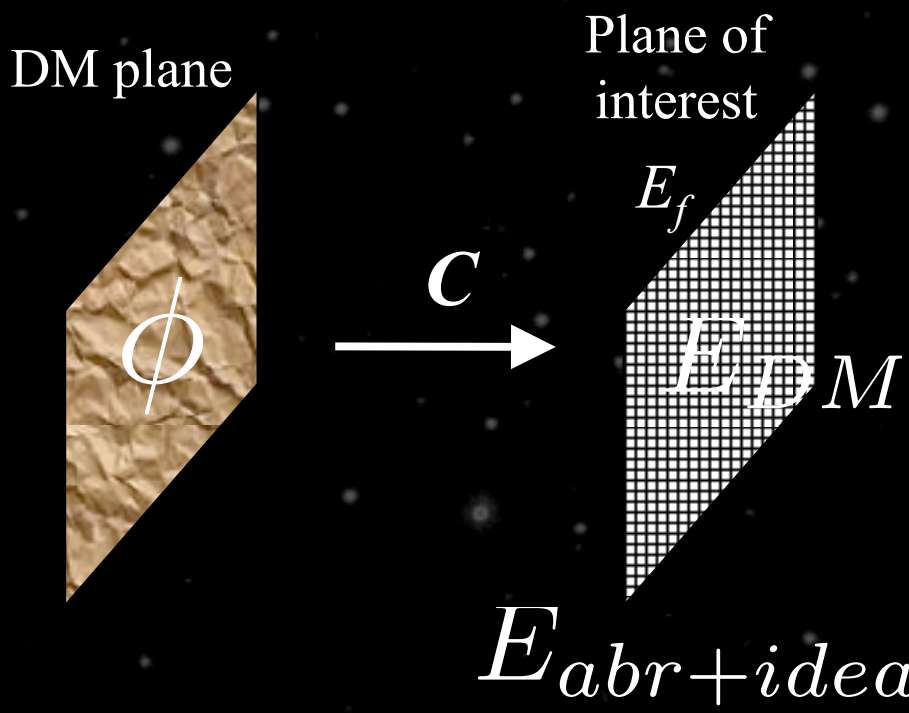
All correction algorithms do the same thing...



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

Electric Field Conjugation



Find the shape of the DM such that its effect in the plane of interest negates the electric field present in this plane due to the coronagraph and the aberrations

$$E_f = \quad + \quad = 0$$

Linearize w.r.t actuators heights

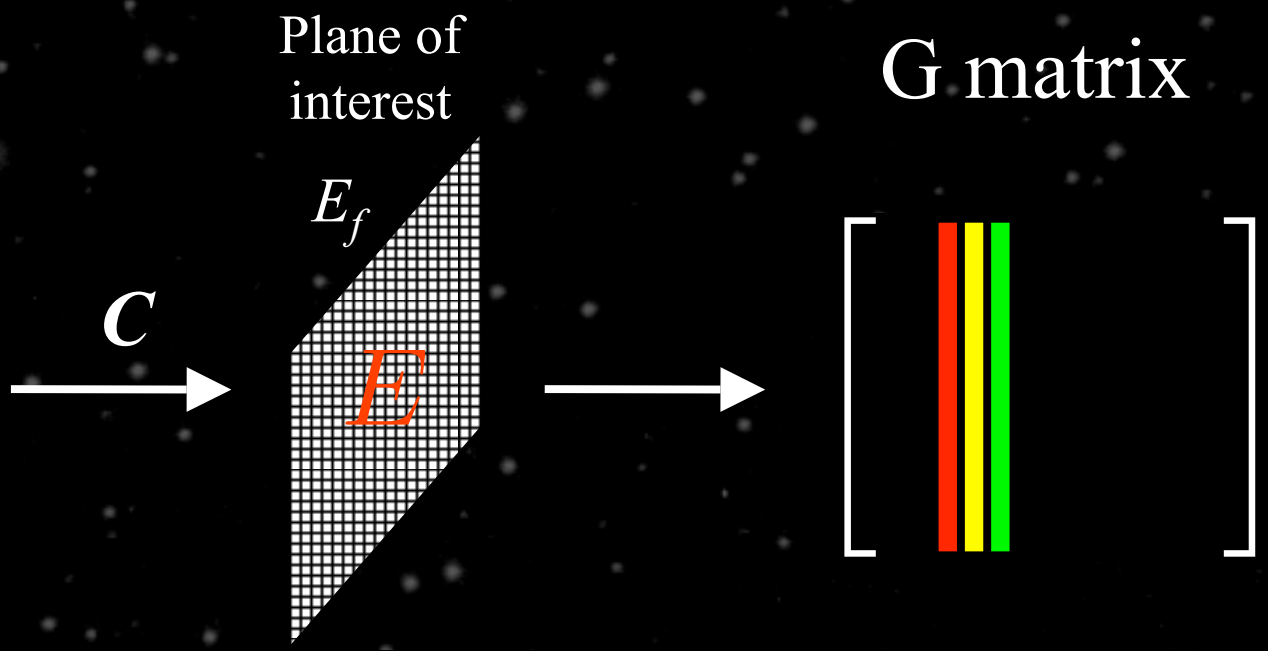
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

