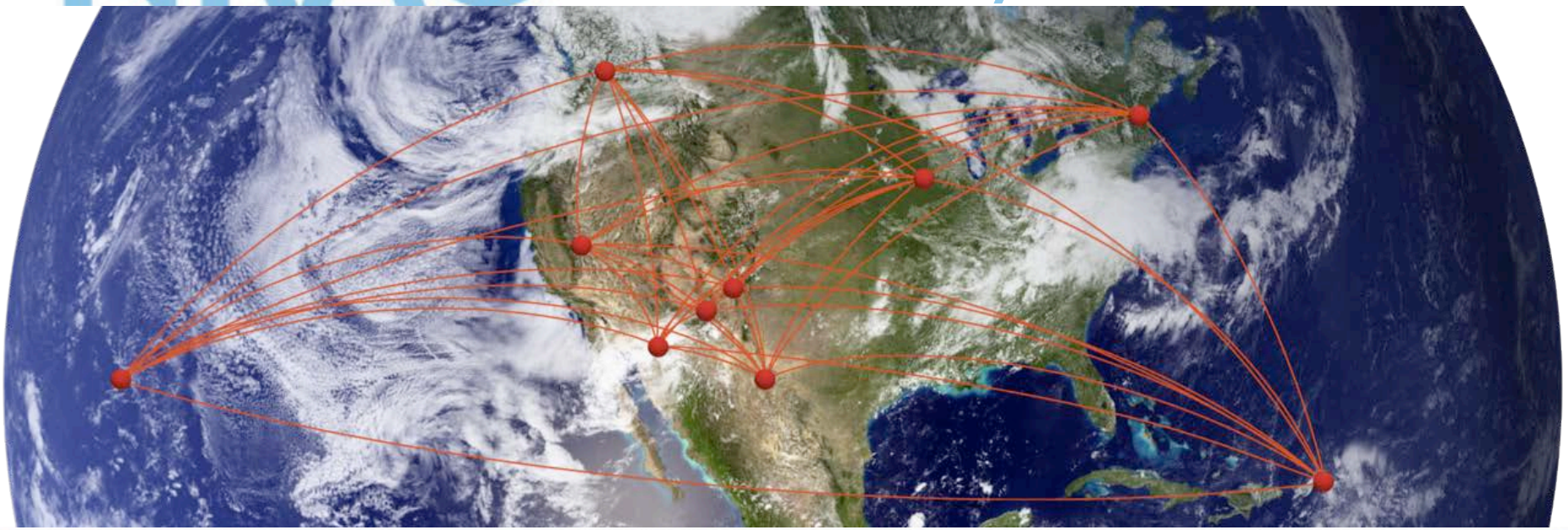
# NRAO

## An NSF Facility



## National Radio Astronomy Observatory

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NSF

Associated Universities, Inc.

NRAO

# New VLBA Capabilities

- Jon Romney
- NRAO / Socorro

- Third China-US Workshop on Radio Astronomy Science and Technology
- Held at NRAO / Green Bank
- 2014 / 5 / 19-21

# Initial Instrumentation, August 1992

- Ten antennas
  - 25-m diameter, wheel-and-track design, rapid slewing.
- Receivers
  - P, L, S, C, X, U, K, Q bands. State-of-the-art at the time.
- Data Acquisition System
  - Analog BaseBand Converters / Formatter / Magnetic tape recorders.
  - Magnetic tape – 26 μm x 1 in x 11,000 ft / 14 passes x 32 tracks.
  - These elements developed by Haystack Observatory.
- Correlator
  - Began 1985 in CV; moved to AOC in 1992.
  - First large-scale FX system in radio astronomy; radical for its time.
  - Fixed hardware, closely linked to original data system.
  - 20 inputs, to allow for double correlation.

# "Minor" Updates Along the Way

- W-band —
  - Not part of original VLBA project.
- Thin tape — 1992-97
  - 16 μm x 1 in x 18,000 ft
- Second formatter — 1998-2000
  - New sustainable rate 256 / Max 512 Mbps.
- Holography for panel / subreflector upgrade — 2000-02
  - Studied but couldn't make it work on a shoestring.
- Mark 5A disk recording system — 2004-05
  - Substantial increase in reliability. Made single-operator array+correlator operation possible. Partly funded by NASA/ESA for Huygens project.
- New K-band LNAs — 2007
  - 38% reduction in SEFD; wider bandwidth. Partly funded by MPIfR.
- MAJOR: New 4-8 GHz C-band Receiver — 2010-12
  - First modern wideband system, copied (and improved) from EVLA. Made 6.7-GHz methanol line accessible. Foreign support organized by MPIfR.

