Hien Vo
Vietnamese German University

Prediction of the 21-cm Line

(1944)

Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting). (*By courtesy of H. C. van de Hulst, Leiden*)

(no apostrophe)

- Astronomers still meeting in the Netherlands during WWII.
- ApJ still reaching Leiden Observatory.
- Excited by Reber's findings, Oort realized that a radio spectral line could be used to map the Milky Way's structure (optical is absorbed).

Prediction of the 21-cm Line

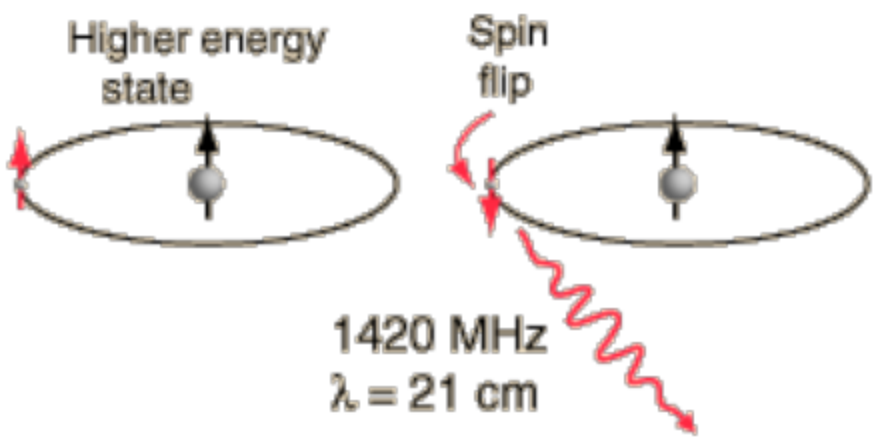
Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting). (*By courtesy of H. C. van de Hulst, Leiden*)

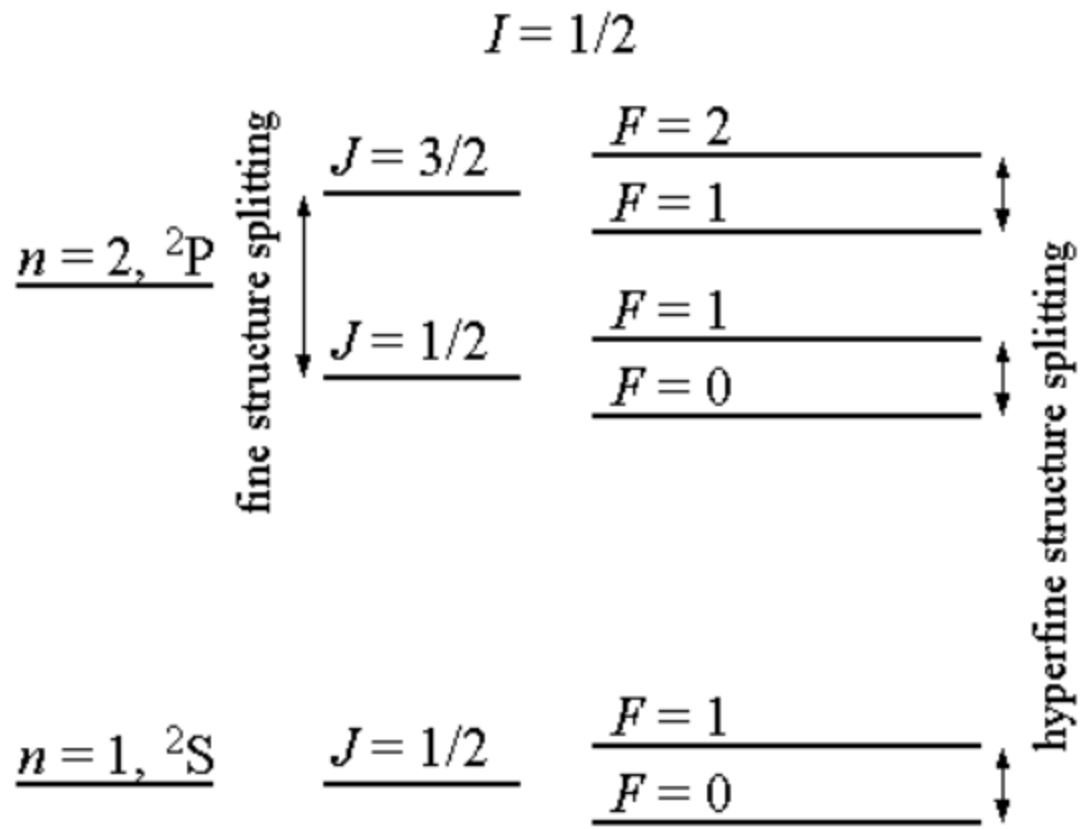
(1944)

- Oort asked van de Hulst to investigate what lines there might be.
- van de Hulst discovered that a 21-cm line would result from an electron flipping its spin in the ground state of hydrogen.
- Published in Dutch in the Ned. Tijdschrift voor Natuurkunde.

(1944)

frequency of 1420.40575177 MHz, which is equivalent to the vacuum wavelength of 21.10611405413 cm in free space.



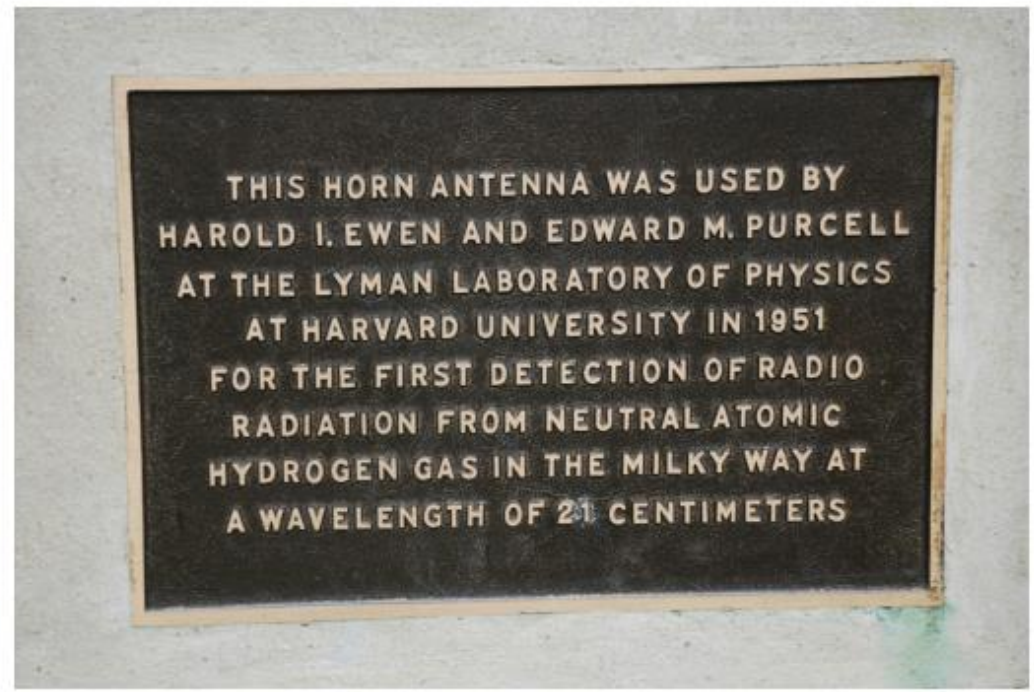


Detection of the 21-cm Line

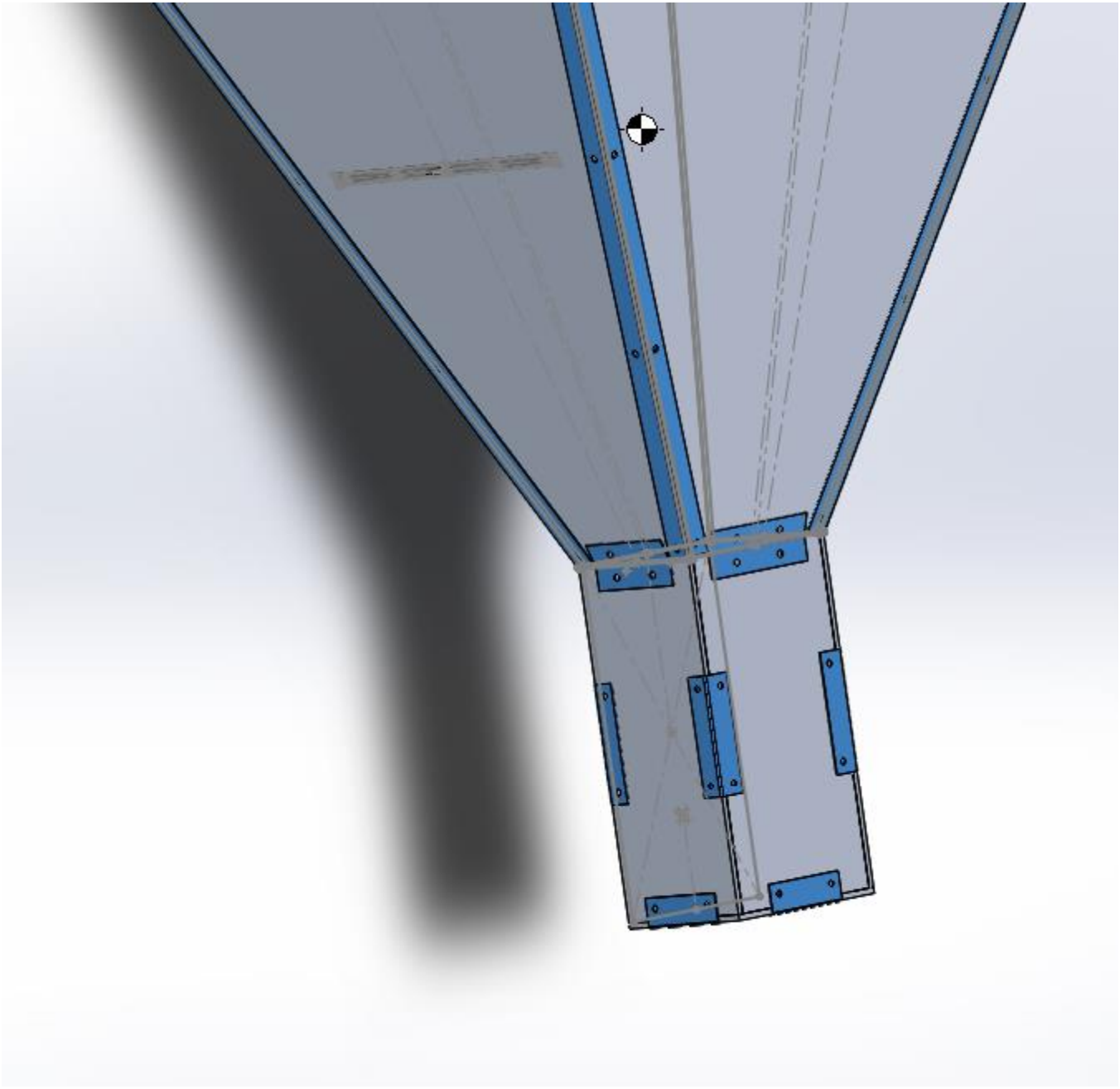
(1951)

- Building a good receiver proved challenging.
- Reber started work but moved on.
- Ewen & Purcell at Harvard made first detection on March 25th, 1951.
- van de Hulst visiting Harvard at that time.
- Talked to Oort on phone for an hour.
- American and Dutch results were published in the same issue of Nature

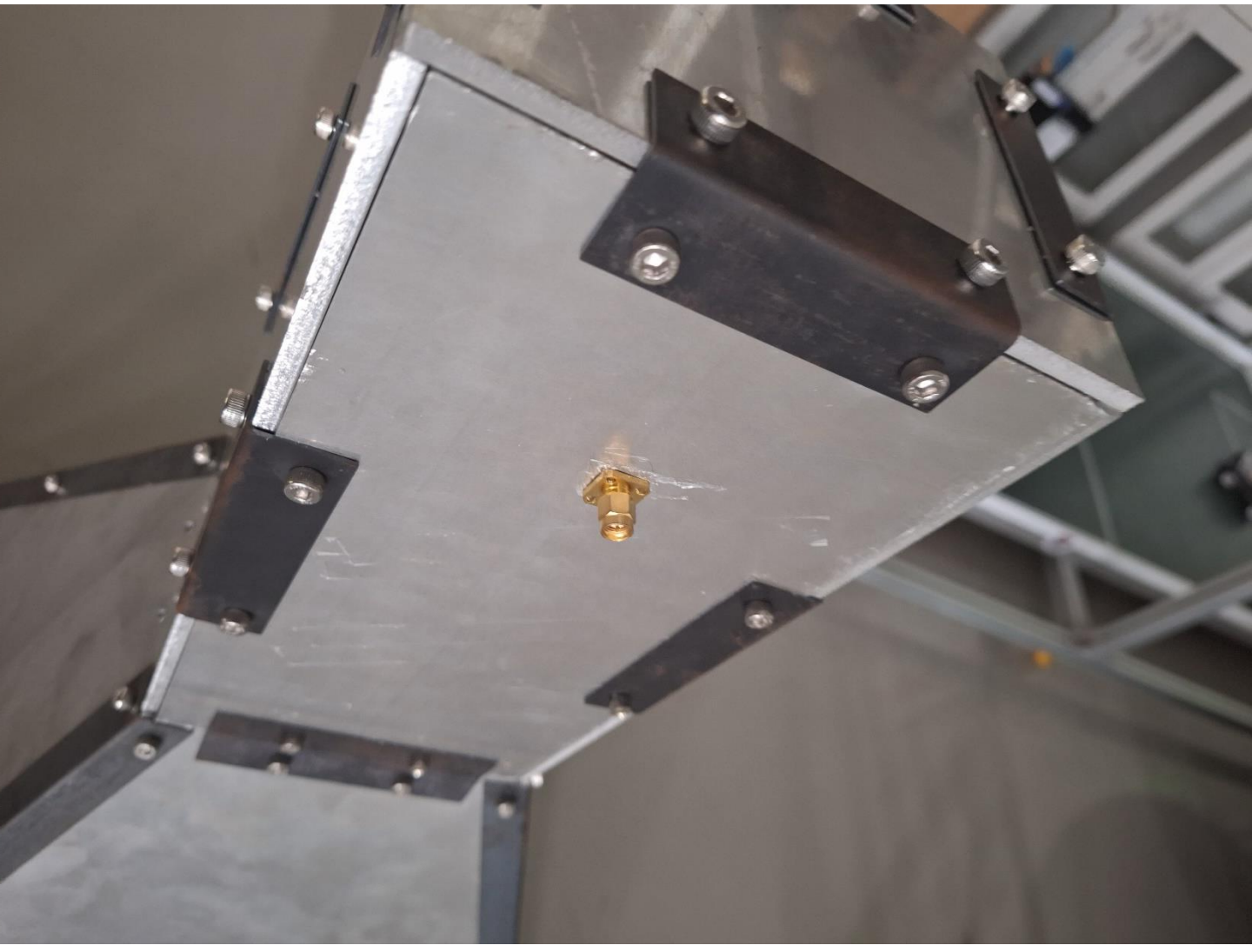
Ewen & Purcell Feed Horn Today



One of the three historic radio telescopes in Green Bank, West Virginia (original).



