Tian Ma 65-m Radio Telescope

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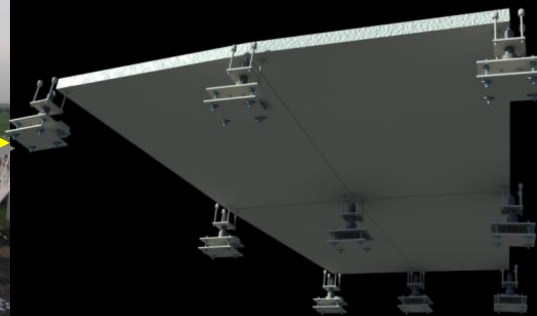
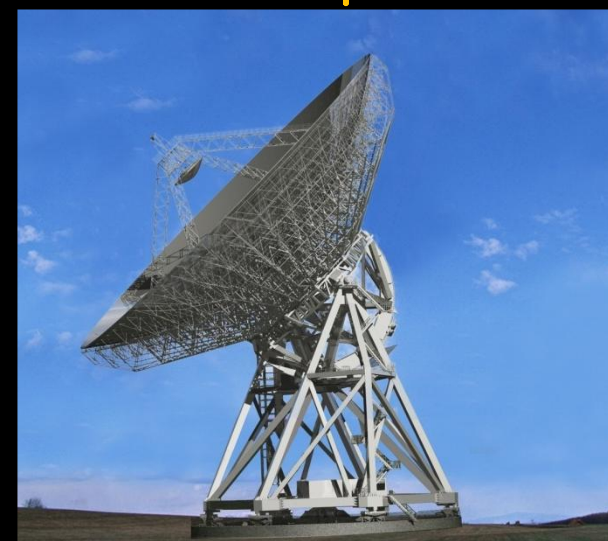
On behalf of the Shanghai 65m RT Team

The 3rd China-U.S. Workshop on Radio Astronomy Science and Technology: Emerging Opportunities
(May 19-21, 2014, Green Bank, West Virginia, USA)



Shanghai 65m Radio Telescope

- 65-m in diameter, fully steerable radio telescope
- Active surface system installed
- Covering 1 – 50 GHz with 8 bands
  - L(1.6GHz), S/X(2.3/8.4GHz) C(5GHz), Ku(15GHz), K(22GHz) Ka(30GHz), Q(43GHz)
- General-purpose (radio astronomy, single-dish, VLBI, geodynamics)



Funding Agencies:

- Chinese Academy of Sciences (CAS)
- Shanghai Municipality
- Chinese Lunar Exploration Project

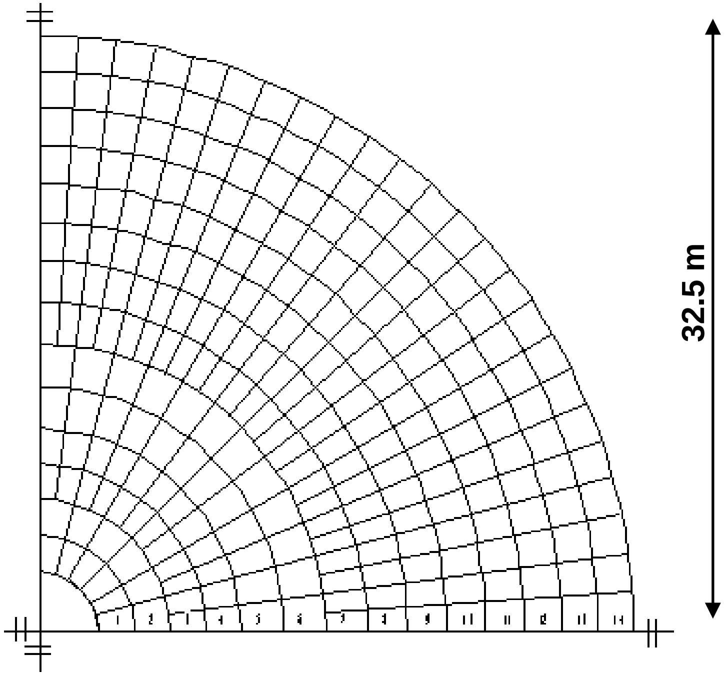
Project Timeline

- **2008: funded; contract to CETC54 for the antenna construction**
- **2009: complete design (international review panel); start manufacturing; foundation laying ceremony on December 29**
- **2010-11: site construction started on March 19, 2010; foundation completed; antenna construction (wheel-on-track, BUS, alidade, panels, …); active surface system (contract, design, fabrication, installation of actuators)**
- **2012-13: L/S/X and C band Rxs in place; first light on October 26, 2012 & inauguration 2 days later; start commissioning; got named (天马); participation in the Chinese Lunar Mission (ChangE); DIBAS installed & tested**
- **2014-15: on-site system testing; science observations at L/S/C/X bands; active surface tested; Ku/K/Ka/Q band commissioning; project accomplished**

Telescope Specs

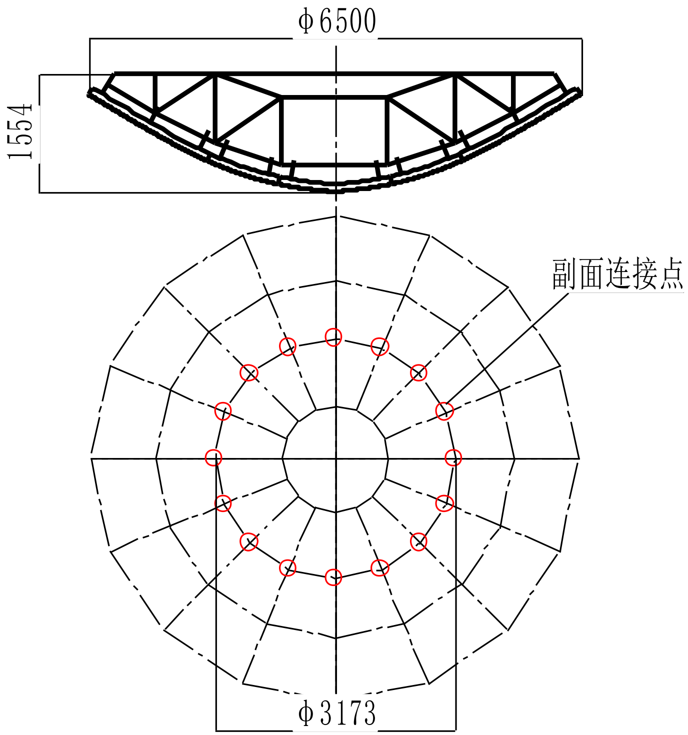
- Frequency coverage: 1 ~ 50 GHz
- Primary reflector adjustable with 1104 actuators
- Surface accuracy (nominal):
  - 0.6mm RMS (without active surface) -> 0.53mm RMS
  - 0.3mm RMS (with active surface)
- Aperture Efficiency:
  - L/S/C > 60%, X > 55%, Ku > 40%, K > 20%
  - Ka > 50%, Q > 45% (with active surface)
- Pointing accuracy:
  - 3 arcsec (wind < 4m/s) [c.f. beam ~ 22 arcsec @43 GHz]
  - 10 arcsec (wind < 10m/s)
  - 30 arcsec (wind < 20m/s) -> 14”
- Elevation limits: 5~90 degree
- Slew rates: 0.5 degree/s (azimuth), 0.3 degree/s (elevation)

Primary & Secondary Reflectors



Primary

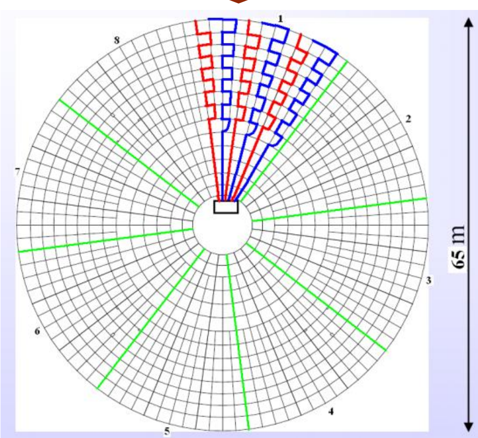
- 1008 aluminum panels - 14 rings
- Measured RMS of individual panels: 0.1mm (1-12 rings), 0.13mm (13-14 rings)

