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Photonic RF Probe Prognostics: Phased Array Example

DARPA Prognosis Bidder's Conference

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Abstract

- Photonic RF probes allow prognostics of a wide variety of systems, subsystems, or individual circuits through non-invasive monitoring of RF radiation, either intentional (e.g., from a system antenna) or un-intentional (RFI/EMI). MRC has developed a variety of fiber-optic RF probes for this and other purposes. As a prognostics application example, a prognostic/diagnostic method for phased-array antennas has been developed and demonstrated which uses a single, fixed-position, non-invasive RF probe to detect and identify faulty array elements, or groups of elements, as the array operates normally. After system calibration, zero array down time is required for extensive prognostics and diagnostics. The system has been demonstrated both in several computer simulations of arrays to over 1000 elements and in experimental tests at NSWC, Crane, IN. Identified faults include array elements which were not working, stuck at constant phase, low in power, including both single faults and large numbers of simultaneous faults. An RF radiating probe (a fiber-optic version of which has also been demonstrated) can be used to diagnose array receive mode operation. Results of both the simulations and the tests are reported along with descriptions of several MRC photonic RF probes.

- This work was supported in part by NSWC, Crane, IN under contract N00164-97-C-0056.

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Motivation/Introduction

- Radiated emissions can be used for prognosis of large circuits, subsystems, systems
  - Intentional (e.g., phased array)
  - Unintentional (e.g., EMI/RFI from circuit boards)
  - “Tricorder” for electronics
- Fiber optic radiated emissions sensors are ideal
  - Minimally perturbing
  - Penetrate bulkheads without compromising EMC
  - Lightweight sensor and cables
  - Don’t pick up unwanted signals
- Small, lightweight chip- or board-level receivers/signal analyzers plus software to generate prognostic information from RF signals
- Phased Array Example (NAPS) Presented Here

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Phased Array Prognostic System Example

- Non-Invasive Array Prognostic System (NAPS)
- Identifies faulty elements in phased arrays as the array operates normally, without affecting operation or performance
- Uses a non-perturbing, fiber-optic RF probe and data-processing algorithms
- Requires that some reference or calibration data be obtained at some point
- Primarily funded by NSWC, Crane, IN (Contract N00164-97-C-0056)

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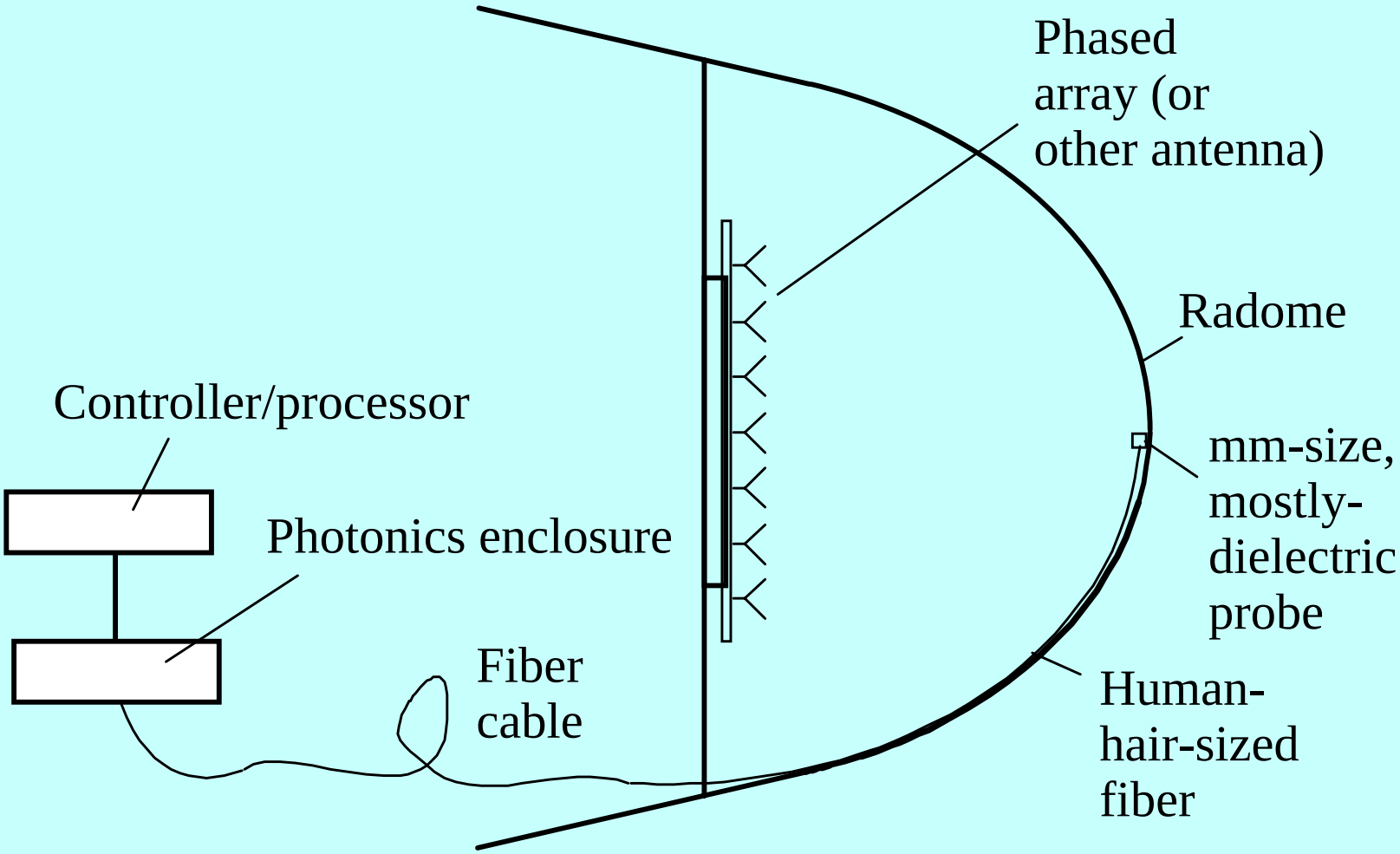
Sample Application of NAPS (Airborne array)



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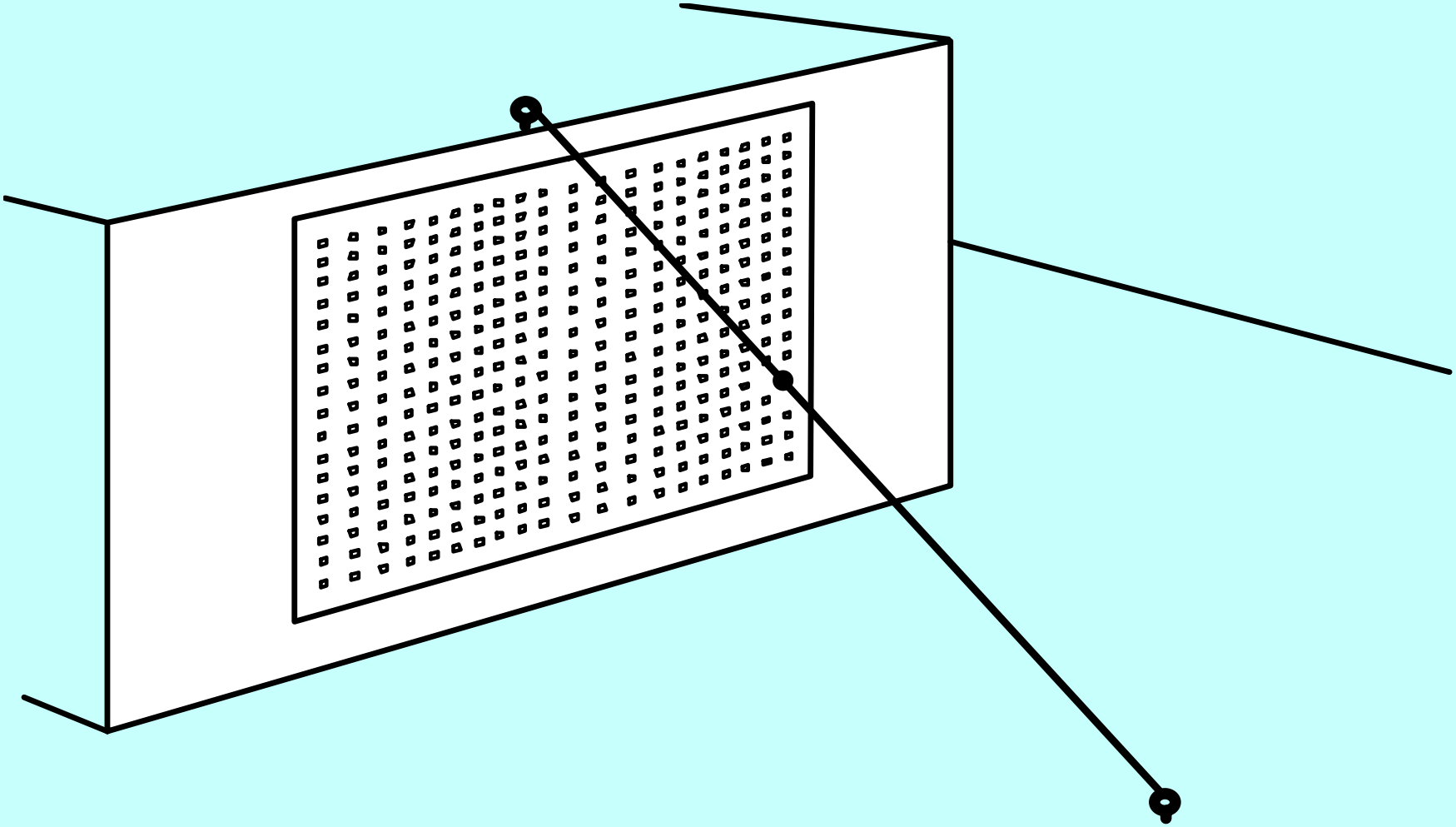
Sample Application of NAPS
(Shipboard or ground-based array)