# The VLBA Sensitivity Upgrade Project

- Origins
  - Initial concepts (presented at Long-Range Planning Retreats in GB & Socorro)
    - 1999: Scientific goals. Sensitivity Upgrade Memo* #2.
    - 2000: Technical requirements. Sensitivity Upgrade Memo* #3.
      - * science.nrao.edu/facilities/vlba/publications/memos/upgrade

# VLBA Science Drivers from 1999 Upgrade Discussions

- AGN jet launching regions.
- Blazars with gamma-ray flares.
- Location and velocity of gamma-ray burst blast waves.
- Mapping ionized gas in AGN cores.
- Galactic microquasars.
- Line absorption against compact continuum sources.
- Astrometry, parallax, proper motion of galactic objects.
- Cosmological distance scale.
- Extragalactic astrometry.

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  - Organization
    - 2007: Project established, informally, by AD J. Ulvestad. First major, overall upgrade of the VLBA.
  - Funding
    - $812K awarded by AUI, from L-M settlement.
  - Mission
    - "4 Gbps by 2011" [JSU].

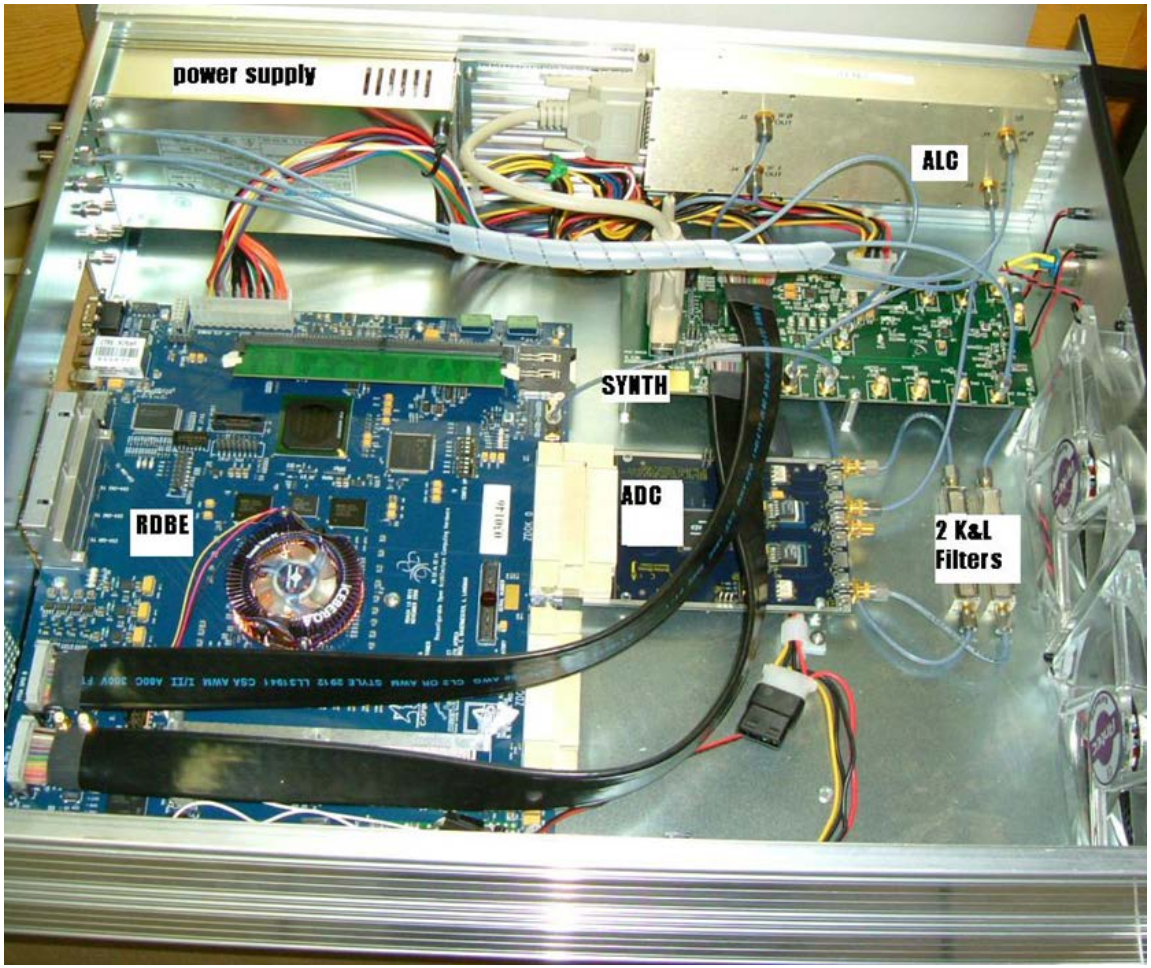
# The VLBA Sensitivity Upgrade Project

- Overall Concept
  - Replace everything downstream from IFs with modern technology. Match limits of existing IF system. Sample directly in IF (at 8-bit precision). All further processing digital.
- Elements
  - **RDBE:** ROACH Digital Backend
  - **Mark 5C:** Disk-based recording system
  - **DiFX:** Software correlator

DiFX had already been developed at the time this project began. Although some early consideration was given to a mini-Widar correlator, DiFX became the obvious choice for the VLBA, and received ~1/3 of initial project funding. After a ~1-year integration into the VLBA's operational system, it began full-time use at the end of 2009. It is not considered further in this review.

