Configuration Evaluation - I

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To do

- Bow-tie correlation map
- Motivate need to separate planets
- Add null depth definitions
- Separate slide for MMZ
- Sequence of time series

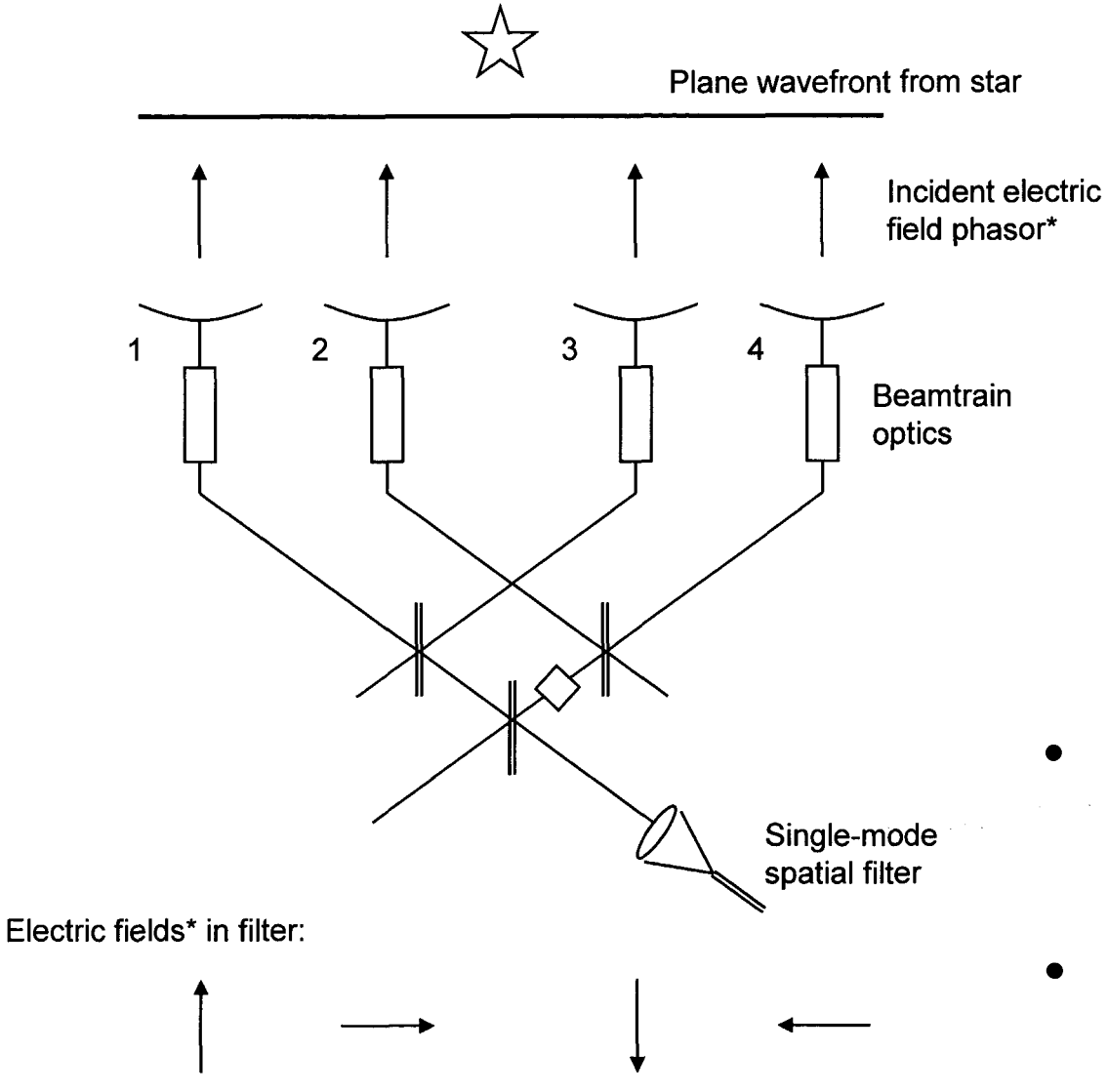
Overview

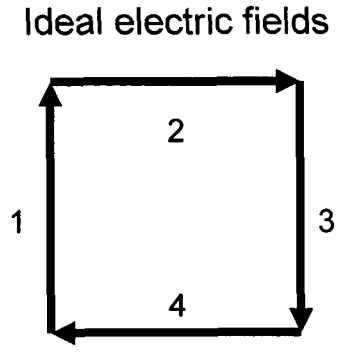
- Intended Result:
  - Basic
    - Agree on Definitions of key performance parameters and Figures of Merit
    - Present performance evaluation based on figures of merit
  - Extra credit (future)
    - Agree on performance evaluation based on common figures of merit
- Outline
  - Definitions of key performance parameters (Common ESA/NASA
    - Mod efficiency, SNR, response
  - Figures of Merit Definitions (Common ESA/NASA)
  - Perf eval based on Figures of Merit (Separate ESA/NASA)
    - Spectroscopy for single system
    - Number of stars for detection
    - Planet Isolation
  - Discussion leading to common perf eval.

Summary of nulling configuration

- Table from D'Arcio & Dubovitsky
  - Bow-tie
  - SCI (Structurally Connected Interferometer)
  - Regular Dual Chopped Bracewell
  - SCI 4:1
  - Combiner-less DCB
  - Three Telescope Nuller (TTN)
  - X-Array

Example for illustration



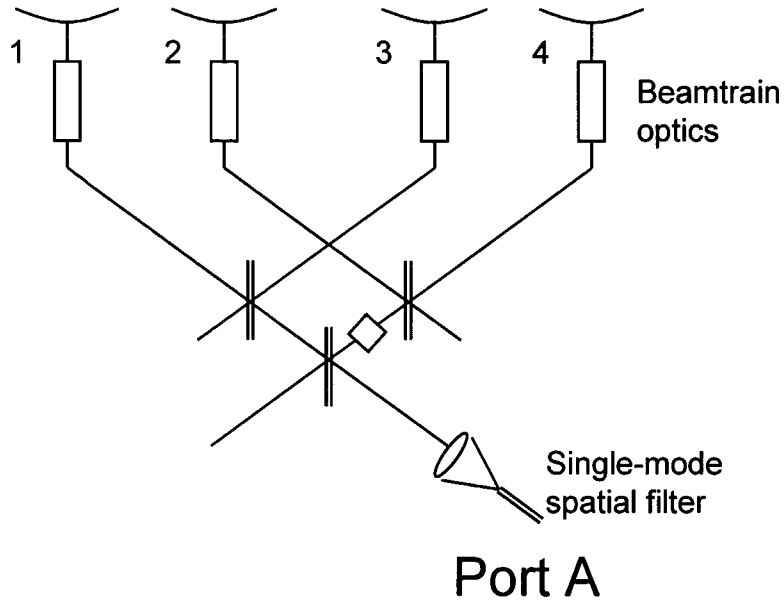


- Regular Dual Bracewell – simple, and familiar to everyone
- Single nulled output port

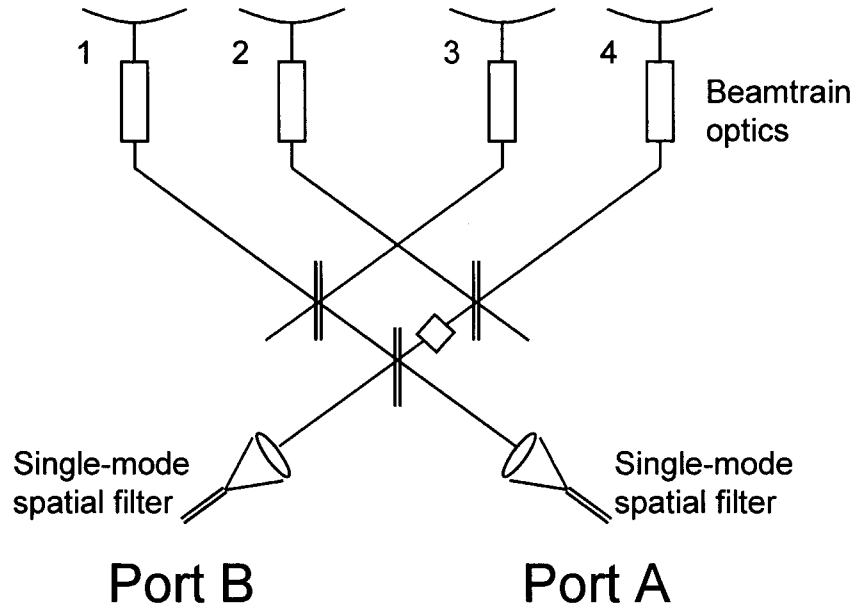
* Phasor angle represents electric field phase, not polarization

Number of output ports

- One output port:



- Two independent output ports:



- *Classic hierarchical beam combiner is twice as efficient as direct fiber combiner*
- MMZ has two independent pairs of output ports, but does not impact SNR

Outline sequence

- Instantaneous single chop
- Chopped
- Chopped & rotated

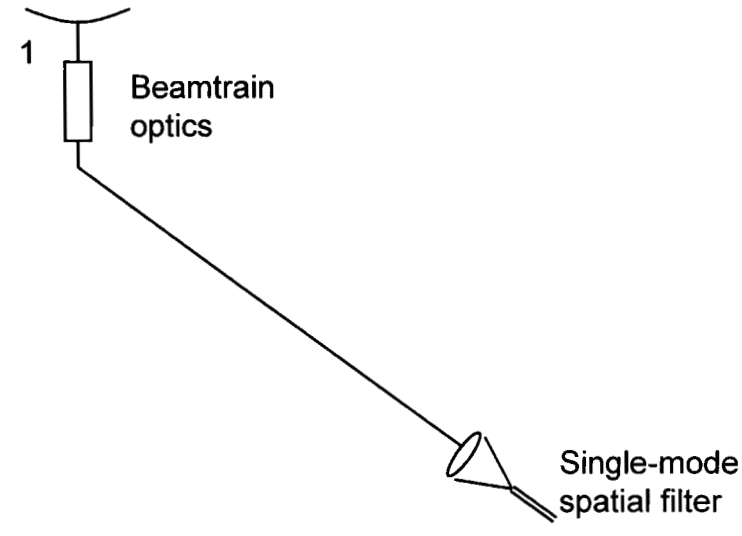
Planet signal

$$\underset{\text{Photo-electrons / s}}{\begin{array}{c}\text{planet photo-e}\\ \text{rate left chop}\\ \text{port A}\end{array}} = \underset{\text{Photons / Hz / m}^2\text{ / s}}{\text{planet flux}} \times \underset{\text{Hz}}{\begin{array}{c}\text{spectral}\\ \text{bandwidth}\end{array}} \times \underset{\text{m}^2}{\begin{array}{c}\text{total}\\ \text{area}\end{array}} \times \text{throughput} \times \begin{array}{c}\text{left chop}\\ \text{response}\end{array}$$

- Planet signal rms
  - Per independent output port
- total area = $N \pi d^2 / 4$
  - N = number of collectors, diameter d
  - Obscuration included in throughput

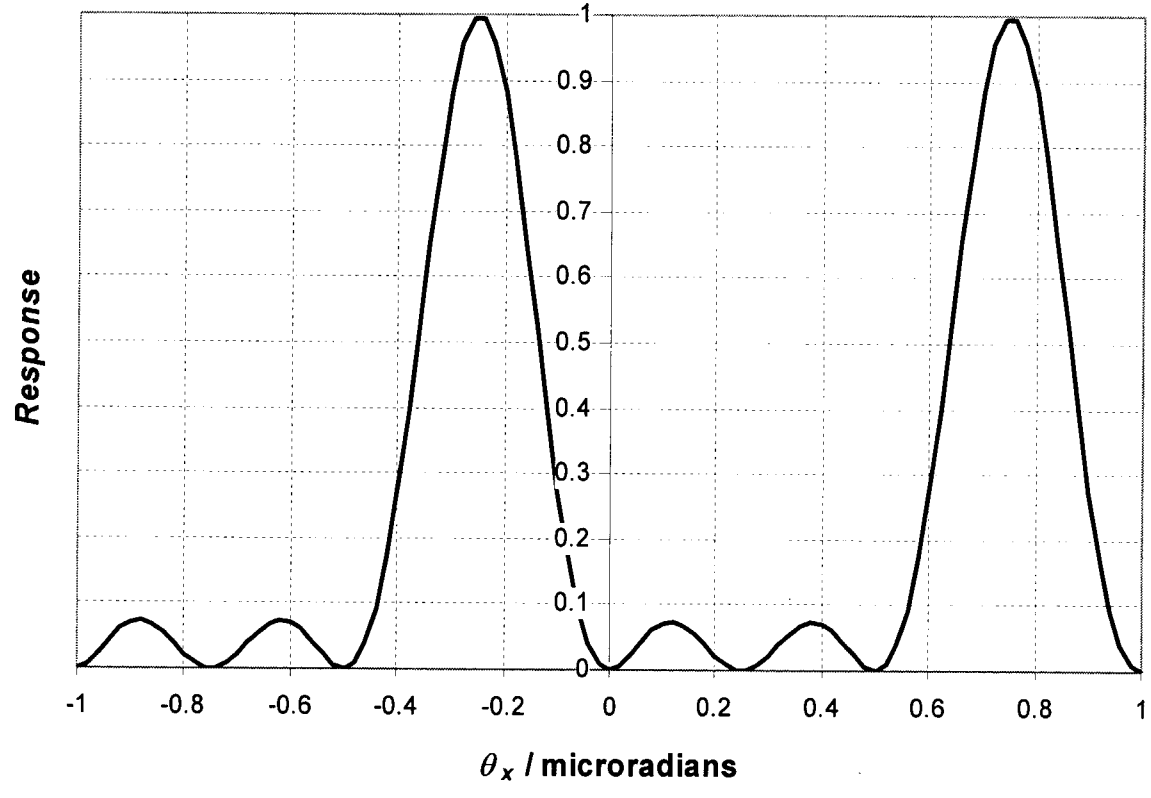
Throughput

- *Definition*
  - *Fraction of photons incident on a single collector that are converted to photo-electrons at a single output port, EXCLUDING THE EFFECT OF IDEAL BEAMSPLITTERS IN THE BEAM COMBINER*
- *Includes*
  - *Coatings, Strehl, coupling to single-mode filter, detector QE*
- *Excludes beamsplitters to make throughput somewhat independent of nulling configuration and beam combiner design*
- *Value assumed: 10% for all configurations*



Left chop response

$$\text{planet photo-e rate left chop port A} = \text{planet flux} \times \text{spectral bandwidth} \times \text{total area} \times \text{throughput} \times \text{left chop response}$$



- Regular Dual Chopped Bracewell

Phase chopping

$$\begin{matrix}\text{chopped planet}\\ \text{photo-e rate}\\ \text{port A (t)}\end{matrix} = \frac{1}{2}\left(\begin{matrix}\text{planet photon}\\ \text{rate left chop}\\ \text{port A (t)}\end{matrix} - \begin{matrix}\text{planet photon}\\ \text{rate right chop}\\ \text{port A (t)}\end{matrix}\right)$$

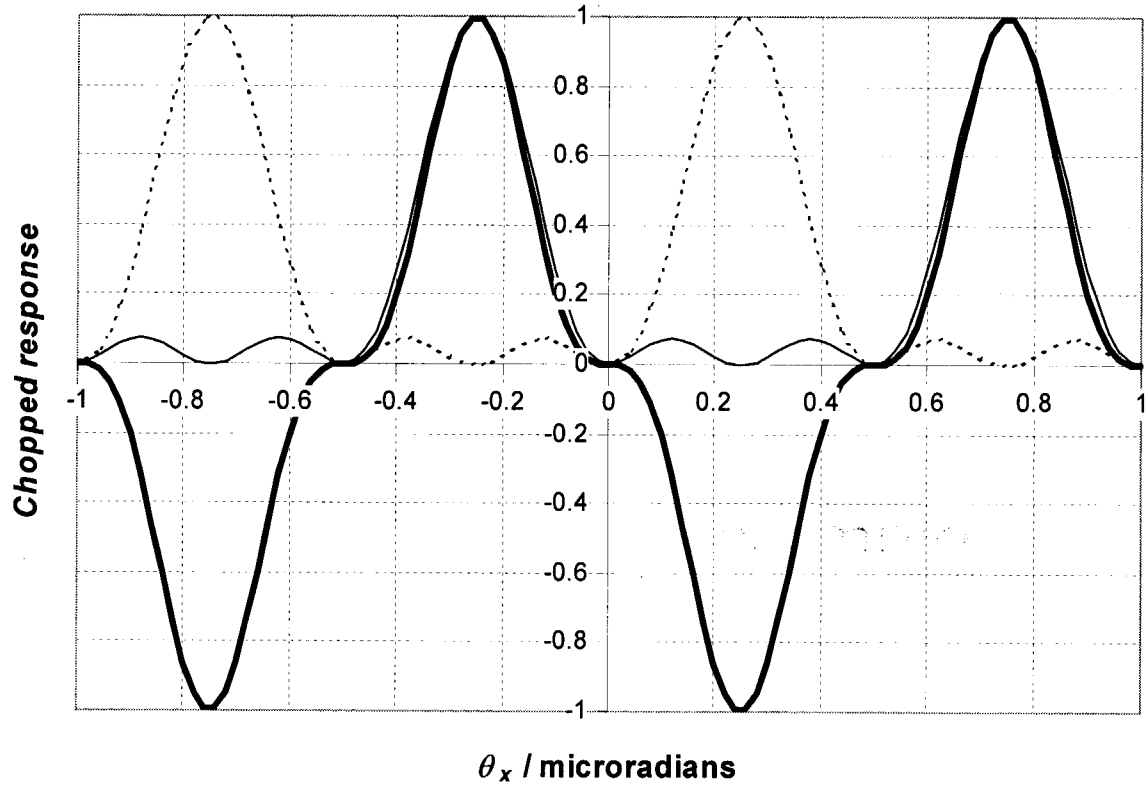
$$= \frac{1}{2} \times \text{planet flux} \times \begin{matrix}\text{spectral}\\ \text{bandwidth}\end{matrix} \times \begin{matrix}\text{total}\\ \text{area}\end{matrix} \times \text{throughput} \times \begin{matrix}\text{chopped}\\ \text{response}\end{matrix}$$

$$\text{chopped response} = \text{left chop response} - \text{right chopped response}$$