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Advantages of NAPS

- Fiber optic RF probe
  - Negligibly perturbing of radiation (shown to be true in aircraft phased-array radome tests)
  - Small, lightweight, cables and hardware
  - Route through platform without compromising EMC
  - MRC's probes work in high fields with high (compression) dynamic range
  - Easy to make extremely rugged
  - MRC has also demonstrated a fiber-optic RF-radiating probe for checking antenna receive functions

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Advantages of NAPS

- Method
  - No down-time or special diagnostic operation of array (except for periodic collection of reference data) - works as array operates normally
  - Self calibrating
  - Highly immune to noise, multi-path, other effects
  - Periodic collection of reference is usually done in minutes
  - Allows complete history of individual element failures over array lifetime
  - Checks for false alarms can usually be done in seconds

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NAPS vs. the Other Diagnostic Techniques

- No special diagnostic mode or interleaving
- Don’t need second beam-forming network (as in the mutual coupling approach)
- May allow significant simplification of TR module internal diagnostics

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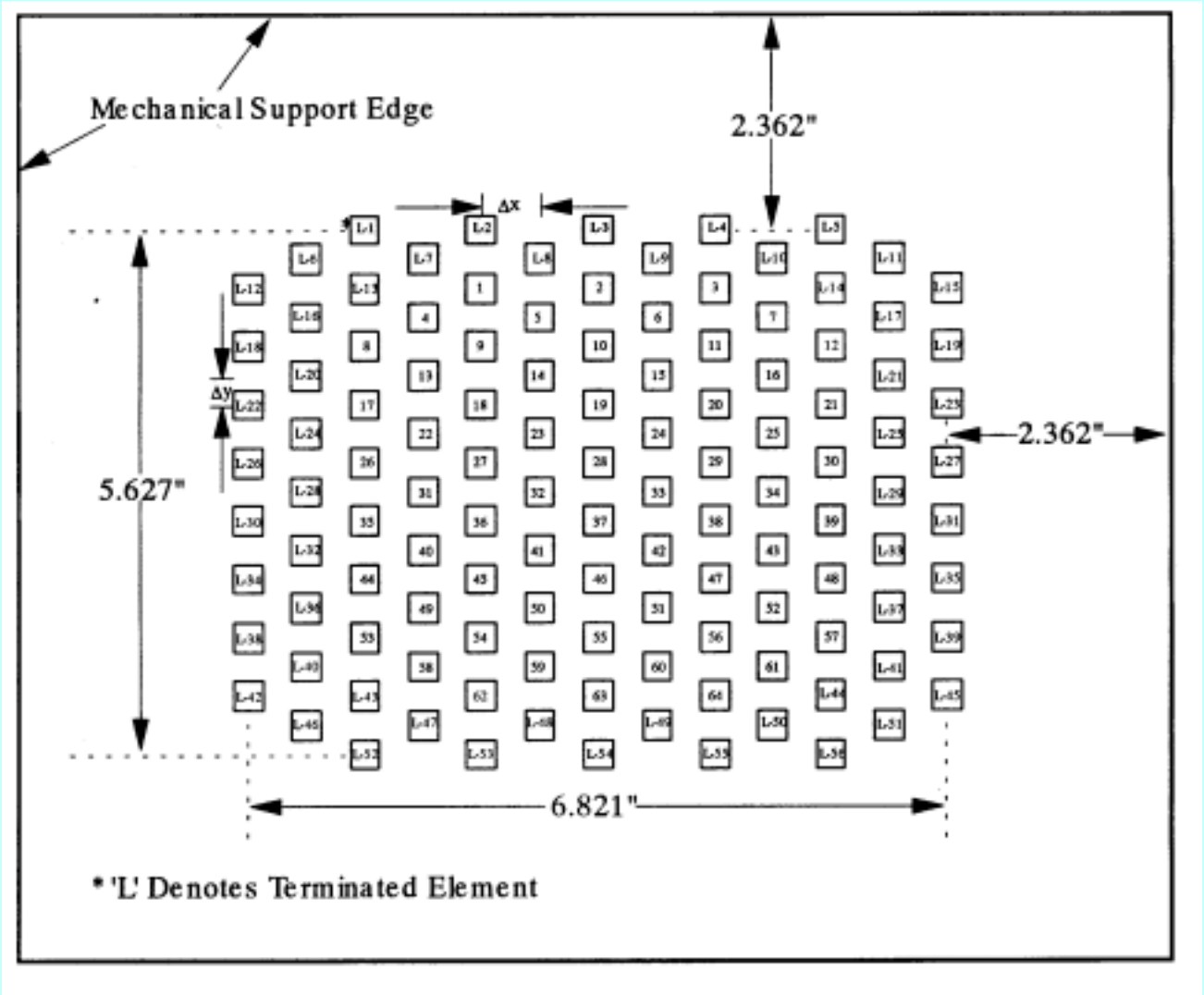
Experimental Demonstration of NAPS

Using X-band Active Array Measure Test Vehicle at NSCW, Crane, IN



Originally 64 Active elements, but 25 of these not working at time of demo

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Initial Single-Fault Demos

- The MRC fiber optic probe was used, 24 inches away, 16-degrees off bore site
- 128 different beams used
- Reference probe data taken
  - Probe signals for all beams without any imposed faults
  - Probe signals with each element working alone (all phase angles)
- Crane and TSC personnel induced faults; didn't tell MRC what they were
- Single element faults: not working, 6-dB down, or stuck in phase
- MRC applied three different algorithms differing in
  - (1) which reference data set is used
  - (2) the way they compare the data with faults present to the reference data
- MRC was able to correctly identify faulty element in each case
- Also identified an unknown fault (1st true use as a diagnostic)

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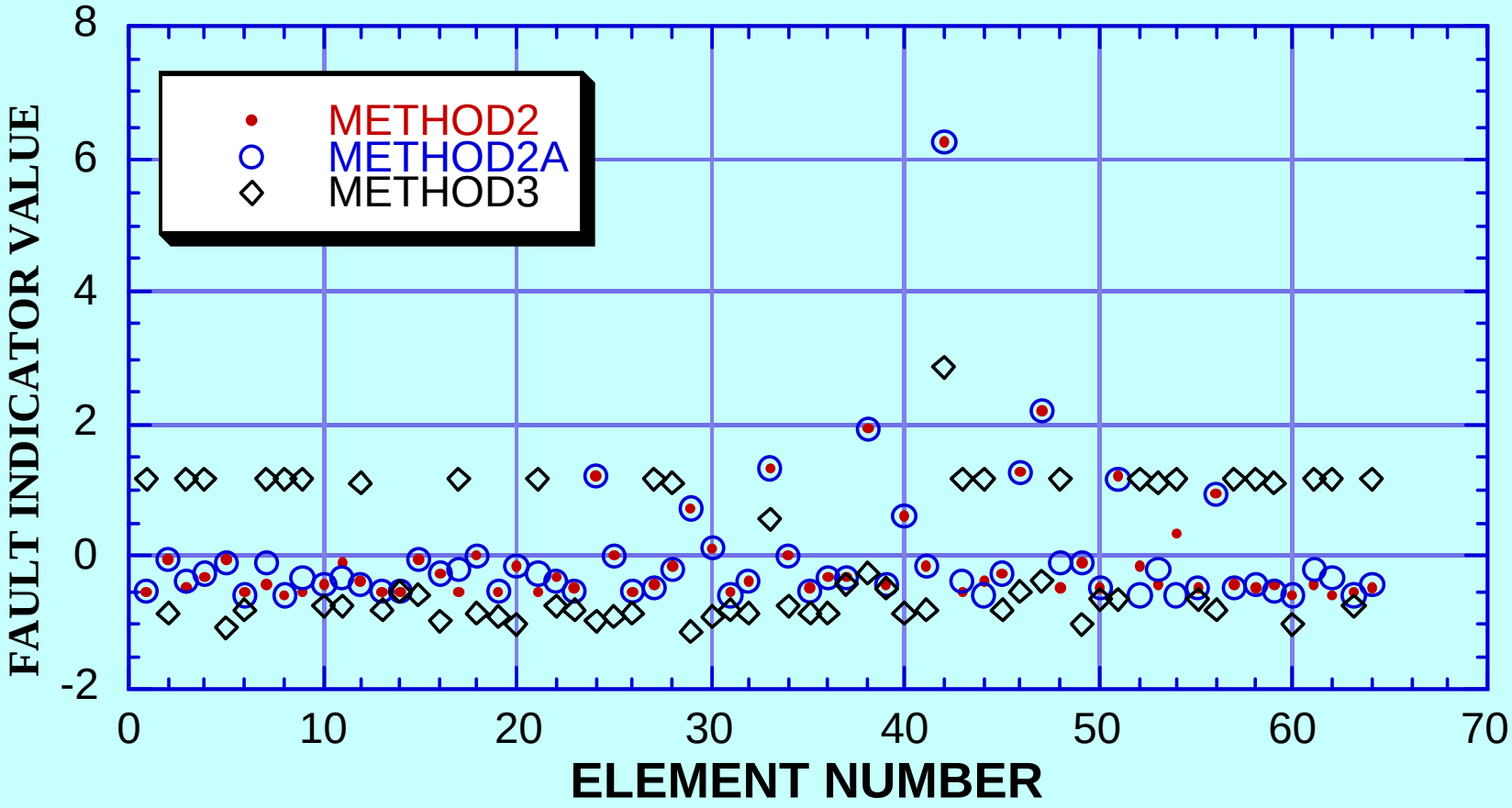
Sample Output (Element 42 6-dB down)