Electric Field Conjugation

How do we linearize the effect of the DM in the image plane?

Assume that the overall effect of the DM in the image plane is the sum of the effects of each of the actuators



The effect of the DM in the image plane will now be Ga , where a are the DM actuator heights.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

Electric Field Conjugation

$$G\bar{a} = iE_{ab}$$

$$\bar{a} = \begin{bmatrix} \Re\{G\} \\ \cdots \\ \Im\{G\} \end{bmatrix}^{-1} \begin{bmatrix} \Re\{iE_{ab}\} \\ \cdots \\ \Im\{iE_{ab}\} \end{bmatrix}$$

This guarantees a real valued solution for the DM actuators heights

$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|E_{ab} + iG\bar{a}\|^2$$

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

The EFC correction method requires the complex wavefront at the image plane...

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

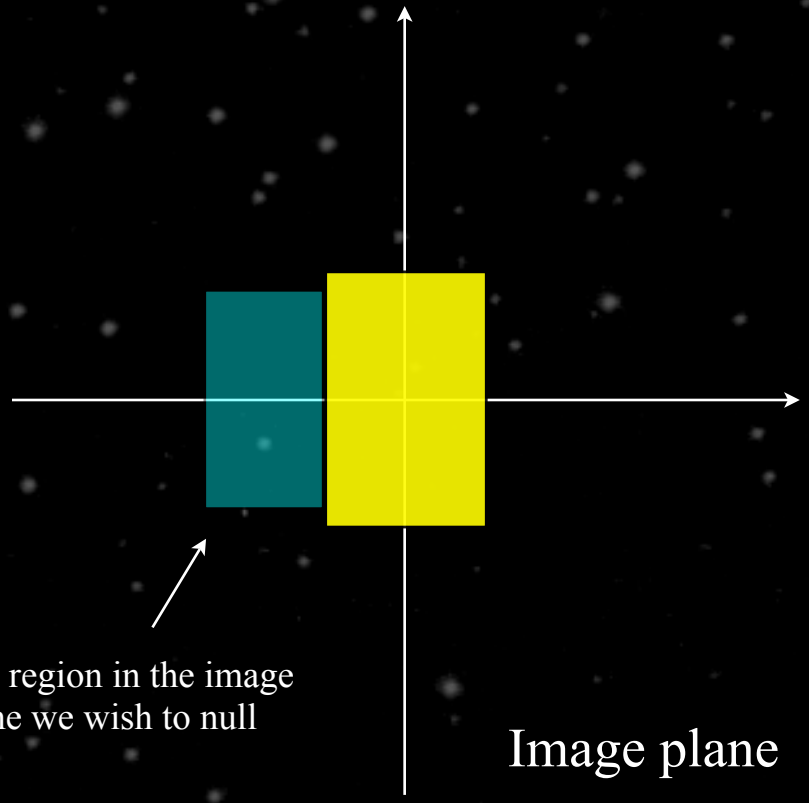
The cosine spatial frequency determines the center location of the diversity region