- Factor of ½ accounts for time interleaving of the two chop states

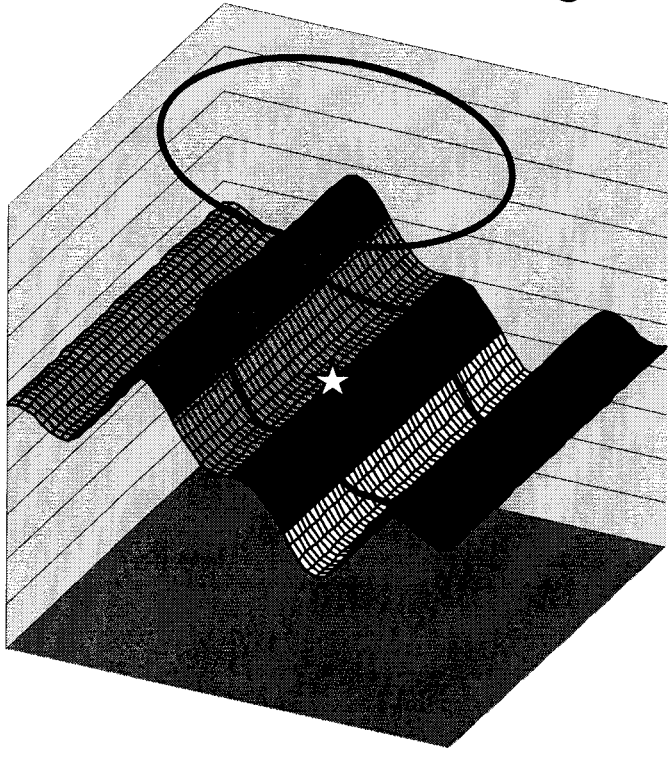
Phase chopping example

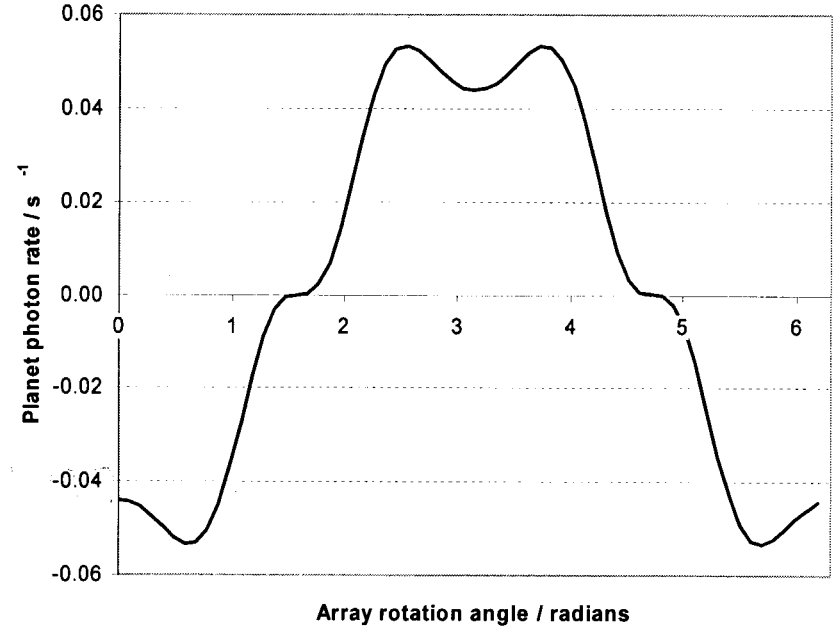
- Regular Dual Chopped Bracewell



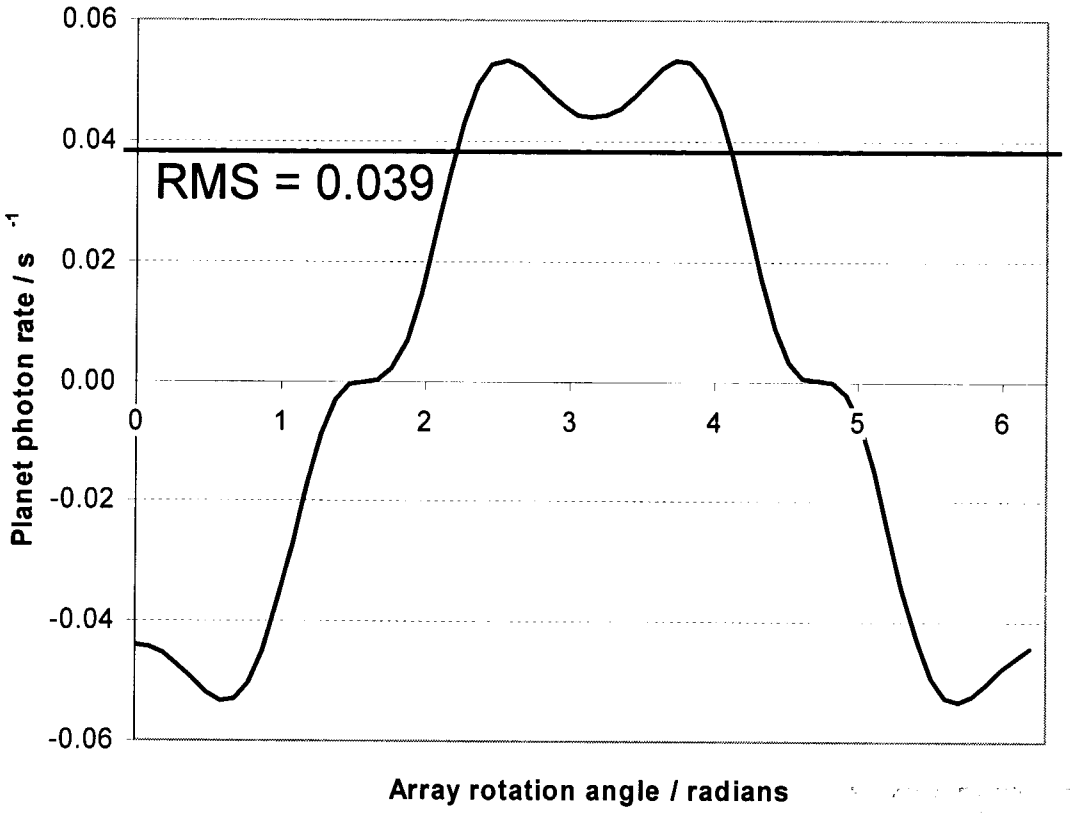
Array rotation to produce time series

- Assume continuous rotation
  - Equivalent to discrete steps, as long as step size is small enough to sample all harmonics
- This kind of thing:





Chopped planet rms photon rate



- RMS is the metric to use when Maximum Correlation Method used for signal extraction

Modulation efficiency

$$\begin{array}{c}\text{planet photo-e}\\ \text{rate left chop}\\ \text{port A (t)}\end{array} = \left\{\text{planet flux} \times \begin{array}{c}\text{spectral}\\ \text{bandwidth}\end{array} \times \begin{array}{c}\text{total}\\ \text{area}\end{array} \times \text{throughput}\right\} \times \begin{array}{c}\text{left chop}\\ \text{response}\end{array}$$

Difference between two chops

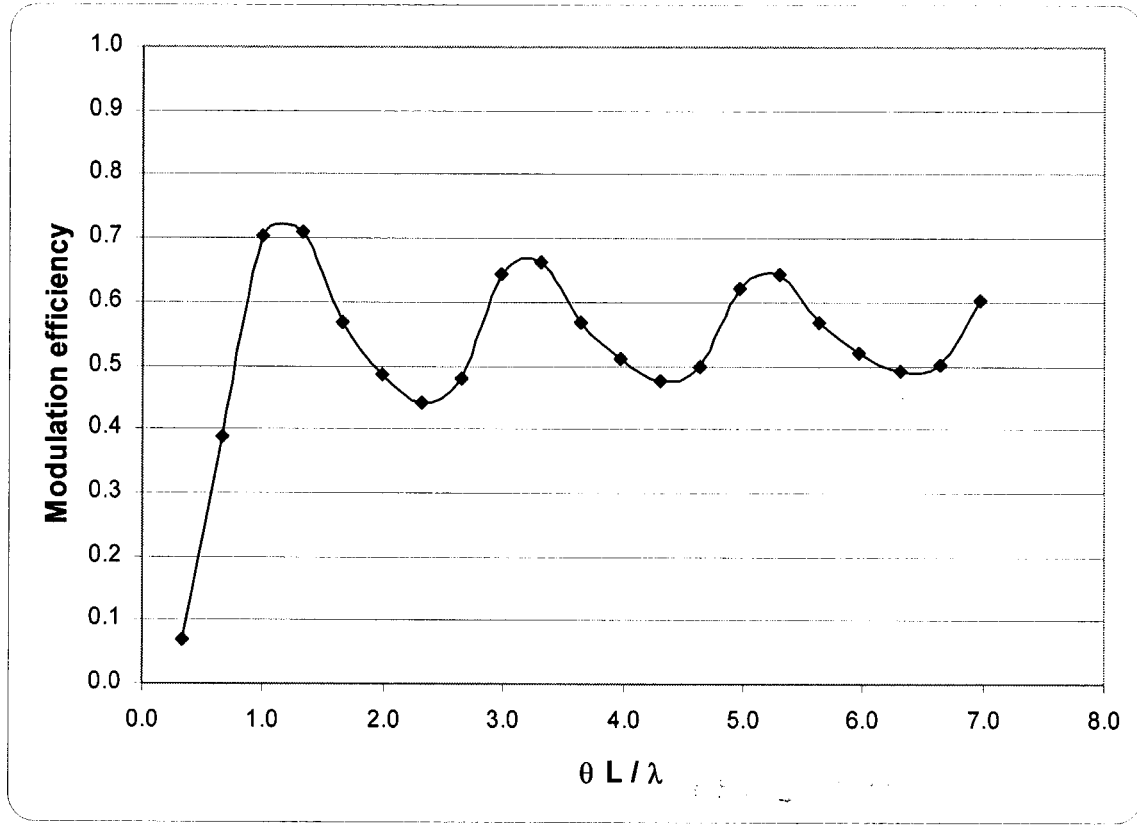
$$\begin{array}{c}\text{chopped planet}\\ \text{photo-e rate}\\ \text{port A (t)}\end{array} = \frac{1}{2} \times \left\{\text{planet flux} \times \begin{array}{c}\text{spectral}\\ \text{bandwidth}\end{array} \times \begin{array}{c}\text{total}\\ \text{area}\end{array} \times \text{throughput}\right\} \times \begin{array}{c}\text{chopped}\\ \text{response}\end{array}$$

Rotate array & take rms

$$\begin{array}{c}\text{chopped planet}\\ \text{rms photo-e rate}\\ \text{port A}\end{array} = \frac{1}{2} \times \left\{\text{planet flux} \times \begin{array}{c}\text{spectral}\\ \text{bandwidth}\end{array} \times \begin{array}{c}\text{total}\\ \text{area}\end{array} \times \text{throughput}\right\} \times \begin{array}{c}\text{modulation}\\ \text{efficiency}\end{array}$$

- Modulation efficiency contains all the configuration-dependent factors in the planet signal
- A measure of the useful signal per photon entering the beam combiner

Regular DCB (hi-res)



- θ = angular offset of planet from star on sky / rad
- L = array length / m
- λ = wavelength / m

- Have not included taper due to primary beam pattern of collectors

SNR formula

$$\text{Planet SNR} = \frac{\text{chopped planet rms photon rate}}{\text{Integrated noise}} \times \sqrt{\text{Number of output ports}}$$

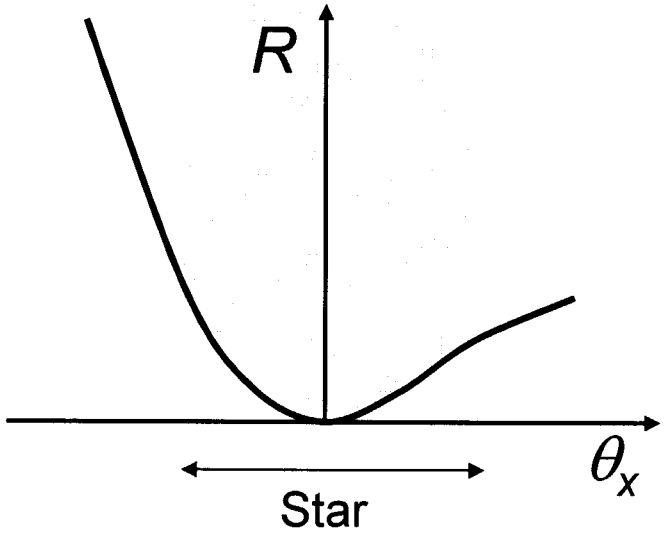
$$\text{Integrated noise} = \left\{ (\text{Random noise})^2 + (\text{Systematic noise})^2 \right\}^{0.5}$$

- 'Integrated' means averaged over observation time
- To simplify comparison
  - Consider only photon noise from astronomical sources
  - Ignore systematic noise
  - Ignore detector and thermal noise

$$\text{Integrated noise} \sim \left\{ \frac{\text{Total photon rate per output port}}{\text{Observation time}} \right\}^{0.5}$$

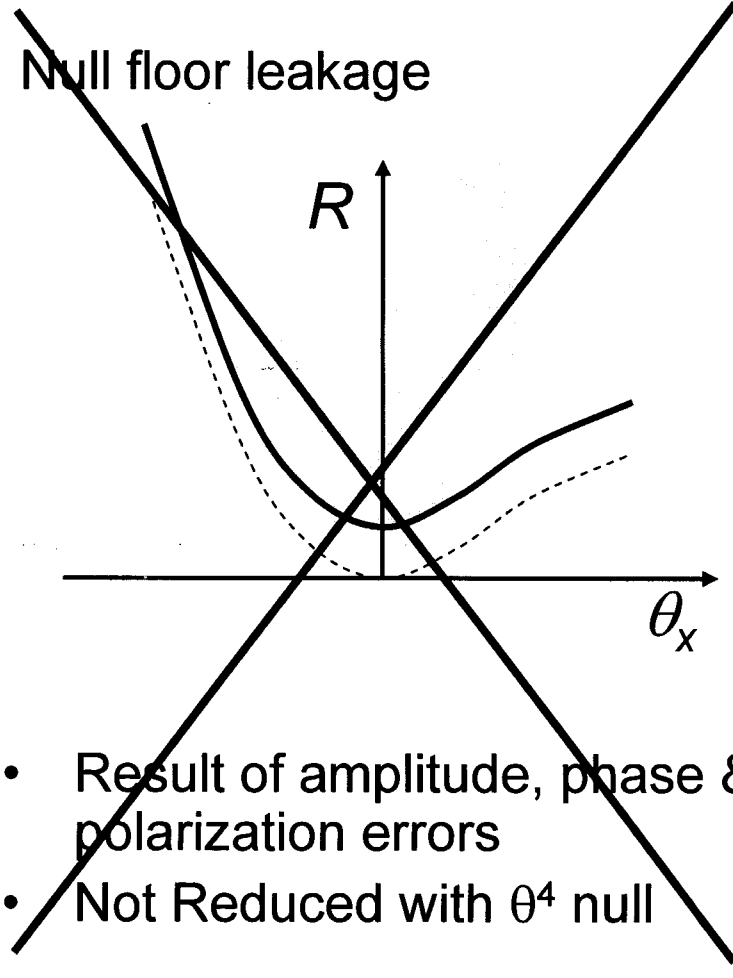
Noise sources

Stellar geometric leakage



- Also EZ and LZ geometric leakage
- Occurs for ideal instrument
- Reduced with θ^4 null

Null floor leakage



- Result of amplitude, phase & polarization errors
- Not Reduced with θ^4 null

Not included

Figures of Merit

- Engineering (not covered here)
  - e.g. beam combiner complexity, beam relay
- Performance
  - Sensitivity
    - SNR, integration time
    - Star counts
  - Locating and separating planets