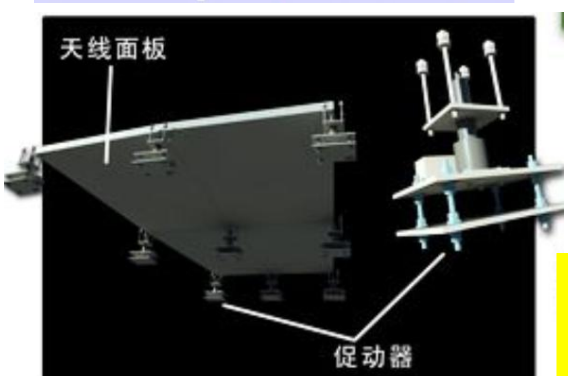


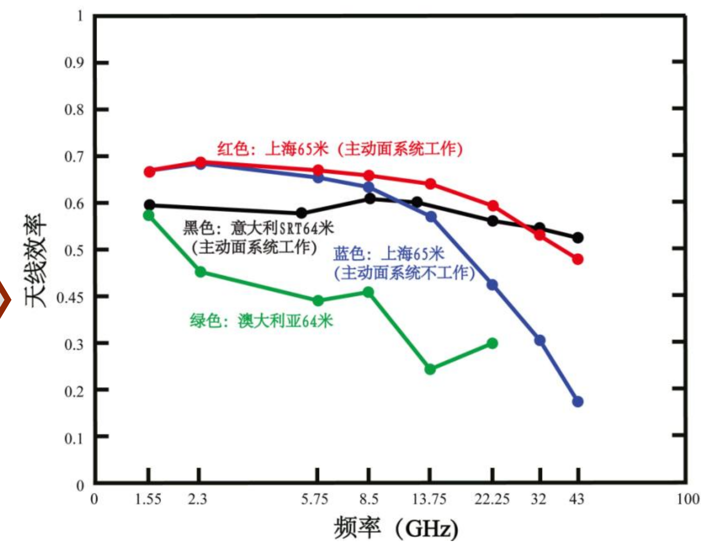
Secondary

- 25 aluminum honeycomb panles – 3 rings
- Measured RMS of individual panels: 50 μm
- Overall RMS: 0.1 mm

- Compensate (repeatable) gravitational deformations, to maintain the nominal shape of the primary reflector (to improve the efficiency at high freq)
- Work on the USA GBT 100-m and Italy Noto 32-m (SRT 64-m)







Active Surface Control System

The Actuators (1104)

±0.015mm/30mm
0.36mm/s
≦13kg
-10 ~ 60℃
20 yrs

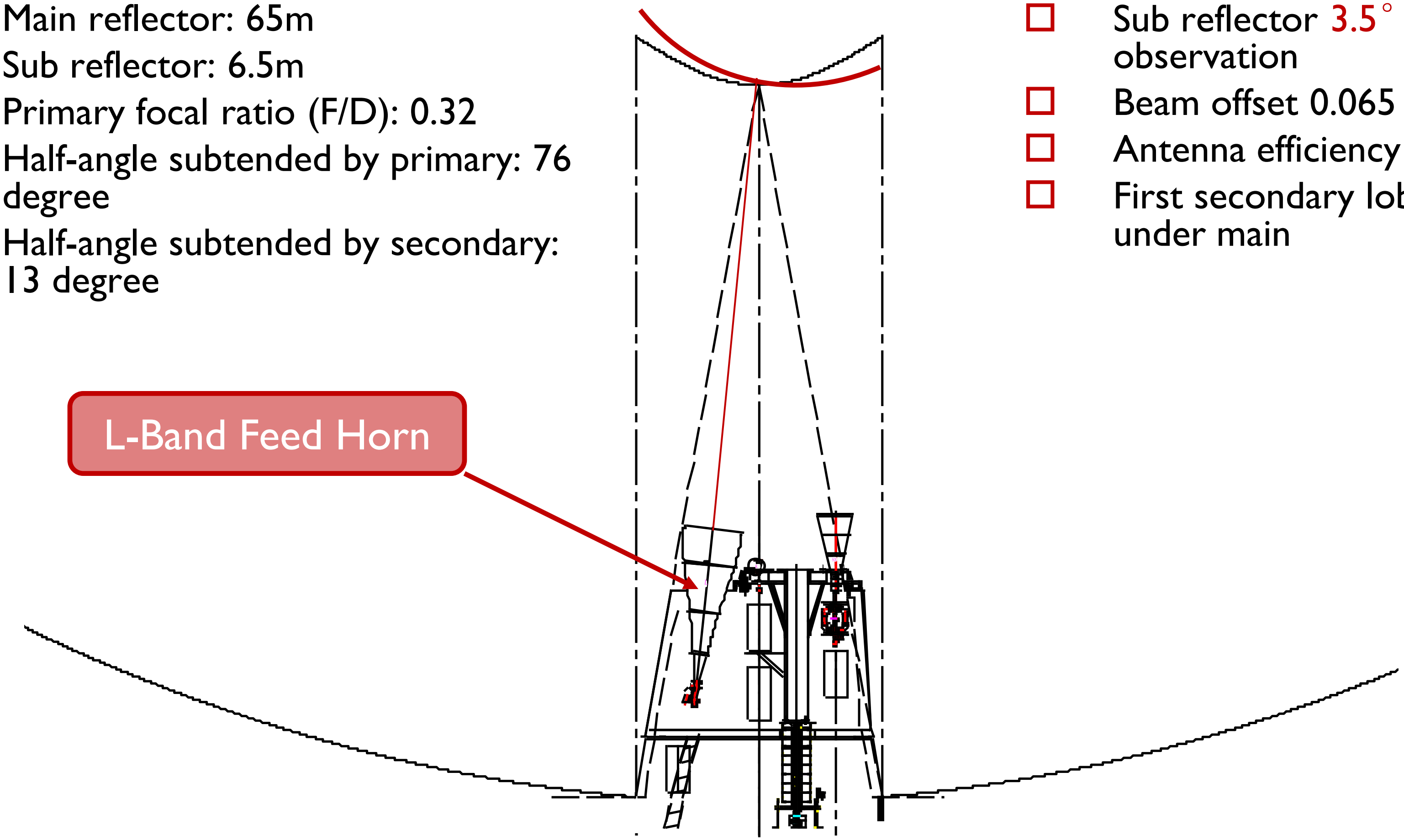
Antenna Microwave Optics

- Antenna Style: Shaped Cassegrain
- Main reflector: 65m
- Sub reflector: 6.5m
- Primary focal ratio (F/D): 0.32
- Half-angle subtended by primary: 76 degree
- Half-angle subtended by secondary: 13 degree

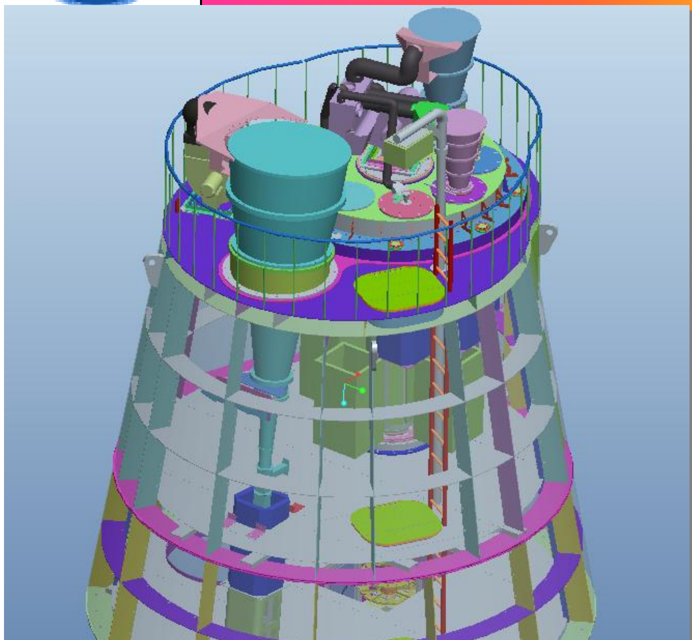
L-Band Optics

- L-band feed off focus mount
- Sub reflector 3.5° rotated for observation
- Beam offset 0.065 degree
- Antenna efficiency 55%
- First secondary lobes 18 dB under main