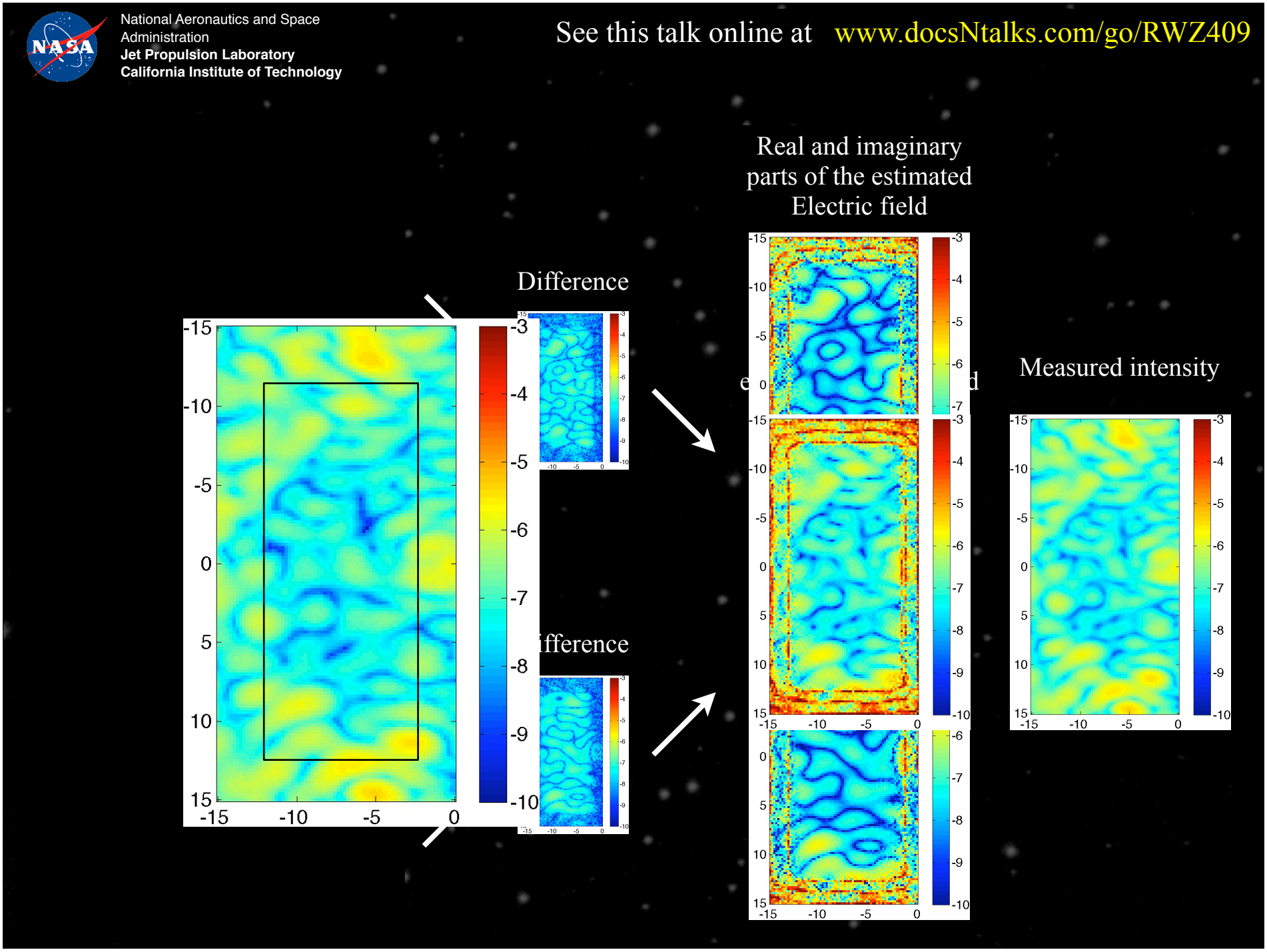
The spatial phase of the cosine determines the overall phase of the diversity

$$DM(x,y) = ?$$

The sincs determine the general amplitude shape of the diversity

- The wavefront is reconstructed by applying 4 different shapes on the DM ("probes").
- The additional probes to the current DM shape is chosen such that the diversity is uniform over the region of interest with the ability to change the spatial phase.