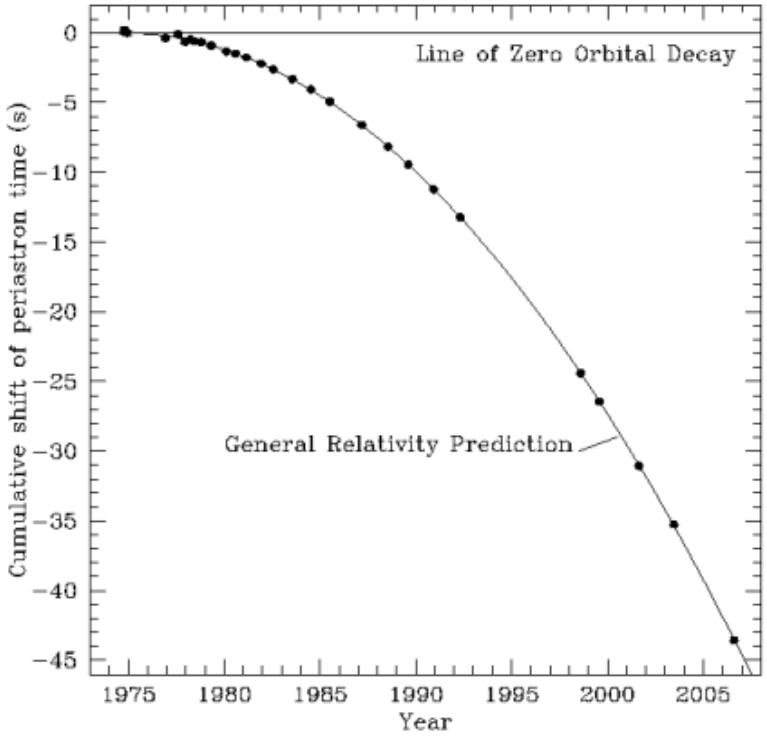
TRUMPF
TruLaser 2030



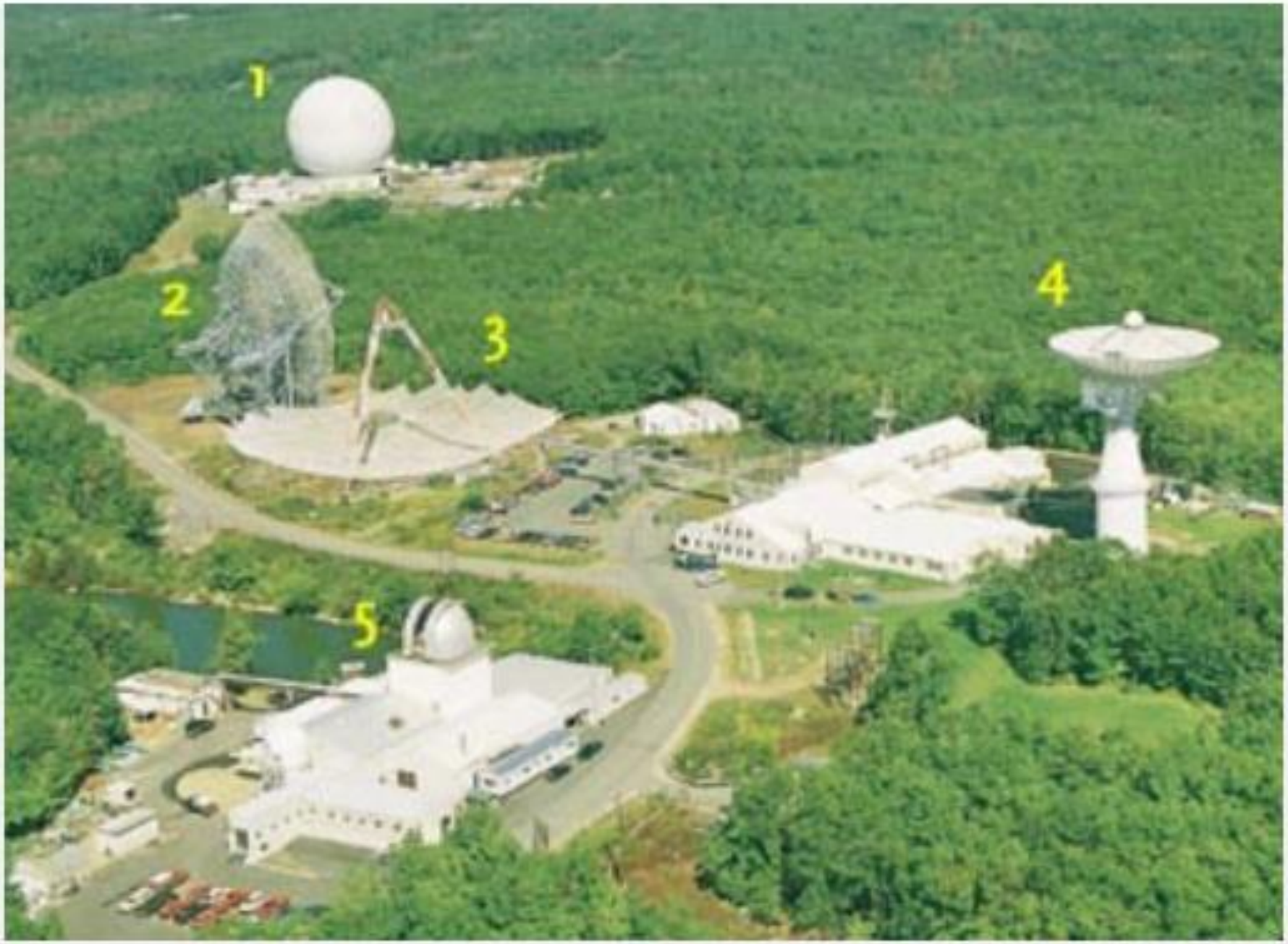
Nobel Prize Physics 1993

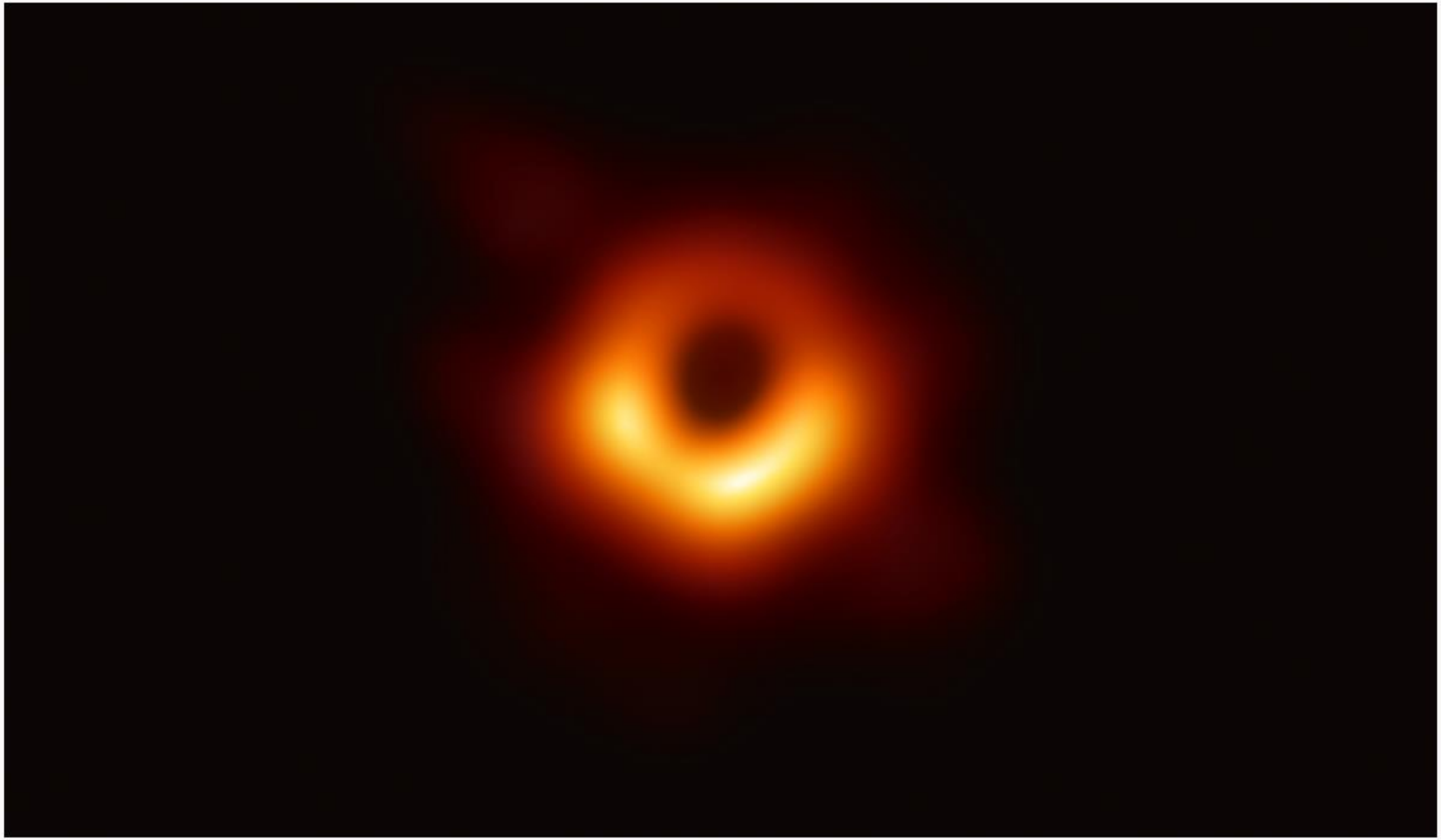
Russell Hulse & Joseph Taylor

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



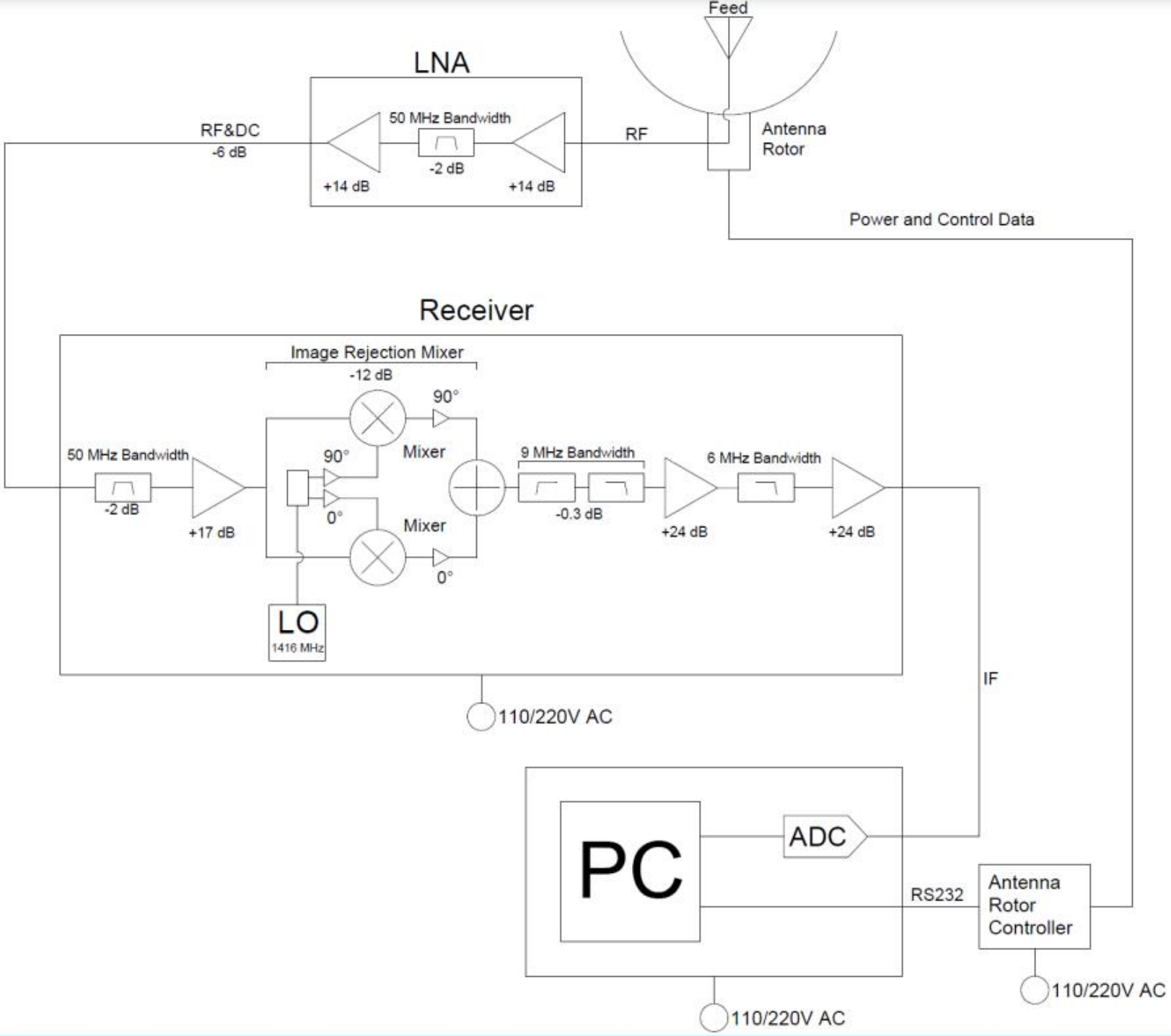
Activate Windows
Go to Settings to activate W


1
2
3
4
5



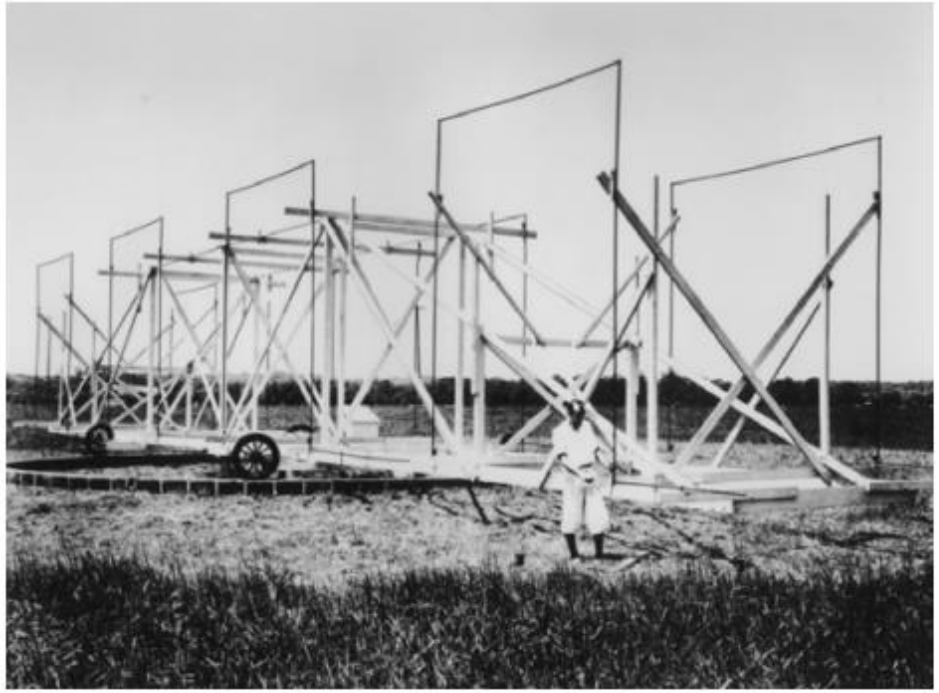
Scientists have obtained the first image of a black hole, using Event Horizon Telescope observations of the center of the galaxy M87. The image shows a bright ring formed as light bends in the intense gravity around a black hole

WATCH
FOR
STRIANS

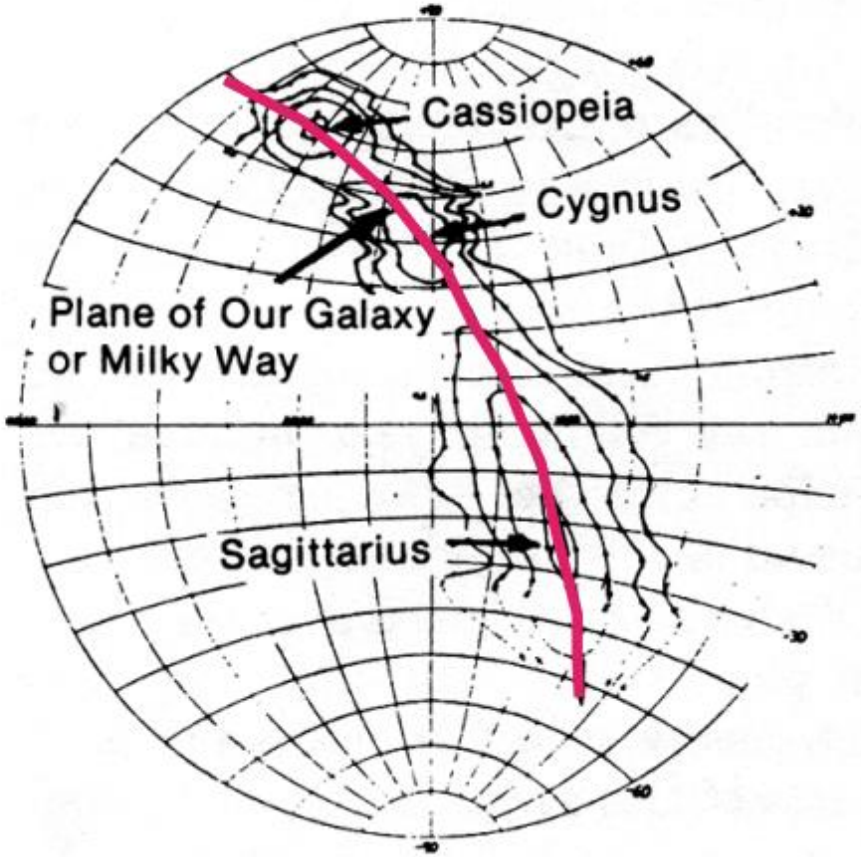

Feed
LNA
RF&DC
-6 dB
50 MHz Bandwidth
-2 dB
+14 dB
+14 dB
RF
Antenna
Rotor
Power and Control Data
Receiver
Image Rejection Mixer
-12 dB
90°
Mixer
90°
0°
Mixer
0°
50 MHz Bandwidth
-2 dB
+17 dB
9 MHz Bandwidth
-0.3 dB
+24 dB
6 MHz Bandwidth
+24 dB
LO
1416 MHz
110/220V AC
IF
PC
ADC
RS232
Antenna
Rotor
Controller
110/220V AC
110/220V AC

2024/07/23 13:09

Low Frequencies: Origin of Radio Astronomy



Karl Jansky's work at 20.5 MHz



Grote Reber continued work at 160 MHz (1.9 m)

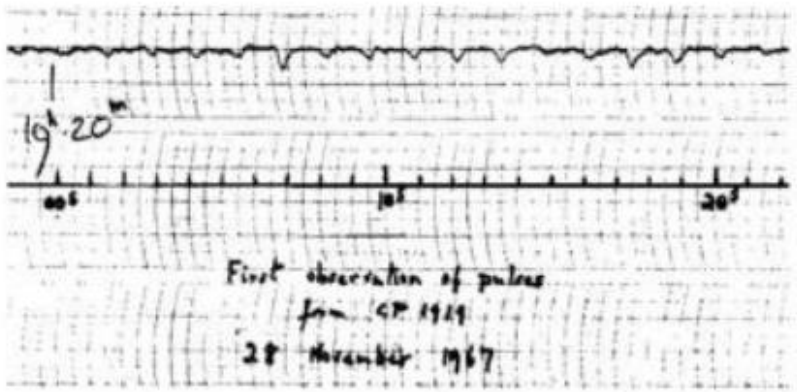
Observation of a Rapidly Pulsating Radio Source

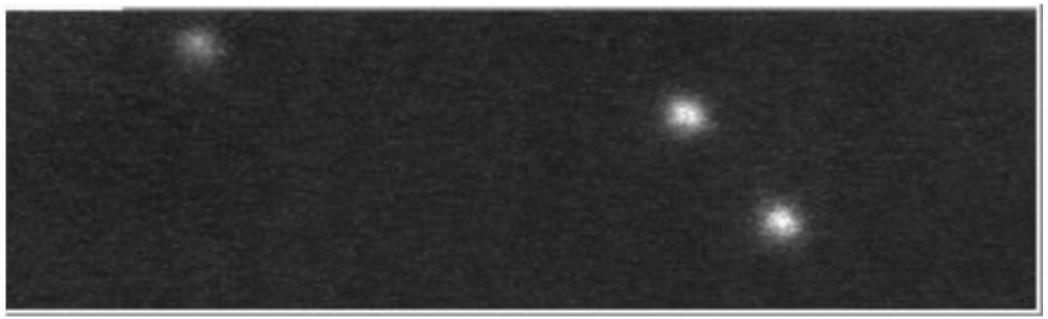
by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