# R D B E: "ROACH Digital Backend"

- Central element of the Sensitivity Upgrade instrumentation.
- Developed jointly by NRAO and Haystack Observatory.
- NRAO/Socorro built units for VLBA stations, plus GBT; sold copies at cost to non-NRAO stations of the HSA.
- Commercial vendor established to supply other stations (including Haystack).



# RDBE Basics

- "ROACH Digital Backend"
  - What's a ROACH?
    - "Reconfigurable Open Architecture Computing Hardware".
    - Digital signal processing board — basis of the RDBE.
    - Developed jointly by KAT project, NRAO, and CASPER.
    - Includes a Xilinx V5-SX95T FPGA, PPC 440 controller.
    - NRAO engineers verified design, completed layout, went through many test-respin cycles.
  - Other RDBE elements
    - Anti-aliasing filters.
    - Attenuator module, digitally controlled from Roach.
    - Sampler module, dual IF inputs (512-1024 MHz), 8-bit precision.
    - Synthesizer module for sampler and Roach FPGA.
    - All outputs in 10-GigE packet streams, 2-bit VLBI precision.

# RDBE FPGA Code: "PFB"

- PFB: Polyphase FilterBank
  - Developed (primarily) by Haystack Observatory.
    - NRAO upgrades planned.
  - Operates in second Nyquist zone; fundamentally LSB.
  - Fixed 16 x 32-MHz channel configuration; requantized to 2 bits.
    - Fixed 2048 Mbps output data rate.
  - Channels selectable from 2 IF inputs; placeable in 32-MHz steps.
  - Frequently used observing configurations:
    - Compact dual-polar: 8 contiguous channel pairs, centered in IFs.
    - Spanned single-polar: 16 contiguous channels spanning entire IF.
  - Operational since February 2012.
    - Workhorse for wideband continuum observations.
  - Two-fold reduction in noise level from 512-Mbps confirmed.

# Point-Source Images of SN2008iz at X-band

[Credit: A. Brunthaler]