L-Band Feed Horn



Receiver cabin



Receiver specs

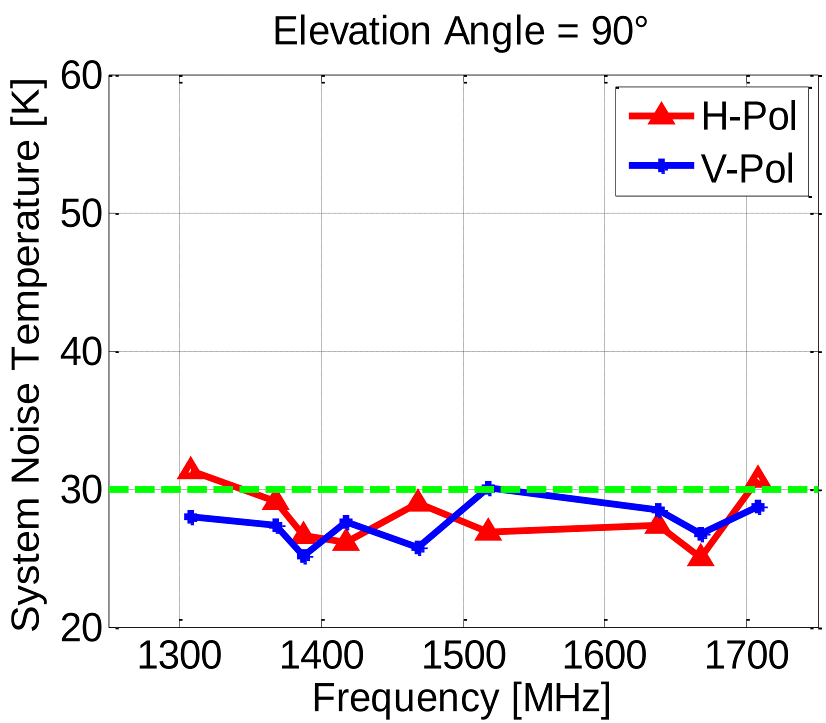
Band	"L"	"S"	"C"	"X"	"Ku"	"K"	"Ka"	"Q"
Wavelength (cm)	21/18	13	6/5	3.6	2/2.5	1.3	0.9	0.7
Freq range (GHz)	1.25-1.75	2.2-2.4	4-8	8.2-9.0	12-18	18.0-26.5	30-34	35-50
Freq low (GHz)	1.25	2.2	4	8.2	12	18	30	35
Freq high (GHz)	1.75	2.4	8	9	18	26.5	34	50
BW (GHz)	0.5	0.2	4	0.8	6	8.5	4	15
BW/CF (%)	33	9	67	9	40	38	13	35
Freq high/low	1.4	1.1	2.0	1.1	1.5	1.5	1.1	1.4
FWHP@CF (")	647.4	422.2	161.8	112.9	64.7	43.6	30.3	22.8
T(Sky) (K)	12	12	10	10	12	25	13	26
T(Rx) (K)	14	21	12	22	15	35	30	40
T(Sys) (K)	26	33	22	32	27	60	43	66
Efficiency	55%	60%	60%	55%	55%	50%	50%	50%
DPFU (K/Jy)	0.66	0.72	0.72	0.66	0.66	0.60	0.60	0.60
SEFD (Jy)	39	46	30	48	41	100	72	110
Sensitivity (mJy) 128MHz BW/10min	0.142	0.165	0.110	0.175	0.147	0.360	0.258	0.396
Sensitivity (mJy) full BW/10min	0.072	0.132	0.020	0.070	0.022	0.044	0.046	0.037
Feed Type	Compact	Conical	Conical	Conical	Conical	Conical	Conical	Conical
Polarization	Lin & Circ	Dual Circ	Dual Circ	Dual Circ	Dual Circ	Dual Circ	Dual Circ	Dual Circ
Refrigerator	1020	1020	350	1020	350	1020	1020	350
Structure	Single Pixel	Dual Band	Single Pixel	Dual Band	Single Pixel	Dual Pixels	Dual Band	Dual Pixels
Status	Installed May 2013	Installed Dec 2012	Installed May 2013	Installed Dec 2012	Building Sep 2014	Building Oct 2015	Building Dec 2014	Building Dec 2015

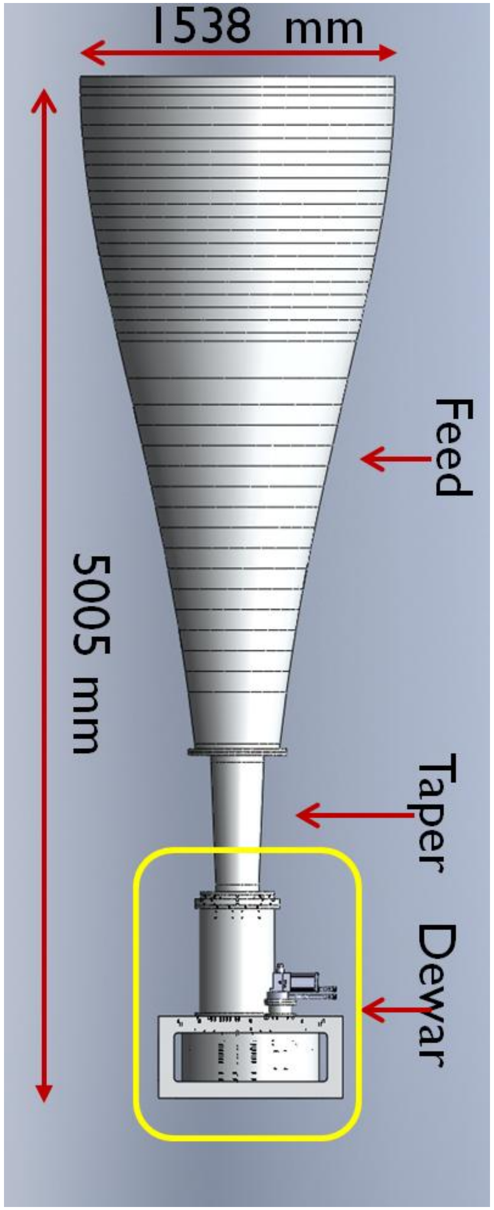
1) Tsky is EVLA value.
2) Trx is maximum value.

opportunity for mJy science

L-band receiver

- **Features**
  - 500MHz BW
  - Self made cooled OMT & LNA
  - Φ270 mm microwave & vacuum window
  - Linear & circular polarization



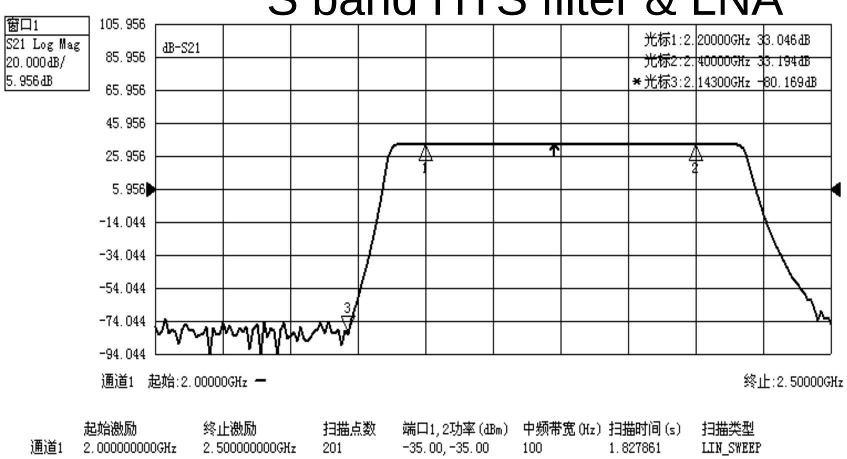


S/X-band receiver

- **Features**

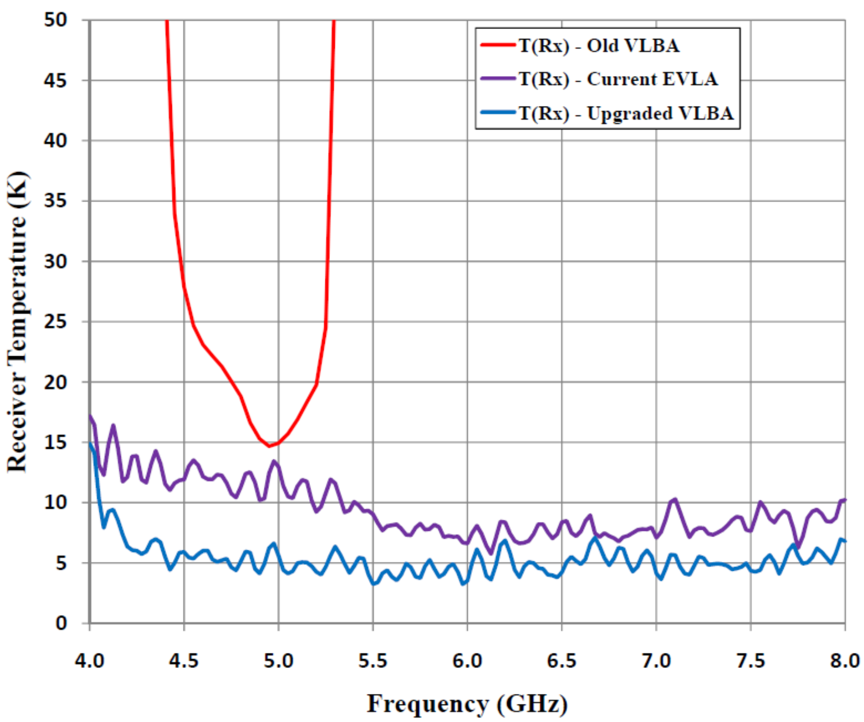
- Dual band & dual polarization
- Self made X-band cooled polarizer
- S-band HTS filter
- Tcal, 50% & 5% Tsys, periodically switching mode
- MTBF 10000h, MTTR 6h
- Astronomy & geodesy research applications