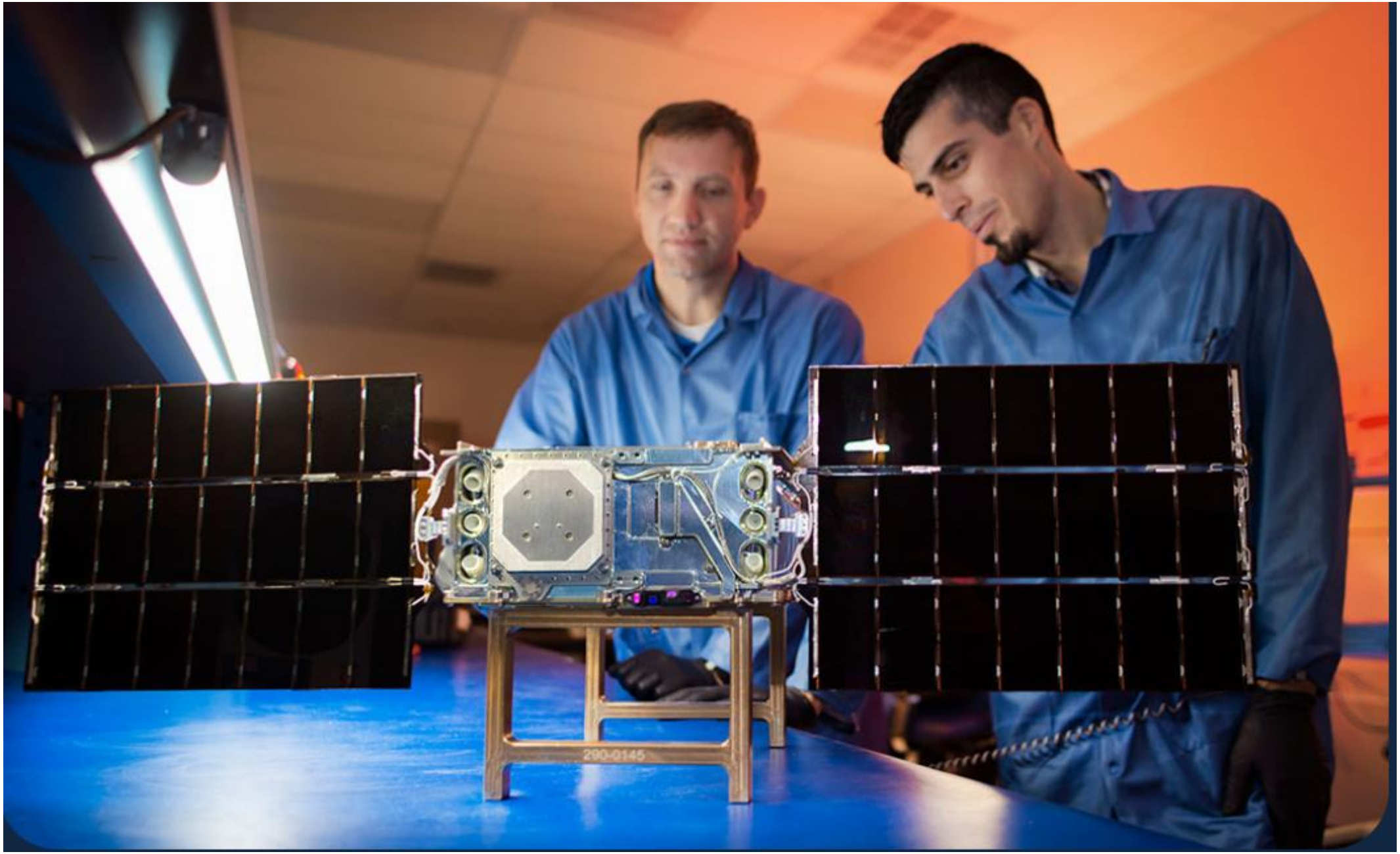


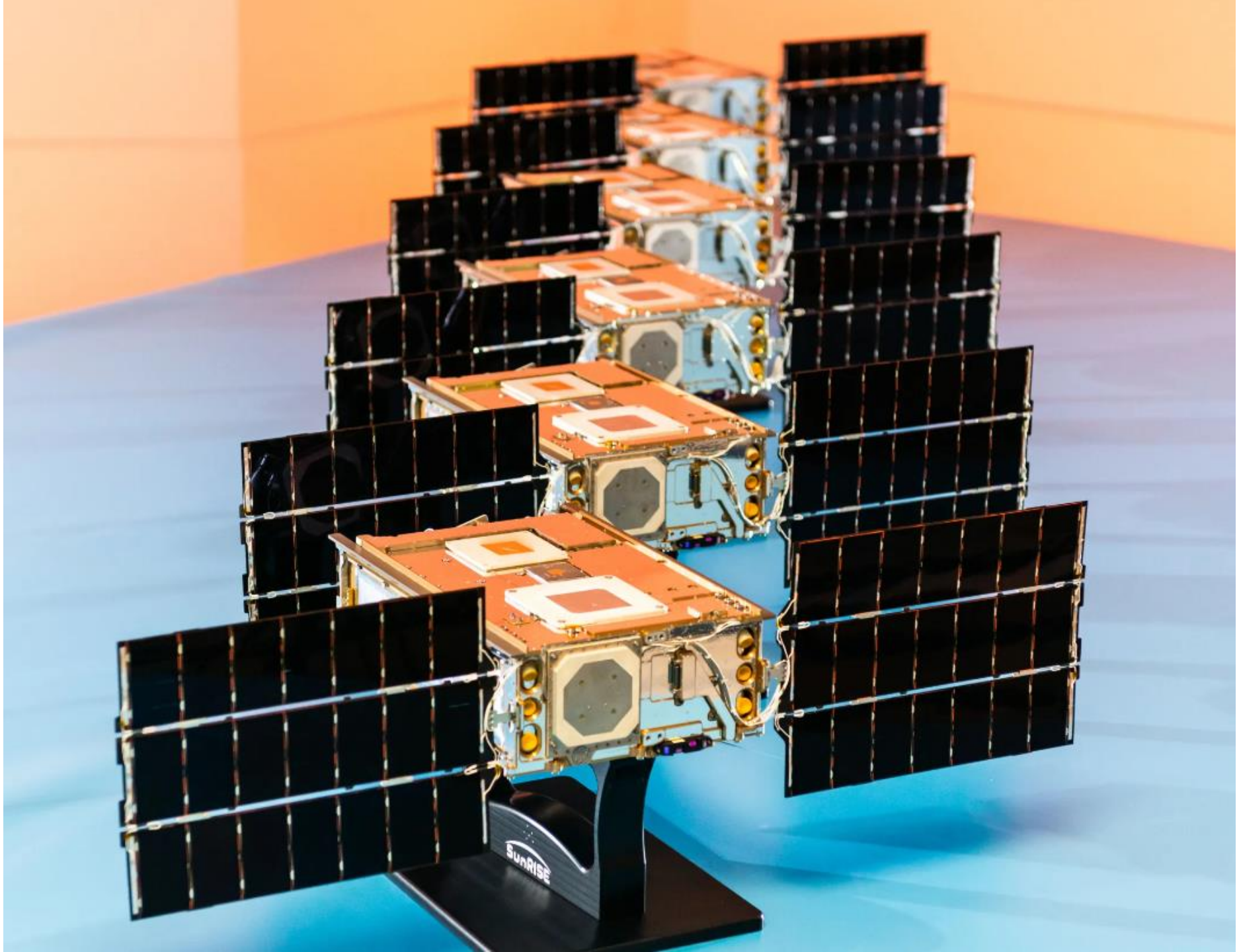


- 1967: Hewish et al. report a radio source pulsing every 1.337 s

- Confirmed the existence of neutron stars

- Observations done with 2048 dipoles at 81.5 MHz


290-0145

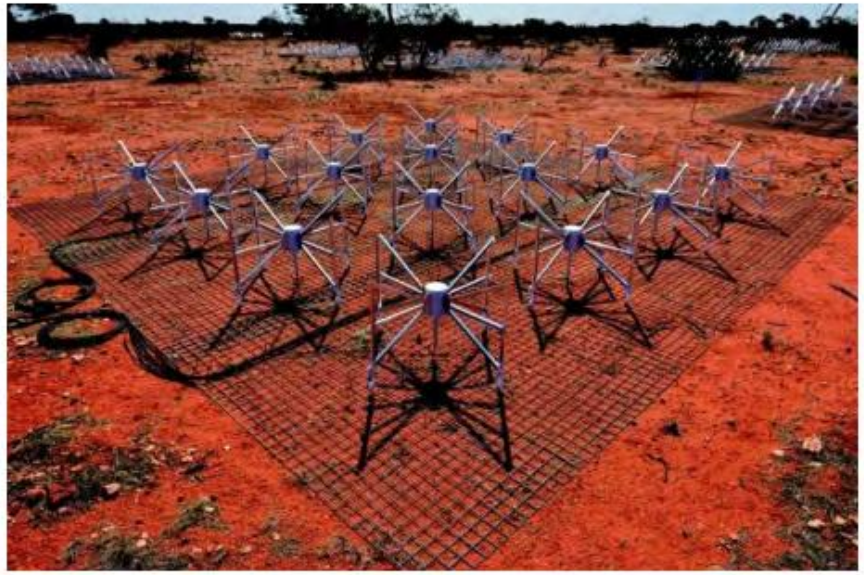

SunRISE

The Return to Low Frequencies: Science Drivers

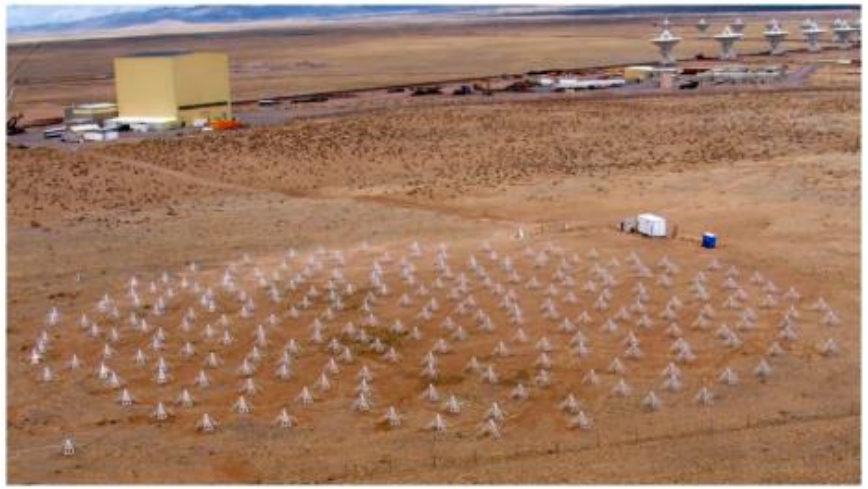
- Key science drivers at low frequencies:
  - Dark Ages (spin decoupling)
  - Cosmic Dawn
  - Epoch of Reionization (highly redshifted 21 cm lines)
  - Early Structure Formation (high z RG)
  - Large Scale Structure evolution (diffuse emission)
  - Evolution of Dark Matter & Dark Energy (Clusters)
  - Wide Field (up to all-sky) mapping
  - Large Surveys
  - Transient Searches (including extrasolar planets)
  - Galaxy Evolution (distant starburst galaxies)
  - Interstellar Medium (CR, HII regions, SNR, pulsars)
  - Solar Burst Studies
  - Ionospheric Studies
  - Ultra High Energy Cosmic Ray Airshowers
  - Serendipity (exploration of the unknown)

The New(ish) Kids on the Block…

LOFAR: 15-88 MHz [LBA] & 110 250 MHz [HBA]
150 million EUR



MWA: 80–300 MHz
A$51 million



LWA: 15-88 MHz: **15 million US$**

Phased Arrays

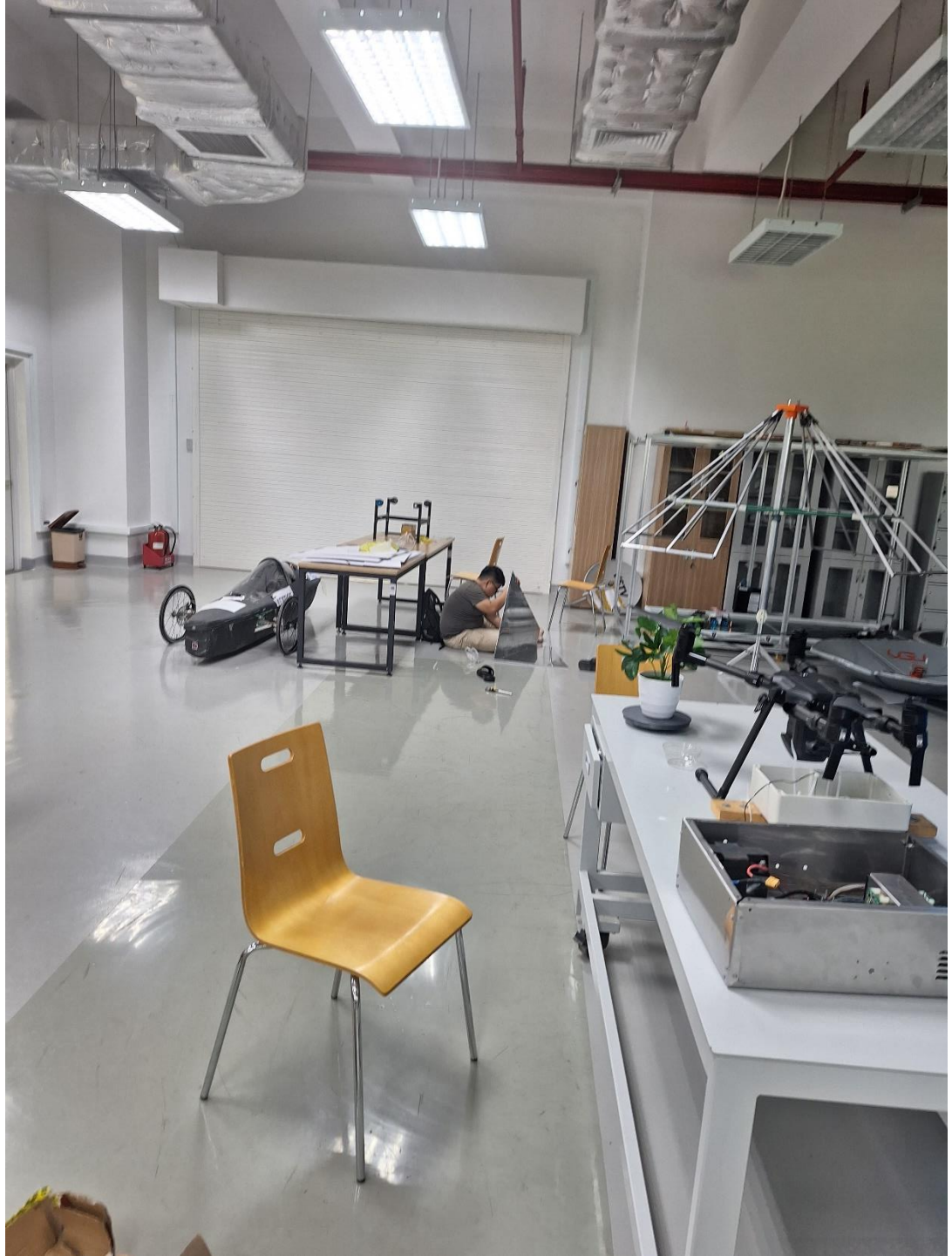
Signals combined via delays in an analog beam-former

Beam size determined by station size – similar to large dish

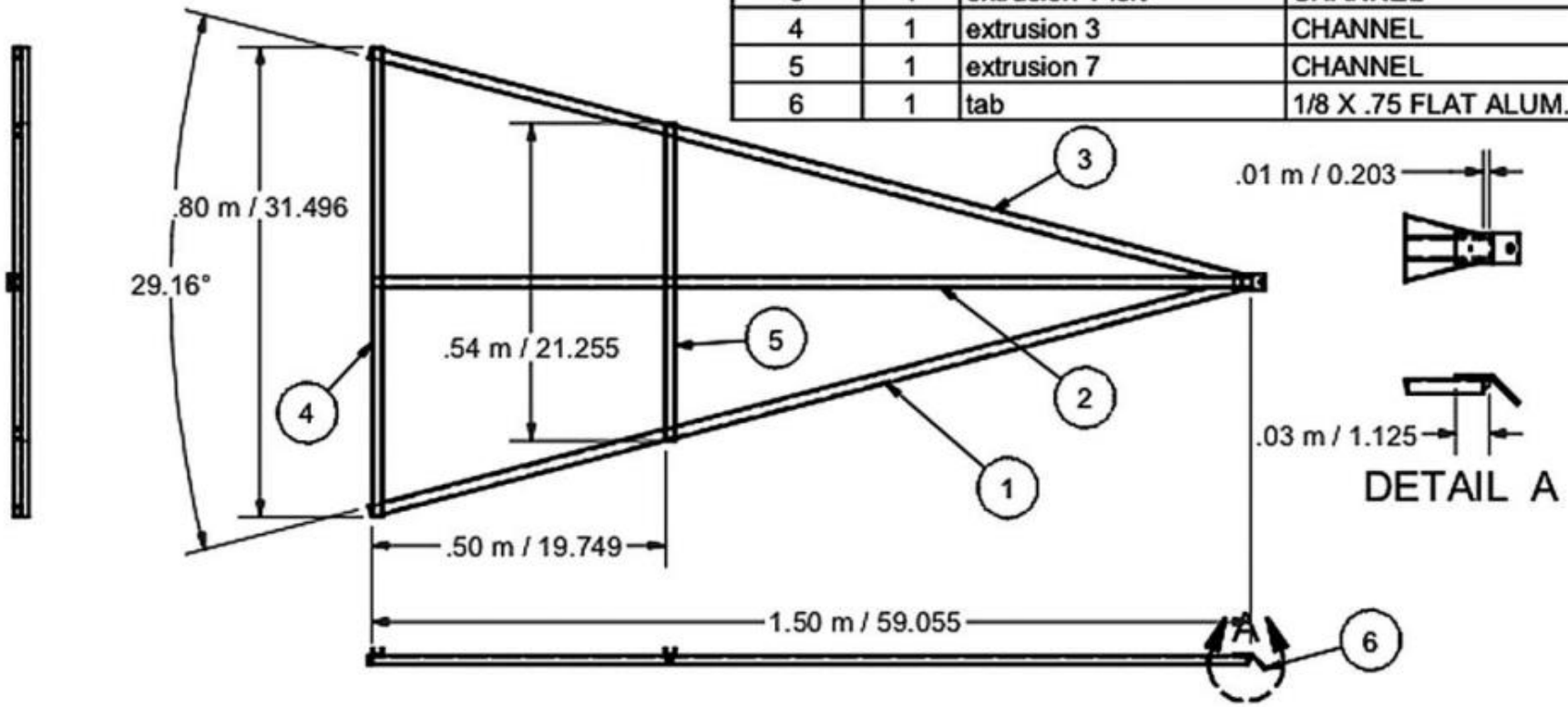
Cross-correlate multiple stations (dishes) to create image, with resolution element size determined by baseline length

Phased arrays over large areas have been the favored choice to allow good sensitivity, good resolution, reasonable field of view - **while minimizing digital hardware costs**

Additional projects – specialized non-imaging arrays with very focused goals: PAPER/HERA

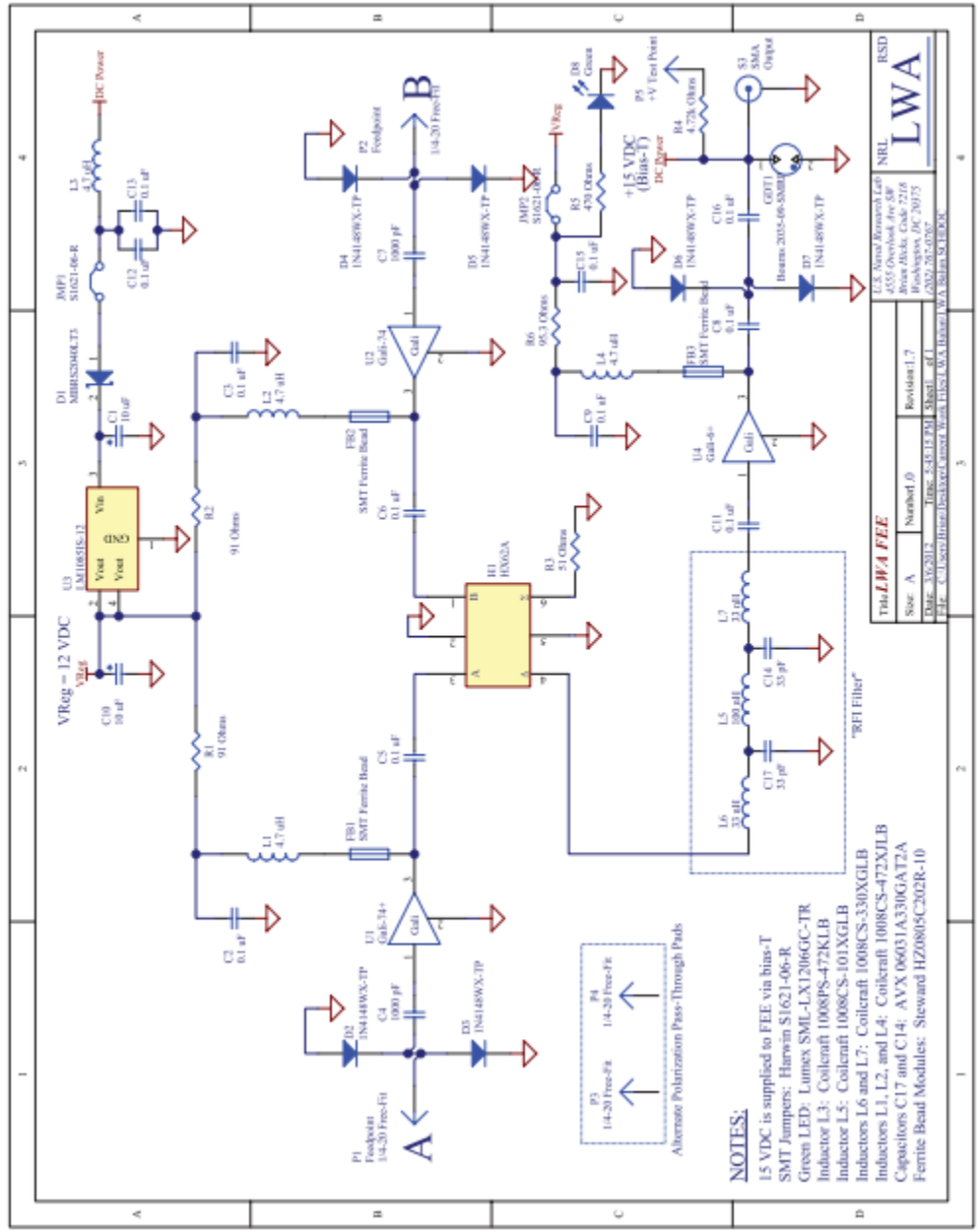


Parts List			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	extrusion 1	CHANNEL
2	1	extrusion 2	CHANNEL
3	1	extrusion 1 left	CHANNEL
4	1	extrusion 3	CHANNEL
5	1	extrusion 7	CHANNEL
6	1	tab	1/8 X .75 FLAT ALUM.