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Mutiple Simultaneous Fault Demos

- All data taken by Crane and TSC personnel using conventional (open-ended waveguide) probe
- Five different tests having three to six simultaneous faults:
  - A: 6 faulty elements: 2 off, 2 6-dB down, 2 stuck in phase
  - B: 3 faulty elements: 1 off, 1 6-dB down, 1 stuck in phase
  - C: 3 faulty elements: all off
  - D: 3 faulty elements: all 6-dB down
  - E: 3 faulty elements: all stuck in phase
- Data was sent to MRC, who applied the algorithms and reported the results

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Mutiple Simultaneous Fault Demos

- Results:
  - Case A: Correctly identified all 6 (mixed) faults
    (However one non-faulty element had a higher fault indicator than one of the 6-dB down elements when when the properly-working-array reference data was used.)
  - Case B: Correctly identified all 3 (mixed) faults
    (However some non-faulty elements had fault indicators not much smaller than the 6-dB-down element.)
  - Case C: Correctly identified all 3 (element off) faults
  - Case D: Correctly identified all 3 (element 6-dB-down) faults with one false alarm for an element that had an unintended fault (sometimes terminated, sometimes not)
  - Case E: Correctly identified all 3 (stuck-in-phase) faults with one false alarm for an element near the center, which is almost stuck in phase
  - Note that false alarms can be identified in milliseconds by operating only those

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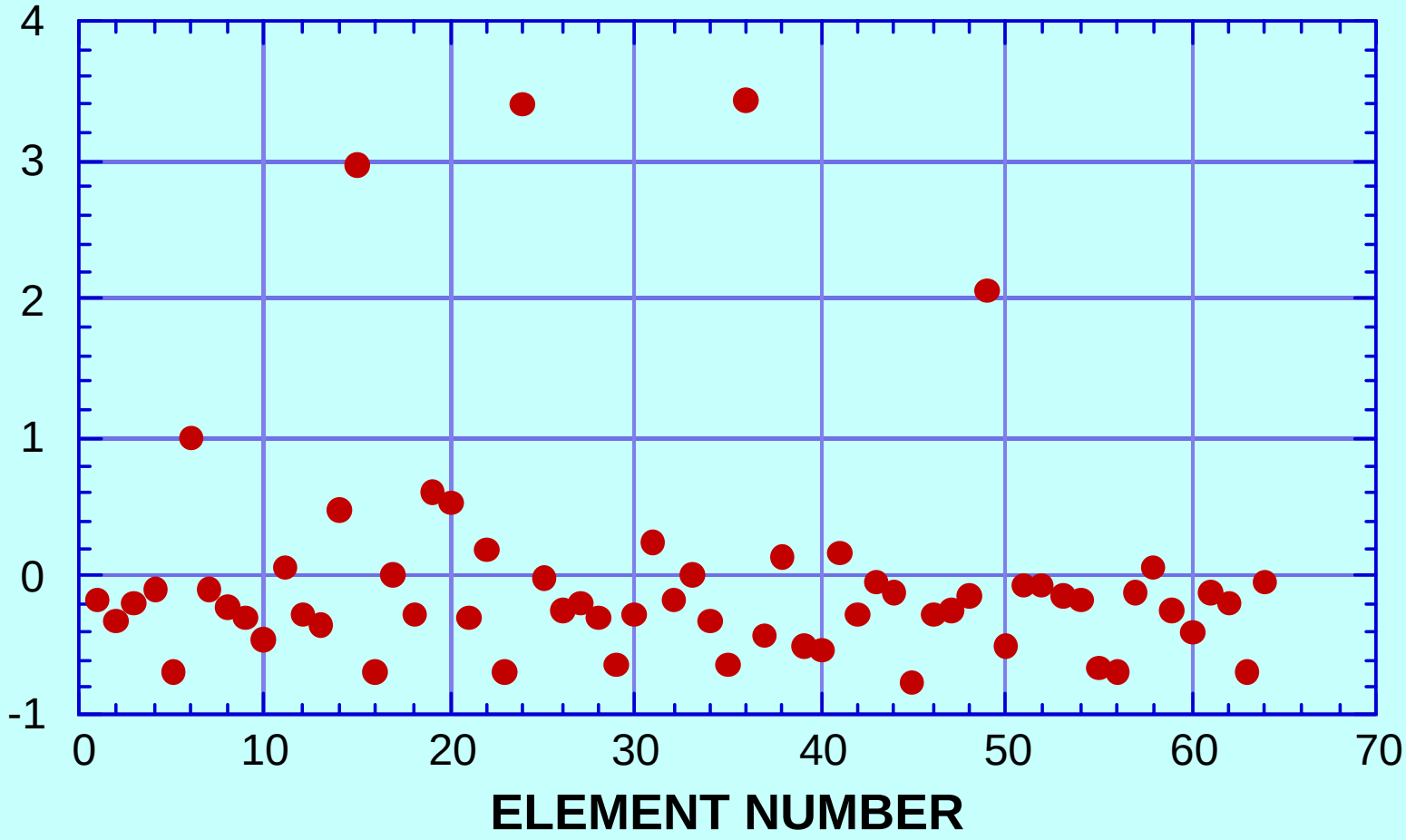
Sample Results for Case A (6 Mixed Faults)



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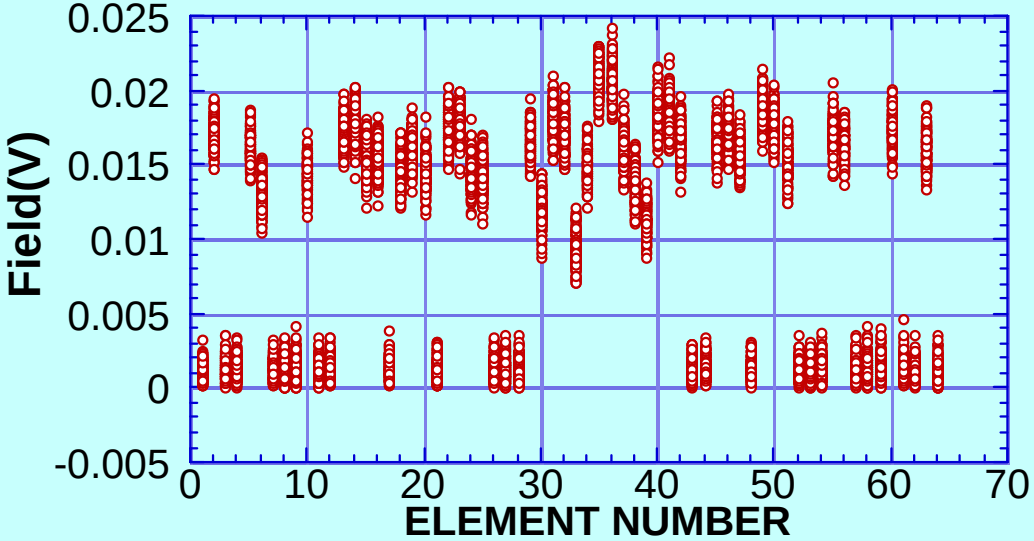
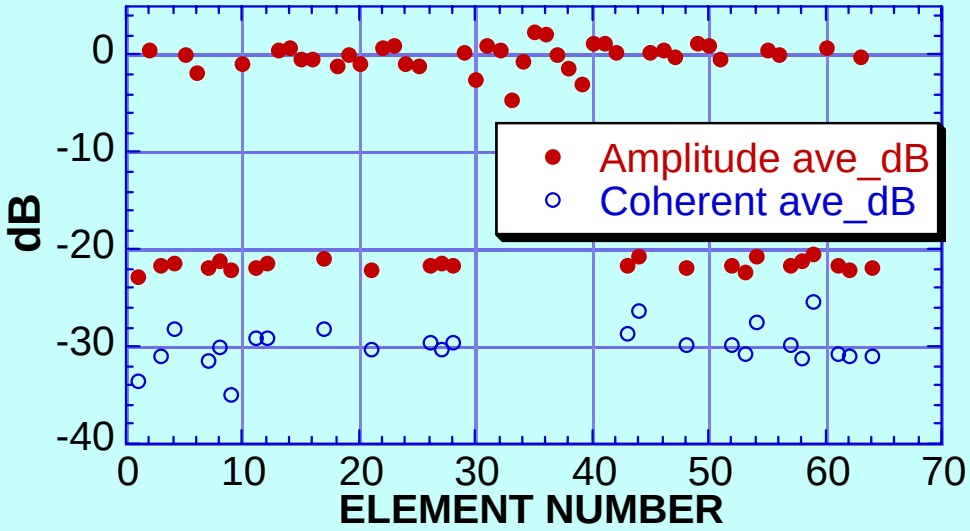
Demo Went Well Despite Problems with Data