S band HTS filter & LNA



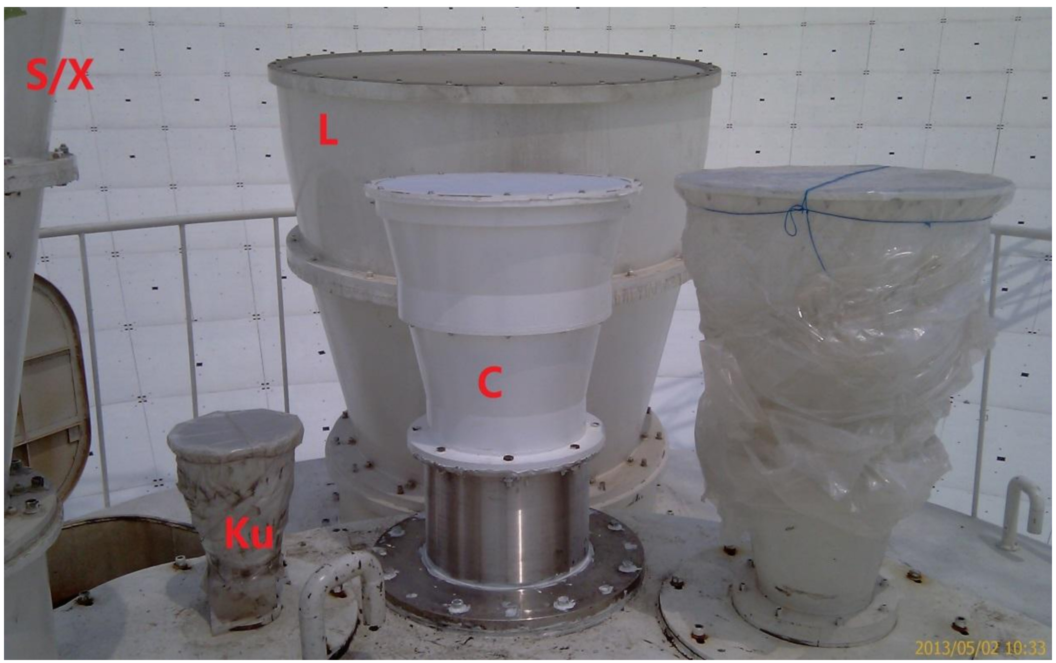
C-band receiver

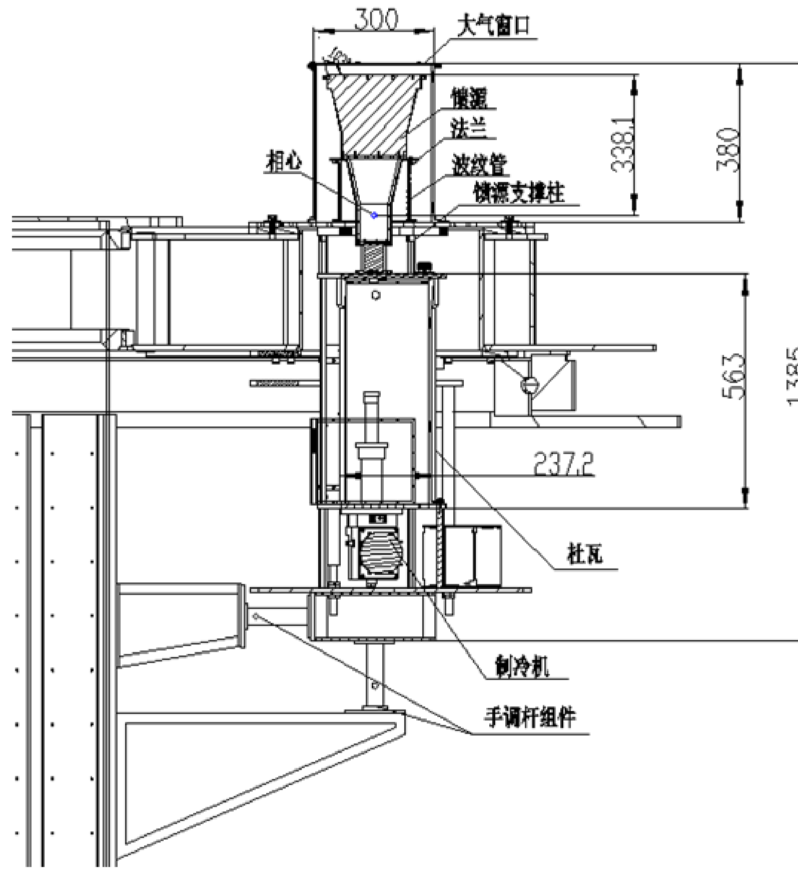
- **Features**
  - Upgraded VLBA structure
  - 4-8GHz BW, 5cm and 6cm observation



Ku-band receiver

- **Features**
  - WR62 waveguide band, 12-18GHz
  - Trx<15K including feed and radom

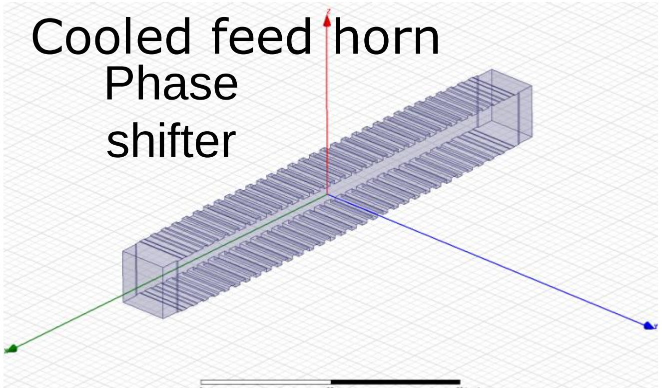




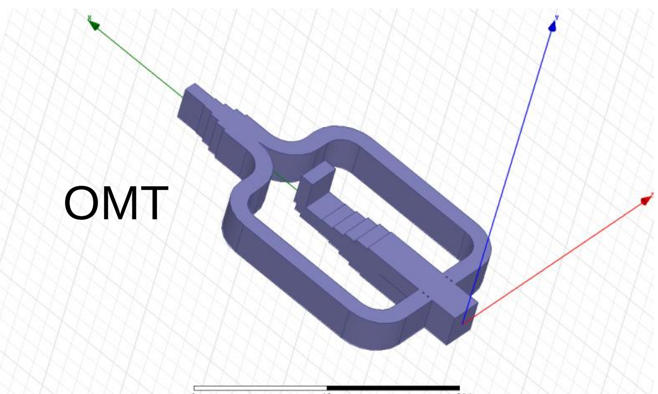
(2-pixel) K-band receiver

- **Features**
  - WR42 waveguide band, 18-26.5GHz
  - Dual-beam nodding observation
  - Cooled feed horn