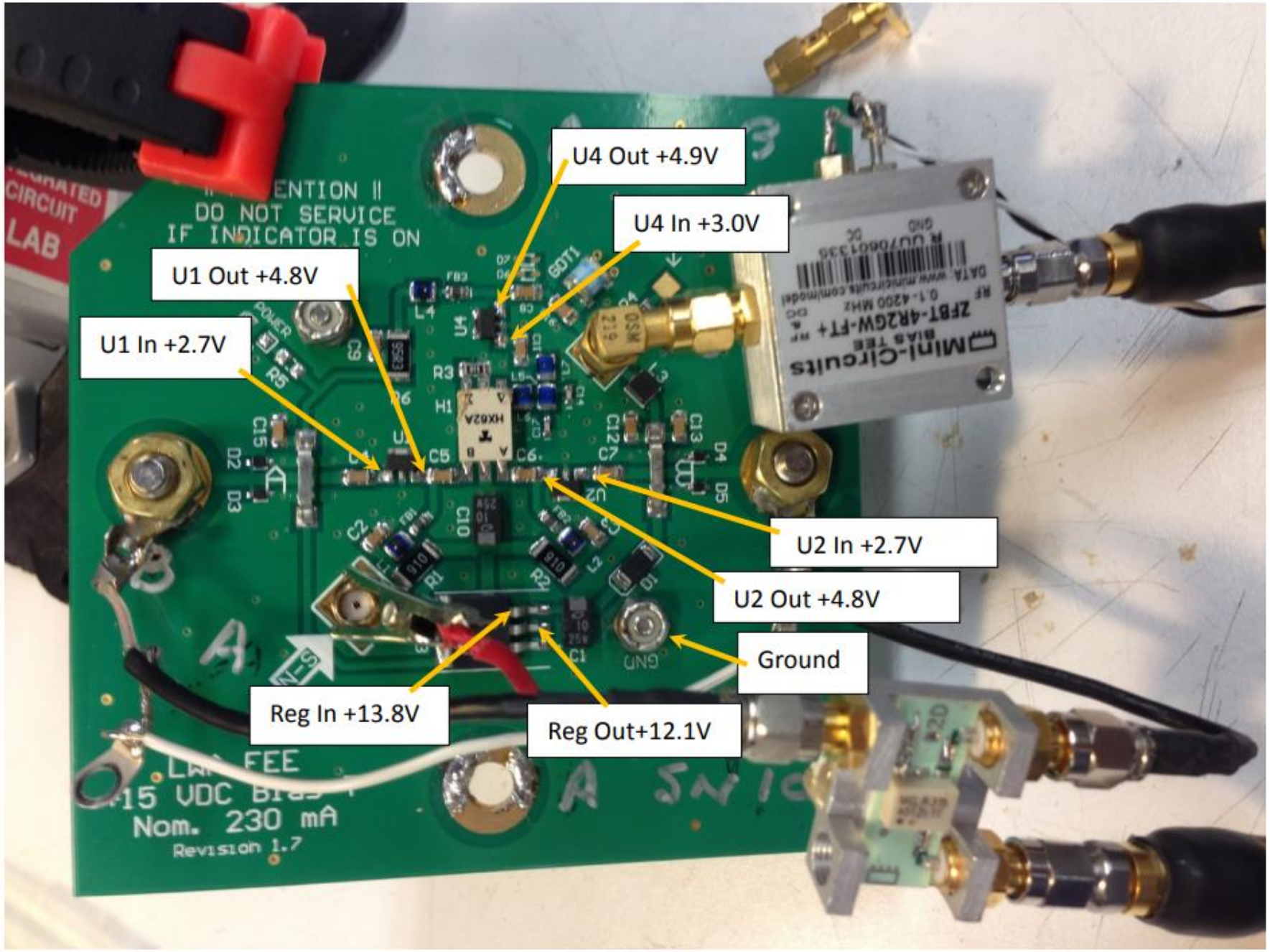


DIMENSIONS IN METERS/inches

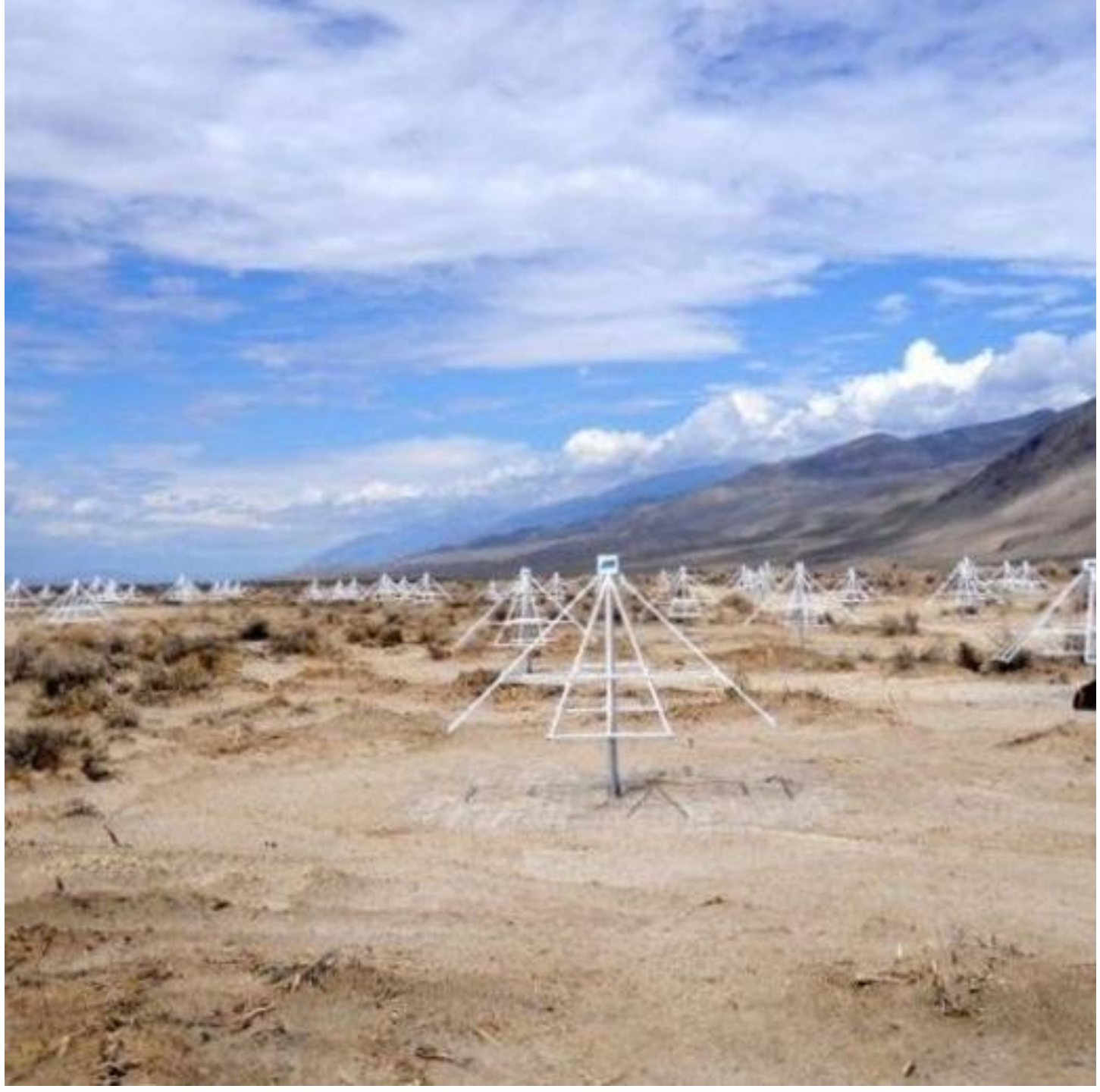
DRAWN Art	7/15/2008	BURNS INDUSTRIES 141 CANAL STREET, NASHUA NH 603-881-8336
CHECKED AAH		
QA		TITLE
MFG		LWA ELEMENT
APPROVED AAH		
		SIZE A / DWG NO element A / REV A
		SCALE / SHEET 1 OF 1

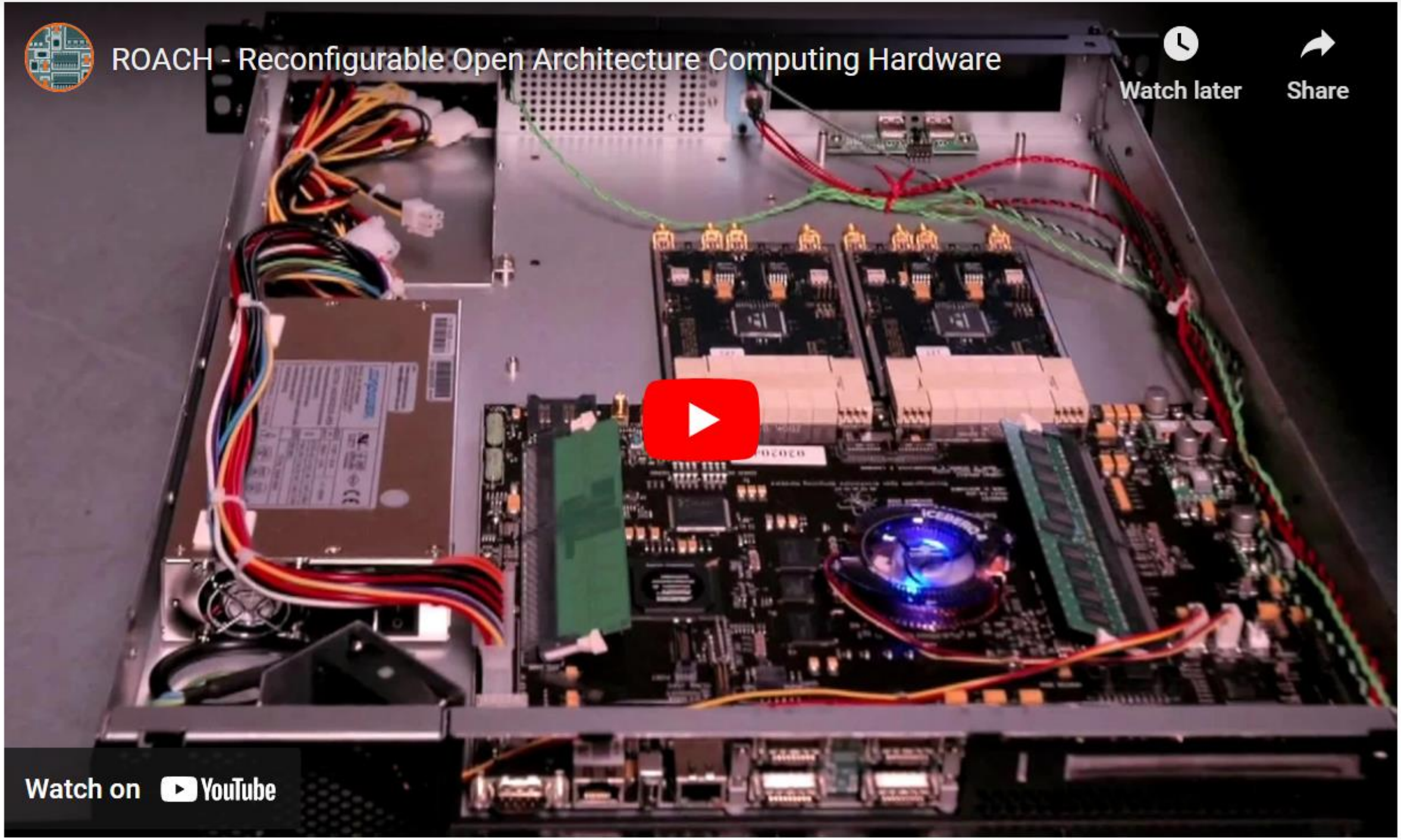

VReg = 12 VDC
DC Power
U3 M10815L-13
D1 MBRS340LT3
JMP1 S1621-06-R
L3 4.7 uH
C13 0.1 uF
C12 0.1 uF
C1 10 uF
C10 10 uF
R1 91 Ohms
R2 91 Ohms
C2 0.1 uF
C3 0.1 uF
L1 4.7 uH
L2 4.7 uH
FB1 SMT Ferrite Bead
FB2 SMT Ferrite Bead
C5 0.1 uF
C6 0.1 uF
U1 Gali-34+
U2 Gali-34
D2 1N4148WX-TP
D3 1N4148WX-TP
D4 1N4148WX-TP
D5 1N4148WX-TP
C4 1000 pF
C7 1000 pF
P1 Footprint 14-20 Free-Fit
P2 Footprint 14-20 Free-Fit
A
B
H1 HX652A
R3 51 Ohms
P3 14-20 Free-Fit
P4 14-20 Free-Fit
Alternate Polarization Pass-Through Pads
JMP2 S1621-06-R
VReg
R5 470 Ohms
C15 0.1 uF
R6 95.3 Ohms
L4 4.7 uH
C9 0.1 uF
D8 Green
P5 +V Test Point
+15 VDC (Bias-T)
DC Power
R4 4.72k Ohms
D6 1N4148WX-TP
FB3 SMT Ferrite Bead
C8 0.1 uF
C16 0.1 uF
GDT1 Bourns 2035-06-SMLF
D7 1N4148WX-TP
S3 SMA Output
U4 Gali-6+
C11 0.1 uF
L7 33 nH
C14 33 pF
L5 100 nH
C17 33 pF
L6 33 nH
"RFI Filter"
NOTES:
15 VDC is supplied to FEE via bias-T
SMT Jumpers: Harwin S1621-06-R
Green LED: Lumex SML-LX1206GC-TR
Inductor L3: Coilcraft 1008PS-472KLB
Inductor L5: Coilcraft 1008CS-101XGLB
Inductors L6 and L7: Coilcraft 1008CS-330XGLB
Inductors L1, L2, and L4: Coilcraft 1008CS-472XJLB
Capacitors C17 and C14: AVX 06031A330GAT2A
Ferrite Bead Modules: Steward HZ0805C202R-10
Title LWA FEE
Size A
Number 0
Revision 1.7
Date: 3/6/2012
Time: 2:45:12 PM
Sheet of 1
File: C:\Users\Hans\Desktop\Local Work Files\LWA\Hans\LWA Solar SCHDOC
U.S. Naval Research Lab
4555 Overlook Ave SW
Brian Hicks, Code 7216
Washington, DC 20375
(202) 767-0707
NRL
LWA
RSD

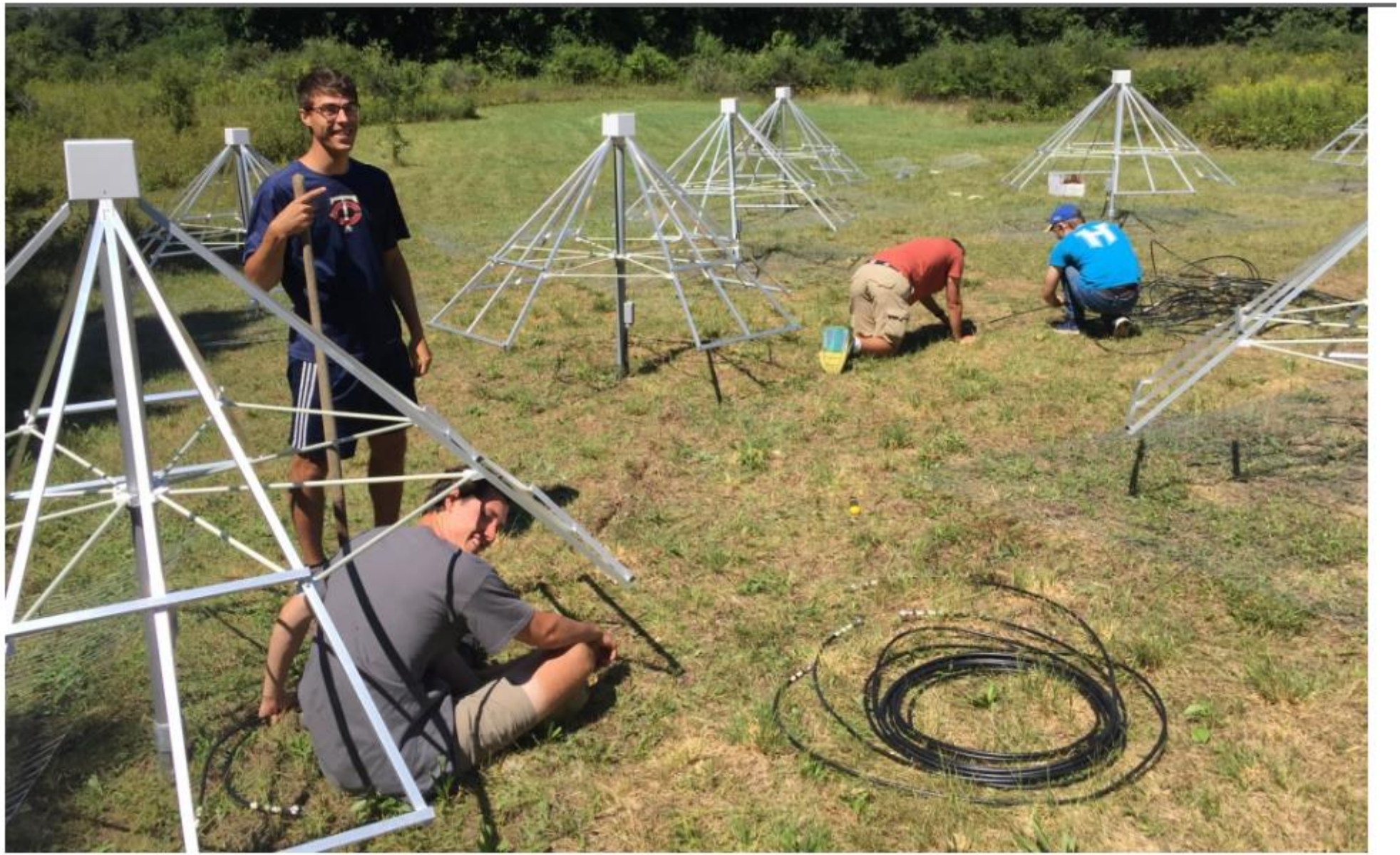
DC Tests of the LNA

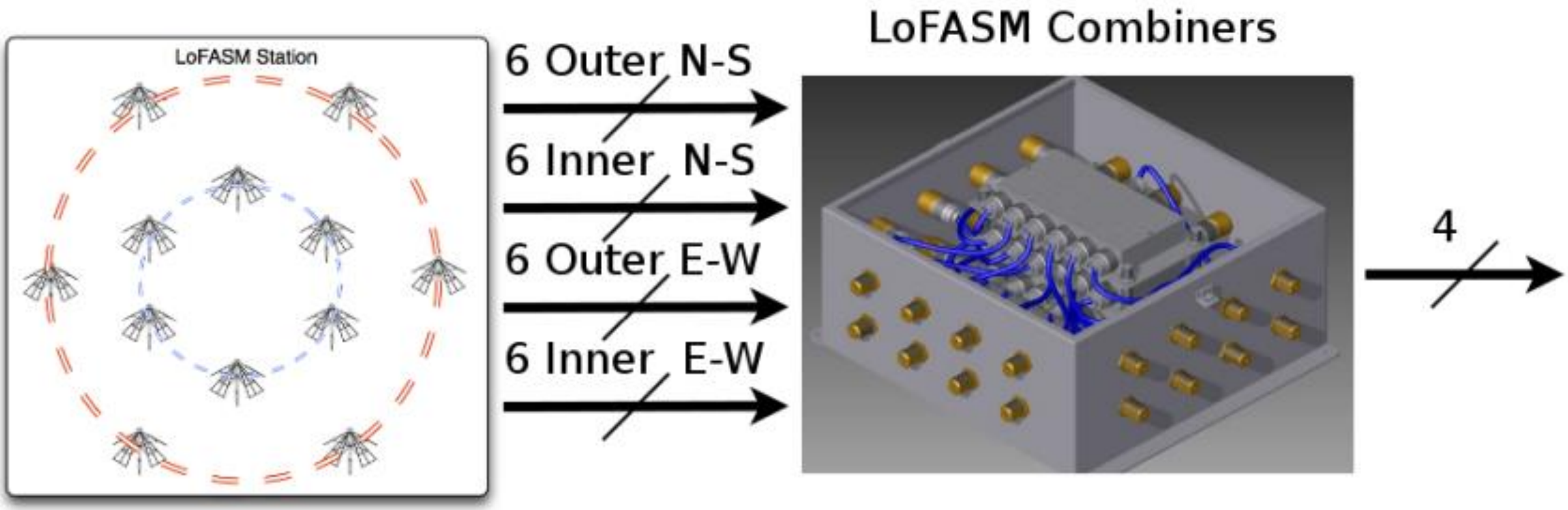


S Parameters of the LWA LNA




ROACH - Reconfigurable Open Architecture Computing Hardware
Watch later
Share
Watch on YouTube




LoFASM Station
6 Outer N-S
6 Inner N-S
6 Outer E-W
6 Inner E-W
LoFASM Combiners
4

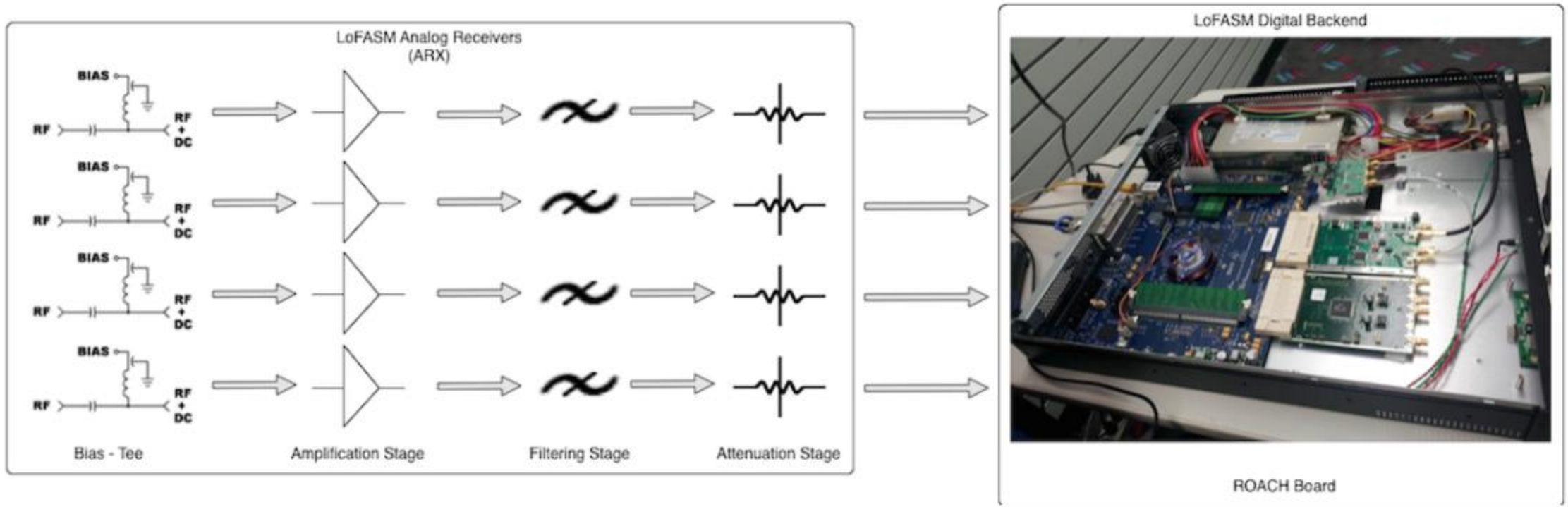


Figure 7: Flow chart portraying the second half of the signal path of a single LoFASM station. The four RF signals are operated on by the mARX and then sent to the LoCo system for digitization and processing.