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NAPS Simulation of a 1004-Element Array

- Computer simulation of round, 1004-element, X-band array included
  - Mutual coupling
  - Mutipath within the radome
  - Tapering of radiated power across array
  - Reasonable number of beams (1024)
- Simulation calculates the field at the position of the single probe for both reference data and faulty-array data
- Several different probe positions tried

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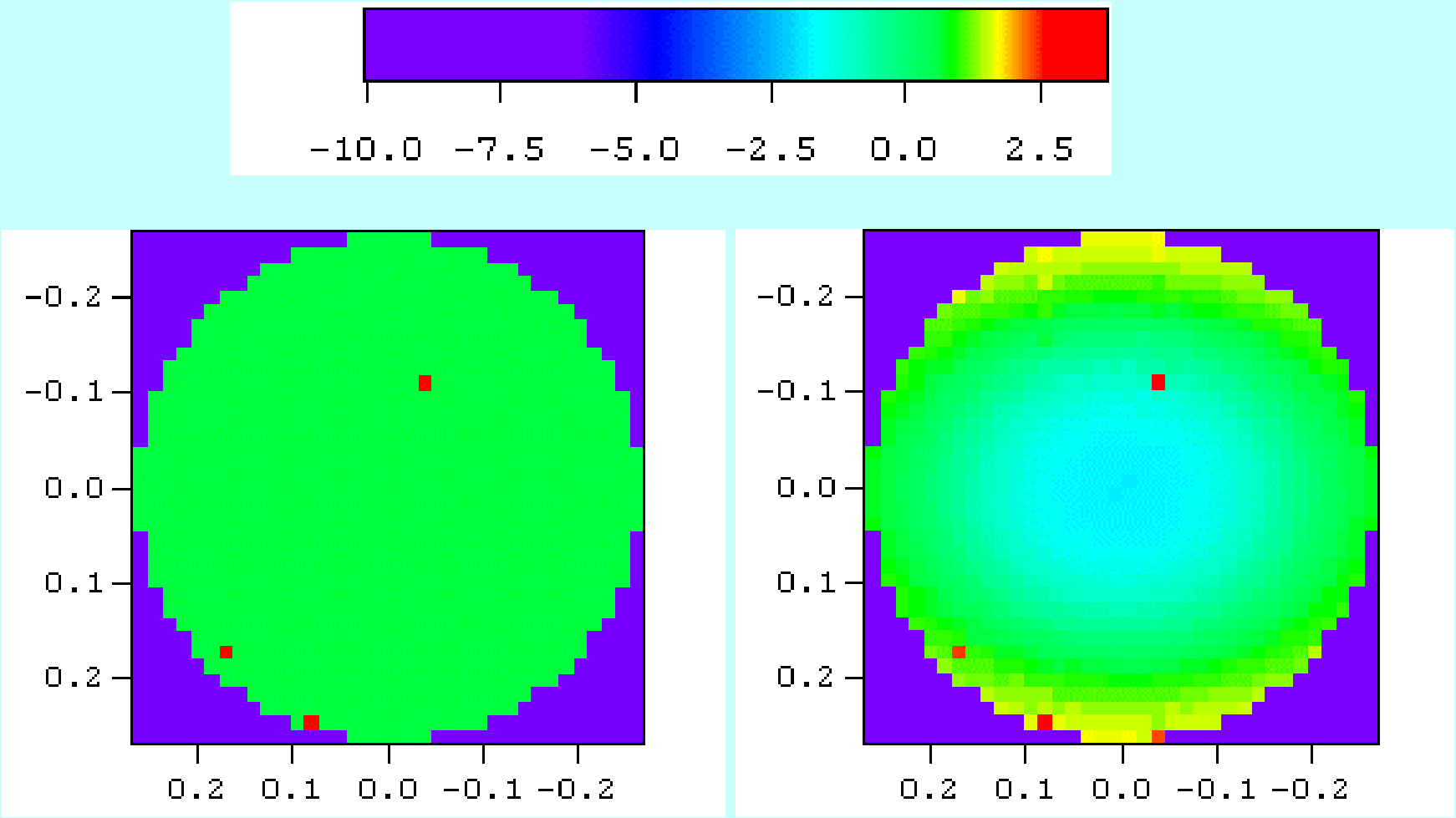
Three Faults



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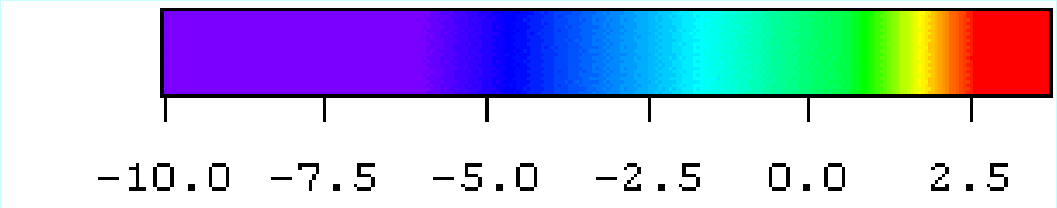
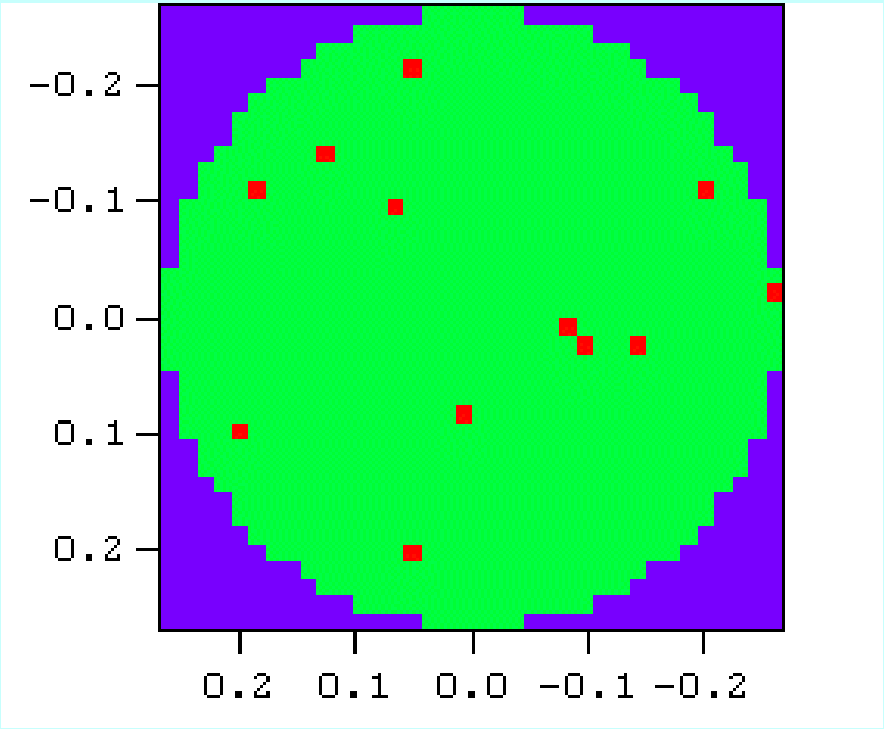
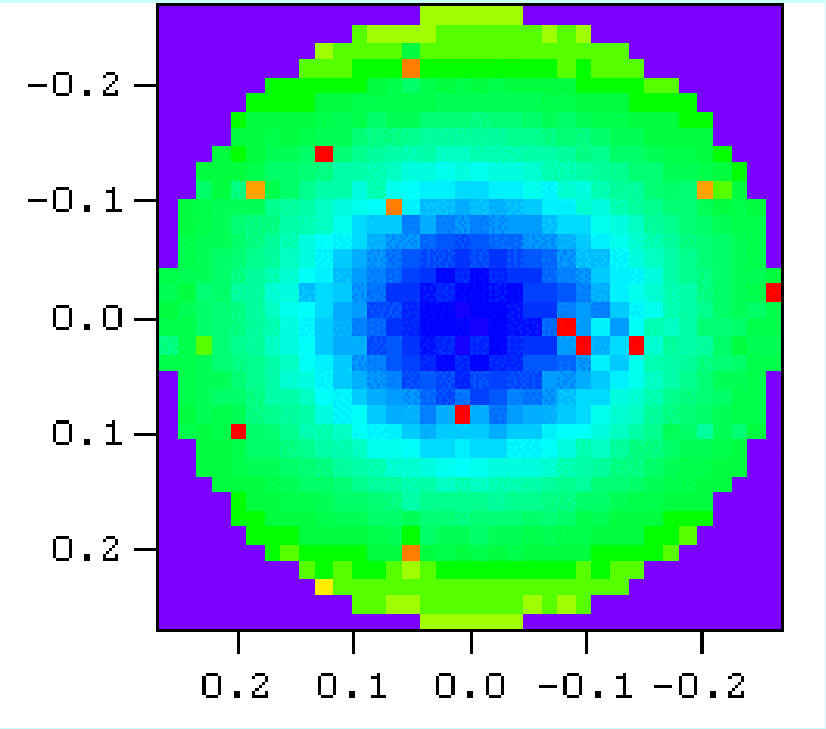
Twelve Fault Case