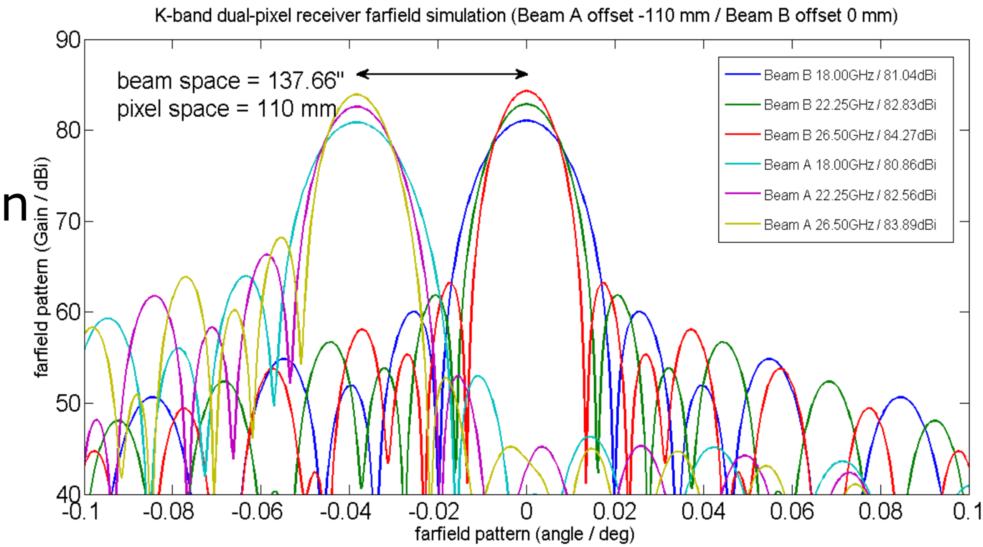
Phase shifter

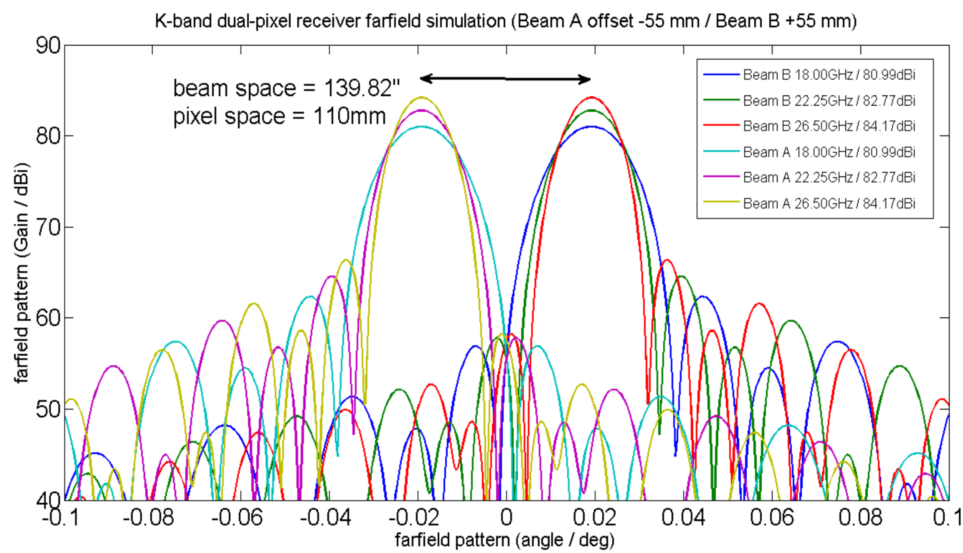


OMT

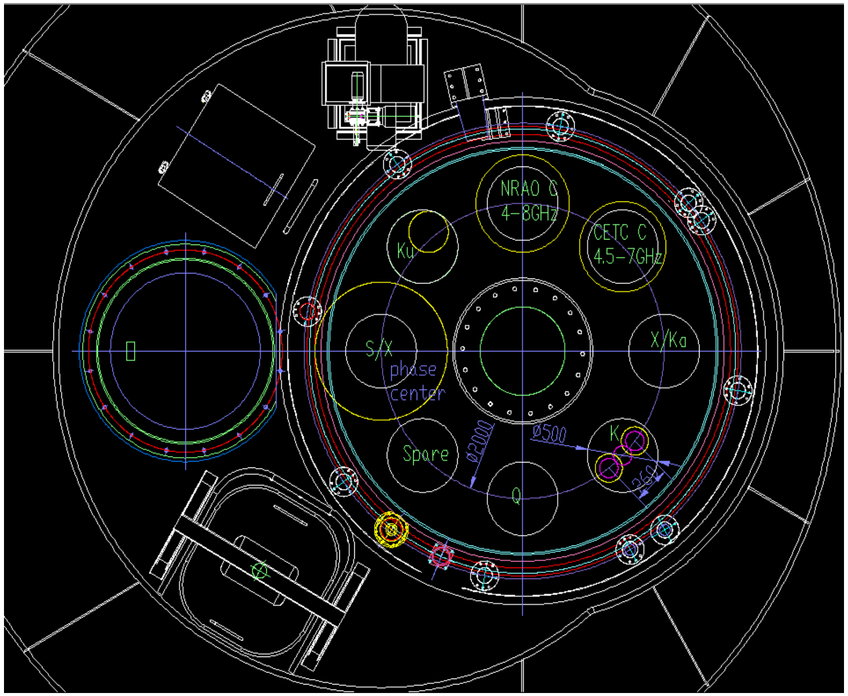


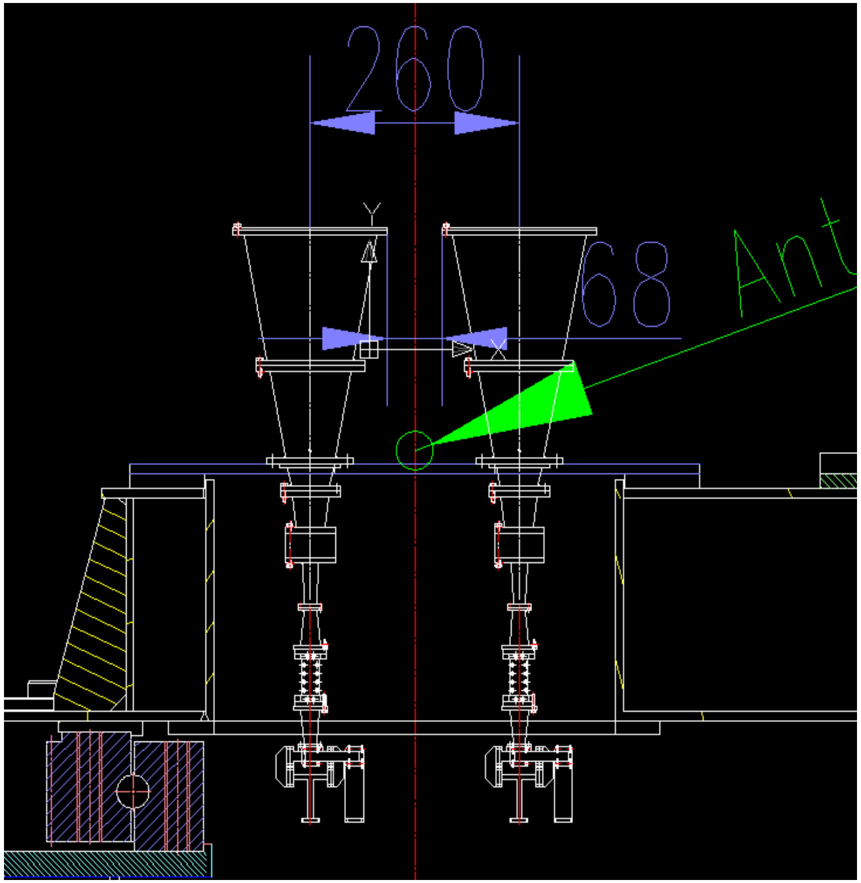
Maximum 110mm beam offset
Maximum 4% aperture efficiency loss at CF

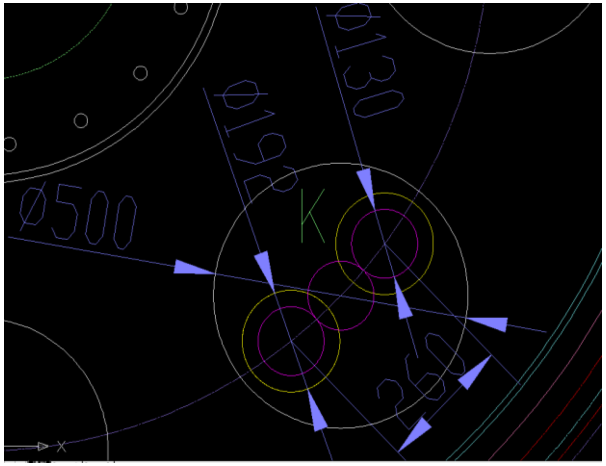




K-band mounting structure



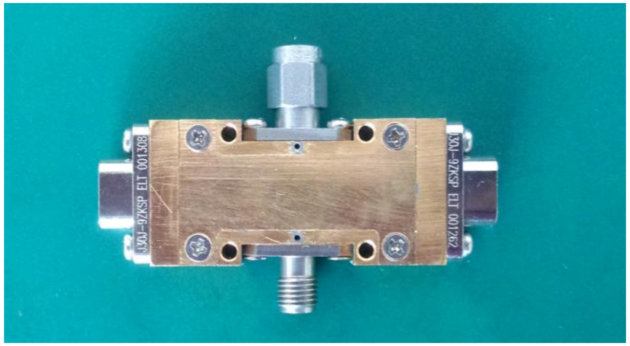




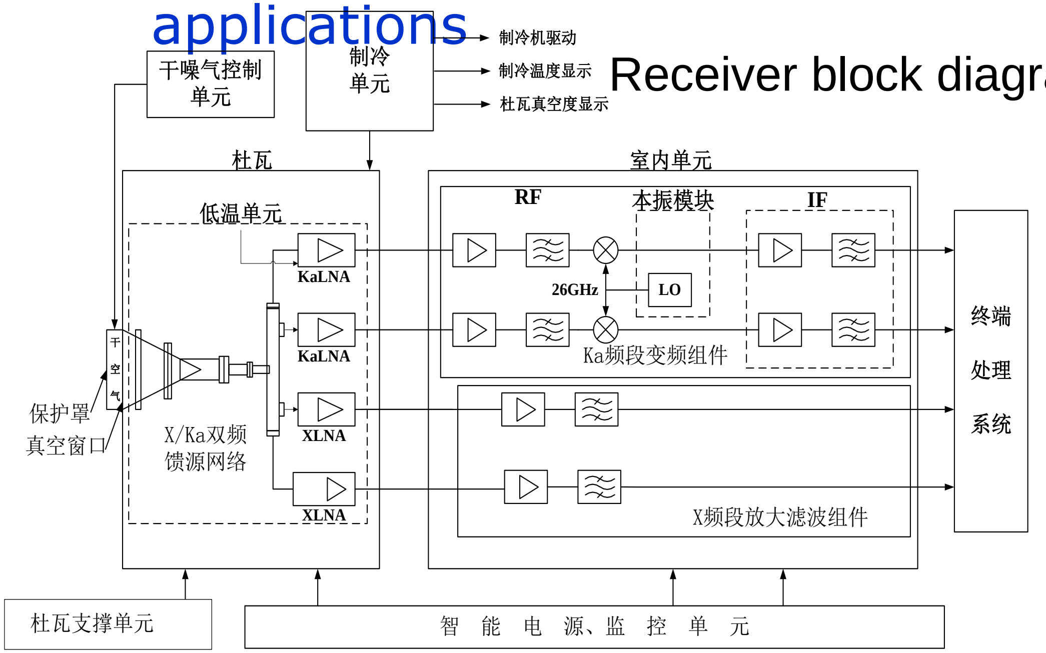
X/Ka-band receiver

- **Features**
  - Dual band & dual polarization
  - Self made Ka-band cooled LNA
  - Cooled dual band polarizer
  - Astronomy & geodesy research applications