SNR comparison

- *Earth-Sun @ 15 pc, 9.5 – 10 μm, 50 mas offset*
- Choose array length to maximize SNR, with S/C no closer than 20 m
- Local Zodi
  - Fit to Kelsall model
  - Ecliptic latitude = 30 deg
- Exo-Zodi
  - Kelsall model
  - 3 zodis

Comparison of integration times for Ozone

Quantity	SCI	SCI x 2	SCI (4:1)	Regular DCB	X-Array	Combiner-less DCB
Array length	36 m	72 m	35 m	93 m	100 x 22 m	52 m
Collector diameter	**3.20** m	**3.20** m	**3.20** m	**3.50** m	**3.50** m	**3.50** m
SNR per rotation	**1.244**	**0.553**	**1.019**	**0.948**	**1.319**	**1.219**
# output ports	**2**	**2**	**2**	**2**	**2**	**2**
Time for SNR = 10	1615471 s	8175037 s	2407641 s	2781784 s	1436979 s	1682413 s
	18.7 days	94.6 days	27.9 days	32.2 days	16.6 days	19.5 days

Quantity	Triangle 1	Triangle 2	Bow-tie
Array length	26 m	60 m	52 m
Collector diameter	**4.00** m	**4.00** m	**2.80** m
SNR per rotation	**1.441**	**0.737**	**0.905**
# output ports	**1**	**1**	**2**
Time for SNR = 10	2407920 s	9205238 s	3052410 s
	27.9 days	106.5 days	35.3 days

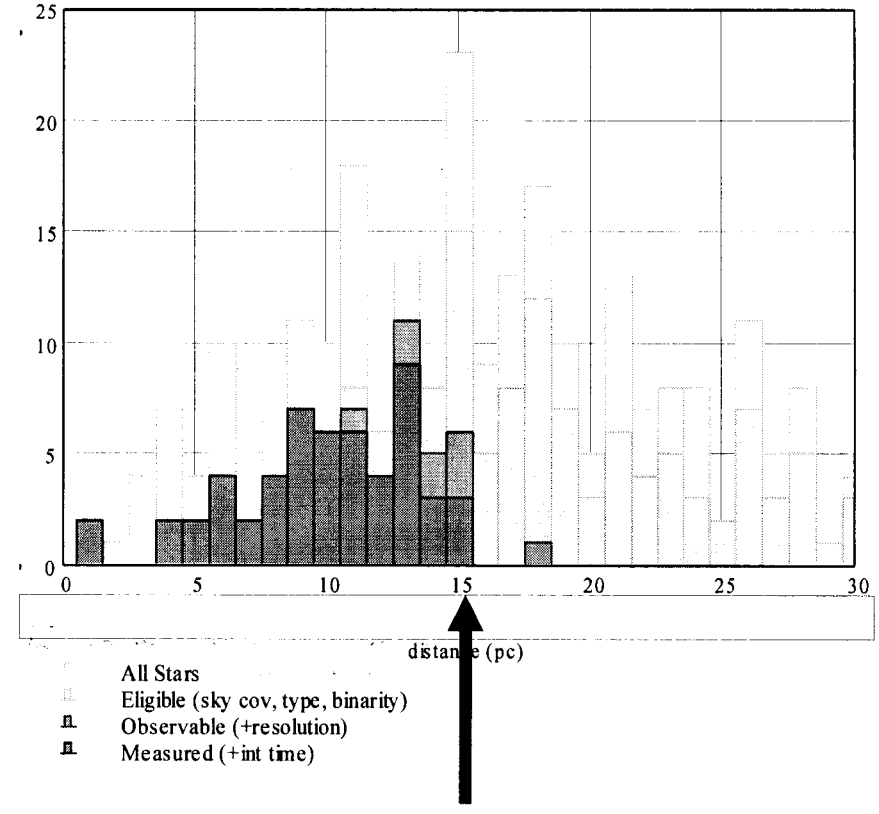
Distance	**15** pc
Ecliptic latitude	**30** deg
Target system inclination	**30** deg
Target system position	**30** deg
Stellar radius	**1** R_{sun}
Stellar effective	**5770** K
Planet radius	**1.00** R_{earth}
Planet effective	**265** K
Planet orbital radius	**1.00** AU
Planet orbital phase	**50.0** deg
Exo-zodiacal emission	Kelsall
Exo-zodiacal level	**3** zodis
Local zodiacal foreground	Kelsall
Array rotation time	**50000** s
Instrument throughput,	**0.1**
Single mode filter beam	**1.096** λ^2
Temperature of optical	**40** K
Net beamtrain emissivity	**1**

Justification for 15 pc test case

- For uniform volume density of sources, number of sources per unit distance interval ~ D^2
- If photon rate dominated by LZ, then required observing time per source T ~ D^4
- => Observing time per unit distance interval ~ D^6
- => Largest distance dominates observing time

Most of the observing time will be spent on sources at distance of ~ 15 pc

From Serge star count analysis



Largest distance ~ 15 pc
(Robust to most assumptions)

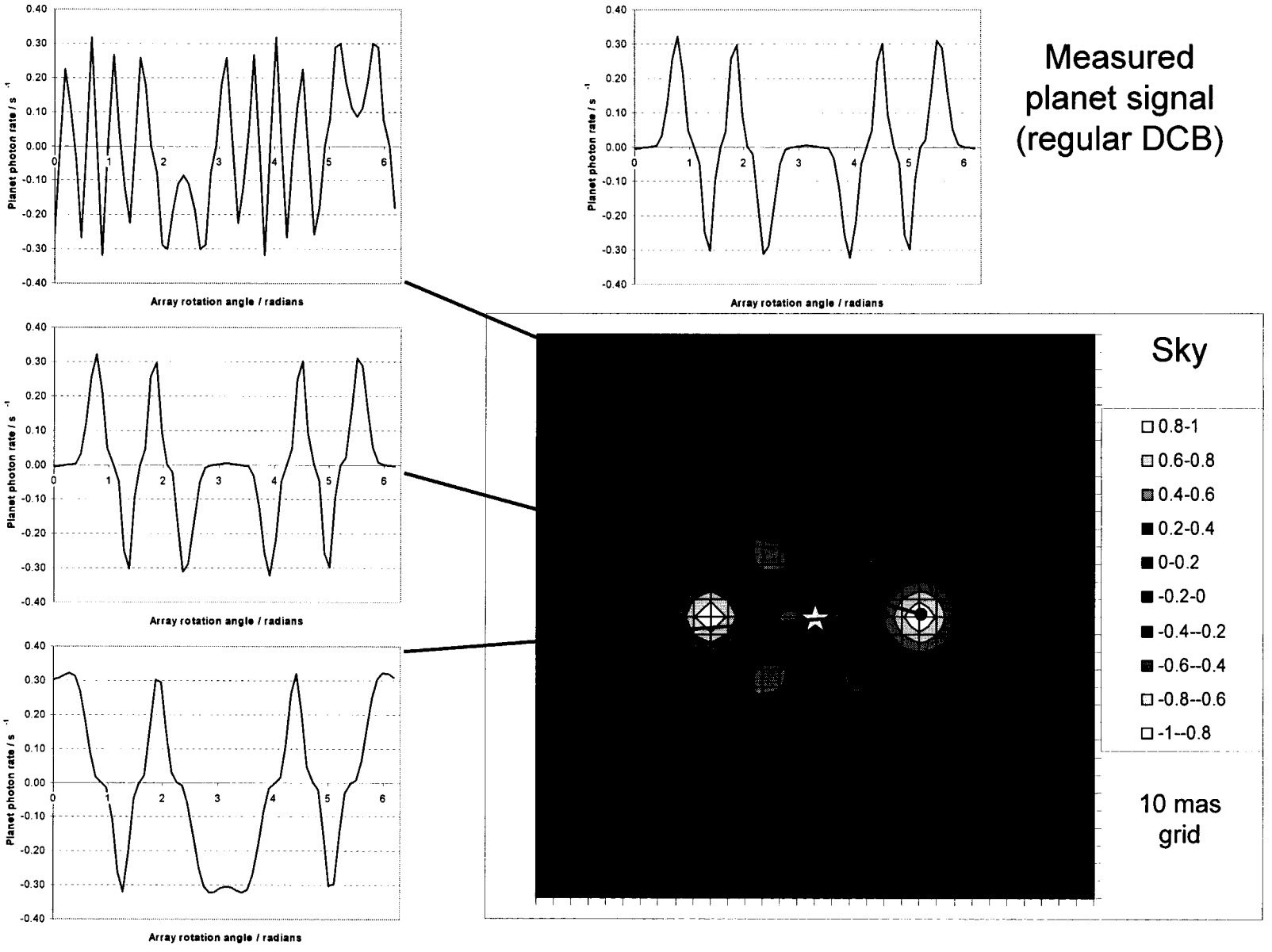
Star counts

- Outline the process
- Table comparing results

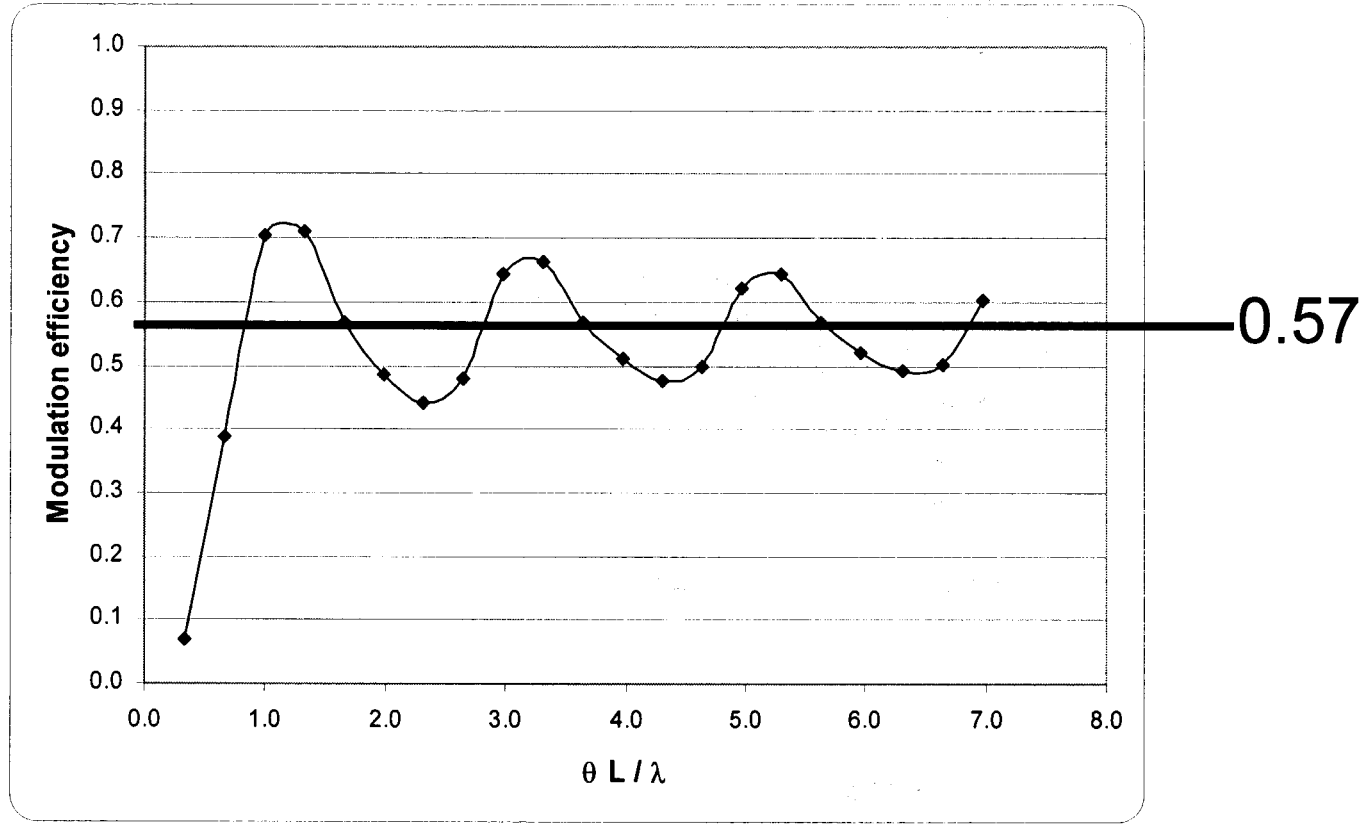
Locating and separating planets

- *An important issue that has not received much attention*

Correlation maps



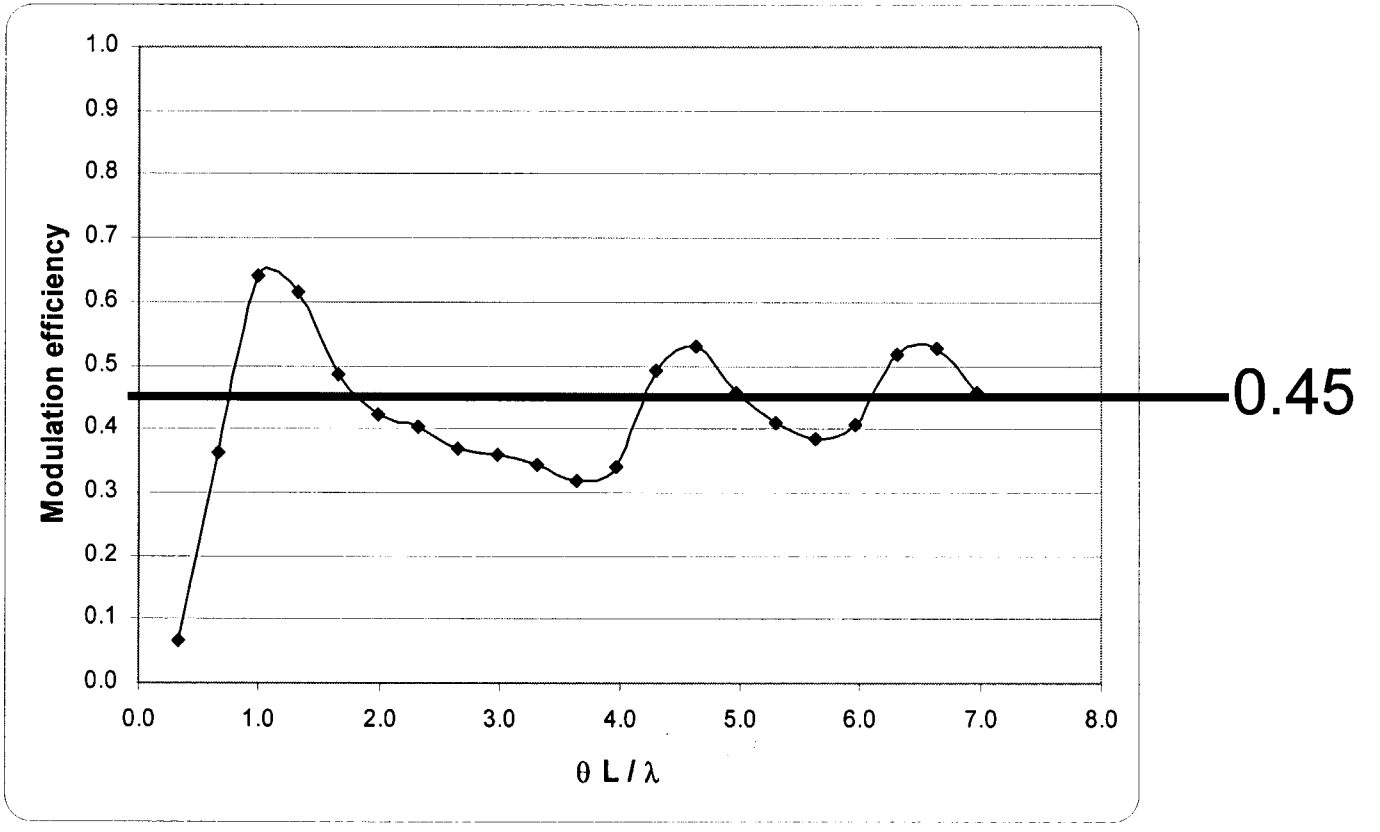
Regular DCB (hi-res)