The Deployable Low-Band Ionosphere and Transient Experiment

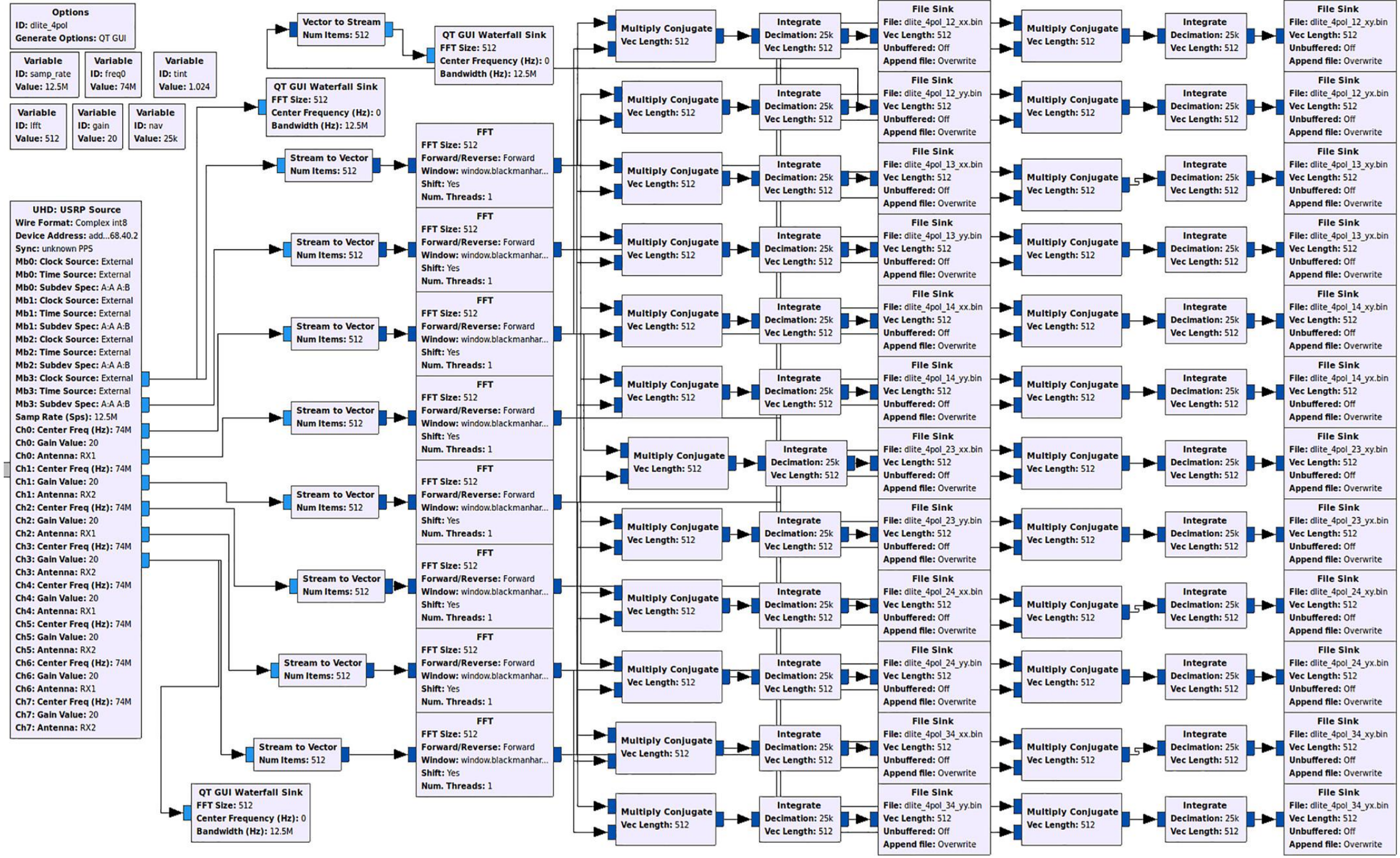
J. F. Helmboldt, B. B. Markowski, D. J. Bonanno, T. E. Clarke, J. Dowell, B. C. Hicks, N. E. Kassim, G. B. Taylor

First published: 28 June 2021 | https://doi.org/10.1029/2021RS007298 | Citations: 5

SECTIONS PDF TOOLS SHAR

Abstract

The Deployable Low-Band Ionosphere and Transient Experiment (DLITE) is a four-element interferometric radio telescope made from mostly commercial off-the-shelf parts to minimize costs and maximize ease of deployment. It operates in the high frequency and very high frequency (VHF) regimes, nominally in a 30–40 MHz band, but with good sensitivity (sky-noise dominated) in the 20–80 MHz range. Its configuration is optimized to probe ionospheric structure using the so-called “A-Team,” exceptionally bright sources of cosmic radio emission. Methods have been developed to track the apparent positions and intensities of A-Team sources without the need for beam forming to enable measurements of VHF scintillations as well as total electron content gradients. Time difference of arrival and frequency difference of arrival methods have been adapted for all-sky imaging to facilitate both statistical measurements of scintillation


Options
ID: dlite_4pol
Generate Options: QT GUI
Variable
ID: samp_rate
Value: 12.5M
Variable
ID: freq0
Value: 74M
Variable
ID: tint
Value: 1.024
Variable
ID: lfft
Value: 512
Variable
ID: gain
Value: 20
Variable
ID: nav
Value: 25k
UHD: USRP Source
Wire Format: Complex int8
Device Address: add...68.40.2
Sync: unknown PPS
Mb0: Clock Source: External
Mb0: Time Source: External
Mb0: Subdev Spec: A:A A:B
Mb1: Clock Source: External
Mb1: Time Source: External
Mb1: Subdev Spec: A:A A:B
Mb2: Clock Source: External
Mb2: Time Source: External
Mb2: Subdev Spec: A:A A:B
Mb3: Clock Source: External
Mb3: Time Source: External
Mb3: Subdev Spec: A:A A:B
Samp Rate (Sps): 12.5M
Ch0: Center Freq (Hz): 74M
Ch0: Gain Value: 20
Ch0: Antenna: RX1
Ch1: Center Freq (Hz): 74M
Ch1: Gain Value: 20
Ch1: Antenna: RX2
Ch2: Center Freq (Hz): 74M
Ch2: Gain Value: 20
Ch2: Antenna: RX1
Ch3: Center Freq (Hz): 74M
Ch3: Gain Value: 20
Ch3: Antenna: RX2
Ch4: Center Freq (Hz): 74M
Ch4: Gain Value: 20
Ch4: Antenna: RX1
Ch5: Center Freq (Hz): 74M
Ch5: Gain Value: 20
Ch5: Antenna: RX2
Ch6: Center Freq (Hz): 74M
Ch6: Gain Value: 20
Ch6: Antenna: RX1
Ch7: Center Freq (Hz): 74M
Ch7: Gain Value: 20
Ch7: Antenna: RX2
Vector to Stream
Num Items: 512
QT GUI Waterfall Sink
FFT Size: 512
Center Frequency (Hz): 0
Bandwidth (Hz): 12.5M
Stream to Vector
Num Items: 512
FFT
FFT Size: 512
Forward/Reverse: Forward
Window: window.blackmanhar...
Shift: Yes
Num. Threads: 1
Multiply Conjugate
Vec Length: 512
Integrate
Decimation: 25k
Vec Length: 512
File Sink
File: dlite_4pol_12_xx.bin
File: dlite_4pol_12_yy.bin
File: dlite_4pol_13_xx.bin
File: dlite_4pol_13_yy.bin
File: dlite_4pol_14_xx.bin
File: dlite_4pol_14_yy.bin
File: dlite_4pol_23_xx.bin
File: dlite_4pol_23_yy.bin
File: dlite_4pol_24_xx.bin
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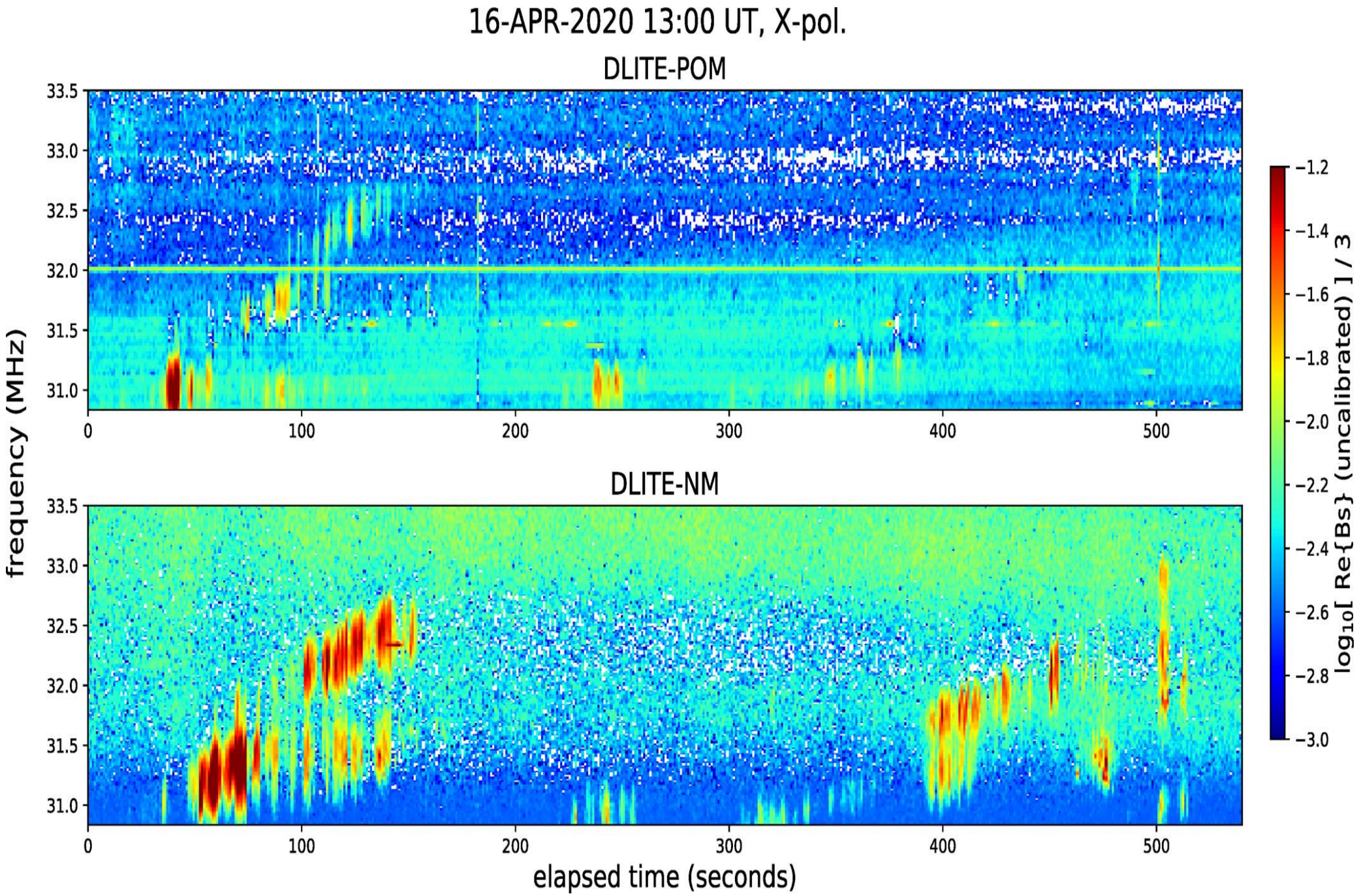
File: dlite_4pol_34_yy.bin
File: dlite_4pol_12_xy.bin
File: dlite_4pol_12_yx.bin
File: dlite_4pol_13_xy.bin
File: dlite_4pol_13_yx.bin
File: dlite_4pol_14_xy.bin
File: dlite_4pol_14_yx.bin
File: dlite_4pol_23_xy.bin
File: dlite_4pol_23_yx.bin
File: dlite_4pol_24_xy.bin
File: dlite_4pol_24_yx.bin
File: dlite_4pol_34_xy.bin
File: dlite_4pol_34_yx.bin
Unbuffered: Off
Append file: Overwrite


16-APR-2020 13:00 UT, X-pol.
DLITE-POM
DLITE-NM
frequency (MHz)
elapsed time (seconds)
log10[Re{Bs} (uncalibrated)] / 3
33.5
33.0
32.5
32.0
31.5
31.0
0
100
200
300
400
500
−1.2
−1.4
−1.6
−1.8
−2.0
−2.2
−2.4
−2.6
−2.8
−3.0

General Description:

Dlite-4000 is an integrated radio telescope with broadband performance capable of taking 10 MHz wide I/Q data recordings from eight antennas simultaneously and storing for later image formation. Data calibrated with GPS derived references and synchronized to local sidereal time.

The basic components of the system are state of the art software defined radios (SDRs) and state of the art single board computers (SBCs).

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Estimated Costs for Components:

LWA Antennas (4)	$2000.00
Bias T	$400.00
PIN switches	$500.00
GPS clock/synthesizer	$1000.00
RSPdx (8)	$1,600.00
Raspberry Pi 5 (8)	$1,223.00
Ethernet Hub	$100.00
PC	$2,000.00
1000m LMR400	$2,064.00
Total:	$10,887.00

Note:

All SBCs include power supplies and fans

Ground planes not included

Configuration 2 does not require PC lowering cost to $8,887.00

Matthew Bailes,
Duncan Lorimer &
Maura McLaughlin

for the discovery of fast radio bursts (FRBs).

CAUTION

Image: G. Hallinan

+

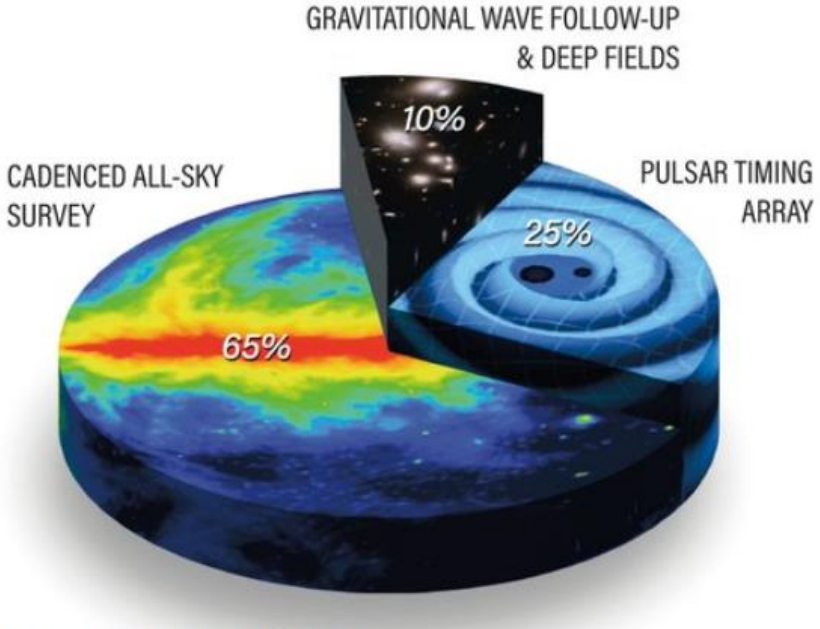
Ambient-temperature low noise amplifier (LNA) designed and built by the OVRO receiver lab, led by Sandy Weinreb, for the DSA-110, delivering 7K noise temperature. The receiver lab also designed and

+

Real-time, autonomous digital backend that performs full cross-correlation, self-calibration, beamforming of the core antennas, FRB searching, and voltage recording. All

200 pulsars monitored monthly

TIME ALLOCATION

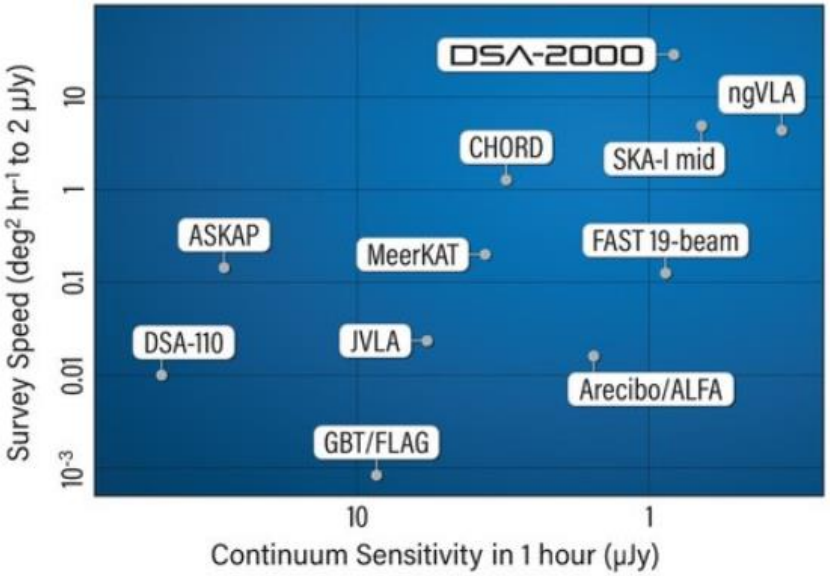


www.deepsynoptic.org

Pulsar timing fields (intermediate)	2000 deg² @ 200 nJy/beam
Deep fields	~30 deg² @ 100 nJy/beam

* Sensitivities assume 65% usable band and 80% usable time

SURVEY SPEED AND SENSITIVITY



福山植
NTHU

Bustling Universe Radio Survey Telescope in Taiwan

Current Status of BURSTT

Kai-Yang Lin 林凱揚
(ASIAA)

on behave of the
BURSTT Team

Team: ASIAA, NTU, NTHU, NCHU, NCUE

Why BURSTT?

FRBs can be anywhere anytime

A large **dipole array** for a wider FoV (no reflector)

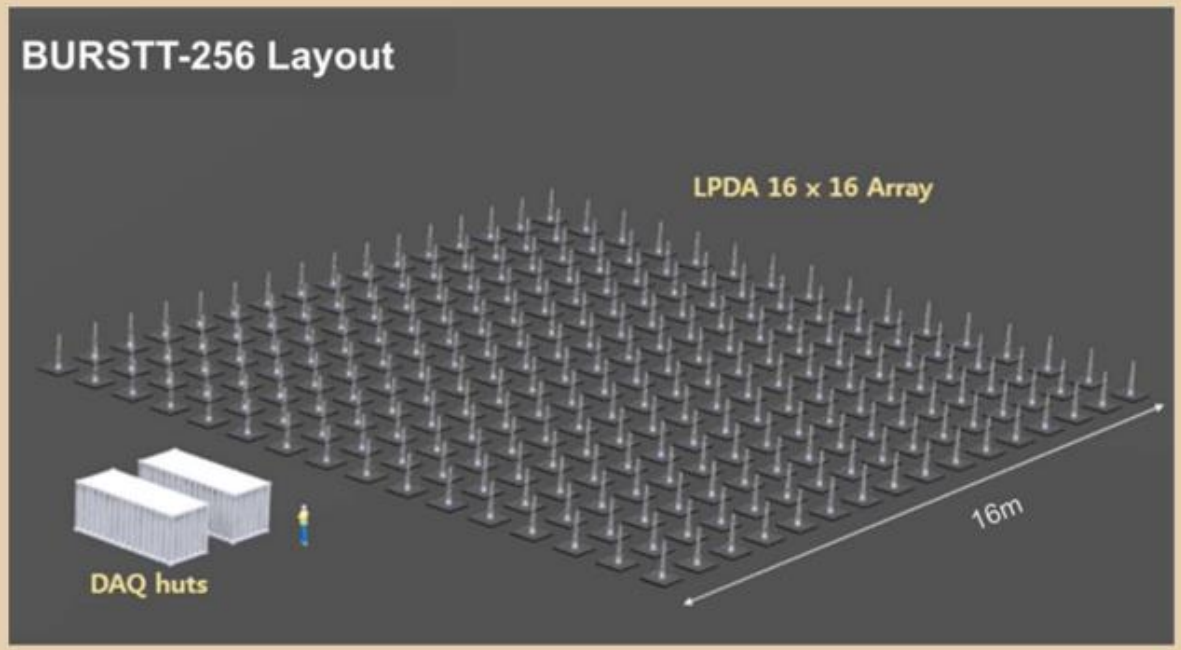
Localization with a single burst

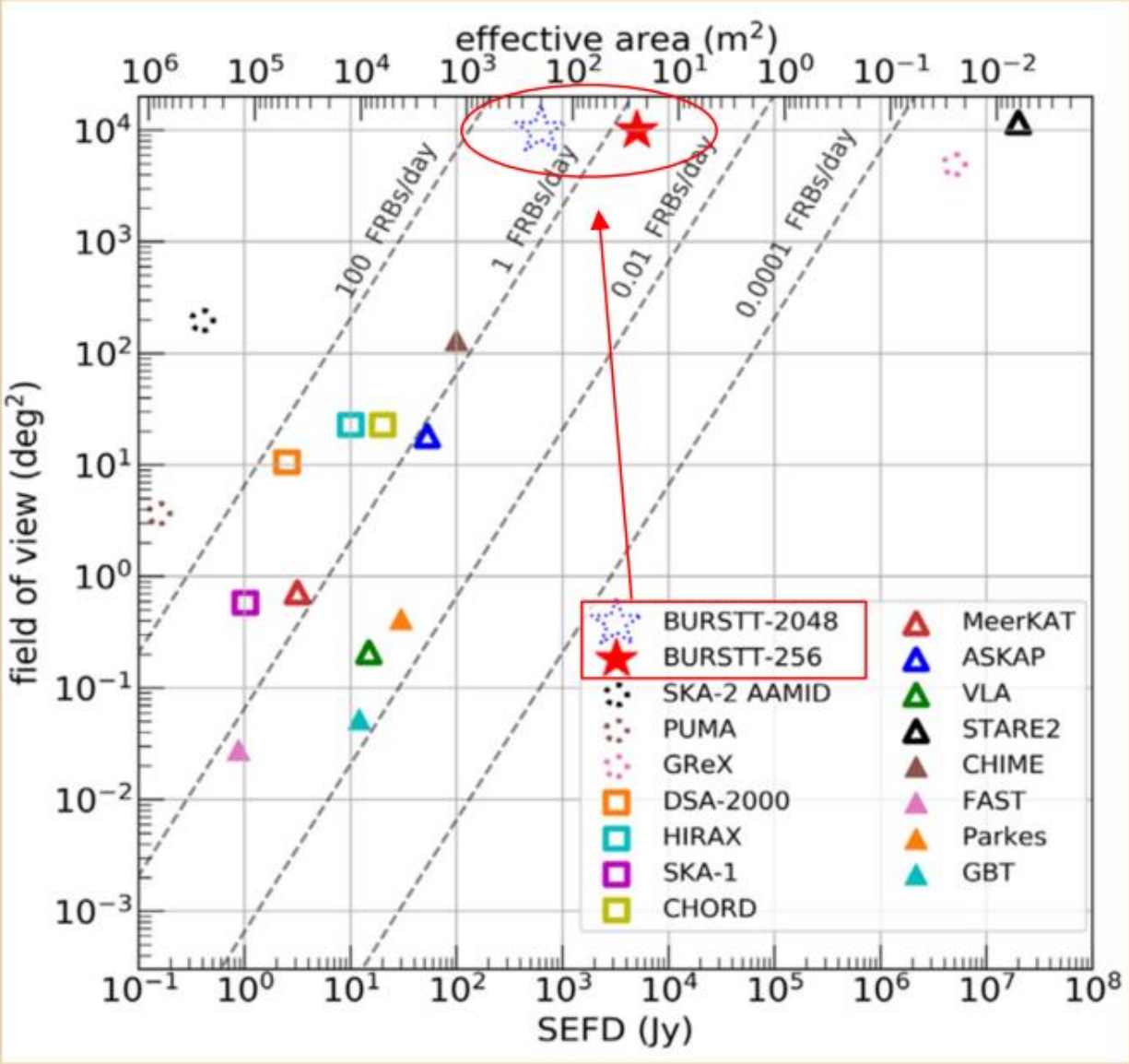
VLBI with **outrigger stations** from buffered voltage data