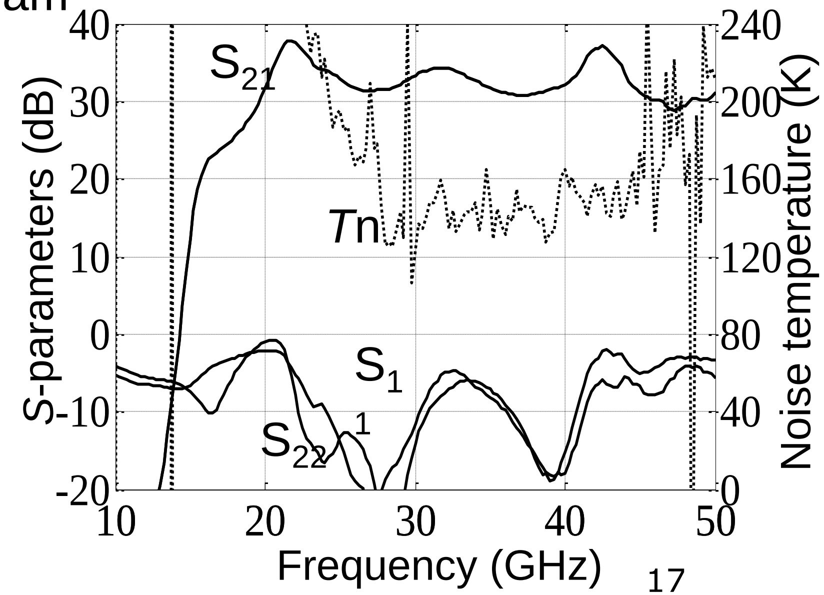
Ka-band LNA



Receiver block diagram

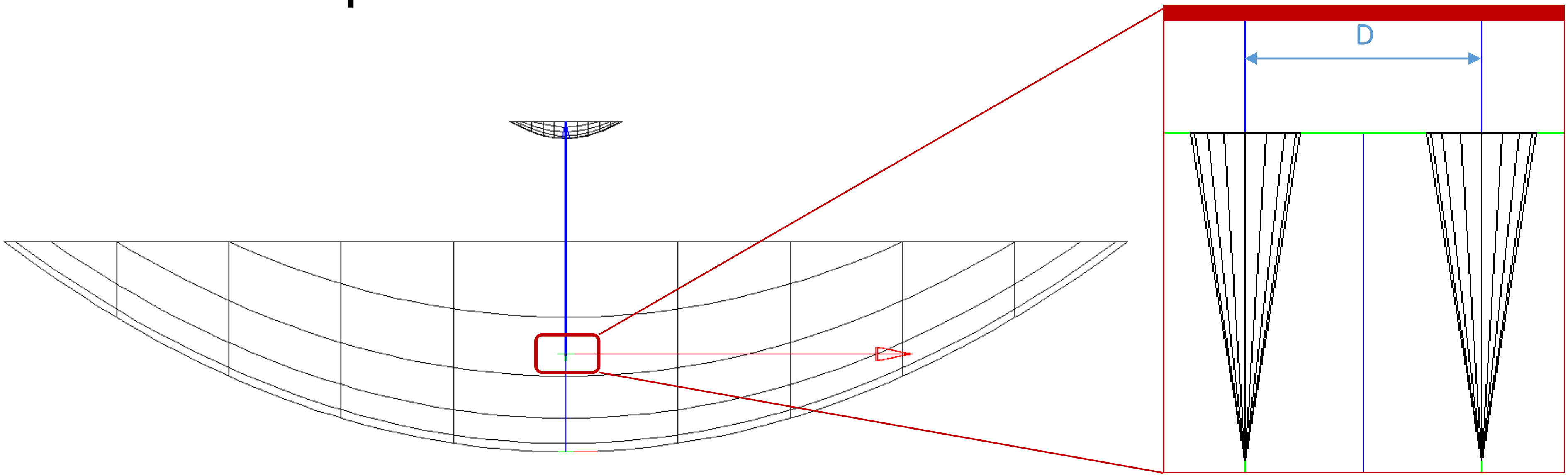


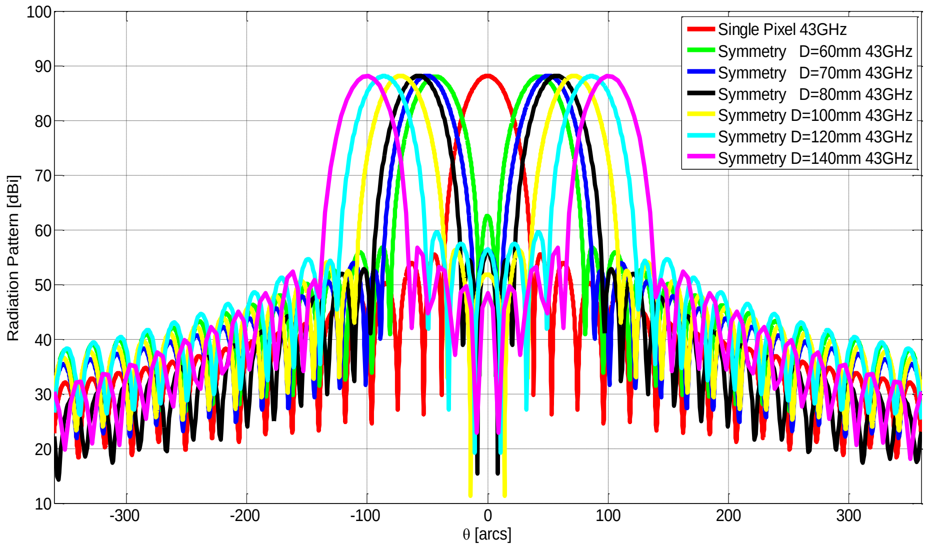
Measurement results at 300K



(2-pixel) Q-band receiver

Microwave Optics Simulation Results





Feed Spacing (mm)	Beam Spacing (arcsec)	Unit of HPBW	Remarks
Single Pixel	27.4	1	
60	86.4	3.2	
70	100	3.7	Our Choice
80	113.8	4.2	
100	144	5.3	
120	172.8	6.3	
140	198	7.2	

DIBAS: DIgital BAckend System

- An updated version of the NRAO-VEGAS (Versatile GBT Astronomical Spectrometer), customized with the addition of NRAO-GUPPI (Green Bank Ultimate Pulsar Processing Instrument)

- **Support two types of observing modes**
  - **Spectral line modes: support 29 modes, including wideband up to 16,384 channels, narrowband up to 524,288 channels and, sub-band modes (higher spectral-resolution over multiple narrow bands (sub-bands) within the sampled bandwidth)**
  - **Pulsar modes: support the incoherent/coherent search and pulsar timing modes.**

DIBAS Spectrometer Specs

Mode Name	Number of Spectral Windows/Pol	Bandwidth of Spectral Window (MHz)	Number of channels per Spectral window per Pol	Spectral resolution (KHz)	Minimum int time[b] (msec)	Max Data rate[a] (MB/sec)	Data rate supported by software[c] (MB/sec)	Max Data rate from 8 spec (GB/sec)
Single Sub-band mode								
Mode 1 (H1K/HBW)	1	1250	1024	1465	0.5	32	32	0.3
Mode 2 (H16K/HBW)	1	1250	16384	92	1.4	188	32	1.5
Mode 3 (H16K/HBW)	1	850	16384	61	2.0	131	32	1.1
Mode 4 (L1/LBW1)	1	187.5	32768	5.7	10	50	32	0.4
Mode 5 (L1/LBW1)	1	187.5	65536	2.9	20	50	32	0.4
Mode 6 (L1/LBW1)	1	187.5	131072	1.4	30	67	32	0.5
Mode 7 (L1/LBW1)	1	100	32768	3.1	10	50	32	0.4
Mode 8 (L1/LBW1)	1	100	65536	1.5	20	50	32	0.4
Mode 9 (L1/LBW1)	1	100	131072	0.8	30	67	32	0.5
Mode 10 (L8/LBW1)	1	23.44	32768	0.7	5	100	32	0.8
Mode 11 (L8/LBW1)	1	23.44	65536	0.4	10	100	32	0.8
Mode 12 (L8/LBW1)	1	23.44	131072	0.2	30	67	32	0.5
Mode 13 (L8/LBW1)	1	23.44	262144	0.1	40	134	32	1.1
Mode 14 (L8/LBW1)	1	23.44	524288	0.05	75	267	32	2.1
Mode 15 (L8/LBW1)	1	11.72	32768	0.4	5	100	32	0.8
Mode 16 (L8/LBW1)	1	11.72	65536	0.2	10	100	32	0.8
Mode 17 (L8/LBW1)	1	11.72	131072	0.1	30	67	32	0.5
Mode 18 (L8/LBW1)	1	11.72	262144	0.05	40	134	32	1.1
Mode 19 (L8/LBW1)	1	11.72	524288	0.02	75	267	32	2.1
8 Sub-band modes[d]								
Mode 20 (L8/LBW8)	8	23.44	4096	5.7	5	100	32	0.8
Mode 21 (L8/LBW8)	8	23.44	8192	2.9	10	100	32	0.8
Mode 22 (L8/LBW8)	8	23.44	16384	1.4	30	67	32	0.5
Mode 23 (L8/LBW8)	8	23.44	32768	0.7	40	100	32	0.8
Mode 24 (L8/LBW8)	8	23.44	65536	0.4	75	107	32	0.9
Mode 25 (L8/LBW8)	8	15.625	4096	3.8	7	71	32	0.6
Mode 26 (L8/LBW8)	8	15.625	8192	1.9	14	71	32	0.6
Mode 27 (L8/LBW8)	8	15.625	16384	0.95	40	50	32	0.4
Mode 28 (L8/LBW8)	8	15.625	32768	0.48	55	72	32	0.6
Mode 29 (L8/LBW8)	8	15.625	65536	0.24	100	80	32	0.6

[a] Maximum data rate is calculated for recording full polarization and all channels at the minimum integration period. Each spectral value is represented by 4 bytes.[b] The integration per switching state should be $\geq$ the minimum integration. For example, if an observation uses 2 switching states, then the minimum integration will be 2 times the value listed in table. [c] The specified rate is for one spectrometer. [d] For modes 20 to 24 the subbands can be placed within the baseband bandwidth of 1500 MHz (usable frequency range 150 MHz to 1400 MHz) and for modes 25 to 29 the subbands can be placed within 1000 MHz (usable frequency range 150 MHz to 950 MHz).