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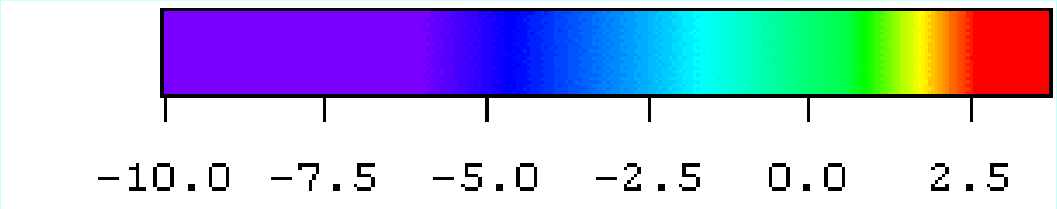
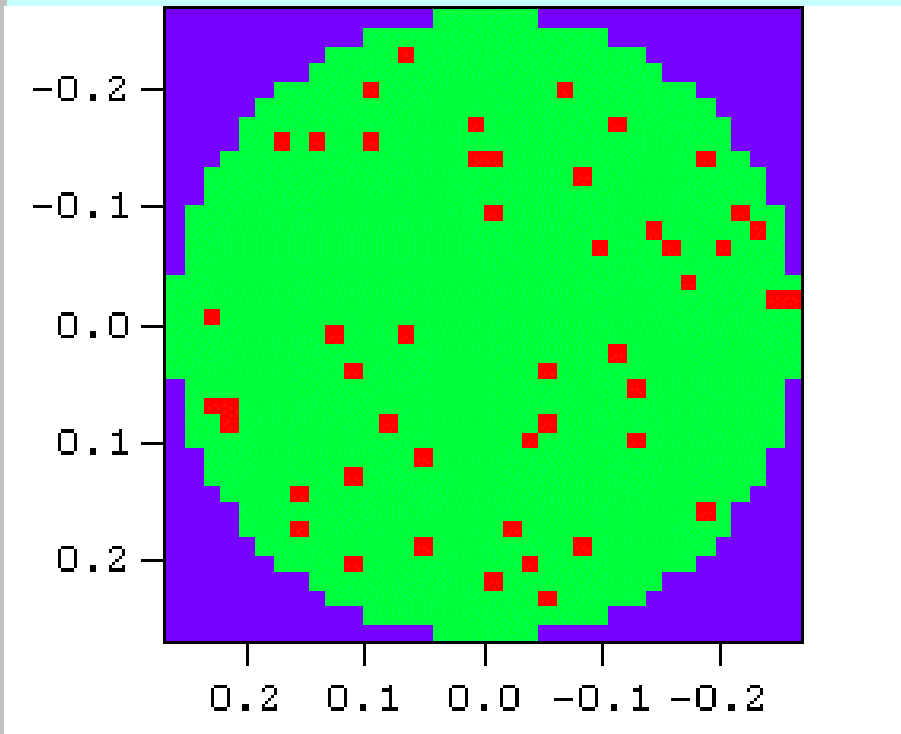
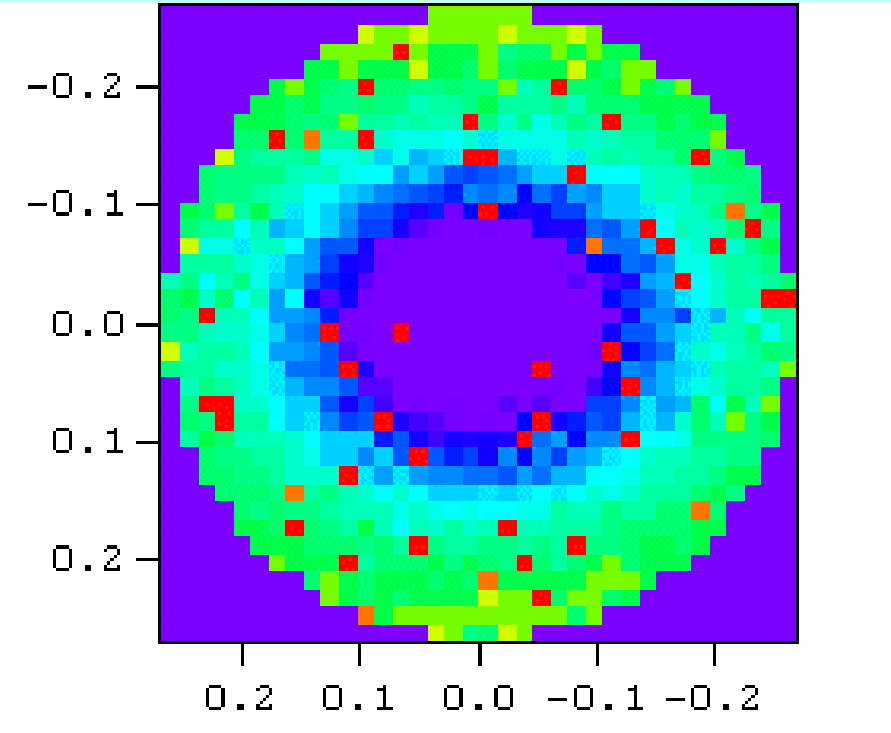
Forty-Eight Fault Case







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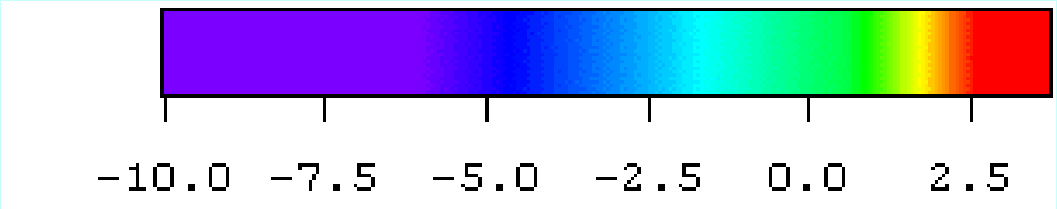
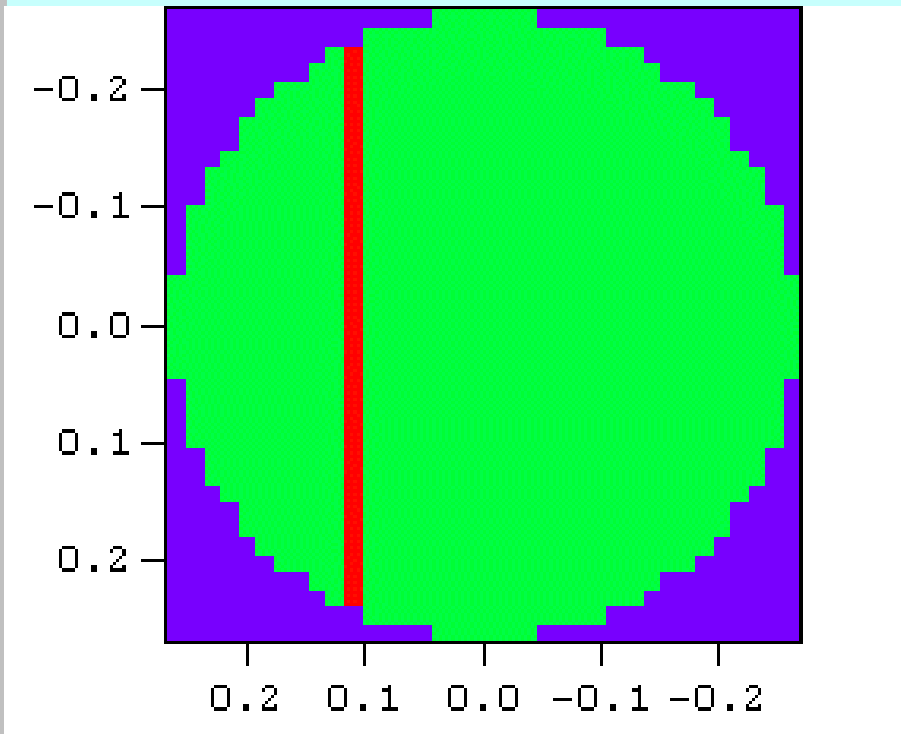
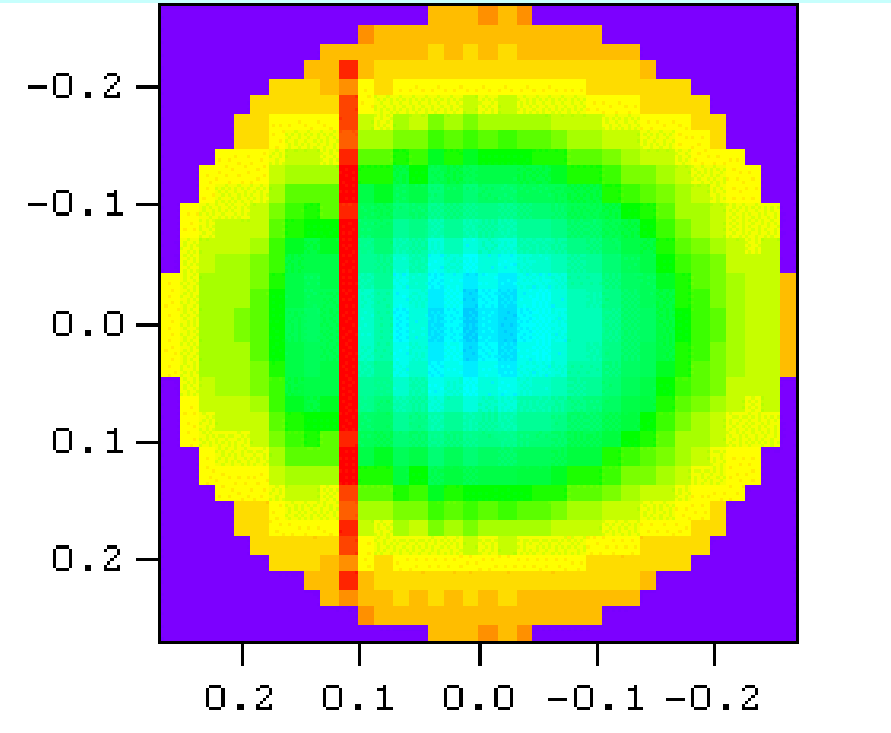
A Faulty 32-Element Column