National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
See this talk online at www.docsNtalks.com/go/RWZ409
Real and imaginary parts of the estimated Electric field
Difference
ifference
Measured intensity

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

How EFC is related to other correction algorithms

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

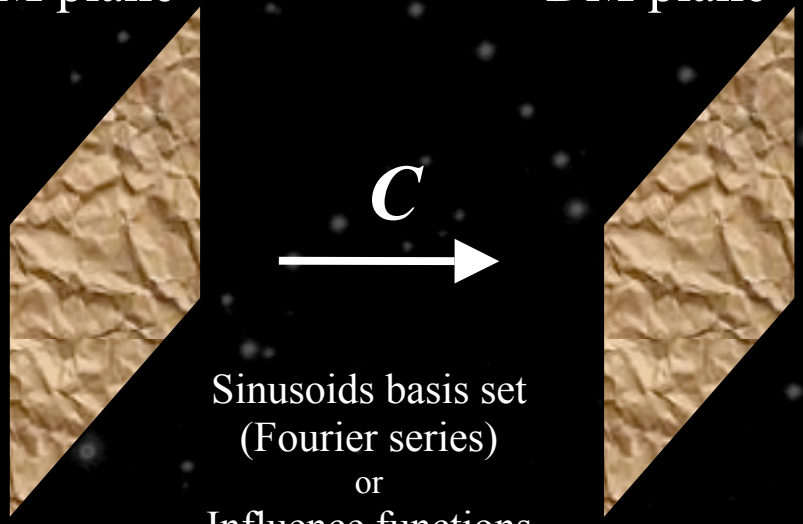
See this talk online at www.docsNtalks.com/go/RWZ409

Phase conjugation

DM plane

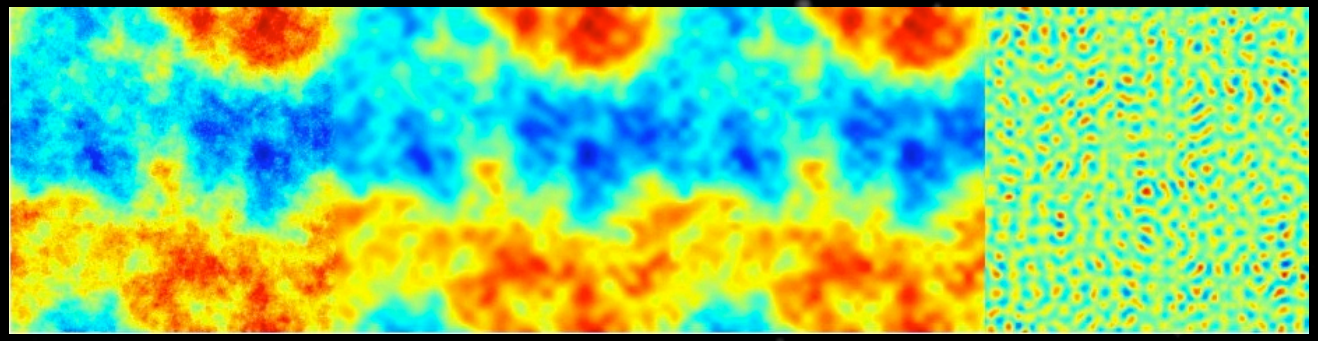
DM plane

Poyneer et. al 2004



Sinusoids basis set
(Fourier series)
or
Influence functions

Original LPF Reconstructed Diffrence (10x)