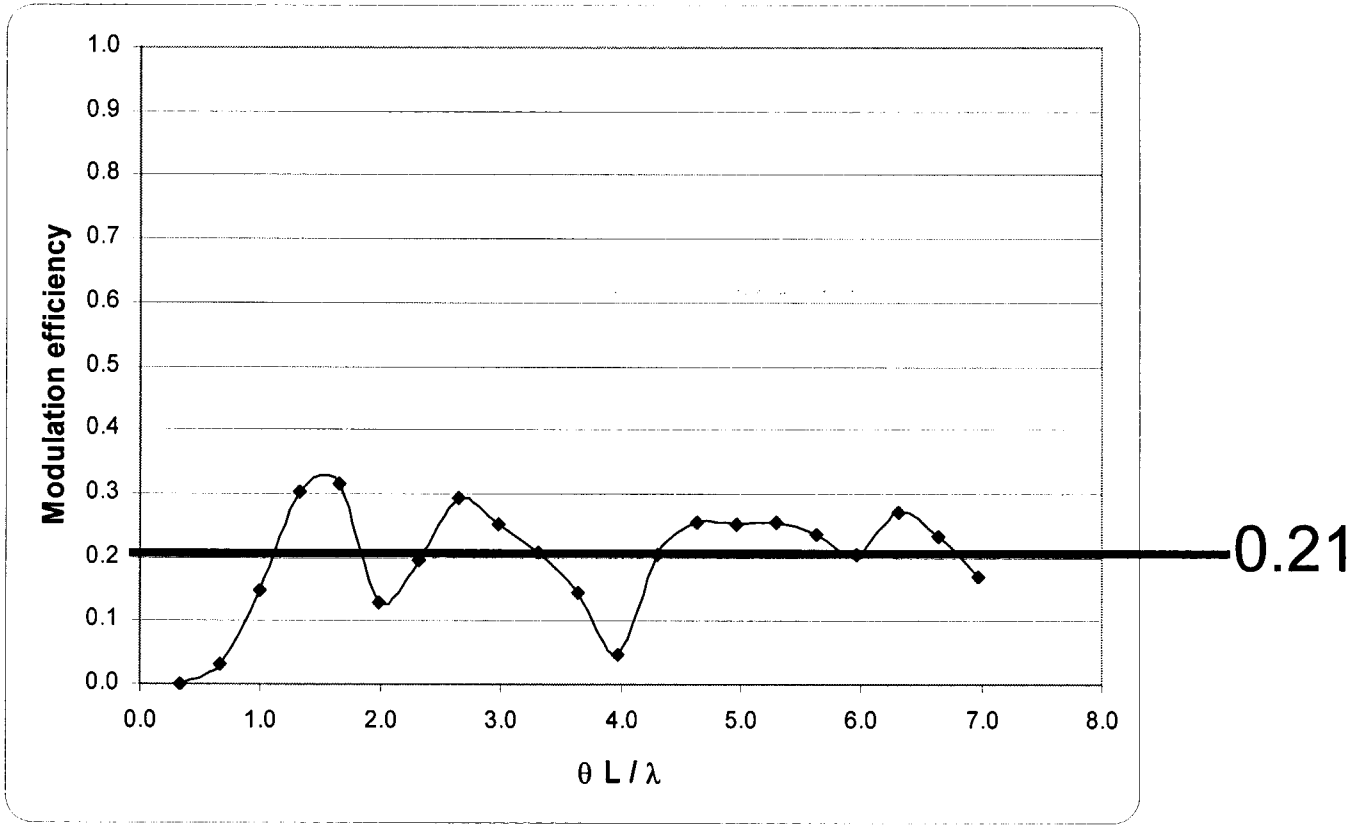
- θ = angular offset of planet from star on sky / rad
- L = array length / m
- λ = wavelength / m

- Have not included taper due to primary beam pattern of collectors

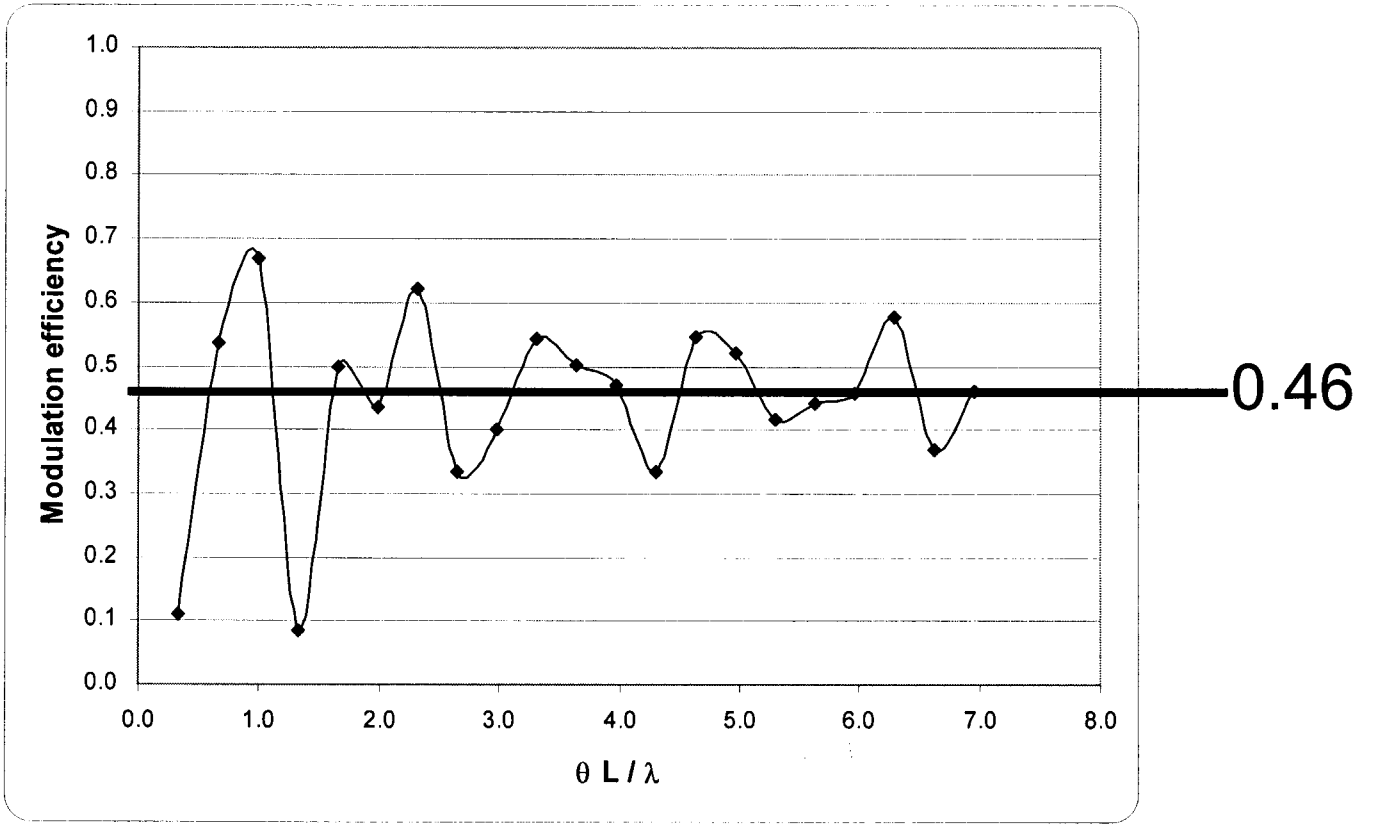
SCI (hi-res)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Modulation efficiency
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
θ L / λ
0.45

Bow-tie

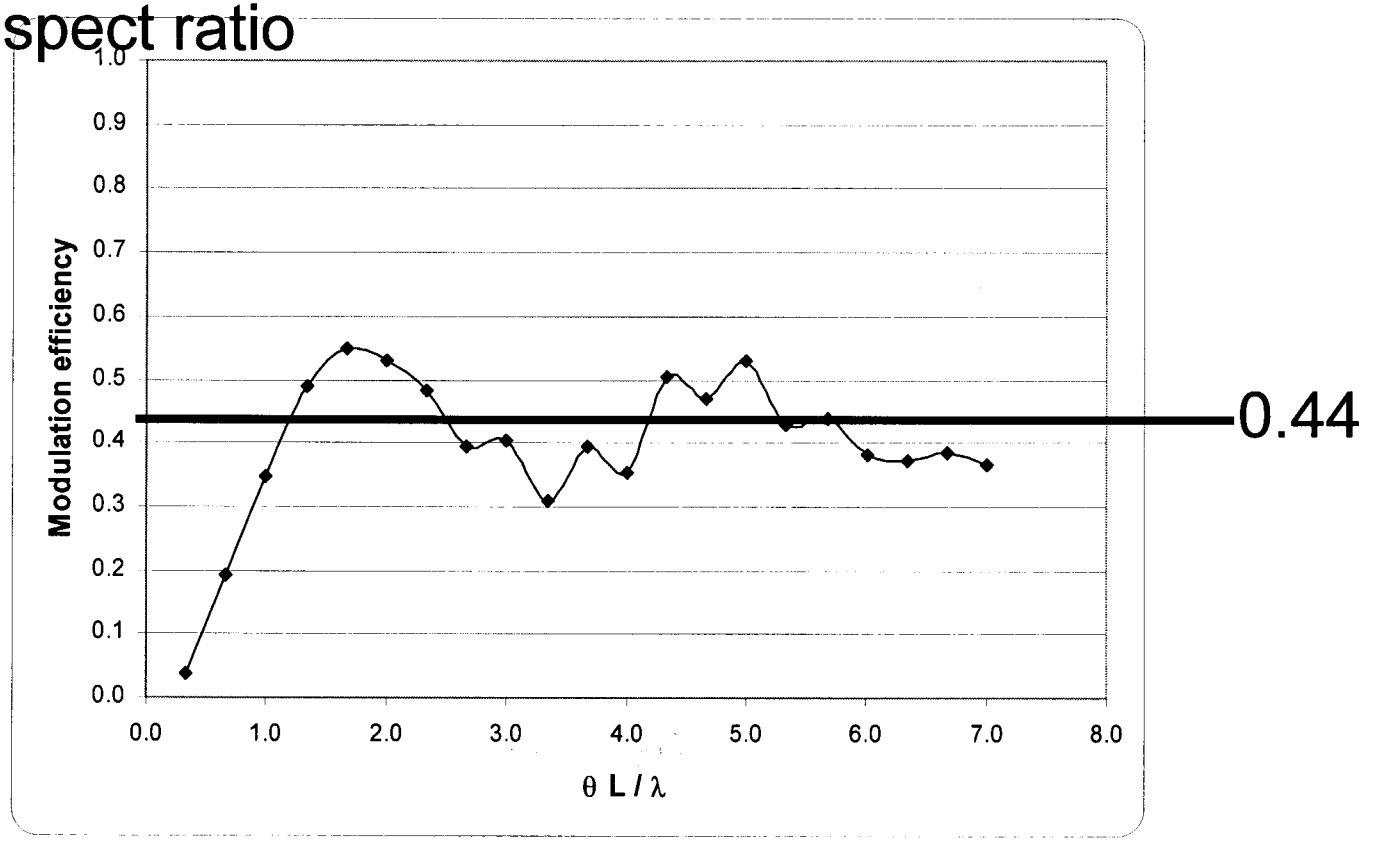

Modulation efficiency
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
θ L / λ
0.21