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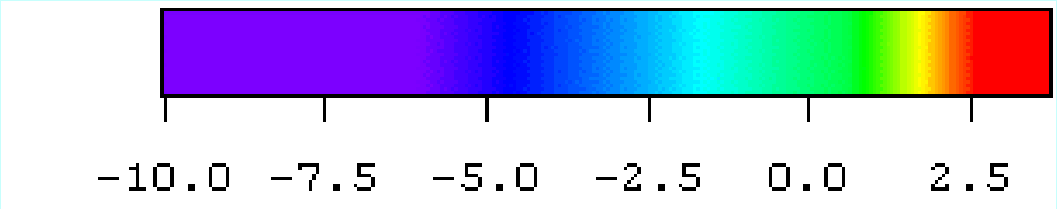
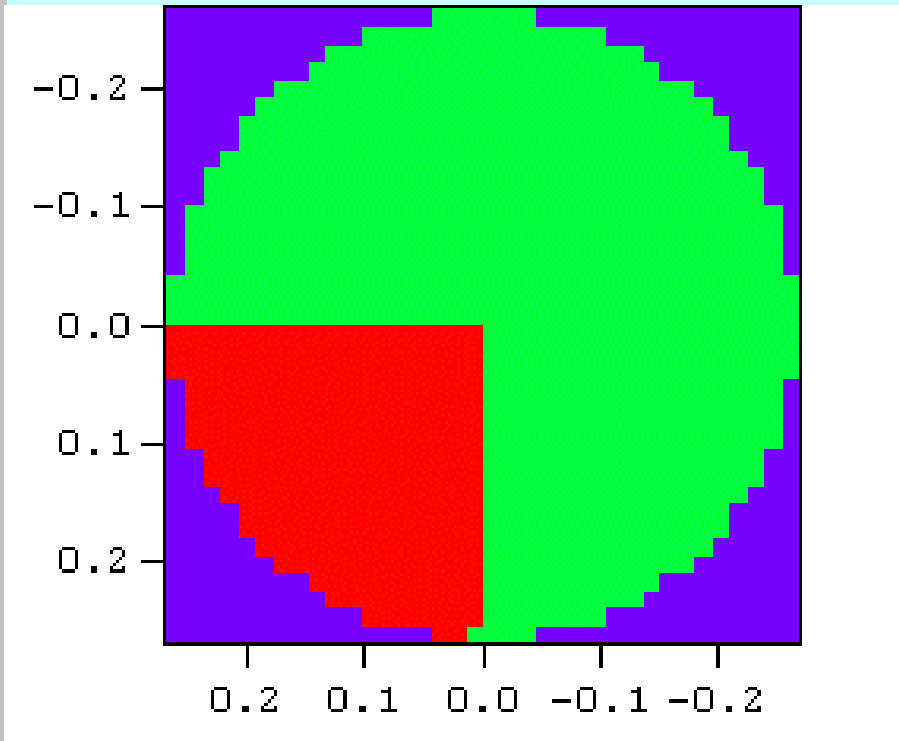
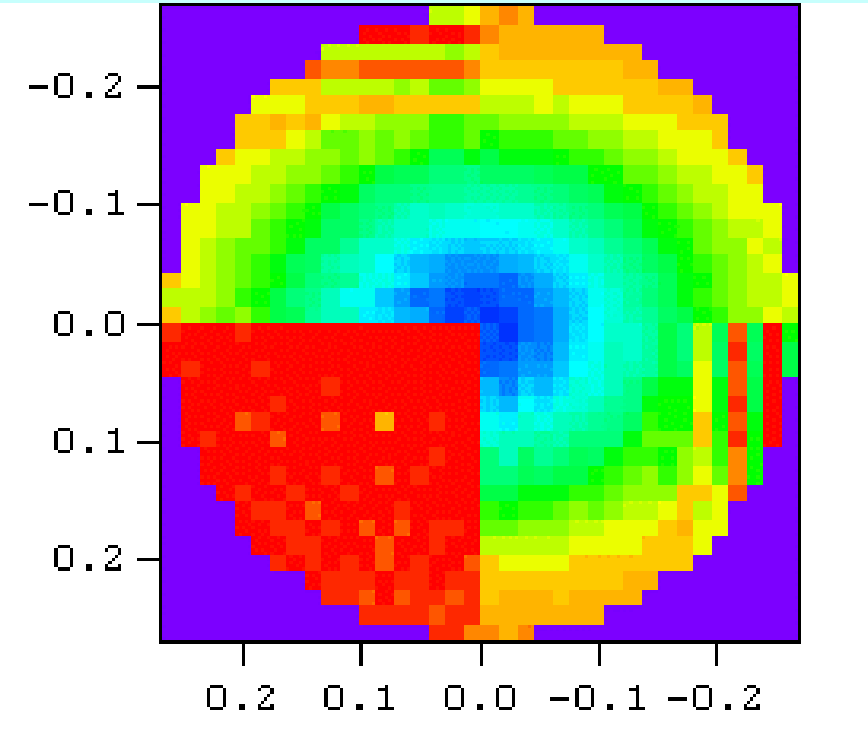
A Faulty 250-Element Quadrant







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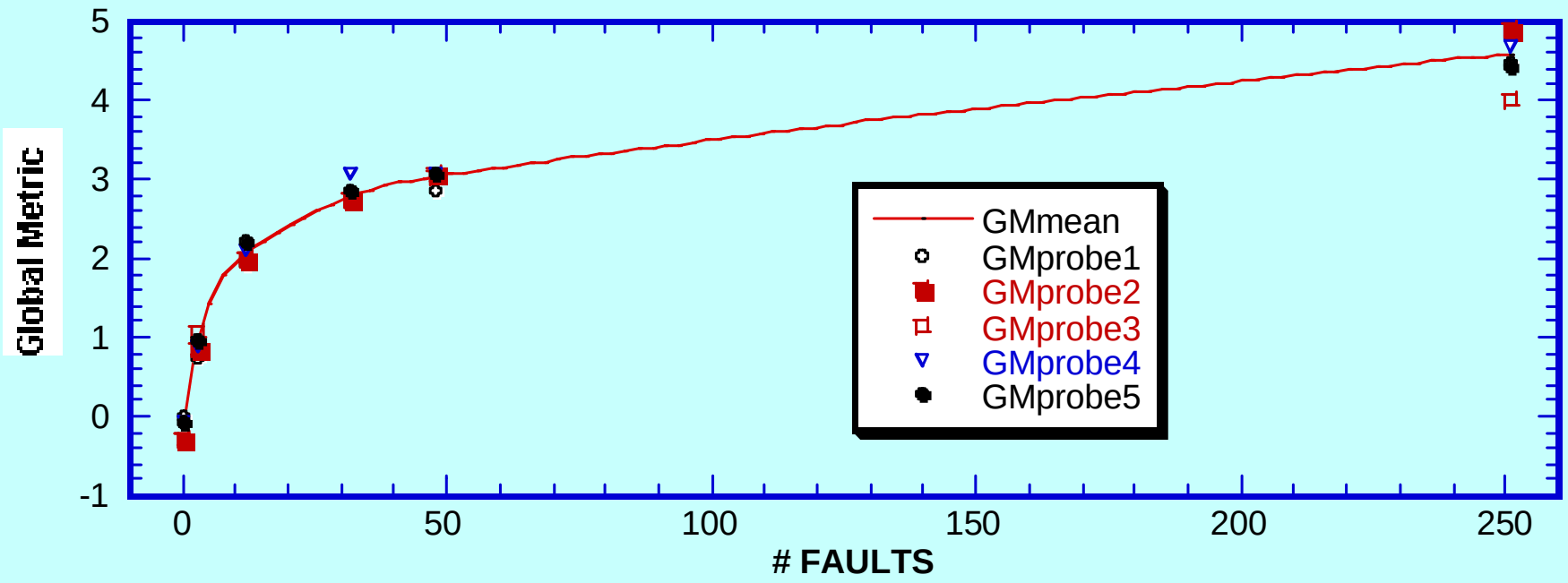
A "Global" Fault Metric



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Conclusions

- MRC has developed and demonstrated a system (NAPS) for complete phased array diagnostics and prognostics
- NAPS has many advantages over other methods including the ability to identify faulty elements as they occur ***while the array operates normally***
- NAPS includes
  - A non-perturbing, fiber-optic RF probe system
  - A set of processing algorithms for identifying faults from probe data
  - (A receiver and processor of some kind)
- NAPS demonstrations included
  - Experimental demo of finding single faults of three types using the fiber-optic probe (using the AAMTV at Crane)
  - Experimental demo of multiple-simultaneous faults (using the AAMTV at Crane)
  - Computer simulation demo for a 1004-element array

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High-Sensitivity, Broadband MRC Photonic RF Probe Heads

Developed under Navy Contract N00421-99-C-1290.