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

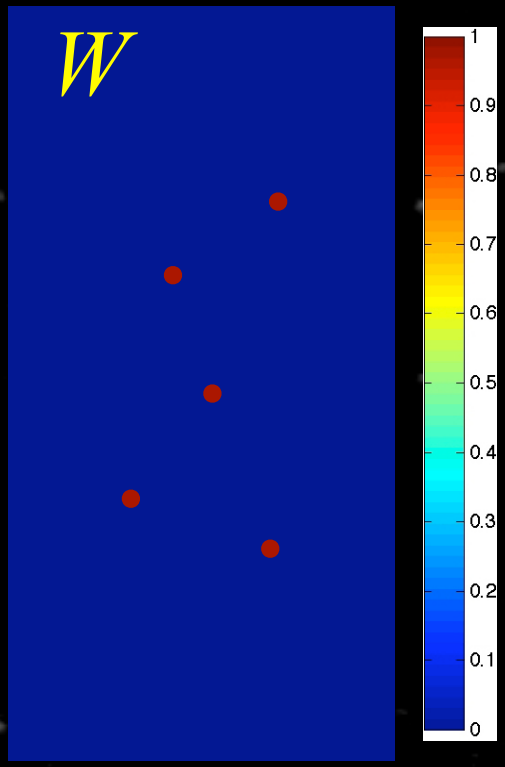
See this talk online at www.docsNtalks.com/go/RWZ409

Speckle nulling

Trauger et. al 2004

$$WG\bar{a} = iWE_{ab}$$

If the system model is reduced to a single Fourier transform of an infinite aperture and the weighting function *W* reduces to isolated pixels that change their location according to the brightest peaks in the region of interest,



↓

EFC = speckle nulling

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

Energy minimization

Borde et. al 2005

$$\mathcal{E} = \|E_{ab} + iC\{\phi\}\|^2$$

$$\frac{\partial}{\partial \bar{a}}\mathcal{E} = 0$$

EFC

$$G\bar{a} + E_{ab} = 0$$

Least squares solution

$$\bar{a}^* = \arg\min_{\bar{a}\in X} \|E_{ab} + iC\{\phi\}\|^2 .$$

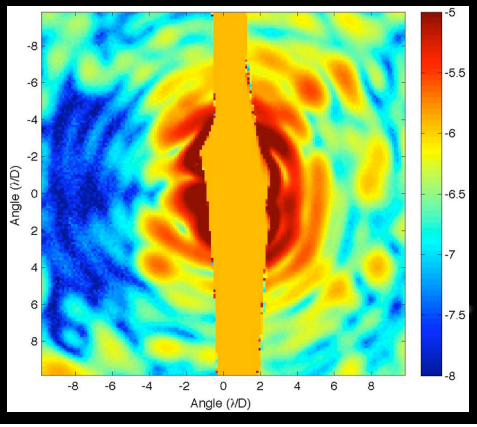
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

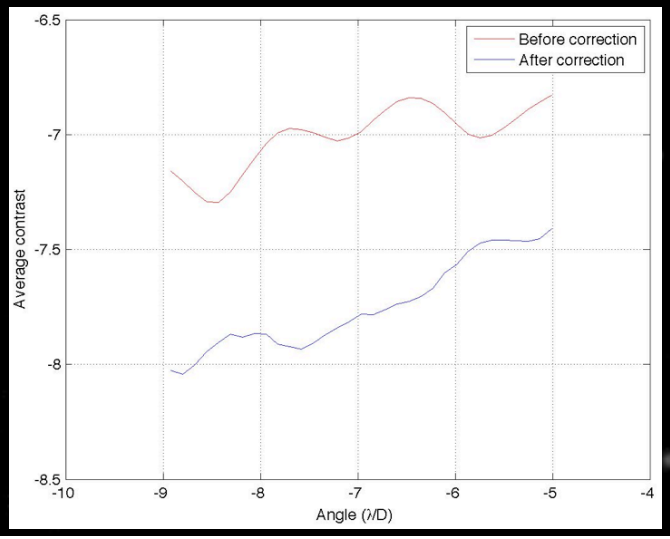
See this talk online at www.docsNtalks.com/go/RWZ409