DIBAS Spectrometer Specs

观测模式	子带数目	子带带宽 (MHz)	子带通道数	频率分辨率 (kHz)	速度分辨率 （km/s）			
					Q 波段@ 43 GHz	K 波段 @ 22 GHz	C 波段 @ 6.7 GHz	L 波段@ 1.7 GHz
1	1	1500	1024	1465	10.2	20.0	65.6	258.5
2	1	1500	16384	92	0.64	1.25	4.1	16.2
3	1	1000	16384	61	0.43	0.83	2.7	10.8
4	1	187.5	32768	5.7	0.04	0.08	0.26	1.01
5	1	187.5	65536	2.9	0.02	0.04	0.13	0.51
6	1	187.5	131072	1.4	0.01	0.02	0.06	0.25
7	1	100	32768	3.1	0.02	0.04	0.14	0.55
8	1	100	65536	1.5	0.01	0.02	0.07	0.26
9	1	100	131072	0.8	0.006	0.01	0.036	0.14
10	1	23.44	32768	0.7	0.005	0.01	0.031	0.124
11	1	23.44	65536	0.4	0.003	0.0055	0.018	0.07
12	1	23.44	13172	0.2	0.0014	0.0027	0.009	0.035
13	1	23.44	262144	0.1	0.0007	0.0014	0.0045	0.018
14	1	23.44	524288	0.05	0.00035	0.00068	0.0022	0.009
15	1	11.72	32768	0.4	0.003	0.0055	0.018	0.07

DIBAS Spectrometer Specs(cont'd)

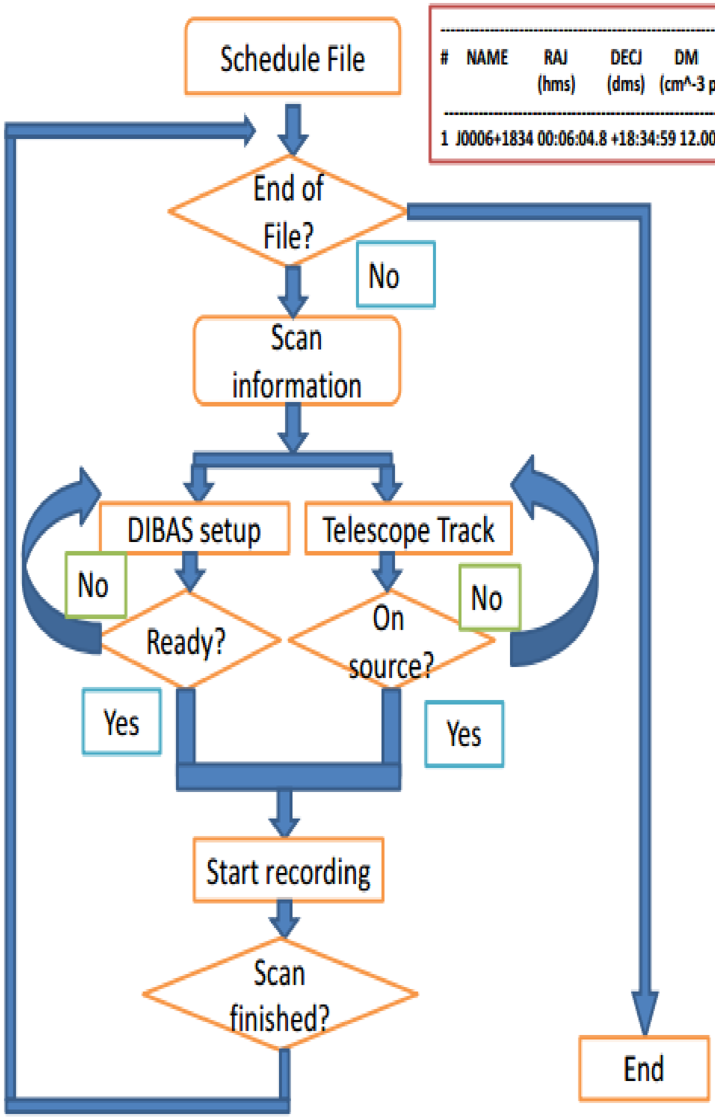
观测模式	子带数目	子带带宽 (MHz)	子带通道数	频率分辨率 (kHz)	速度分辨率 （km/s）			
					Q 波段@ 43 GHz	K 波段 @ 22 GHz	C 波段 @ 6.7 GHz	L 波段@ 1.7 GHz
16	1	11.72	65536	0.2	0.0014	0.0027	0.009	0.035
17	1	11.72	131072	0.1	0.0007	0.0014	0.0045	0.018
18	1	11.72	262144	0.05	0.00035	0.00068	0.0022	0.009
19	1	11.72	524288	0.02	0.00014	0.00027	0.0009	0.0035
20	8	23.44	4096	5.7	0.04	0.08	0.26	1.01
21	8	23.44	8192	2.9	0.02	0.04	0.13	0.51
22	8	23.44	16384	1.4	0.01	0.02	0.06	0.25
23	8	23.44	32768	0.7	0.005	0.01	0.031	0.124
24	8	23.44	65536	0.4	0.003	0.0055	0.018	0.07
25	8	15.625	4096	3.8	0.027	0.052	0.17	0.67
26	8	15.625	8192	1.9	0.013	0.026	0.085	0.34
27	8	15.625	16384	0.95	0.007	0.013	0.043	0.17
28	8	15.625	32768	0.48	0.0033	0.0065	0.021	0.085
29	8	15.625	65536	0.24	0.0017	0.0033	0.011	0.042

DIBAS pulsar observing modes

Averaging

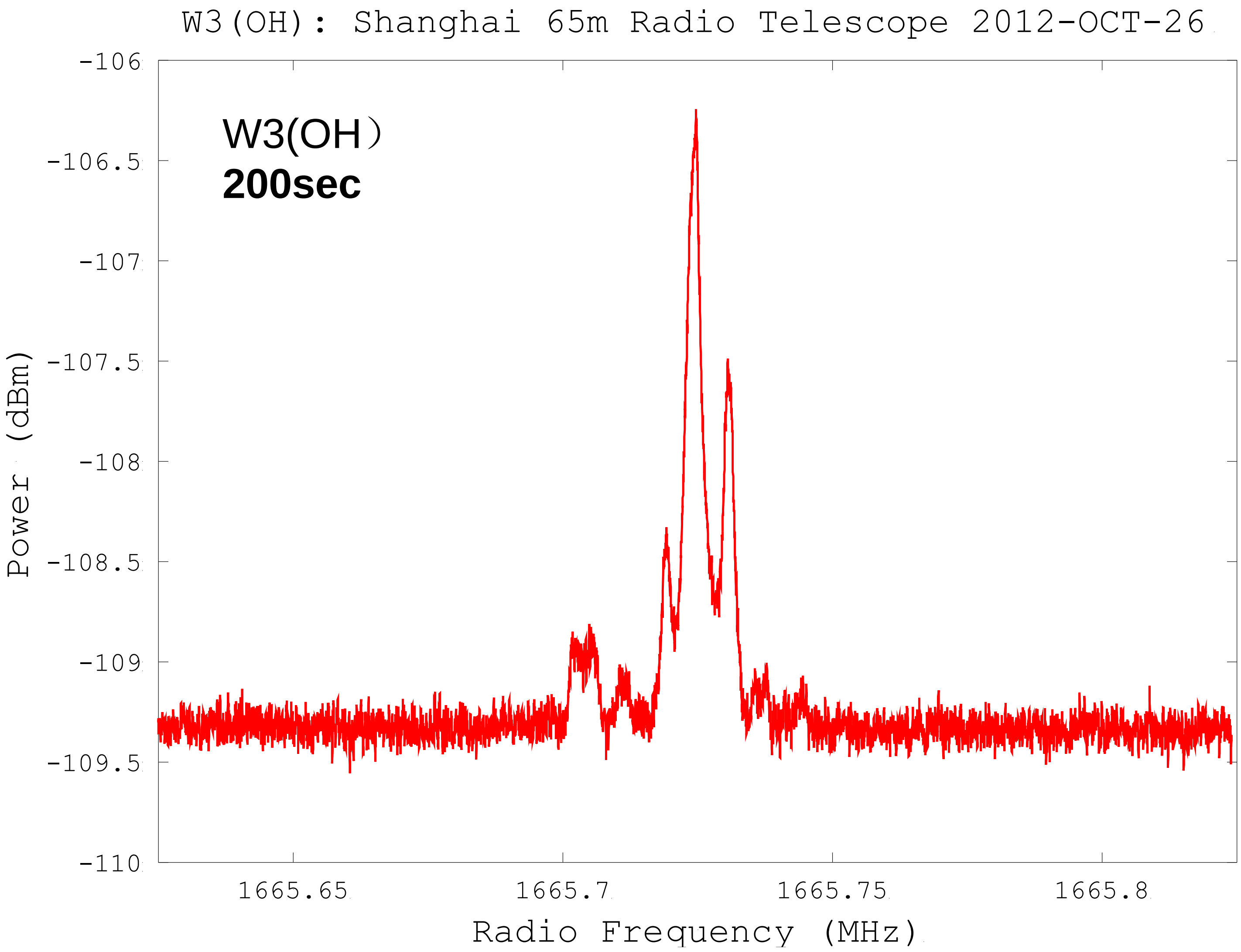
	Incoherent	Coherent
Time average	Incoherent search mode Applications: - Pulsar searches! - Single-pulse studies - General spectroscopy	Coherent search mode Applications: - Multi-pulsar systems (Globular clusters, etc) - High time resolution
Folding	Incoherent fold mode Applications: - Search follow-up - “Slow” pulsar timing - Polarimetry	Coherent fold mode Applications: - MSP timing - High pulse phase resolution - Polarimetry