Three Telescope Nuller

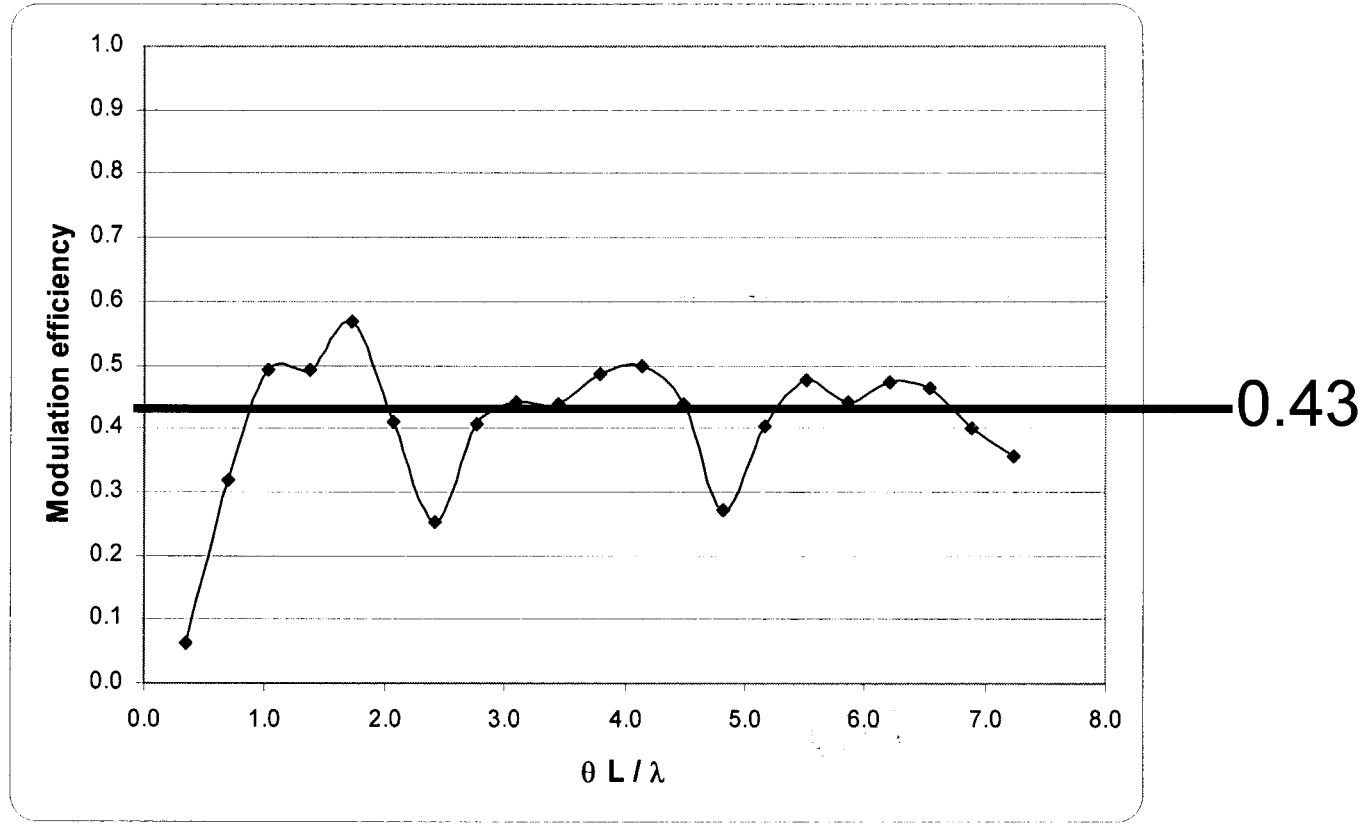


X-Array

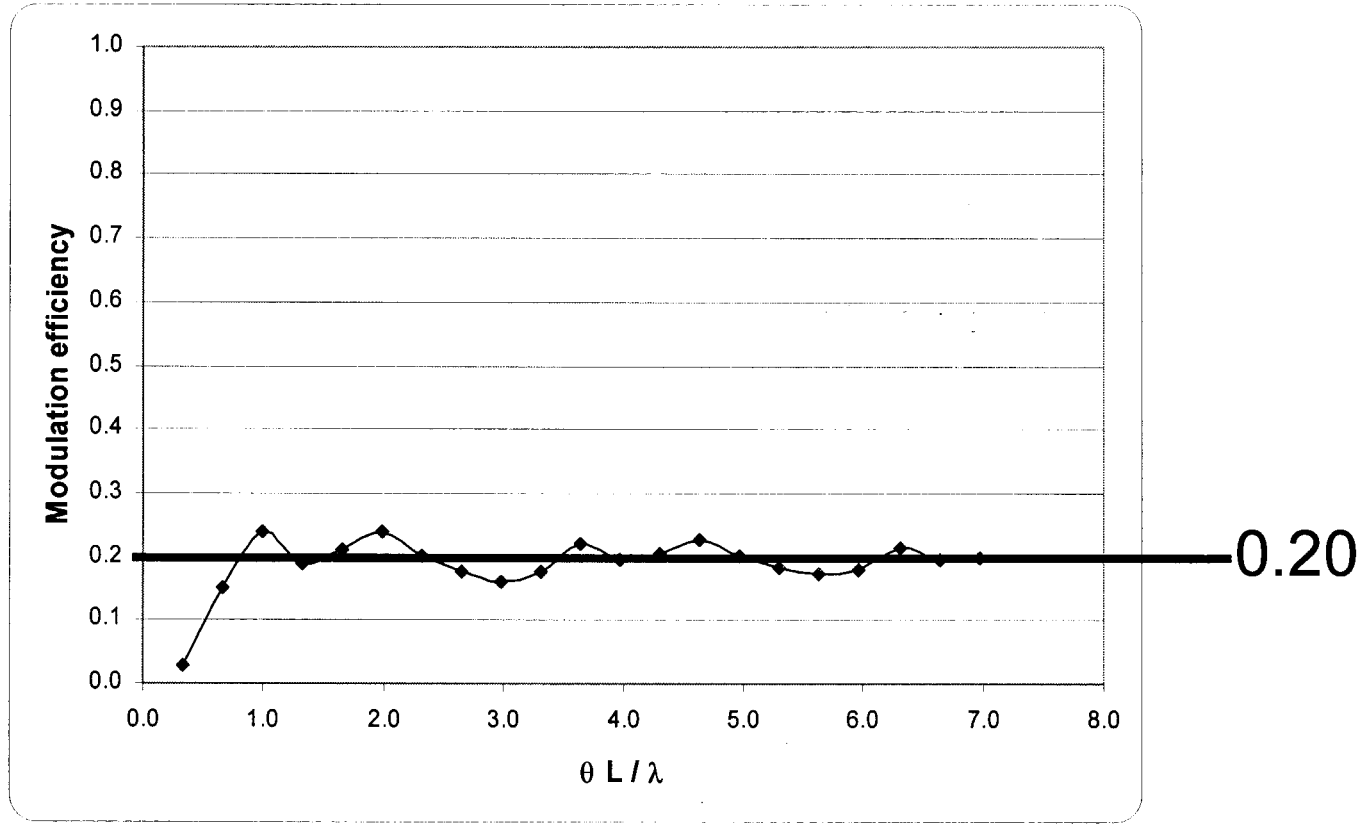
- 2:1 aspect ratio



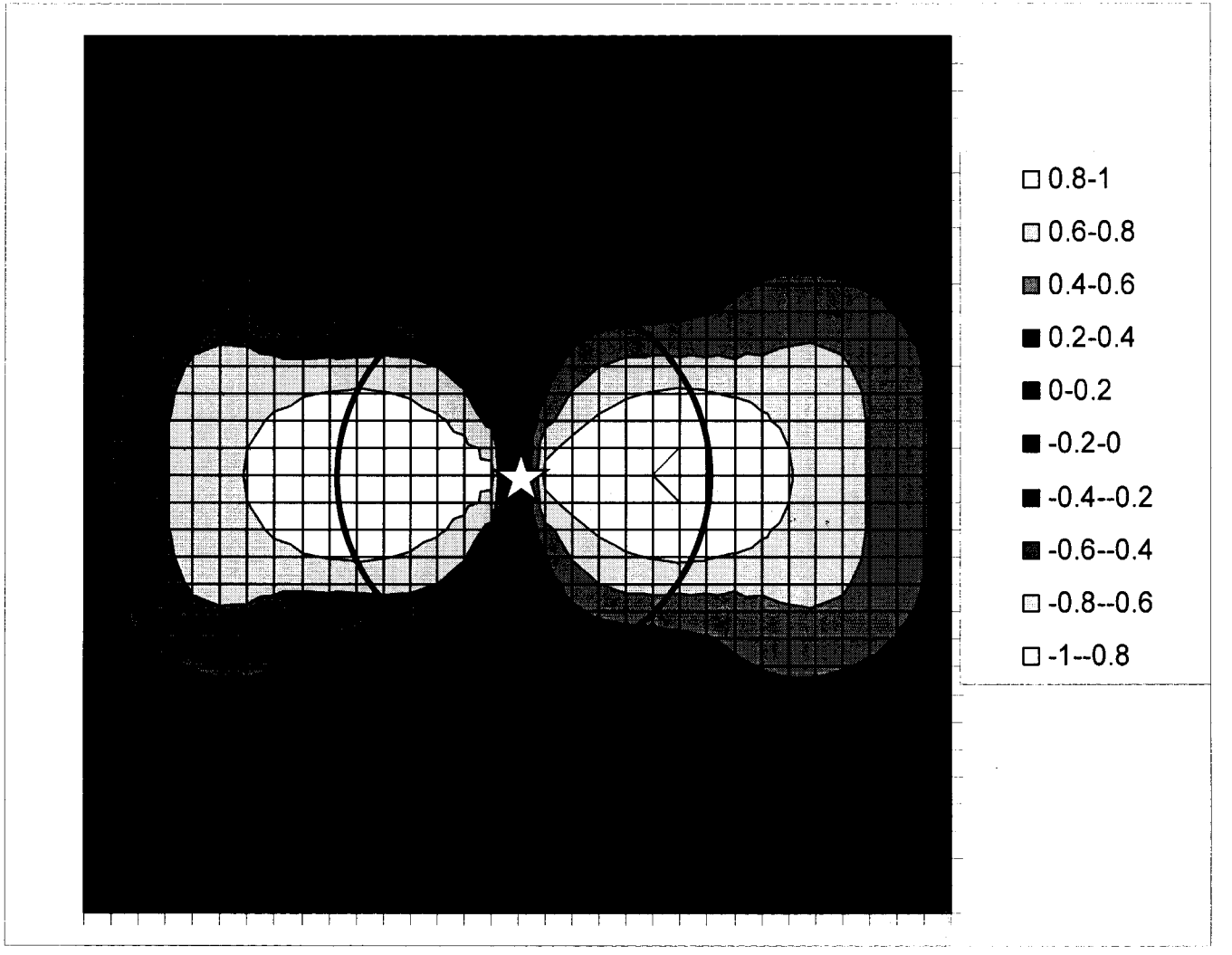
Combiner-less DCB



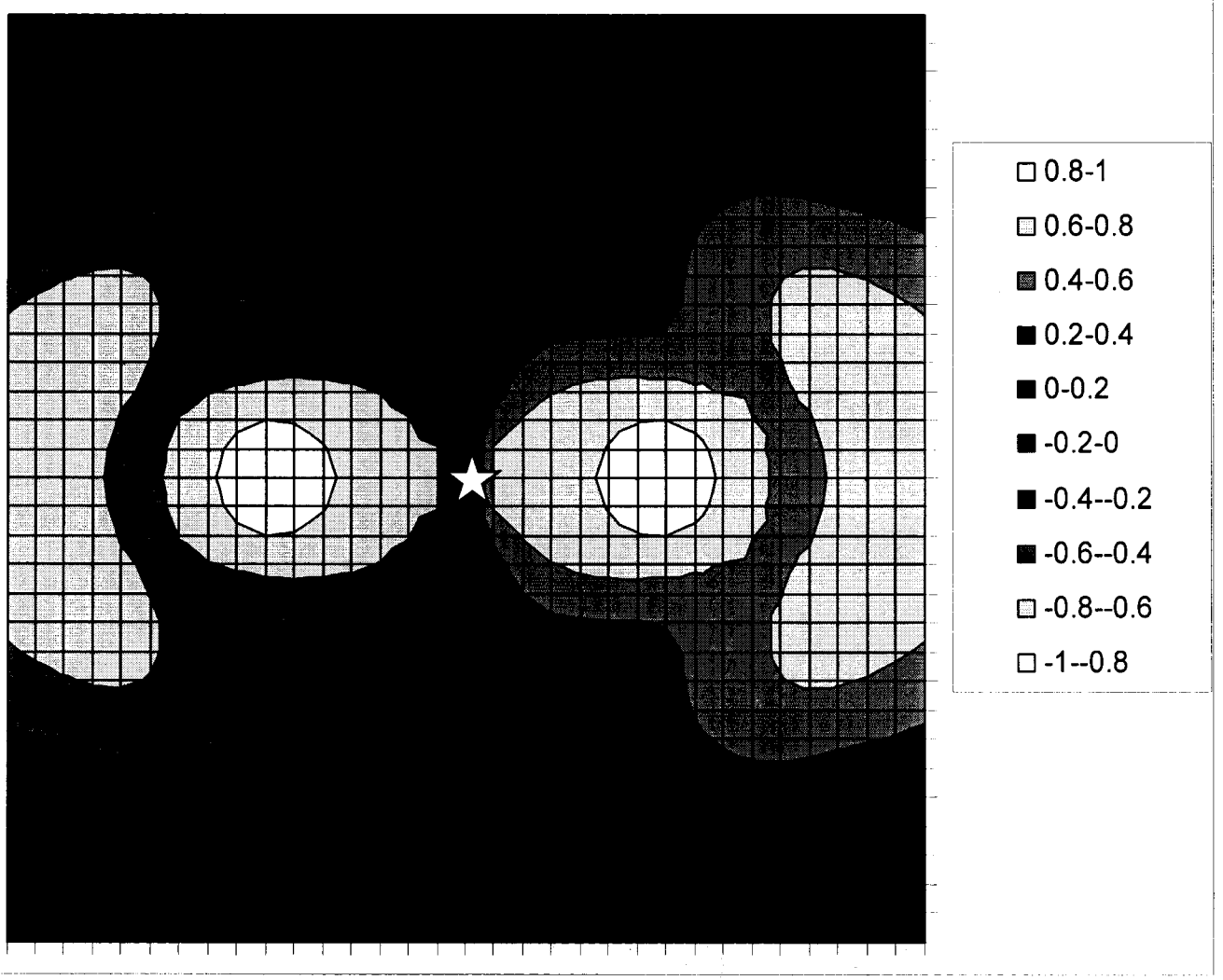
Linear 3 (1:1:-2)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Modulation efficiency
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
θ L / λ
0.20