BURSTT feature

Hsiu-Hsien Lin et al. 2022, PASP, 134, 094106

- A wide-field (~10^4 sq.deg) array to detect FRB events
- VLBI localization to (1”) and better
- Detect and localize bright FRBs → near MW → best candidates for followup





Antenna design

- Log-periodic dipole array (LPDA) antennas for 3(4)00 - 800 MHz

Designed by ASIAA
(300 - 800 MHz)

A commercial antenna
(400 - 800 MHz)

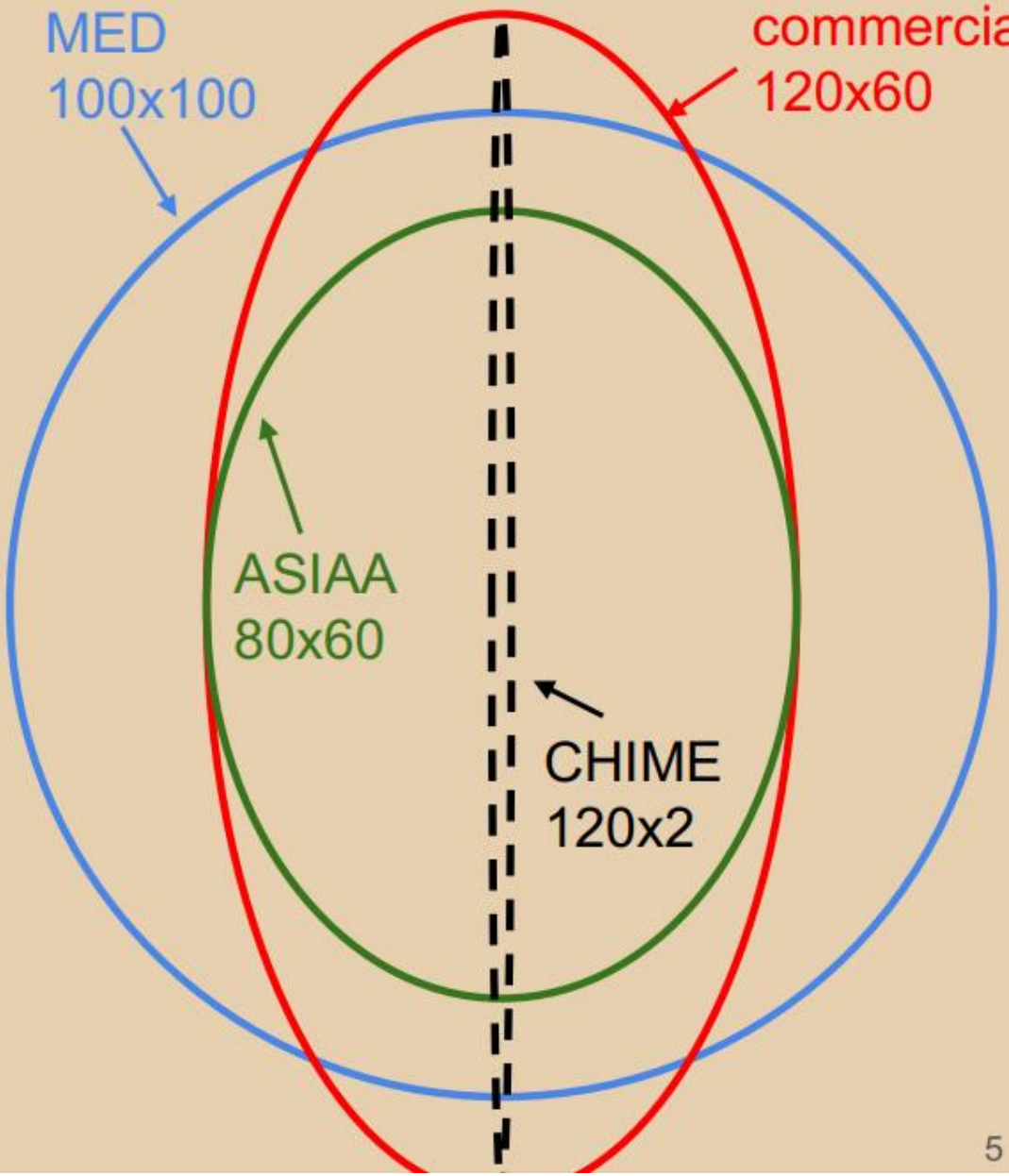
Designed by NTU

9dBi
300-800
MHz

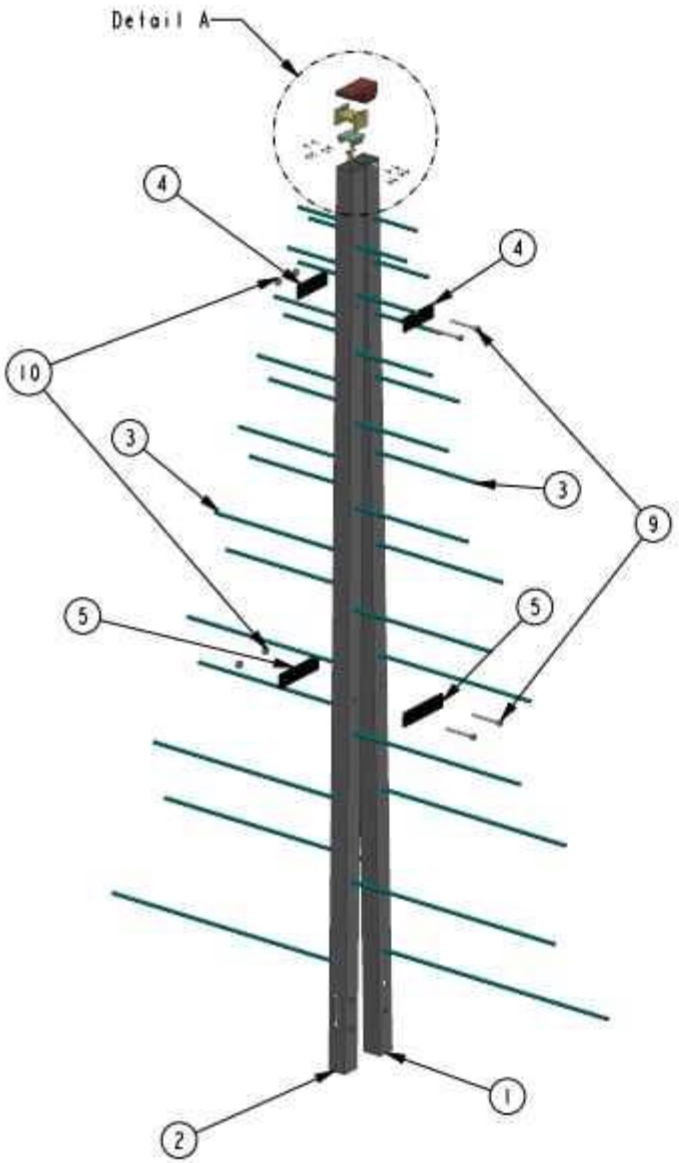
6dBi
400-
800MHz

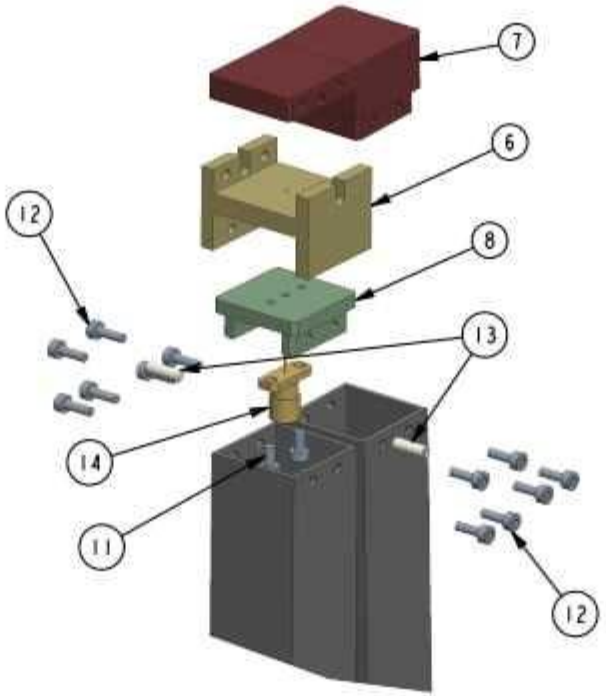
7dBi
300-800
MHz

Field of View (FoV)



REV	SYMBOL	DESCRIPTION	LOCATED	SIGN	DATE
A	-	FIRST RELEASE	-	PAI-AN CHEN	20230928
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-





Detail A(1.000)

No.	Item	Qty.
1	Rod 1 ss	1
2	Rod 2 ss	1
3	Dipole set	2
4	Holder 1	2
5	Holder 2	2
6	Teflon cover ss	1
7	Top cap v2 ss	1
8	Top cap 2 ss	1
9	M4 x 30	4
10	M4 Nuts	4
11	M2 x 4	2
12	M2 x 6	12
13	M2.5 x 8 stop screw	2
14	SMA connector	1

PROJECT			NAME	LPDA SS ASM		
DRN	PAI-AN CHEN	Sep-28-23	MATERIAL	-		
DSN	-	Sep-28-23	FINISH	-		
CKD	-	Sep-28-23	SCALE	1/1	DIM. IN	mm
APPD	TED HUANG	Sep-28-23	SHEET	1 OF 1	SHEET SIZE	A3

ACADEMIA SINICA

TOLERANCE CLASS	PERMISSIBLE DEVIATIONS (mm)					
LINEAR	0.5~3	>3~6	>6~30	>30~120	>120~400	>400
m	±0.05	±0.05	±0.1	±0.15	±0.2	±0.3
f	±0.1	±0.1	±0.2	±0.3	±0.5	±0.5
R & C	>0	>10~50	>50~120	>120~400	>400	
m	±1°	±30'	±20'	±10'	±5'	
f	±2°	±1°	±30'	±20'	±10'	
ANGULAR	0.5~3	>3~6	>6			
m	±0.2	±0.5	±1.0			
f	±0.4	±1.0	±2.0			

BURSTT Sites

100km → 1" @ 0.5m wavelength

Talk: S.H. Wang

Cape Fuguei

Beigan

220km

60km

Nantou

140km

Fushan

230km

Dongsha

650km

Green Island

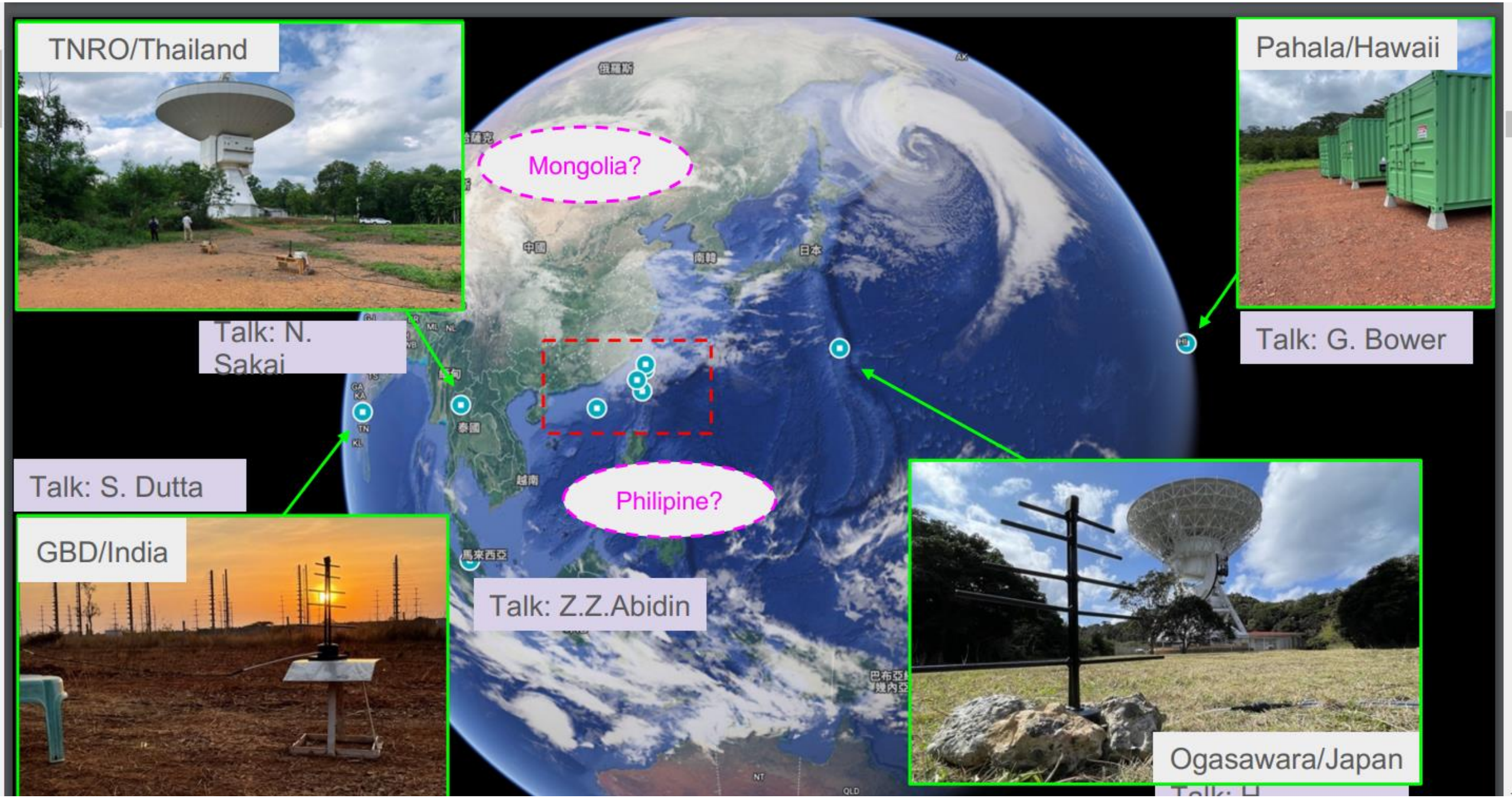
2000km
to Ogasawara

7800km
to Hawaii

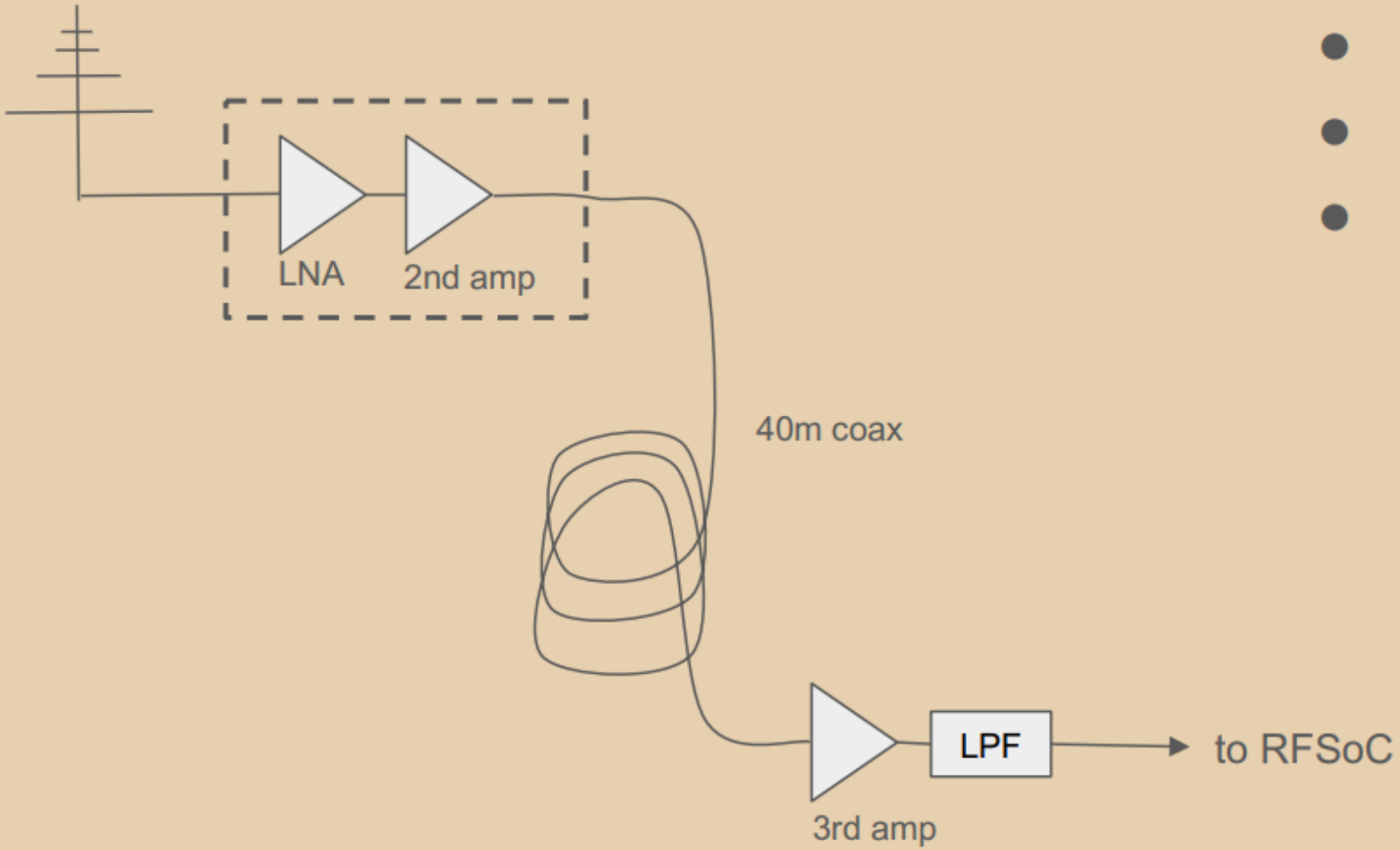
4600km
to India

2300km
to Thailand

1700km
to Taiping Is.