Some results

UC Santa Cruz testbed

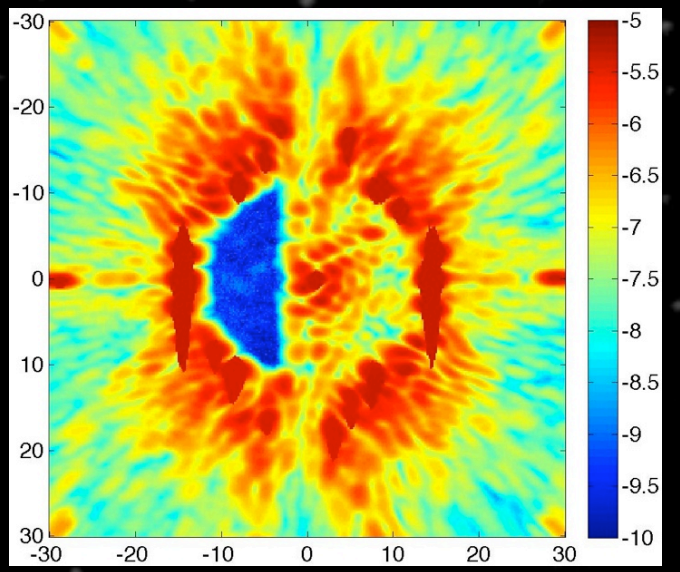
using an Apodized Pupil Coronagraph





JPL's High Contrast Imaging Testbed (HCIT)