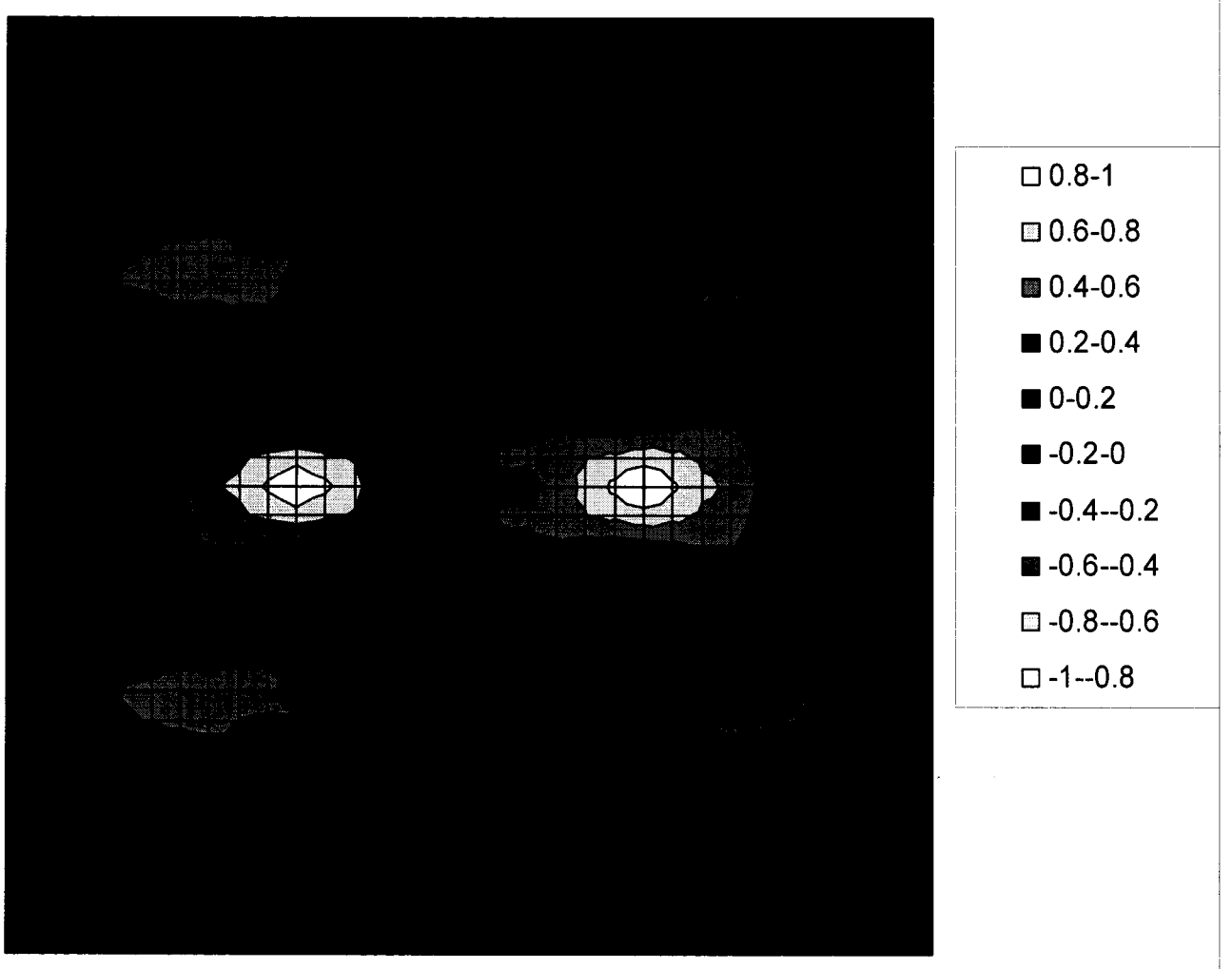
Standard SCI: single source



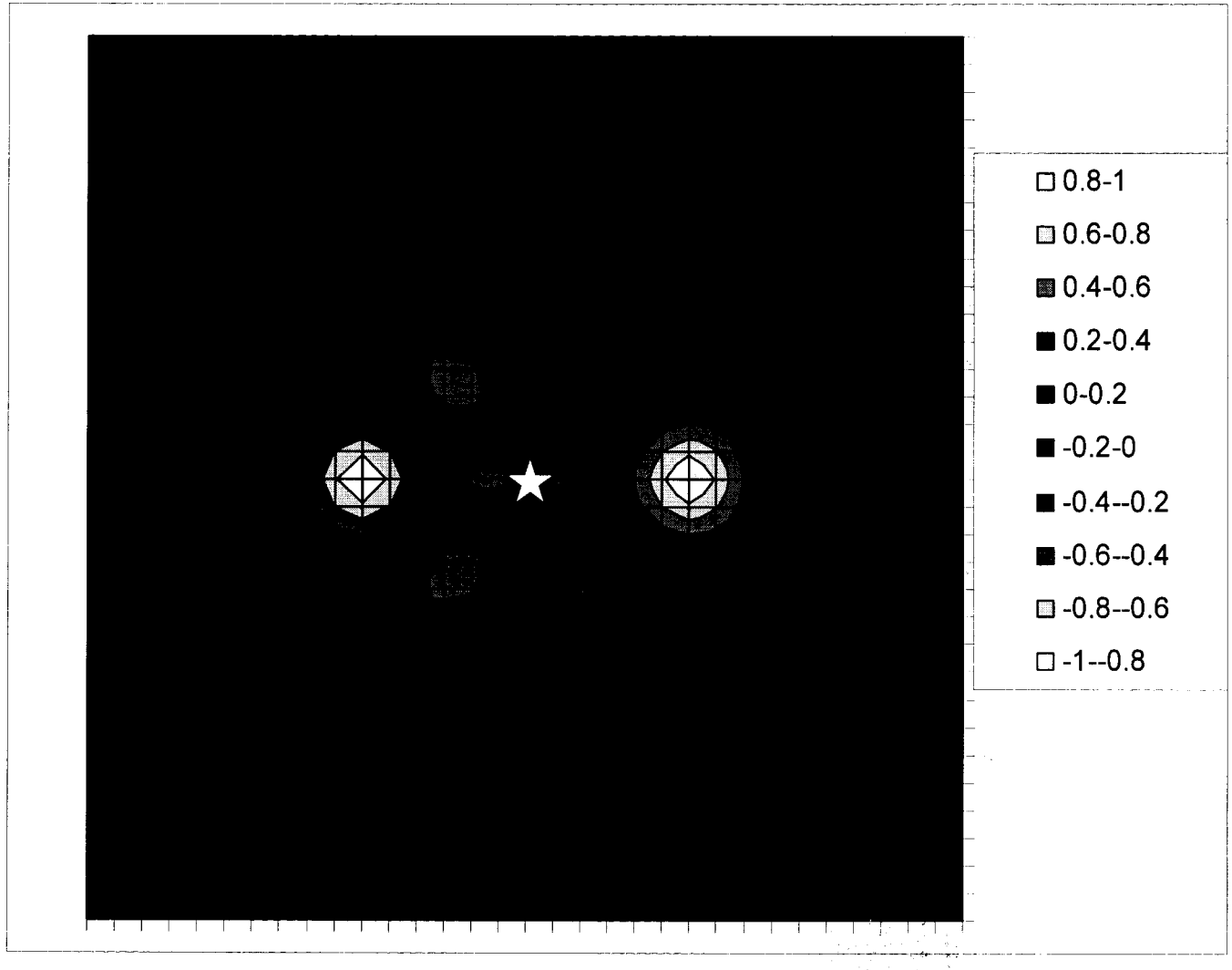
4:1 SCI: single source



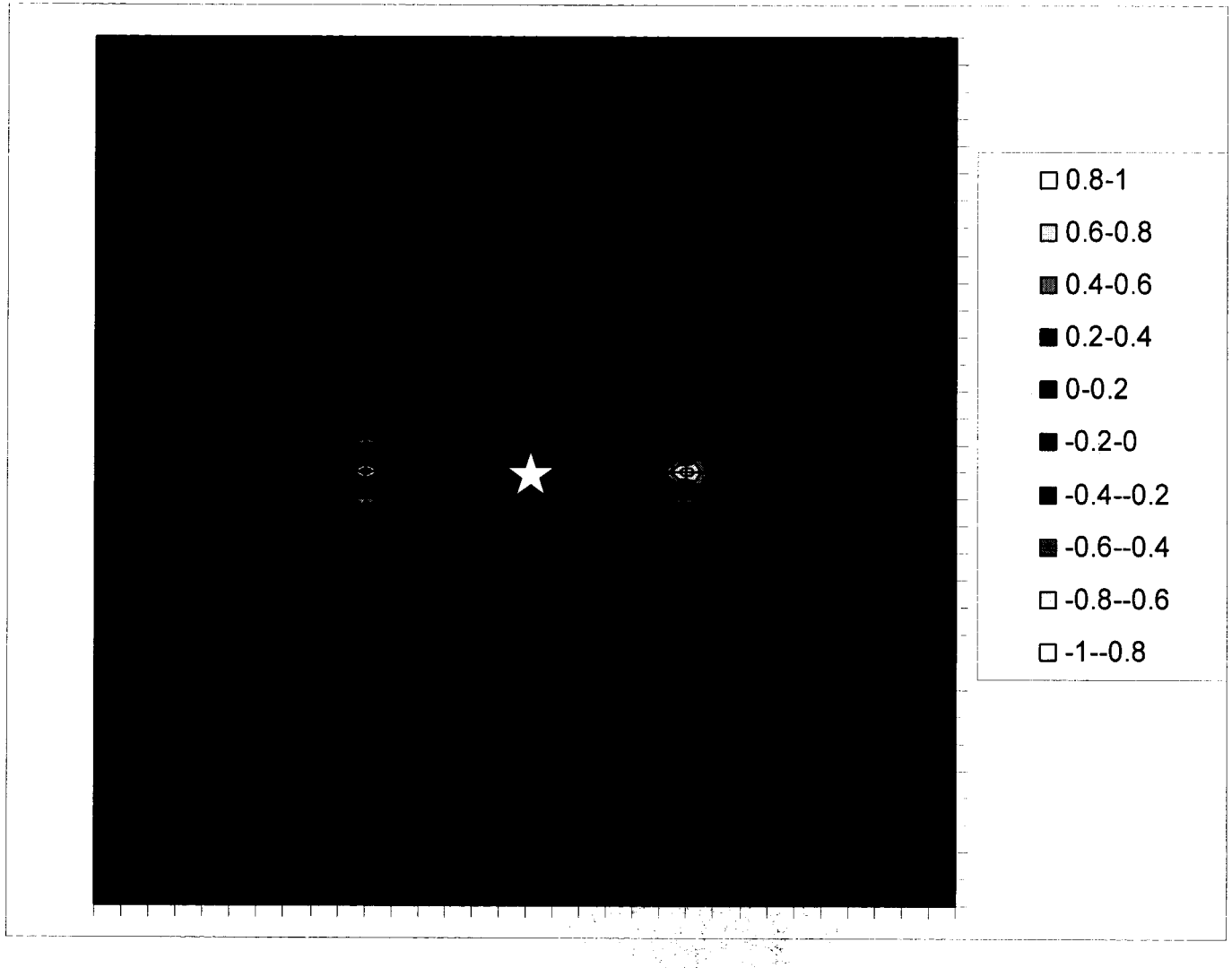
SCI x 2 (72 m): single source



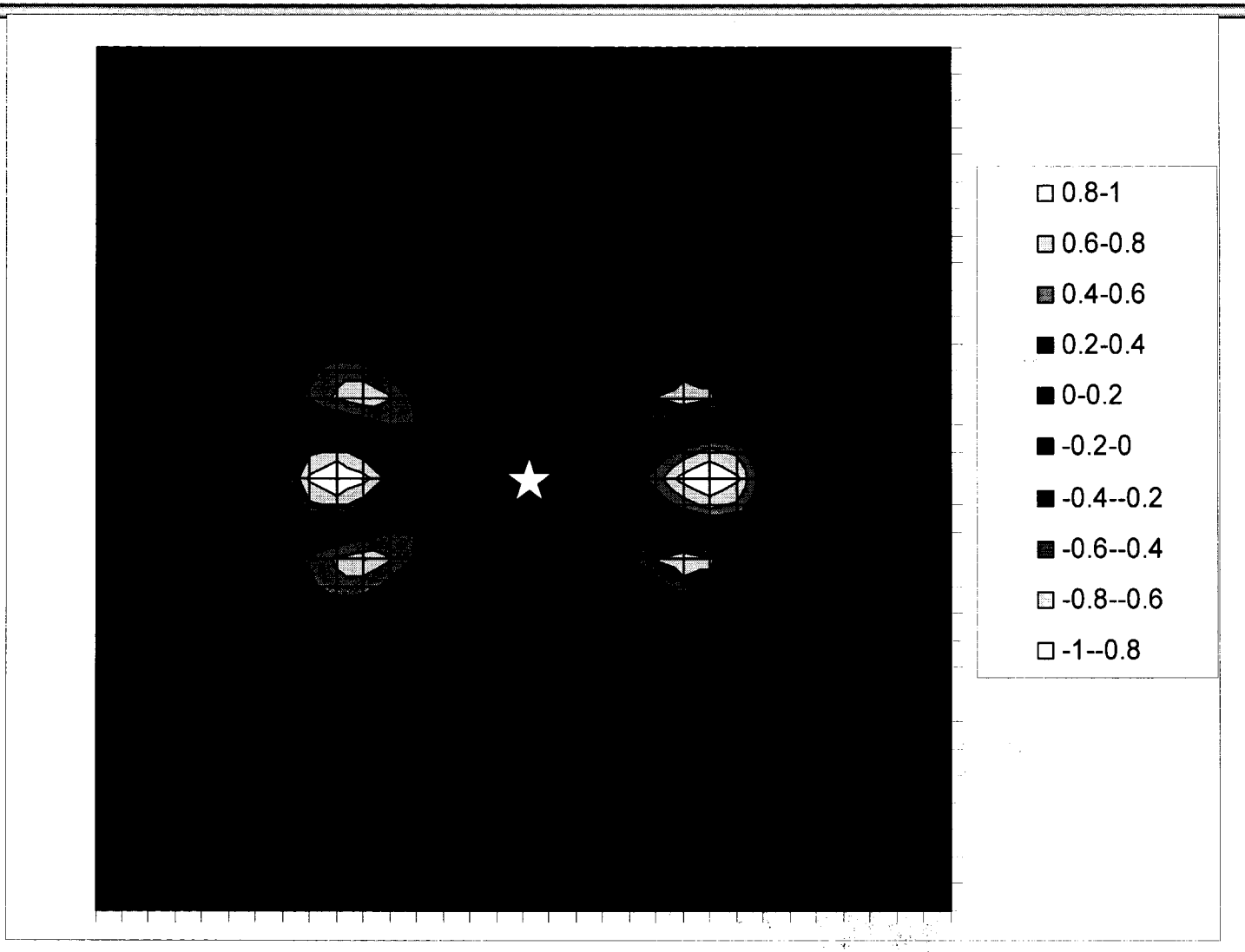
Regular DCB: single source



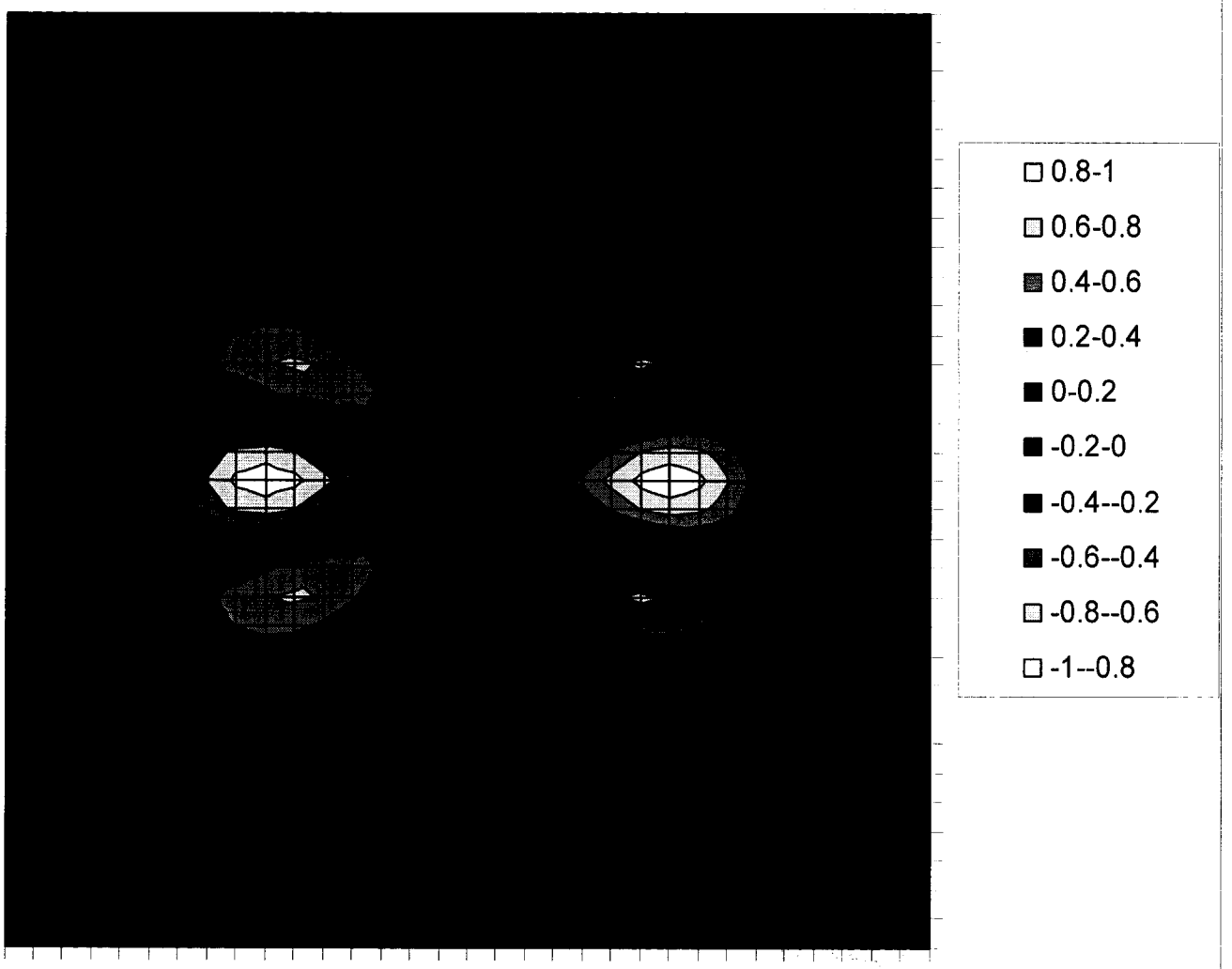
X-Array: single source



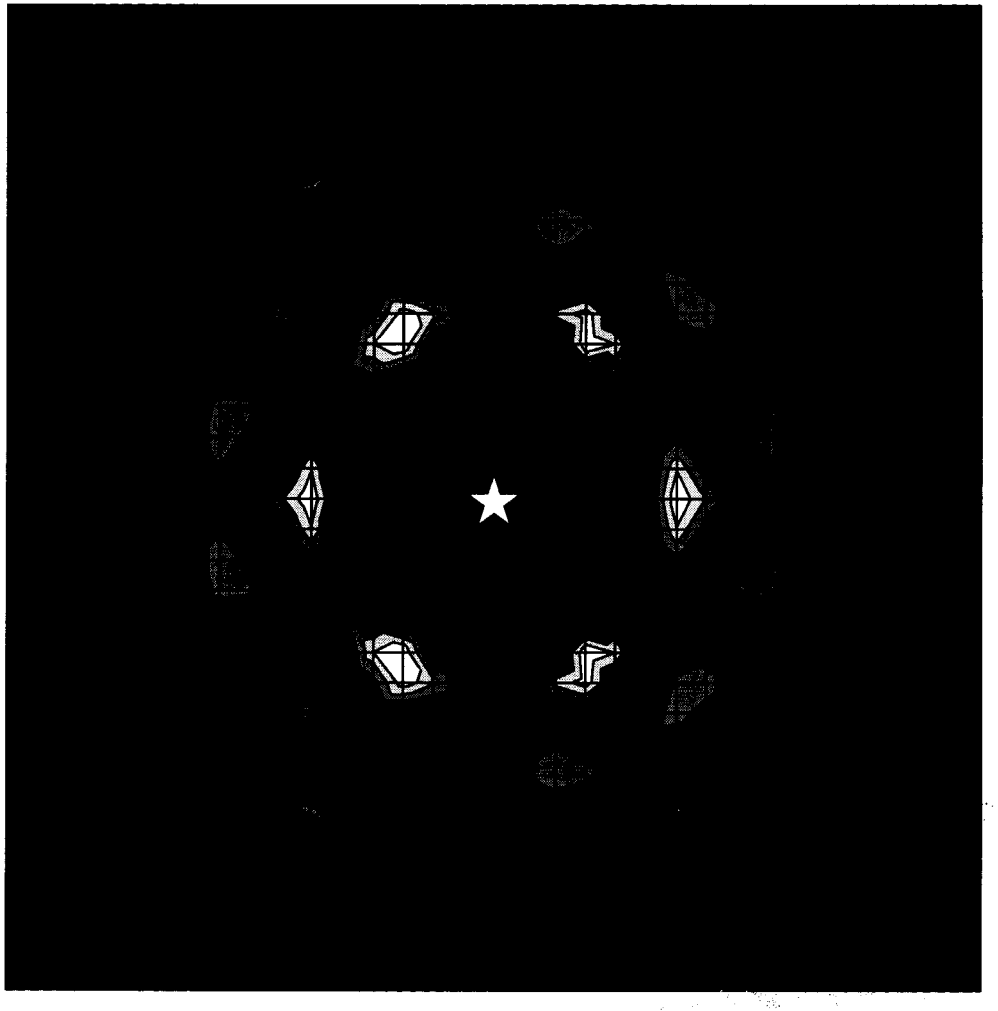
X-Array 20 x 40 m: single source



X-Array 15 x 30 m: single source

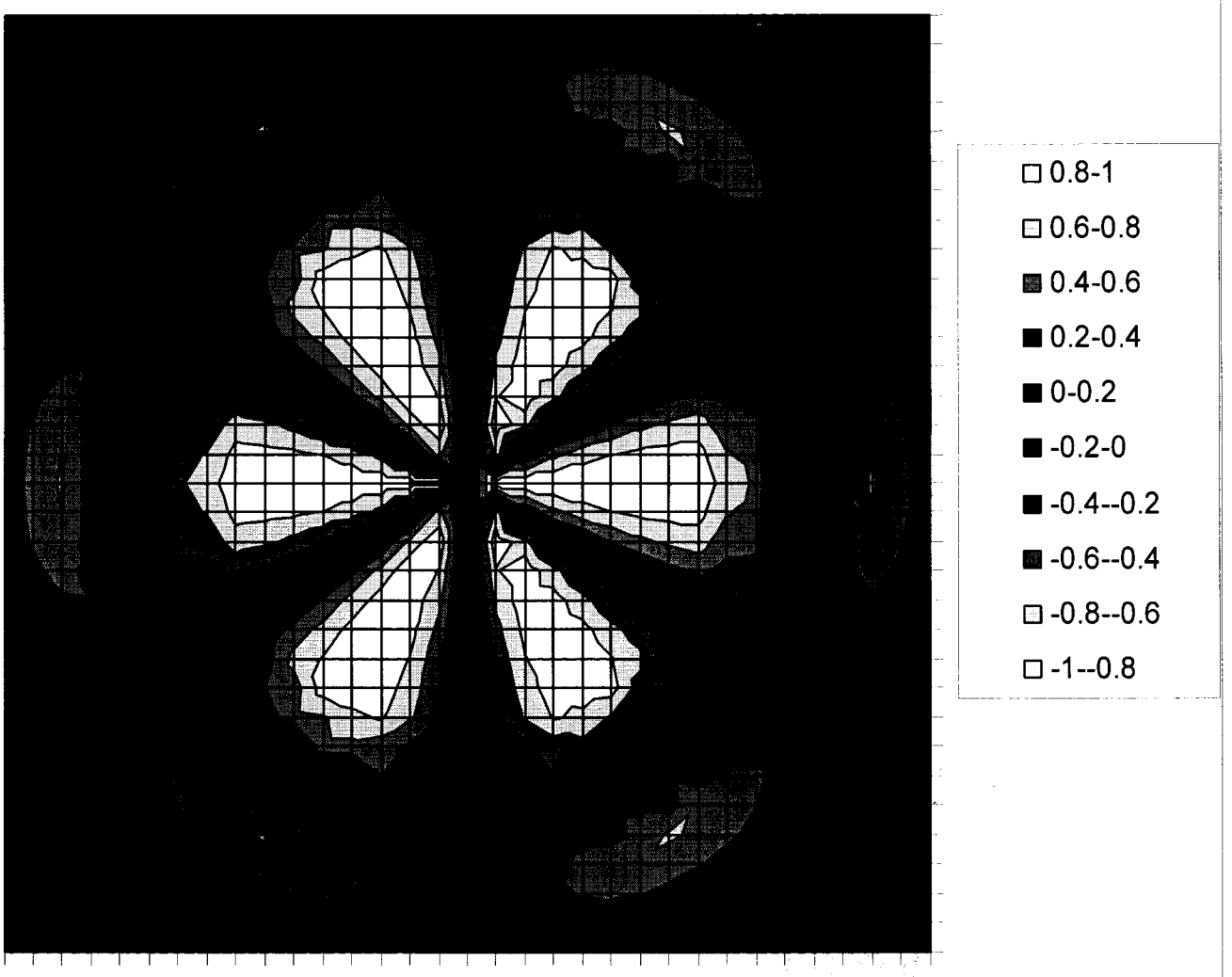


Three Telescope Nuller 2: single source

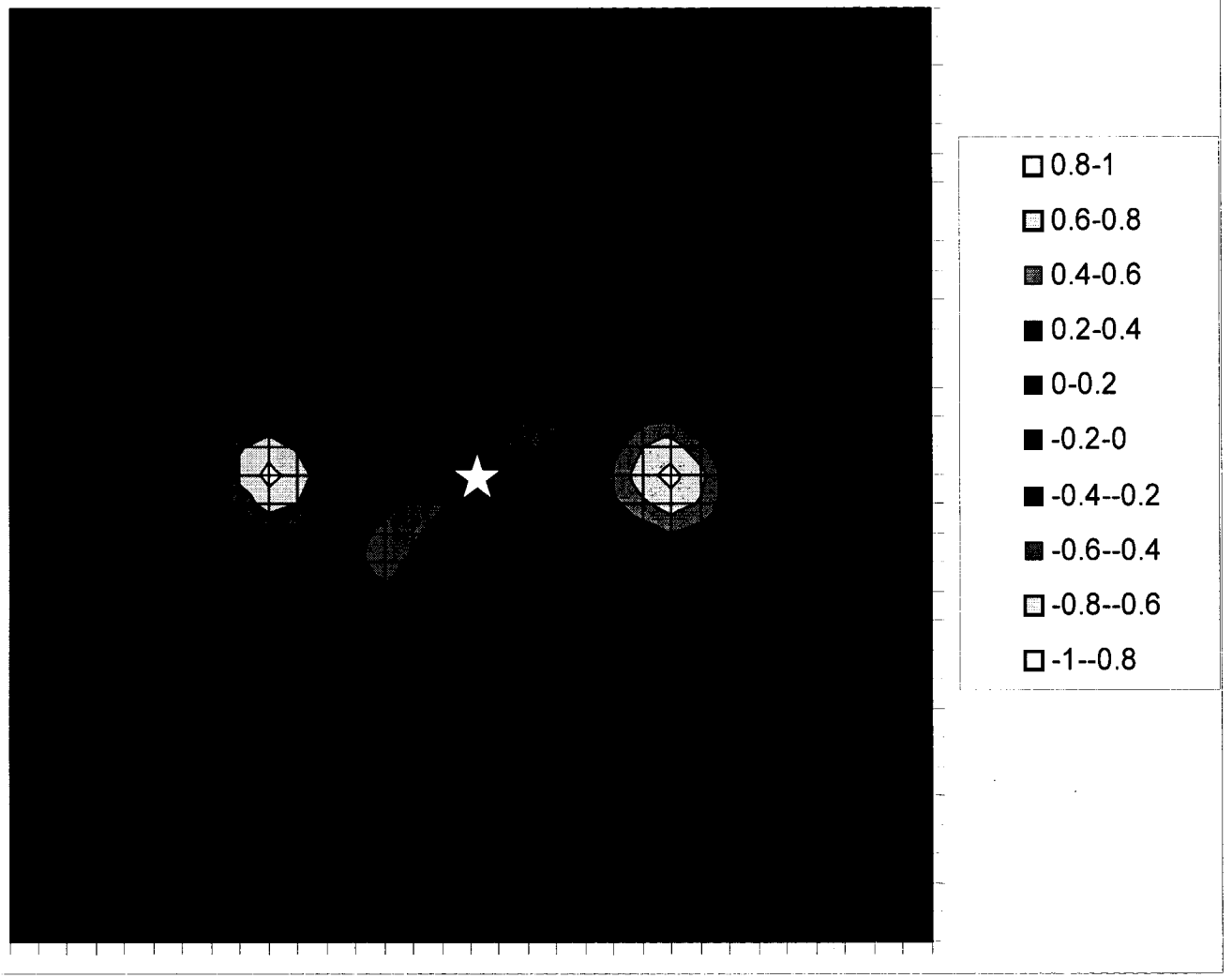


- 0.8-1
- 0.6-0.8
- 0.4-0.6
- 0.2-0.4
- 0-0.2
- -0.2-0
- -0.4--0.2
- -0.6--0.4
- -0.8--0.6
- -1--0.8