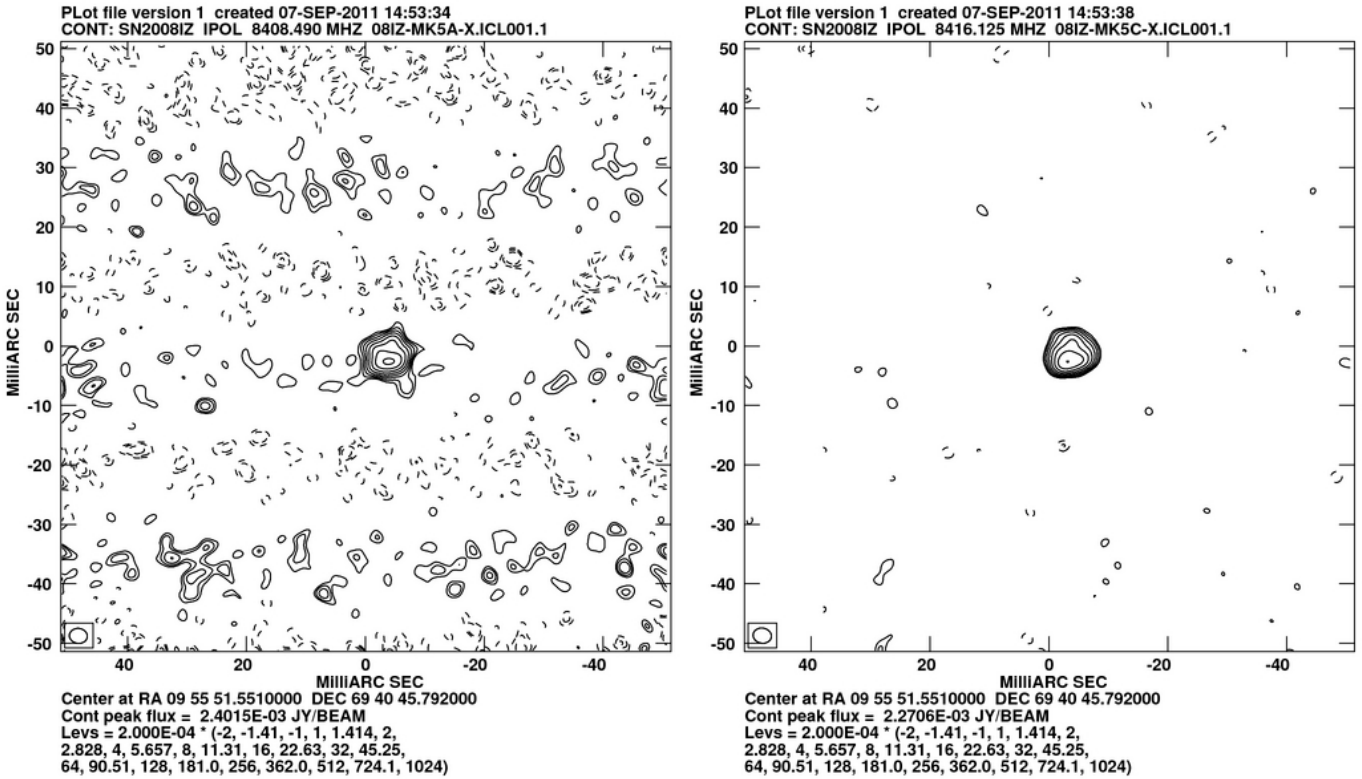



Figure 2: X-band images of SN2008iz using the Mark5A (left) and Mark5C (right) recording. Contours are identical in both images..

# RDBE FPGA Code: "DDC"

- DDC: Digital DownConverter
  - Developed by NRAO engineers
  - Configurations
    - 1,2,4,8* channels; equal bandwidths of 128, 64, … 1 MHz.
      - Possible future upgrade to support varying-bandwidth channels.
    - Channels selectable from 4* IF inputs;
    - * 8-channel or 4-IF modes require dual-RDBE hardware configuration.
    - Frequencies settable in steps of 15.625 kHz.
      - But may not cross IF "zone boundaries" at 640 and 896 MHz.
    - Requantized to 2 bits; possible future upgrade to >2 bits.
  - Single-RDBE mode in use since September 2013.
  - Dual-RDBE available since 2014 February 1
    - >>>> VLBA Sensitivity Upgrade is now complete.
  - All VLBA modes fully supported in SCHED program;
    - Support for CDAS (and similar systems) included in next release.

# Mark 5C Recorder

- Further evolution of Mark 5A, 5B line
- Developed jointly by NRAO, Haystack, and Conduant Corporation.
  - Control software ("DRS") developed by Haystack.
- Uses disk modules identical to Mark 5A, 5B.
- Different I/O concept: formatless "dumb recorder", just accepts input 10GigE packets, stores and reproduces packet payloads.
- Directly accessible by correlator (or other) software.

- Recording capacity **4** Gbps on **two** modules
- Paired-module scheme not viable for full-time operation — second module required for unattended operation.
- Current VLBA configuration: 1 recorder per station; maximum **2 Gbps** data rate.

# Station Configuration

- Input "4x4" IF switch
  - Routes each of 4 IF signals (A,B,C,D) from the antenna vertex room to **any** RDBE input.
- Two RDBEs *
  - Each with two IF inputs.
- Ethernet switch *
  - Sequences input packet streams from RDBEs, and regulates timing to Mark 5C recorder. This switch is a software-based system supplied by XCube Research and Development.
- One Mark 5C recorder.
- * The second RDBE and Ethernet switch are only required for:
  - 4-IF and/or 8-channel modes – or, if/when 4-Gbps recording is available, possibly for 32-channel PFB observations.

# Did We Make the Upgrade Goal?

- "4 Gbps by 2011"
  - "Well, sorta."
  - The entire system was designed to support 4 Gbps, but requires sufficient recording capacity to be present. We would "only" need to buy new or upgrade existing capacity for each station, and double the pool of recording media. Lowest cost estimate in a 2012 ODP proposal : $912K.
  - And we only missed the end of 2011 by two months.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