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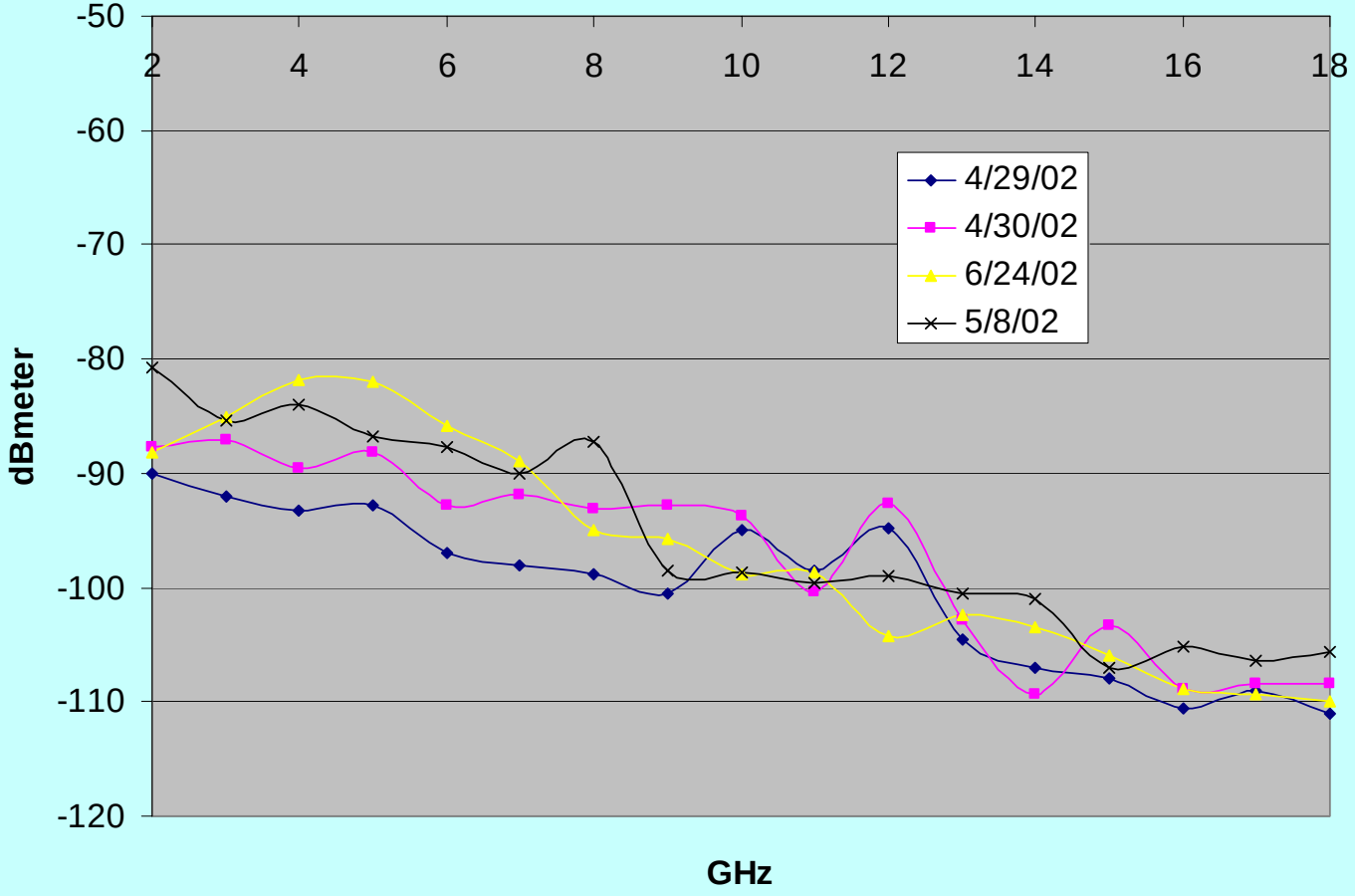
High-Sensitivity, Broadband MRC Photonic RF Probe Performance

Actual Effective Length: V_{RFout}/(E-field at probe)



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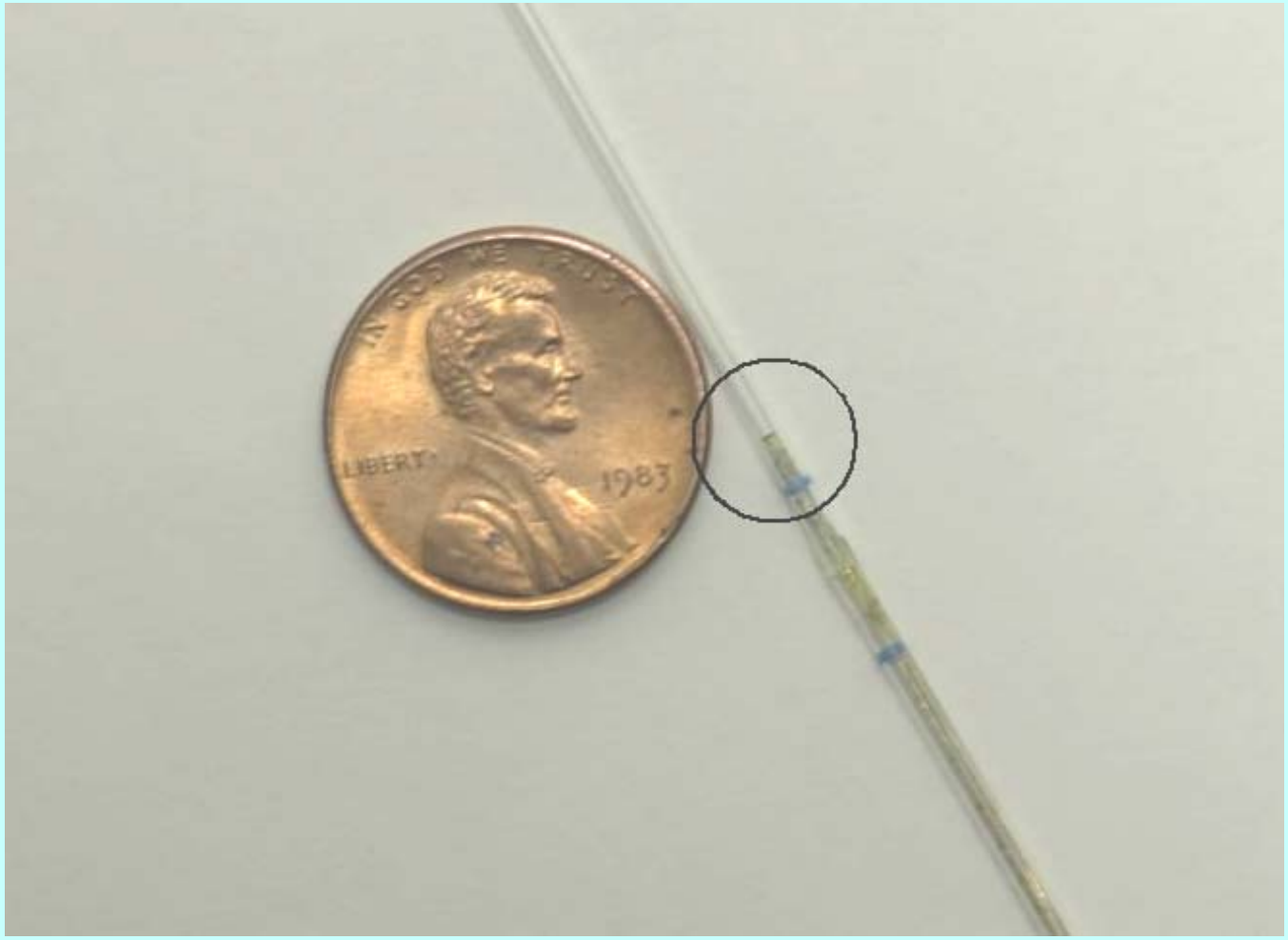
Minature MRC Photonic RF Probe Head