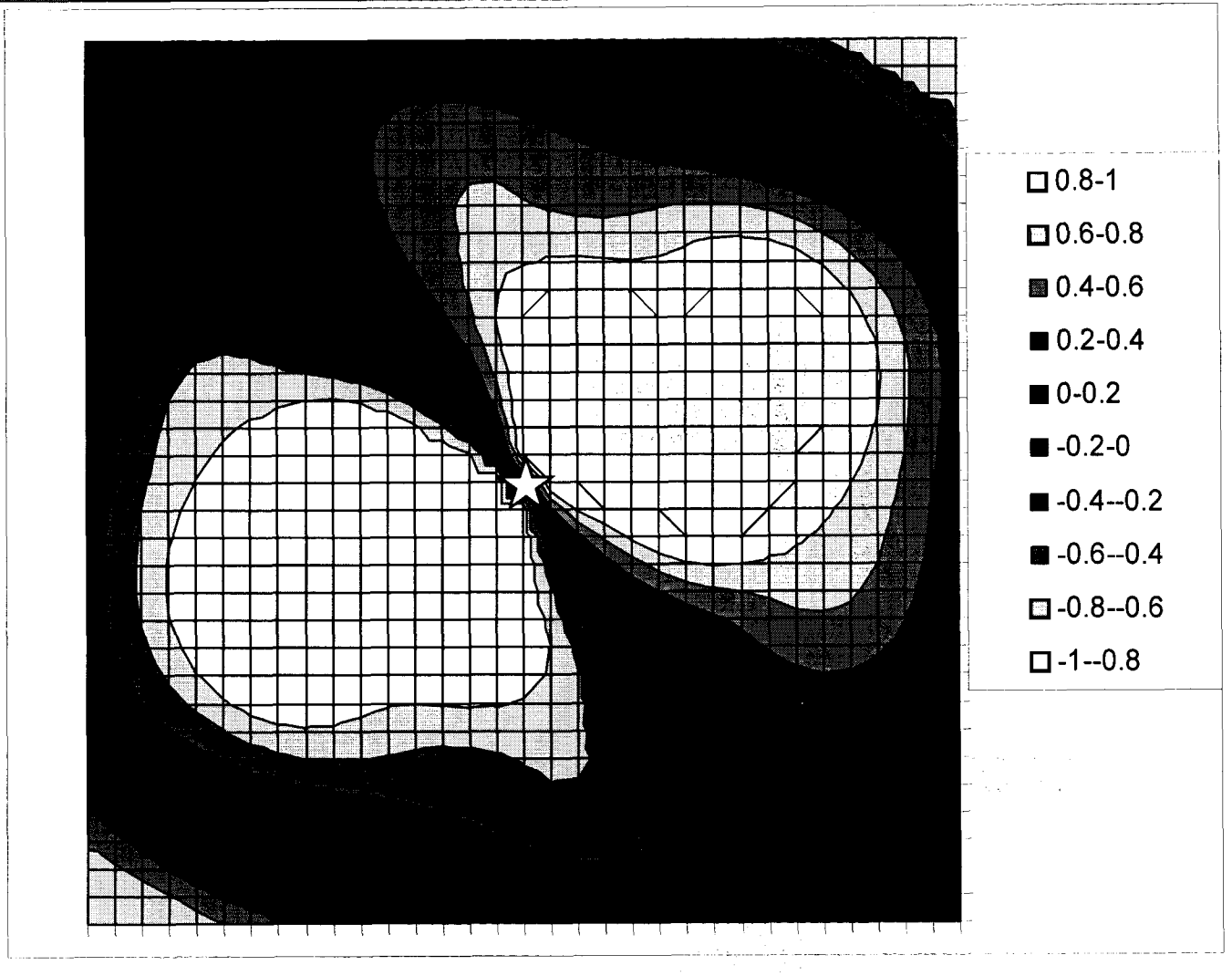
Three Telescope Nuller 1: single source



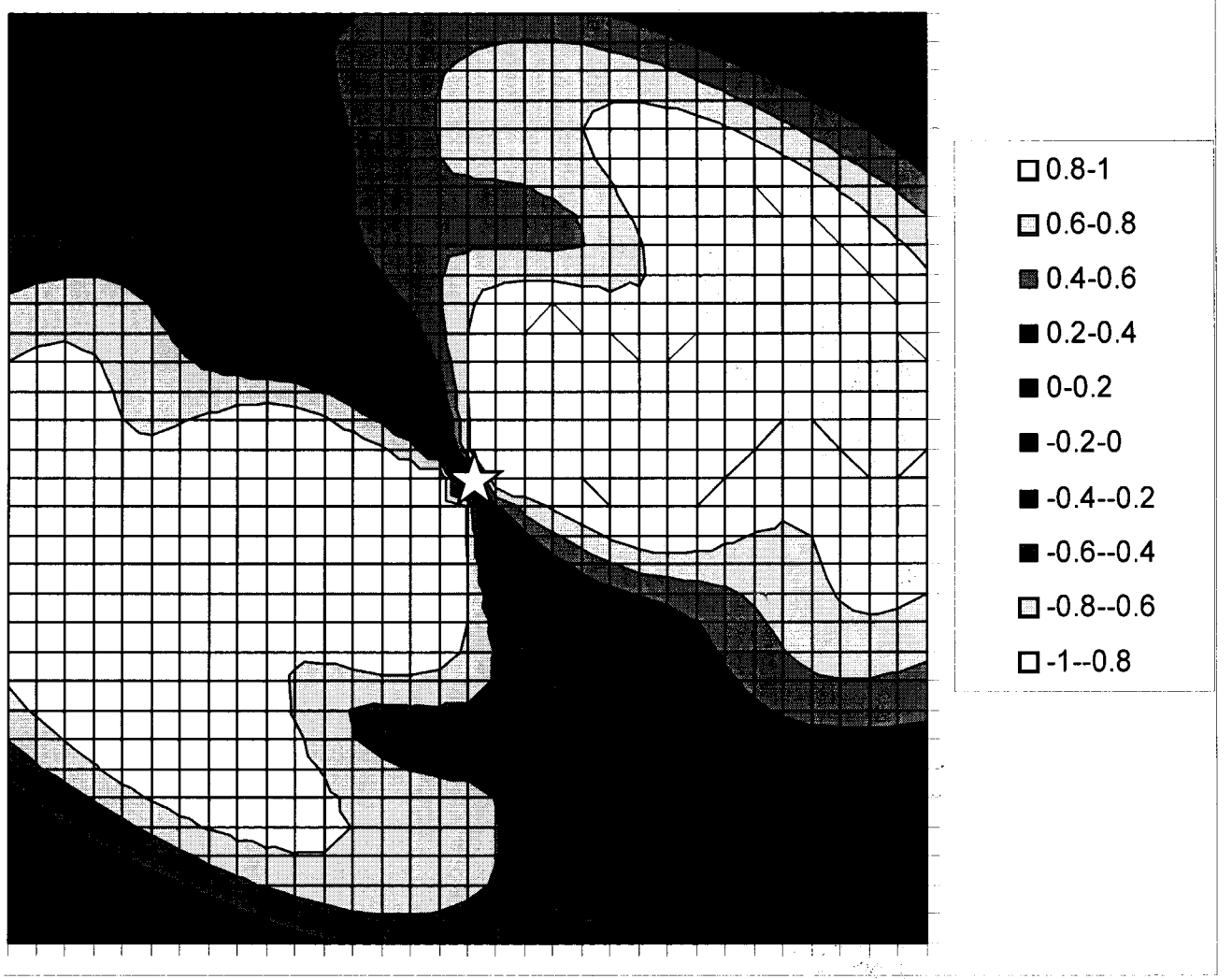
Combiner-less DCB: single source



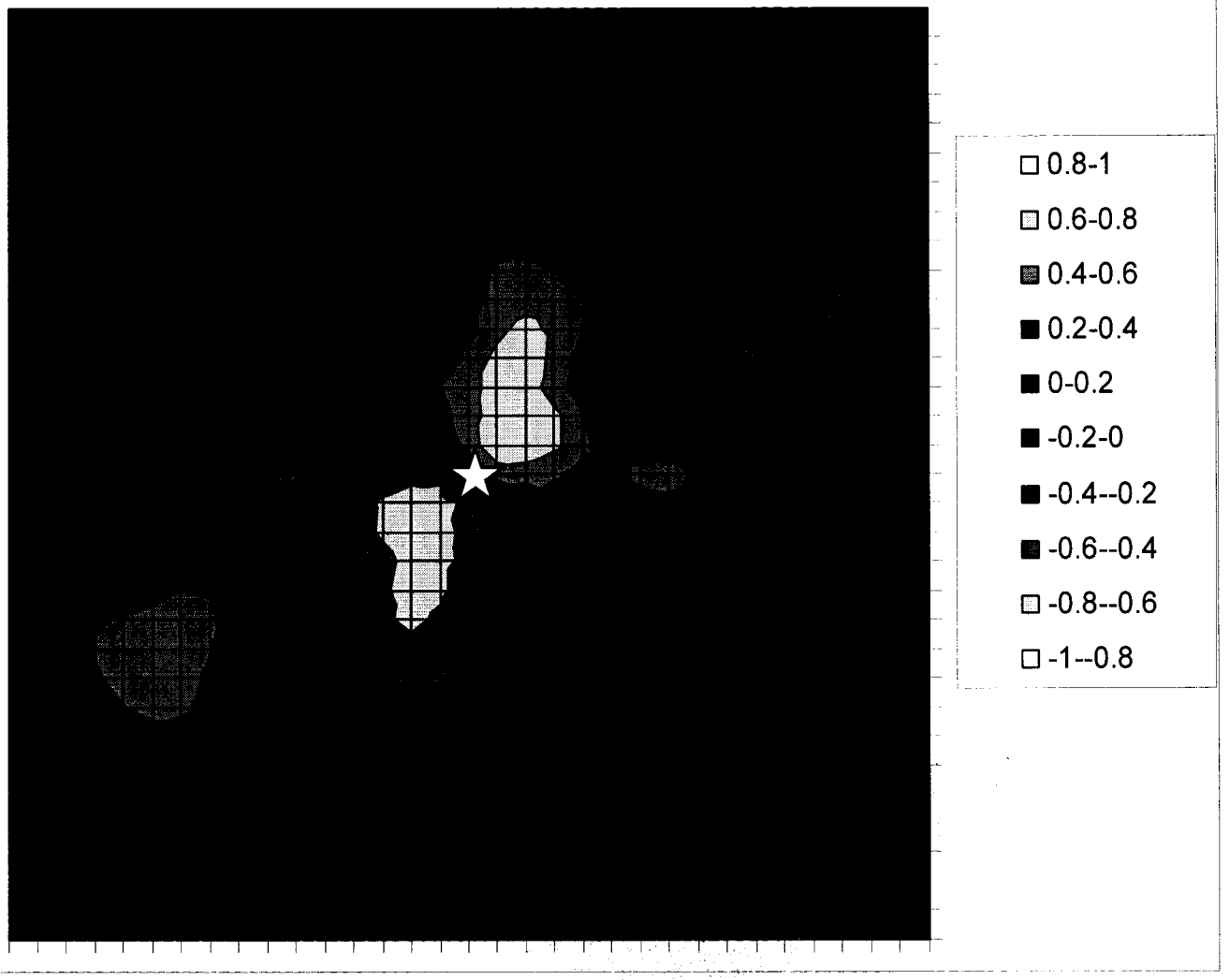
Standard SCI: multiple sources



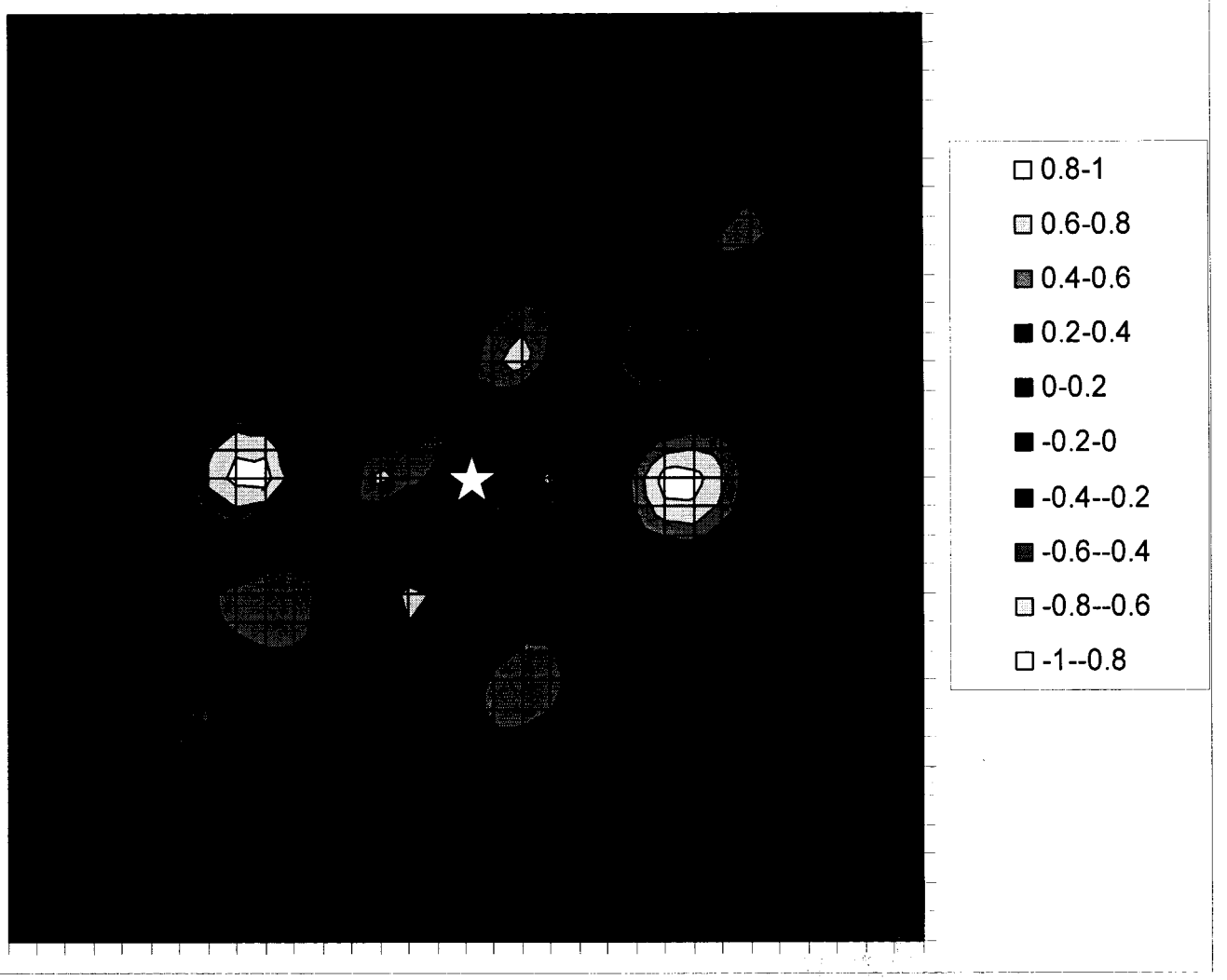
4:1 SCI: multiple sources



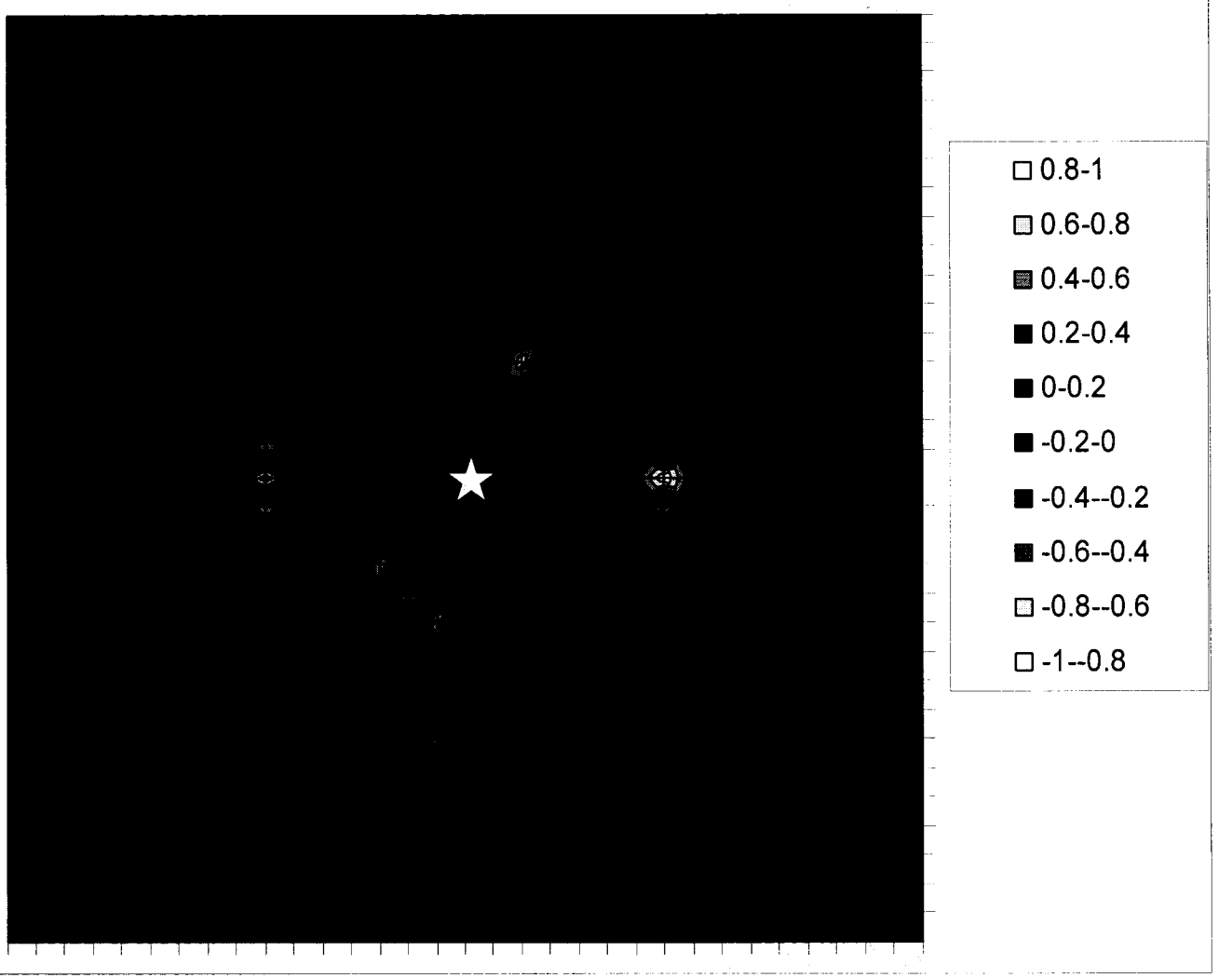