TNRO/Thailand
Talk: N. Sakai
Pahala/Hawaii
Talk: G. Bower
Mongolia?
Philipine?
Talk: S. Dutta
GBD/India
Talk: Z.Z.Abidin
Ogasawara/Japan

Frontend System

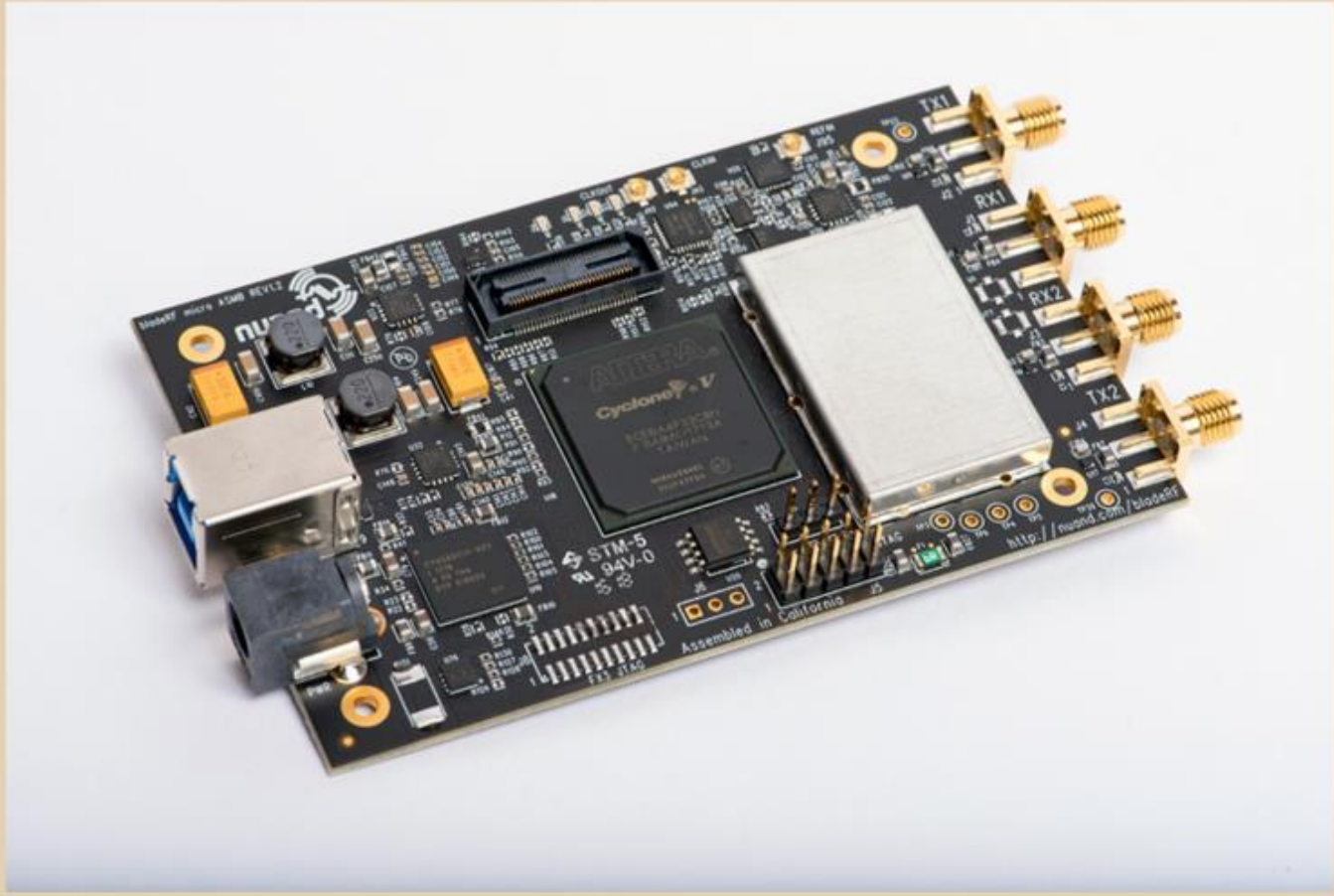


- T_{rx} ~ 35K (lab)
- $T_{gnd} + T_{MW}$ ~ 50K (estimate)
- T_{sys} = 80 -- 150 K (measured)
- T_{RFI} varies
  - reduces by beamforming
  - may be further suppressed with spatial filtering

Prototype SDR backend: bladeRF

software-defined radio

- 2T/**2R** Transceiver chip
- 12-bit ADC depth
  - 2-byte real + 2-byte imag sample
- 50MHz -- 6GHz range
  - digital downconversion (DDC)
- up to 40MS/s sampling / **40MHz** bandwidth (dual-channel)
  - 40MS/s*4bytes/S*2inp=320MB/s
- FPGA (default: bypass)
- USB3.0 connection to PC
  - 500MB/s data rate

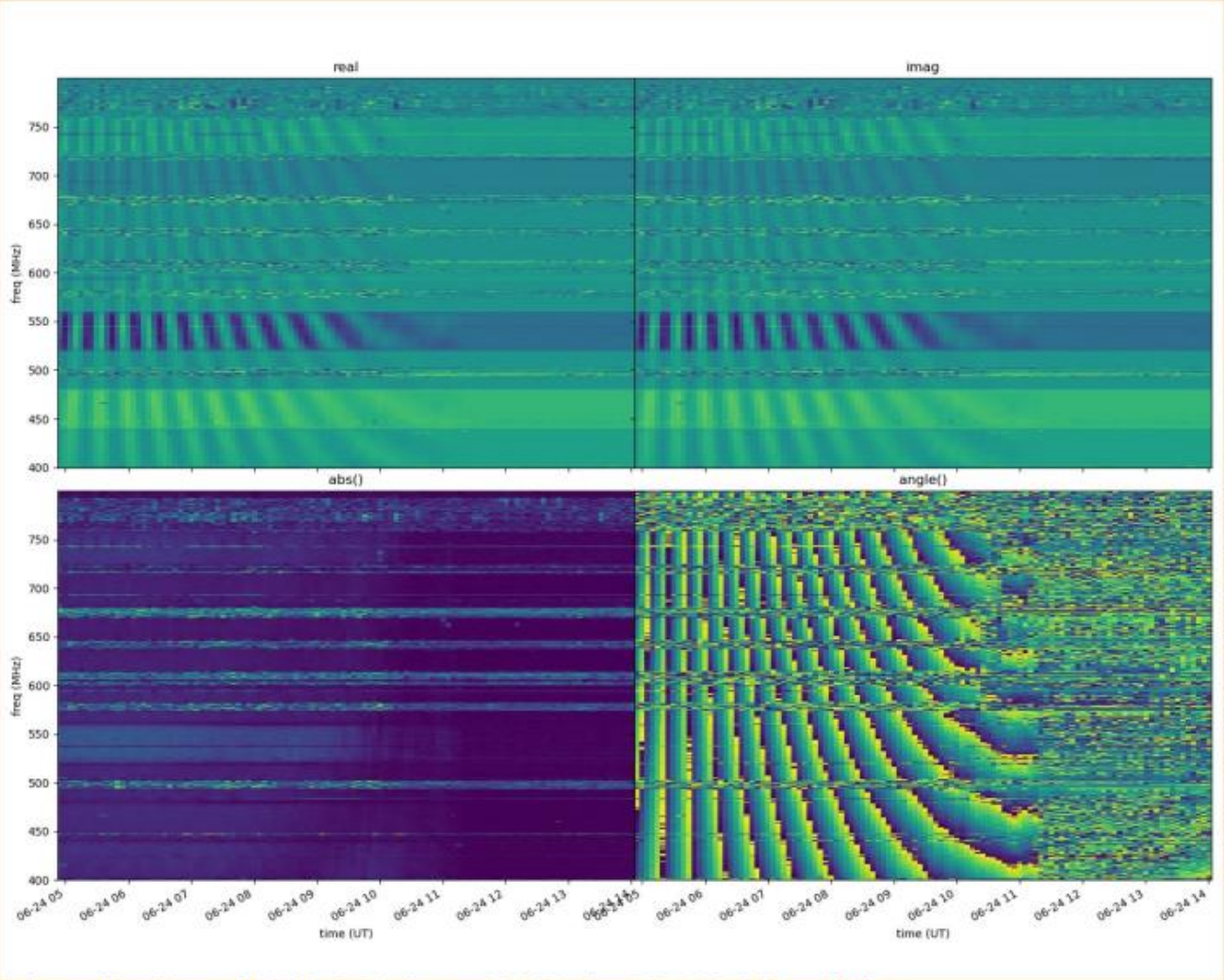


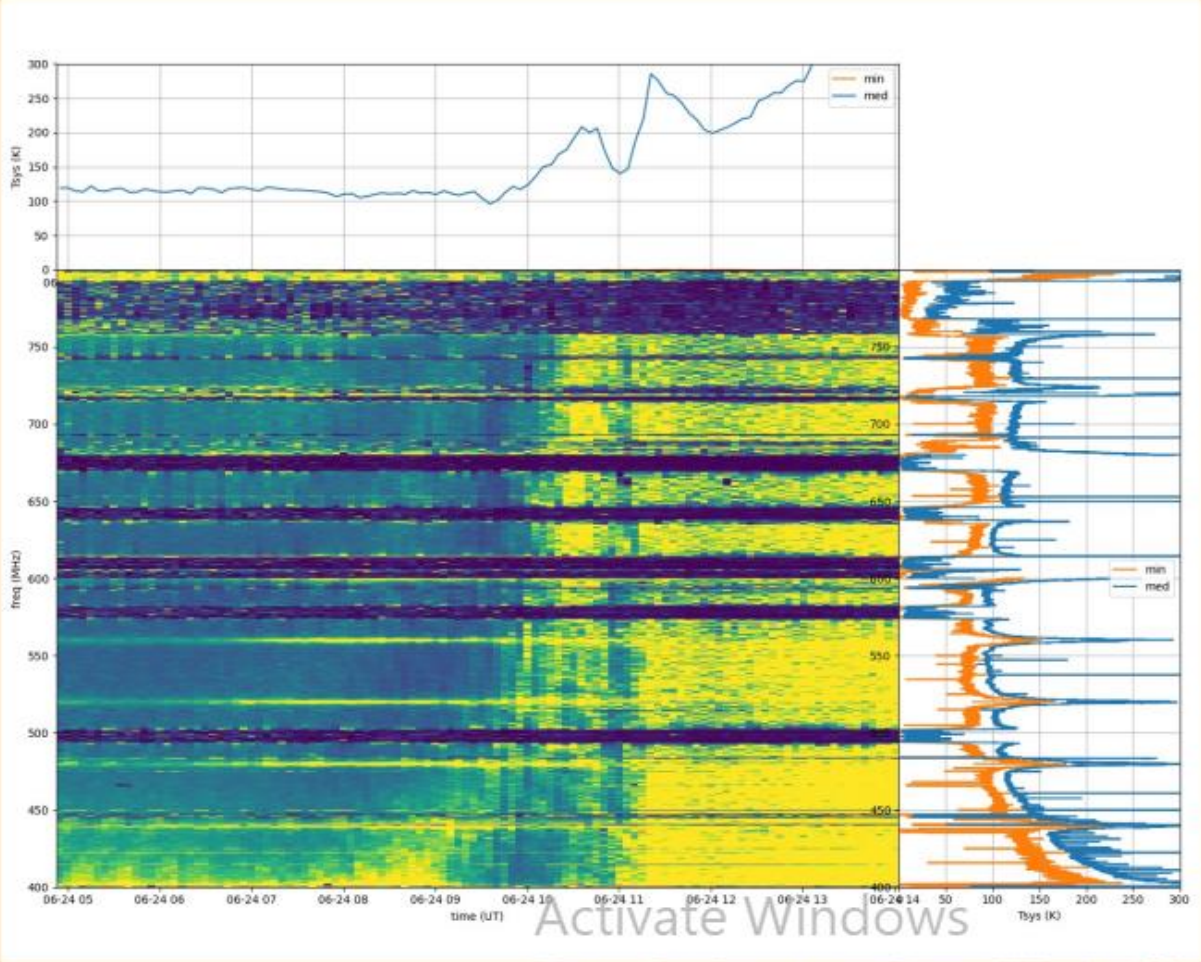
Ettus
Research
A National Instruments Company
USRP B210
70 MHz–6 GHz
ESD
SENSITIVE
RF A
TX/RX
RX2
RF B
RX2
TX/RX

Obs. of Sun

2-ant test with bladeRF in Thailand

SNR = F_sun / SEFD
(SEFD: system noise in Jy)
SEFD ∝ Tsys / (Gλ^2)

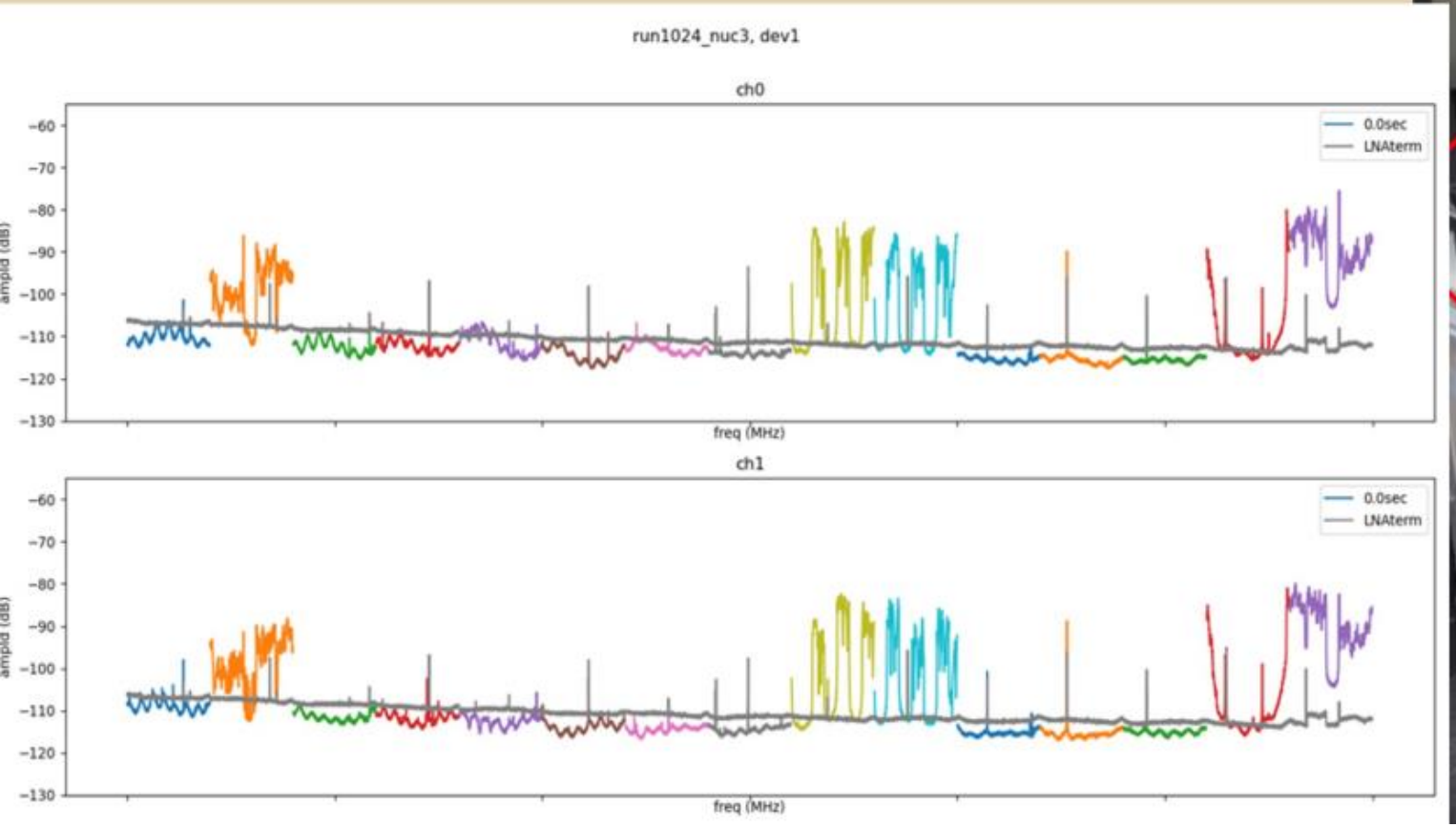


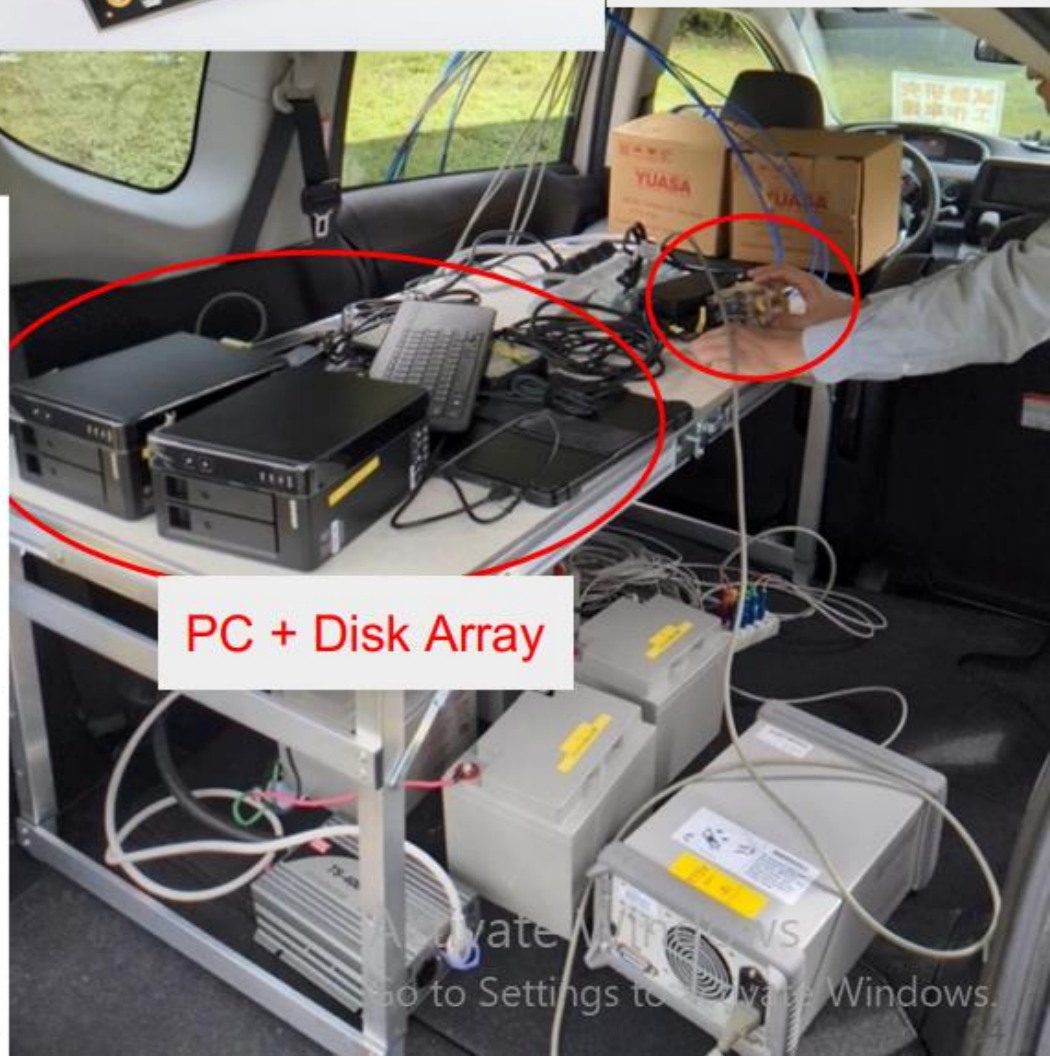


Detailed Cross-correlation Test

Software-defined radio (SDR):
bladeRF
2T/2R
40MHz BW

RFI in Fushan Site6





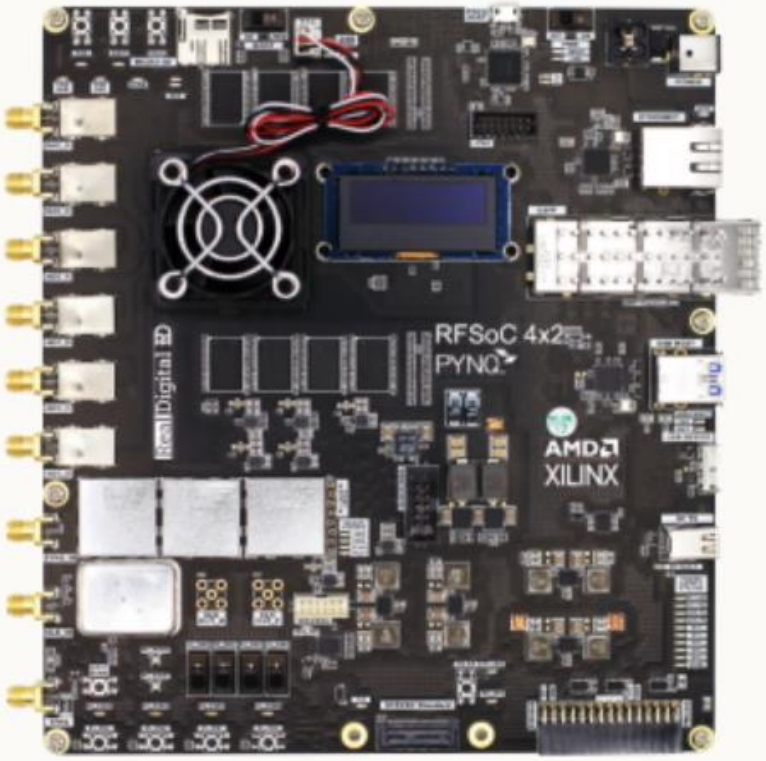
RFSoC: Xilinx Zynq UltraScale+ ZCU216

- input:
  - **16x** 14-bit 2.5Gsps ADC
- output:
  - SFP28 x 4 -- QSFP28 (100GbE)
- implementation
  - CASPER library
  - 400MHz clock (demux 4) → 1600Msps
  - **800MHz** bandwidth at 16-bit I and 16-bit Q
  - truncate to 4-bit I and 4-bit Q for 400--800MHz (52Gbps)

Activate Windows

New RFSoC 4x2

We are delighted to announce the launch of our new RFSoC 4x2 kits. The new kits greatly improve on the performance of the older RFSoC 2x2 kits, at the same $2,149 academic price.