Developed under National Institutes of Health Grant 2R44HL54974-02A1

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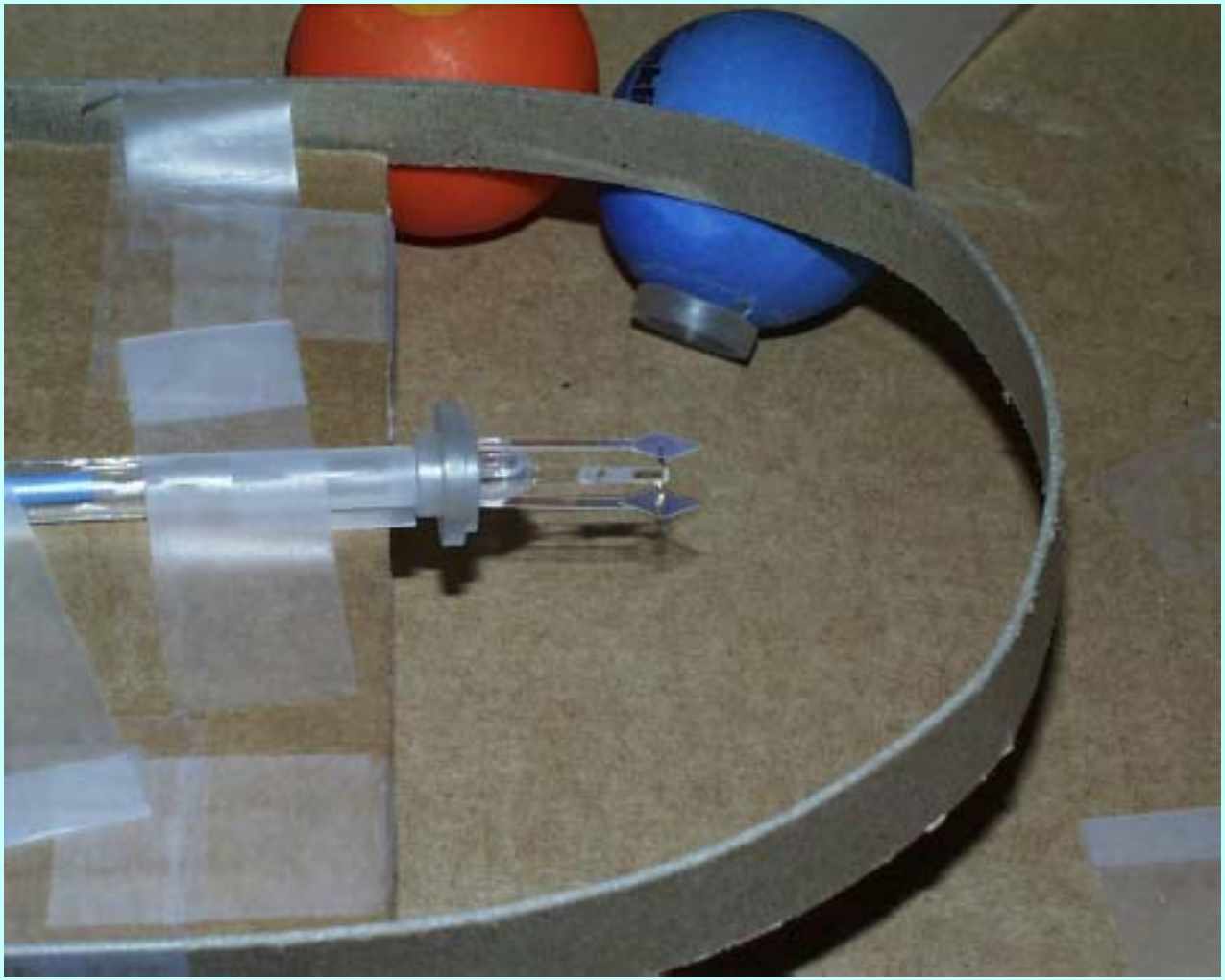
A Lithium Niobate Based Probe Head

- 1/4-inch diameter acrylic support tube----->



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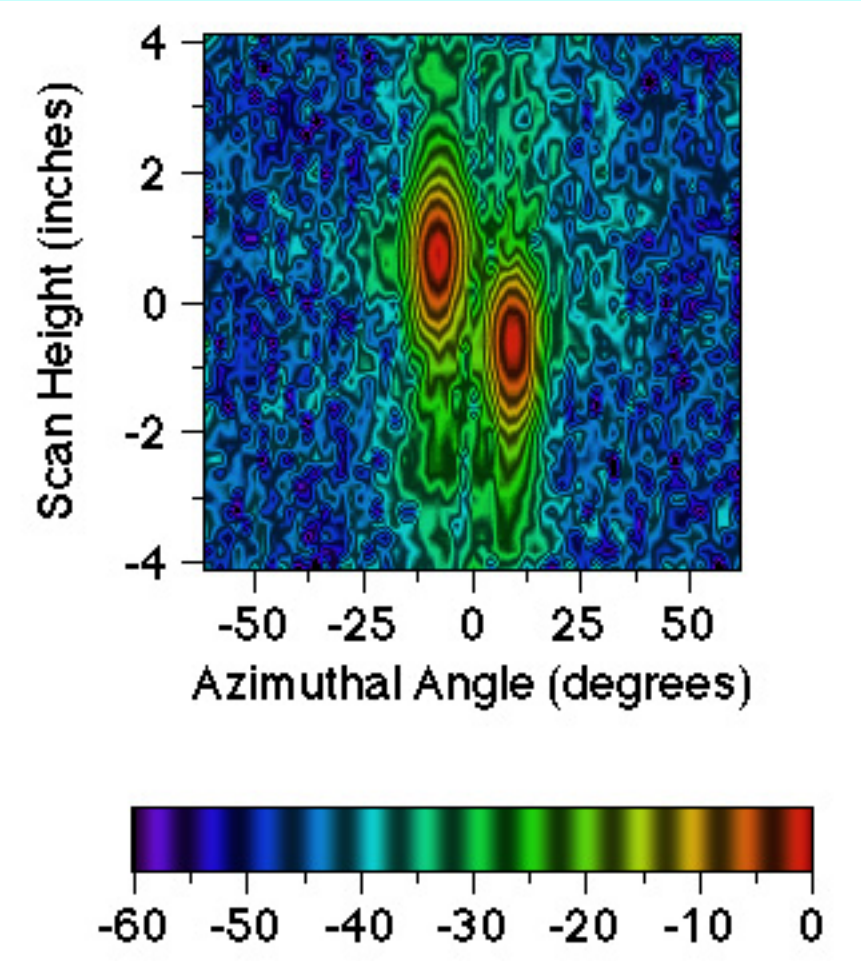
MRC Photonic Probe Evanescent-Region Scan of 2-Element "Array" - Amplitude Data

- Obtained using MRC photonic RF probe
- 2 Ku-band horns
- Data obtained at NRL with Doug Smith
- NRL has since ordered an MRC probe



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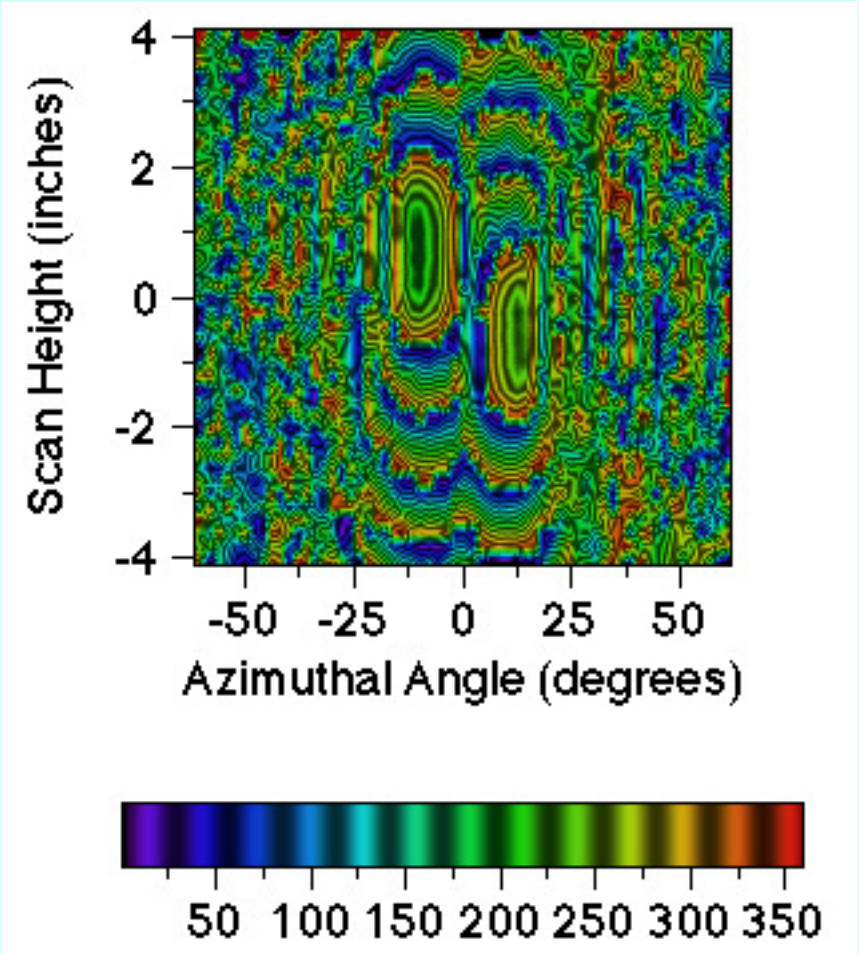
MRC Photonic Probe Evanescent-Region Scan of 2-Element "Array" - Phase Data

- Obtained using MRC photonic RF probe
- 2 Ku-band horns
- Data obtained at NRL with Doug Smith
- NRL has since purchased an MRC probe