SCI x 2 (72 m): multiple sources



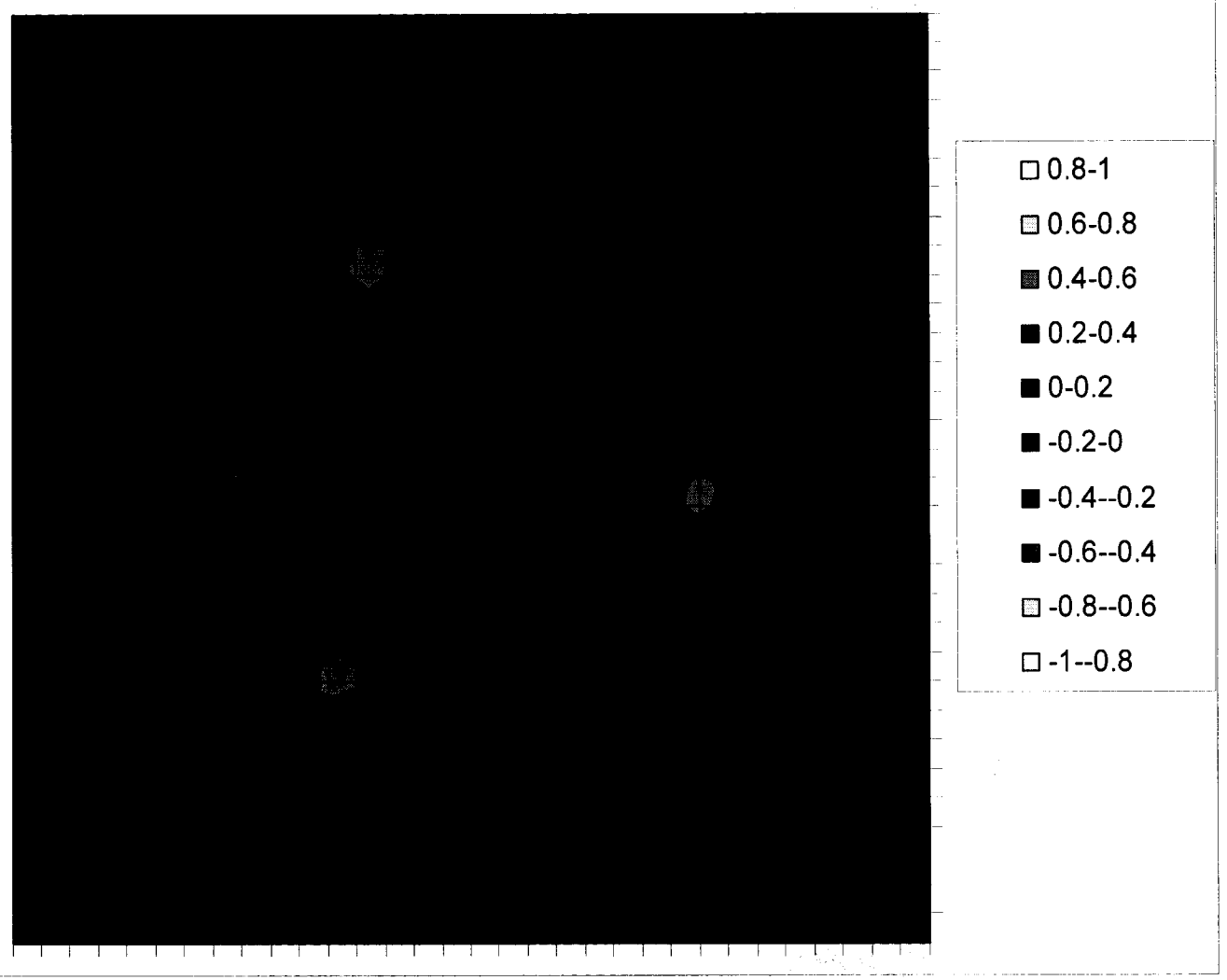
Regular DCB: multiple sources



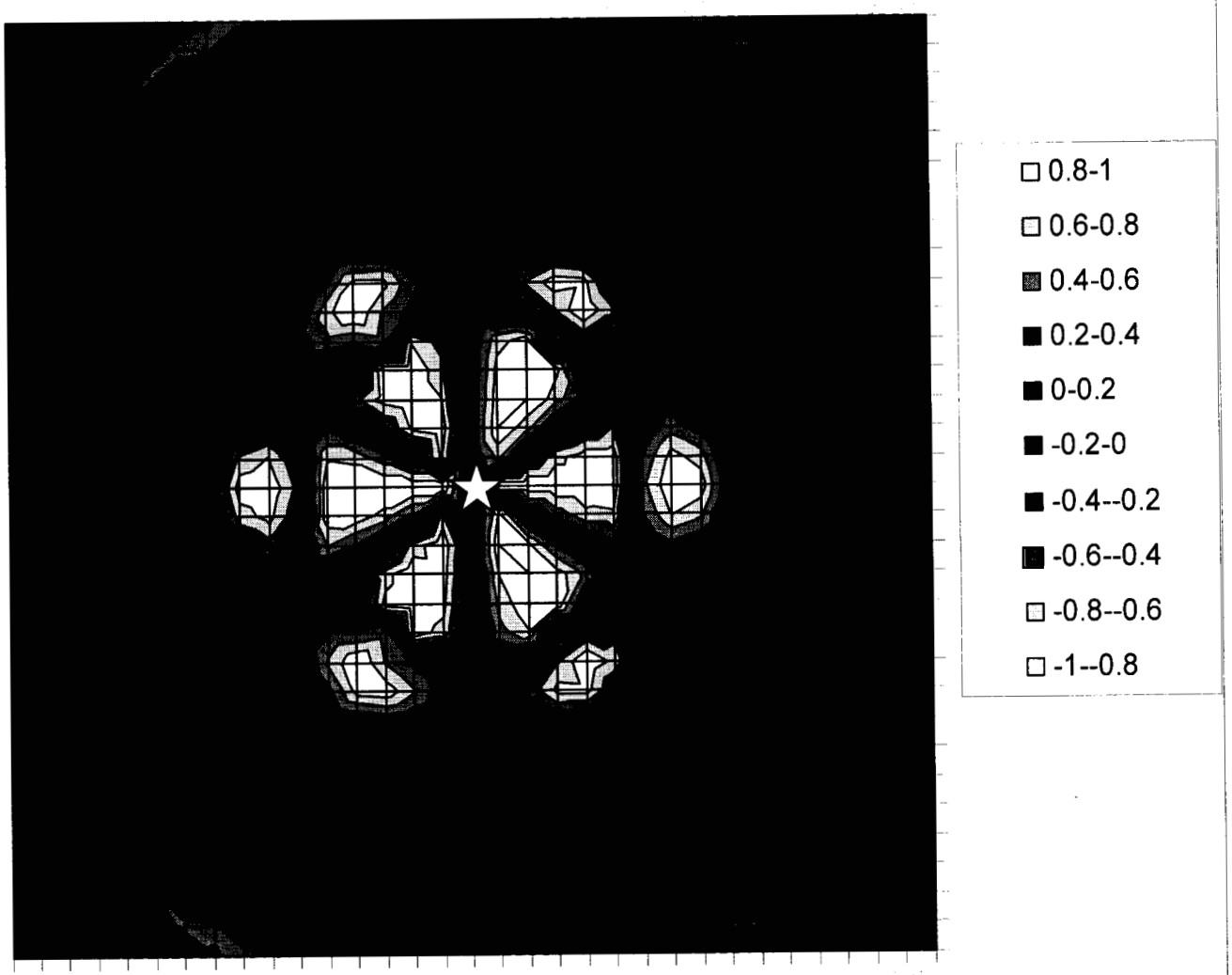
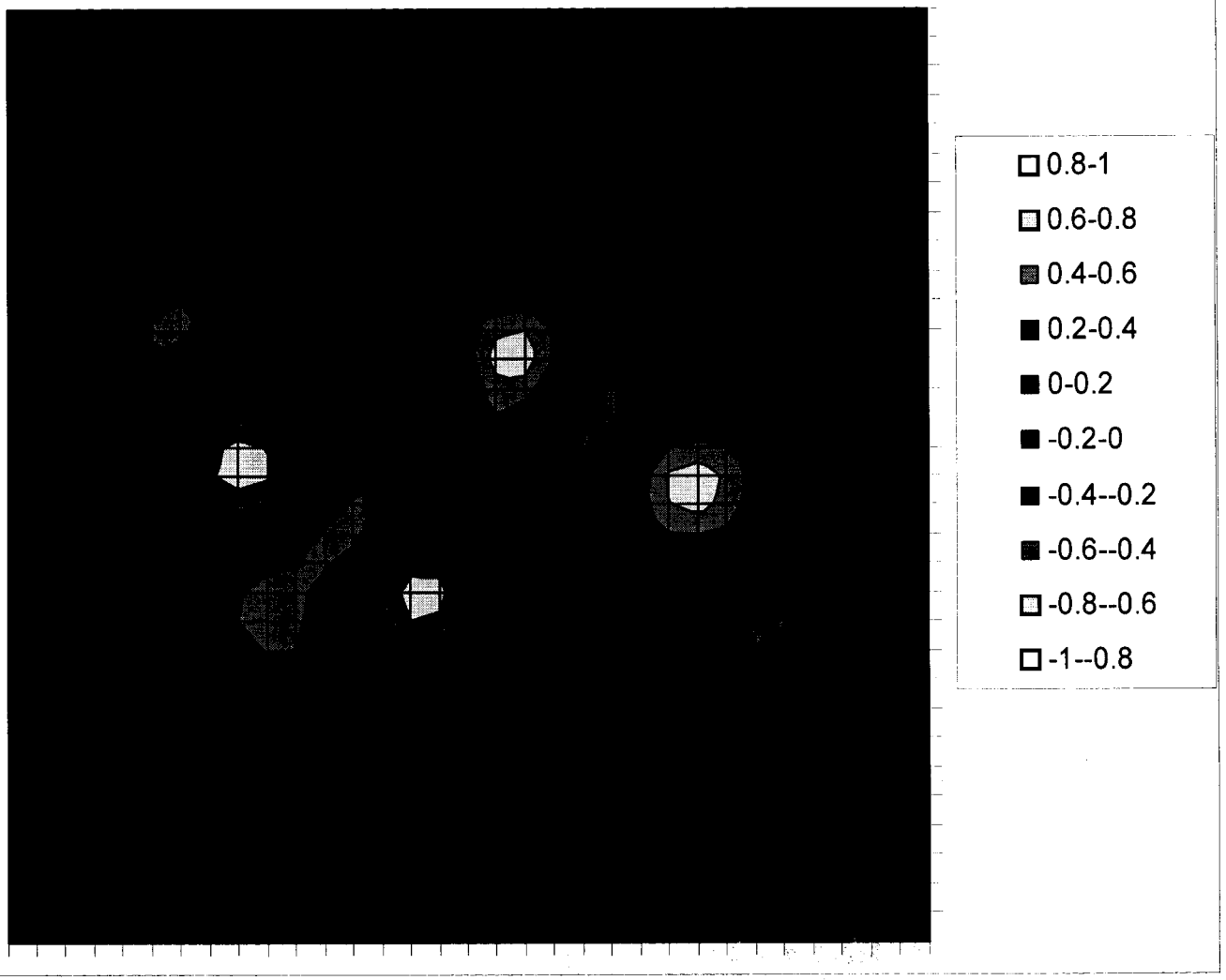
X-Array: multiple sources



Three Telescope Nuller 1: multiple sources



Three Telescope Nuller 2: multiple sources



Combiner-less DCB: multiple sources