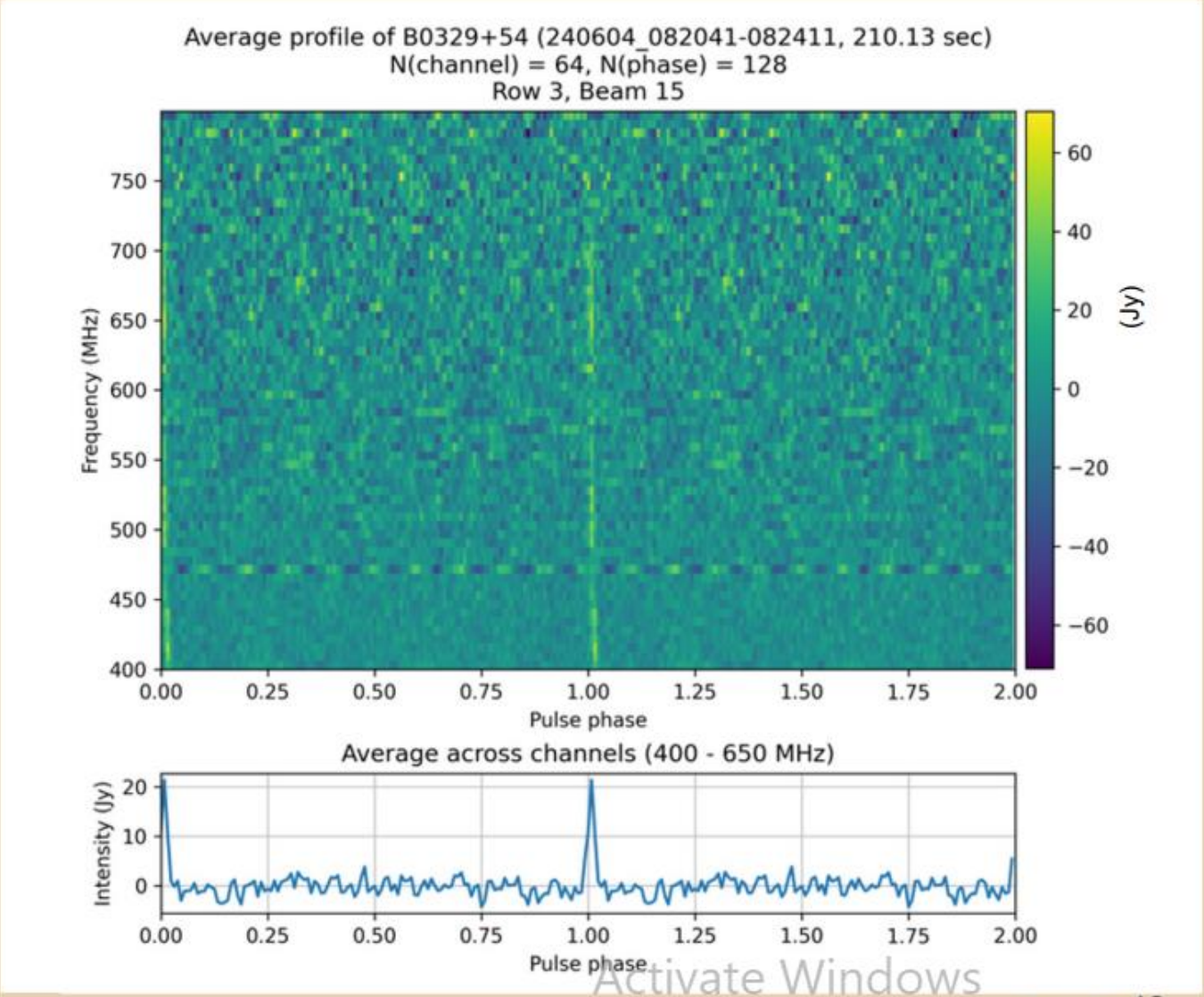
RFSoC 4x2 key features

- New **Gen 3** Zynq UltraScale+ RFSoC ZU48DR
- Faster **5GSPS** ADCs and **9.85GSPS** DACs
- Higher resolution **14-bit** ADCs
- Maximum RF input frequency increased to 6 GHz
- **Two** additional ADCs (four in total)
- New **high-speed QSFP28** interface supporting 4x25Gbps, 2x50Gbps or 1x100Gbps Ethernet
- New **OLED** display for improved boot-time status
- New battery-backed **real-time clock**
- Upgraded open-source **Overlays** including **Spectrum Analyzer** design supporting higher RFSoC Gen 3 ADC/DAC frequencies and wider bandwidth

For more details and purchasing information see the RFSoC 4x2 Overview.

First light: Pulsar B0329+54

- stacking: 2min
- clear detection of pulse up ot 700MHz
- measured at ~25Jy (prelim.)
  - vs. 40Jy from bf16
  - antenna attenuation
  - beam-center offset attenuation
  - under-estimated SEFD



Localization Challenges

Clock difference

Ionospheric delay

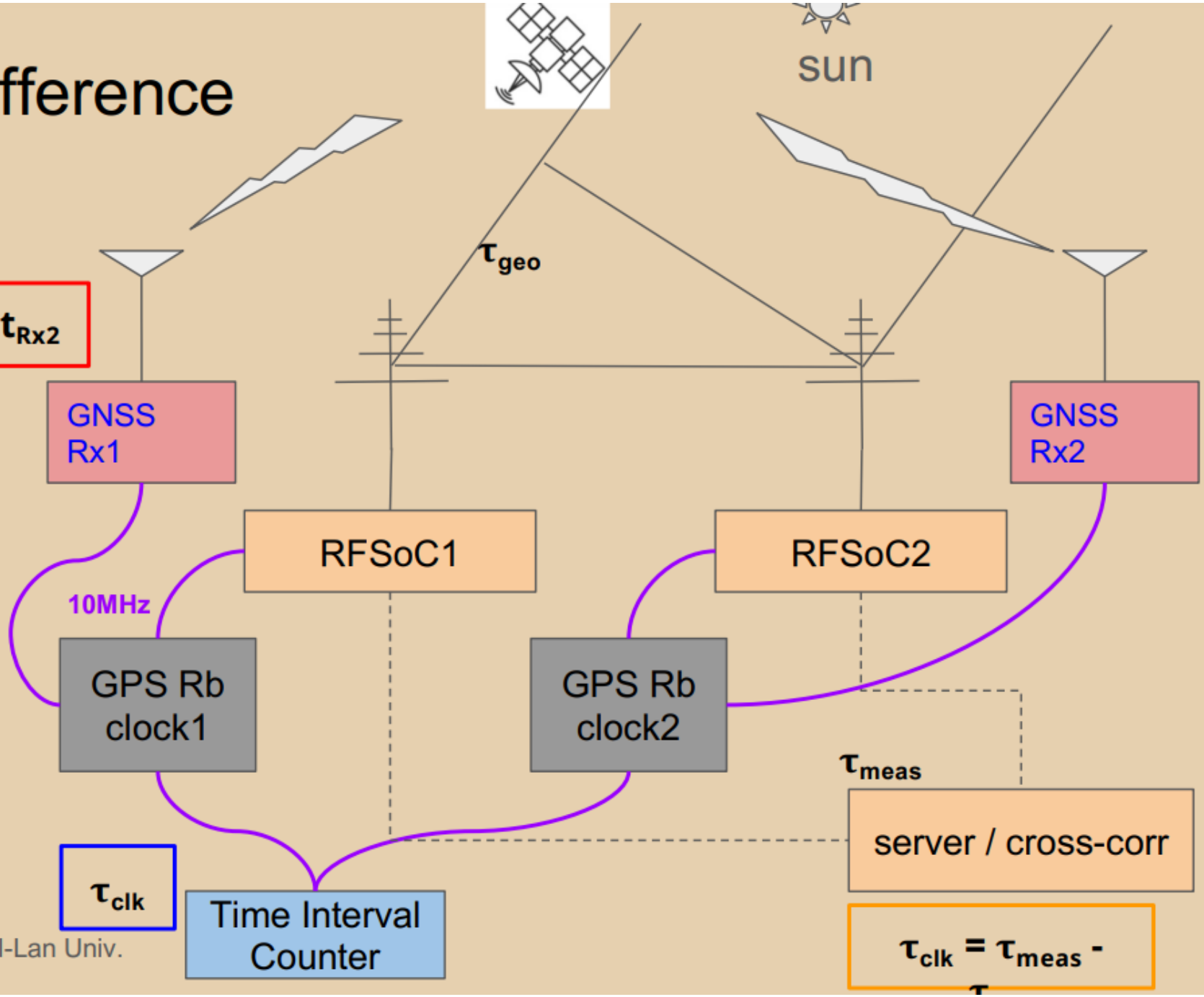
Clock system

- H-maser
  - bulky, very expensive, maintenance
  - very stable.
  - requires less frequent astrometry calibration
- atomic clock
  - more affordable for many outrigger stations
  - less stable
  - more frequent calibration:
    - GNSS satellites!

Measure Clock Difference

GNSS
ppp: precise
point positioning
-- receiver time
(offline process)

$\tau_{clk} = t_{Rx1} - t_{Rx2}$



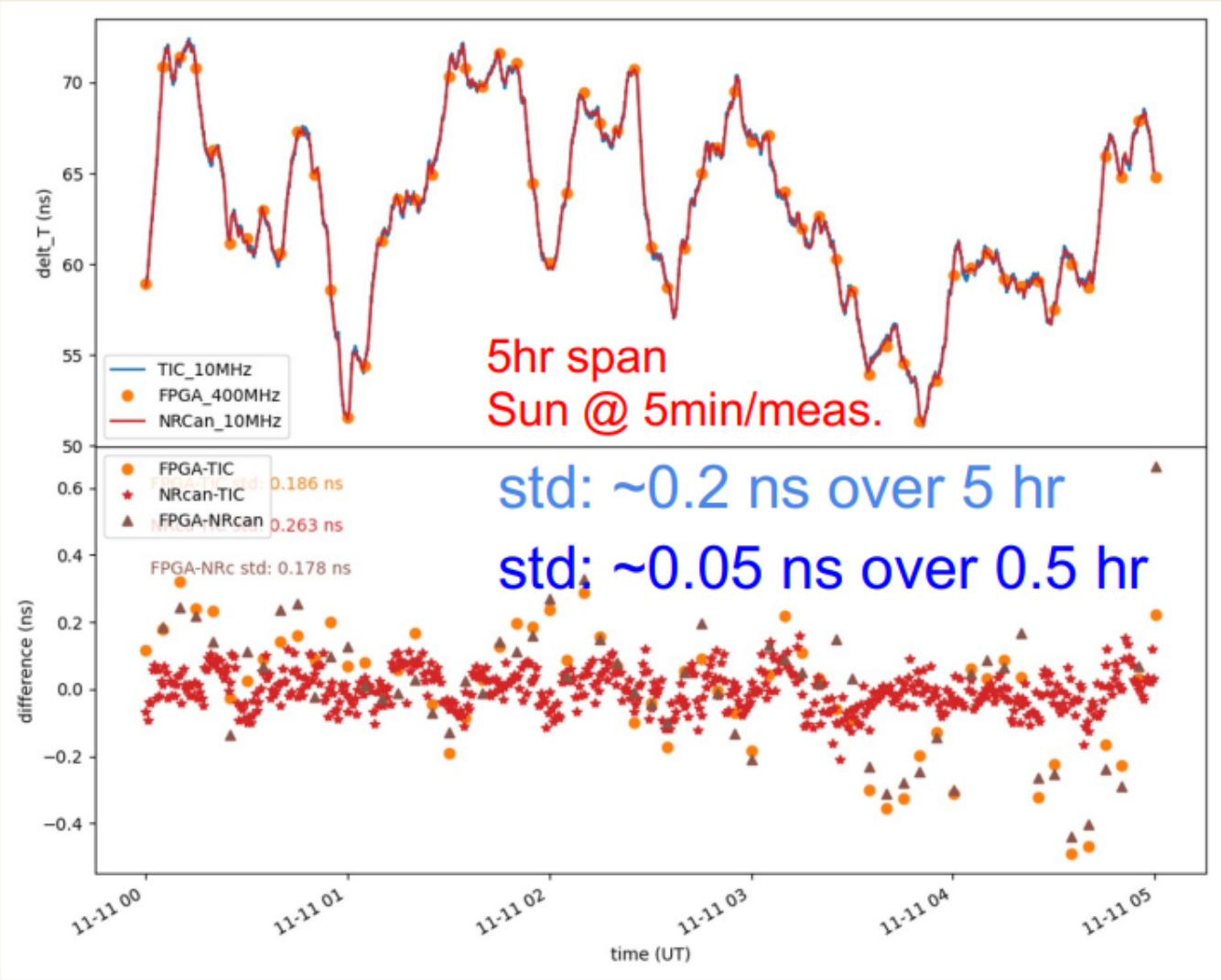
$\tau_{clk} = \tau_{meas} -$

Clock difference

- 10MHz ref dT by time interval counter
- 400MHz clock dT by Sun fringe
- 10MHz ref dT by GNSS-ppp

- 400MHz sampling → 2.5 ns
- 1” at 100km → 1.6 ns
- 0.1” at 1000km → 1.6ns

Timing goal: 0.2 ns



Verification test at the same site

White Rabbit in Radio Astronomy

Paul Boven
boven@jive.eu

JIVE
Joint Institute for VLBI
ERIC

SKA
SQUARE KILOMETRE ARRAY
SIGNAL AND DATA TRANSPORT

Asterics
Astronomy ESFRI & Research Infrastructure Cluster

CAMRAS
DWINGELOO TELESCOOP

White Rabbit in a Nutshell

WR: 1ns accuracy for distances up to 10 km
Standardized on 1000base-BX10 SFPs
(10km reach, bi-directional 1310nm / 1490nm)

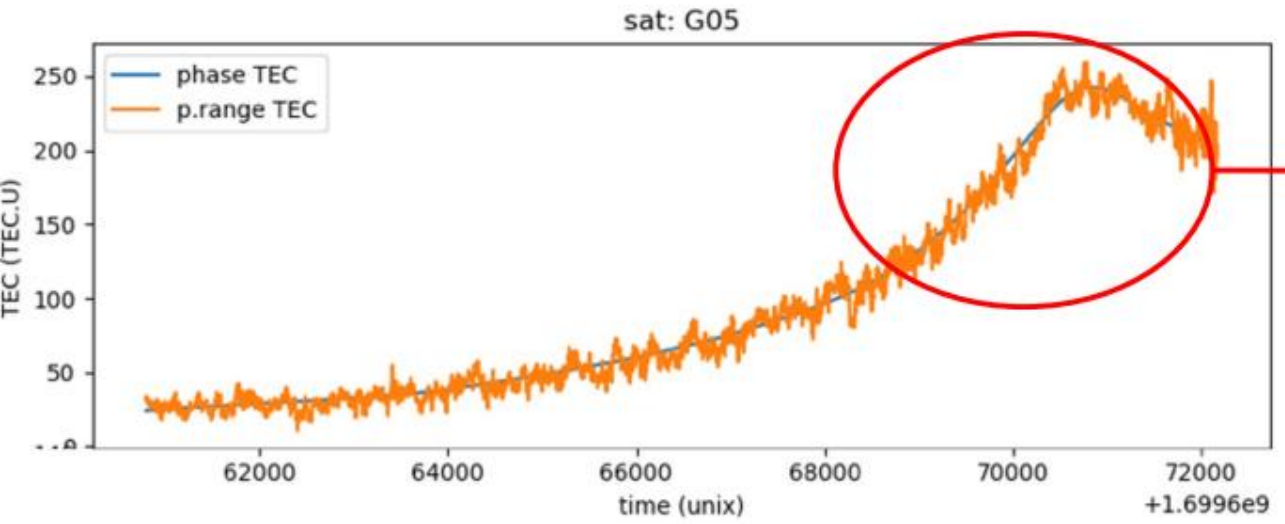
- Calibration:
  - Determine fixed delays (WR equipment, SFPs)
  - Determine differential delay $\alpha = (\delta_{MS}/\delta_{SM}) - 1$
- Operation:
  - Measure RTT, subtract fixed delays; gives cable round trip CRTT
  - Determine one way delay: CRTT * $(\alpha+1)/(\alpha+2)$ + applicable fixed delays
  - Advance local clock to be this much ahead of received timestamps

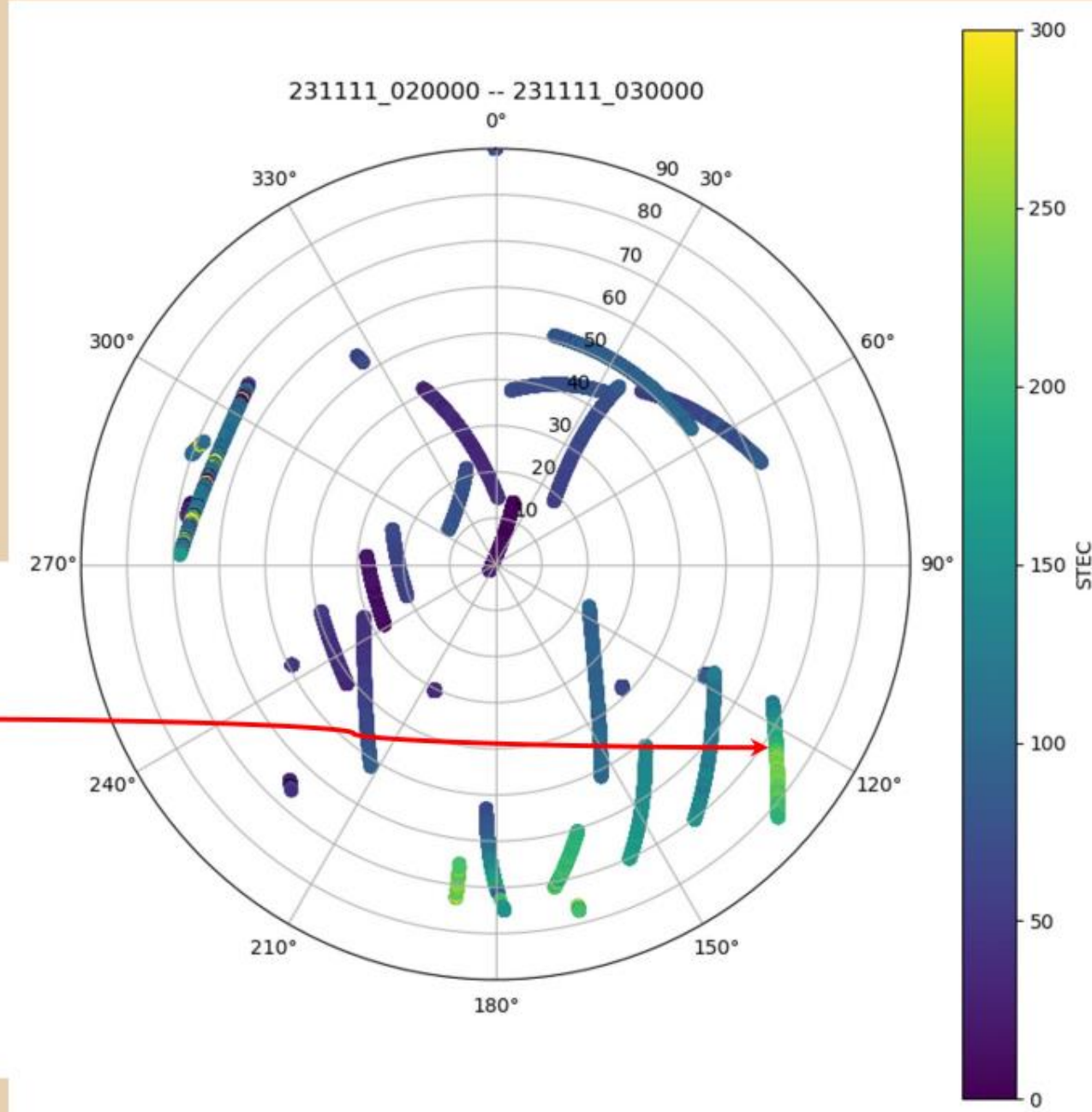
Multi-frequency GNSS

- Required for PPP
- Also returns a slant total electron content (TEC) toward each satellite at each measurement
  - electrons in the ionosphere causes dispersion delay
  - measure delay between signals at two frequencies
- Interpolation between GNSS sightlines toward any FRB?
  - 0.01 TEC unit accuracy required to achieve 0.2ns timing

Slant TEC vs. pointing

10:00--11:00





Fushan Main array

2024 Jan

Activate Windows
Go to Settings to activate Windows.