using a Lyot Coronagraph



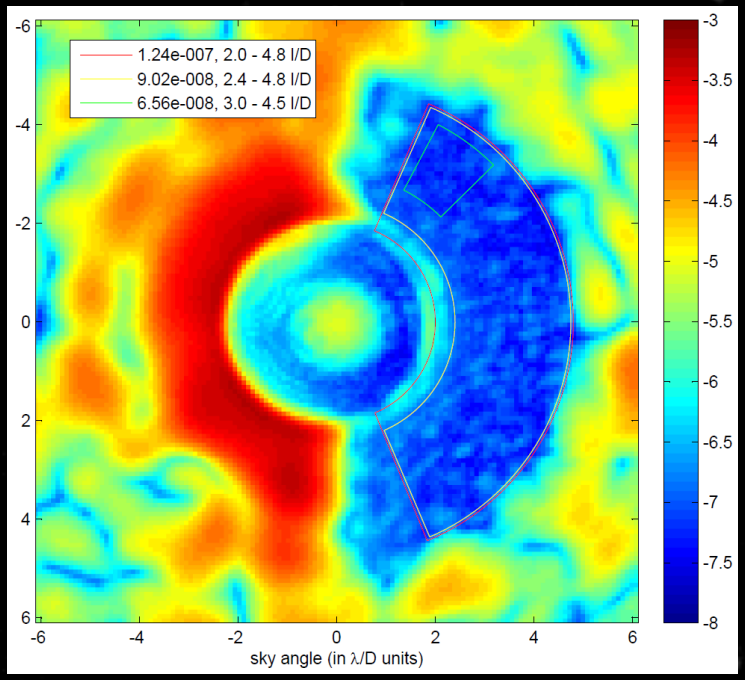
$6.5 * 10^{-10}$ *in* 10% *light*

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

NASA Ames Coronagraph Laboratory

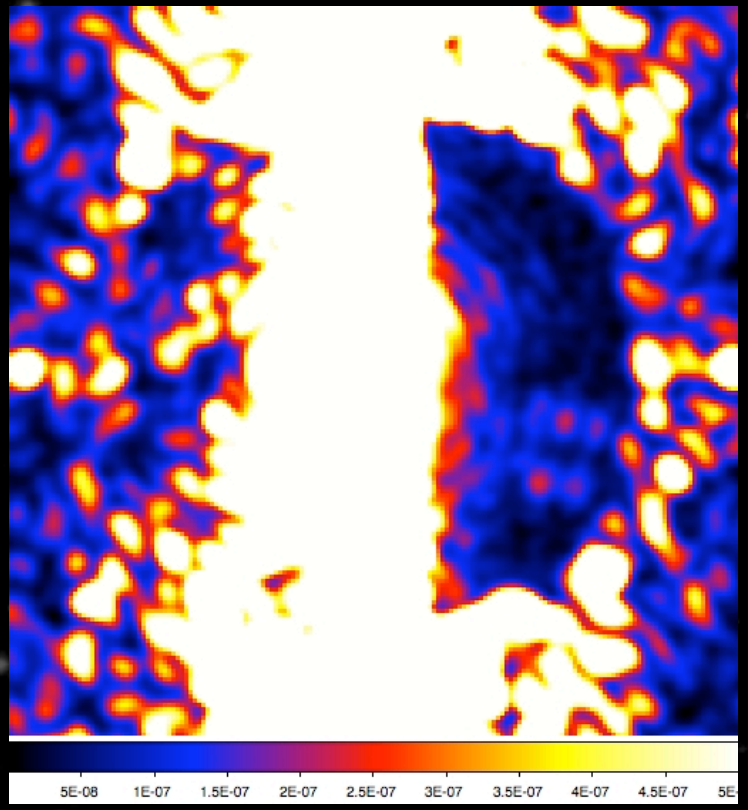
using a Phase Induced Amplitude Apodization Coronagraph



Ruslan Belikov, NASA Ames Coronagraph Laboratory

JPL's High Contrast Imaging Testbed (HCIT)

using a Vector Vortex Coronagraph



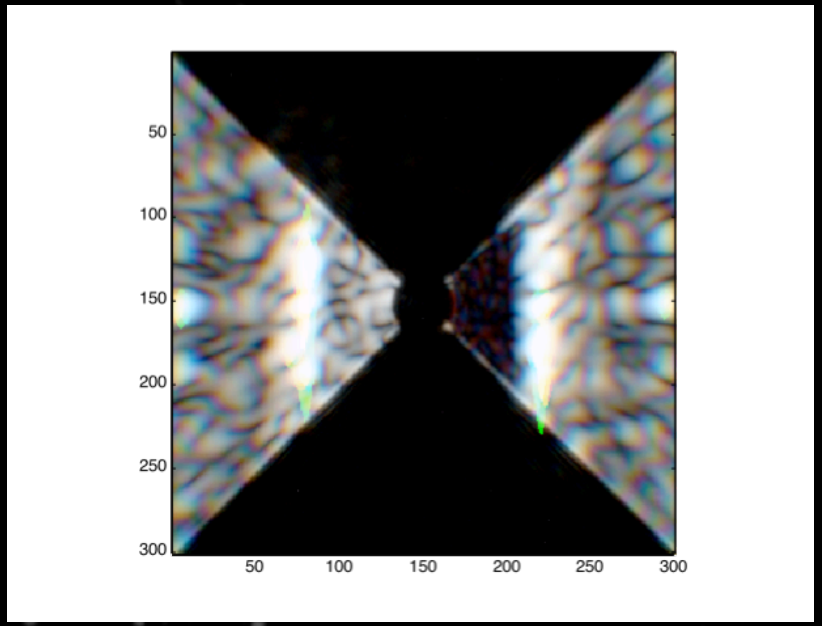
Dimitri Mawet, JPL

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

See this talk online at www.docsNtalks.com/go/RWZ409

JPL's High Contrast Imaging Testbed (HCIT)

using a Shaped Pupil Coronagraph



Contrast:	2.4 x 10^{-9}
Bandwidth:	10% @ 800nm
IWA:	4 λ/D

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Summary

- EFC is a formalism of the correction problem that provides many tools to find a suitable solution.
- All the common correction algorithms, namely, phase conjugation, speckle nulling and energy minimization can be viewed as special cases of EFC.
- EFC has used very successfully on several testbeds using different coronagraphs