Scheduling of pulsar observations

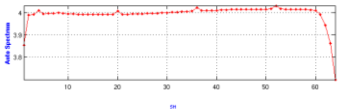


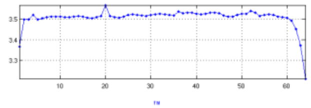
#	NAME	RAJ (hms)	DECJ (dms)	DM (cm^-3 pc)	BAND (L,S,C, X)	MODE (PSR_mode_NCH_BW)	Length (s)
1	J0006+1834	00:06:04.8	+18:34:59	12.00	L	PSR_COFOLD_2048_1000	600

First light on October 26, 2012

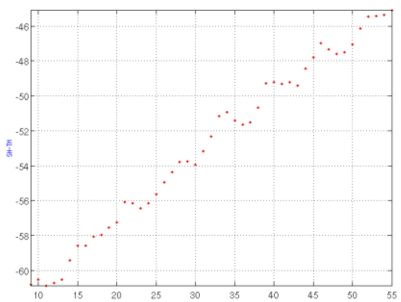


Fringe detected on 65m-25m (Nov. 28, 2012)





===Baseline Cross Phase===



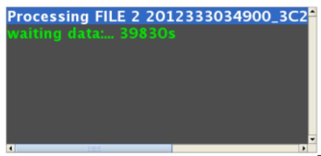
S.Interval 300 NFFT Avg. 64

BandWidth(M 4 Nf 512

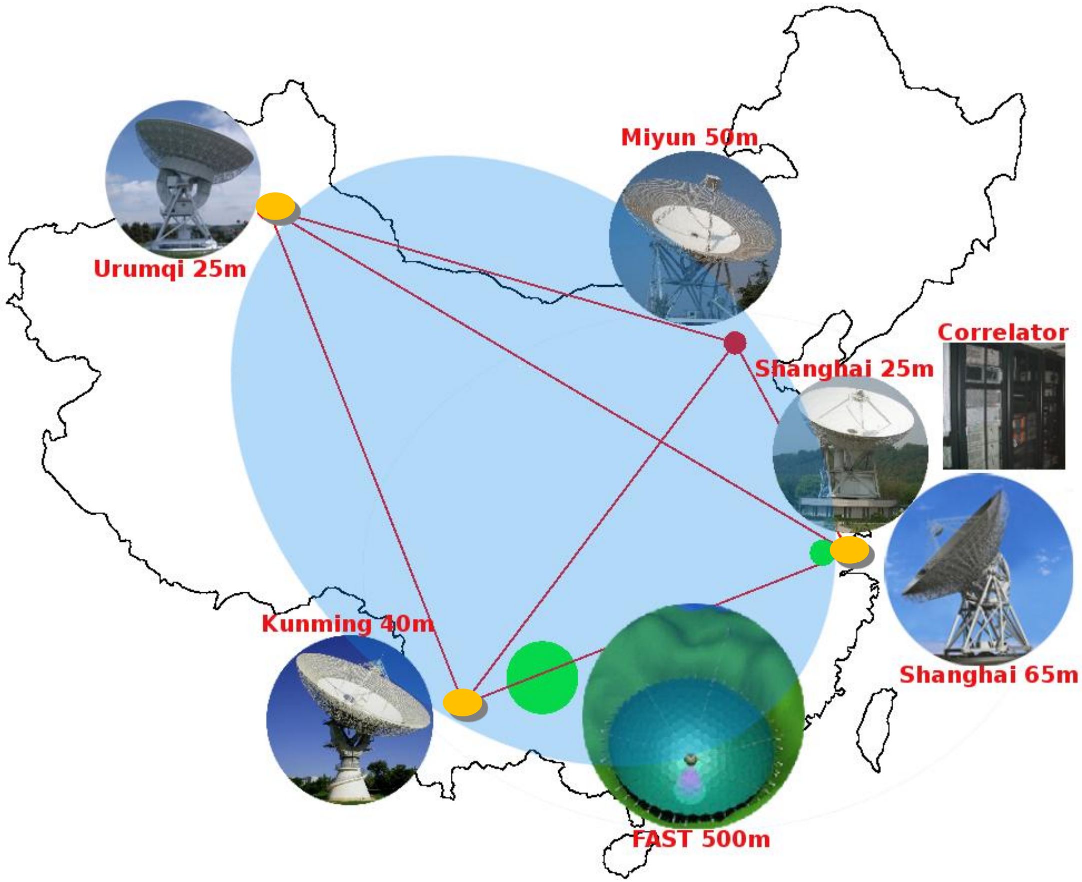
Int.Tim 1.04857 FFTPag 286

BBC Freq.

01#2208.8; 02#2208.8;



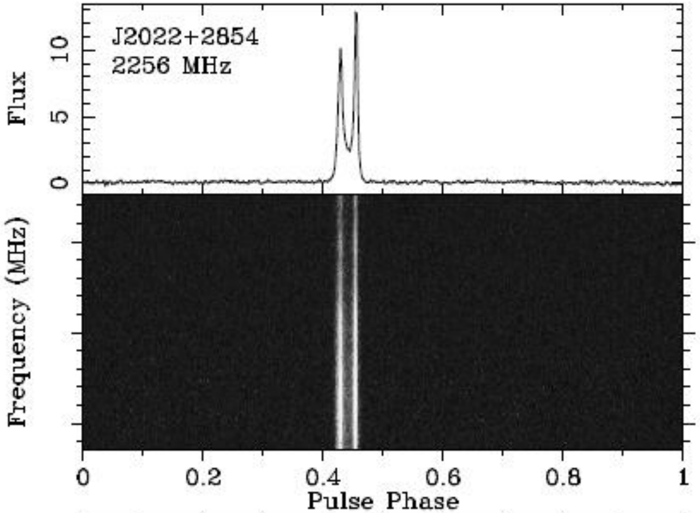
On Dec 1-3, 2012, SH65 joined the OD of CE-2 with the 3 other VLBI stations (Ur25, Km40 and Sh25).



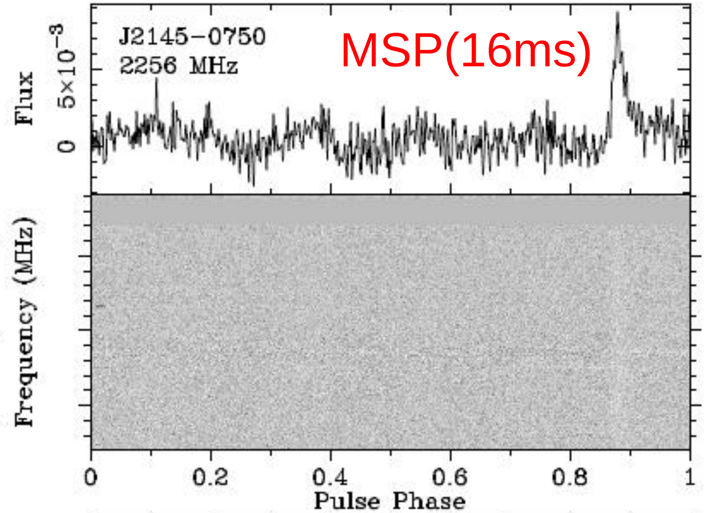
One year later, during the CE-3 landing mission (2013Dec – 2014Jan), TM telescope has done an excellent job!

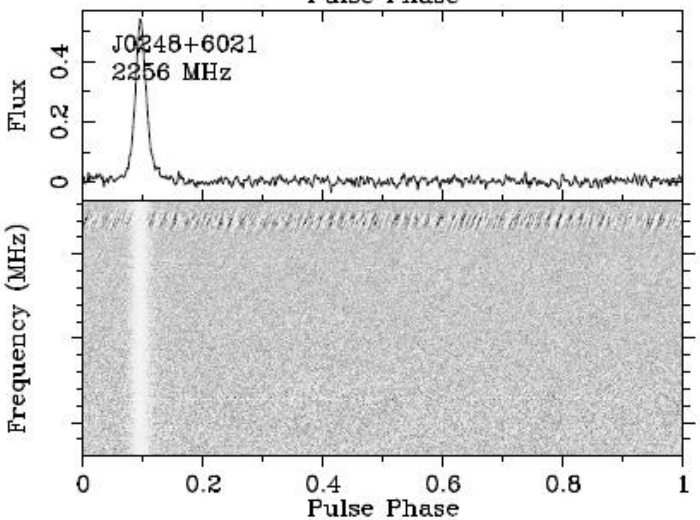
testing results in January 2013 with the PDFB system

38mJy@1.4GHz, Ob: S-band, t_{int}~3min

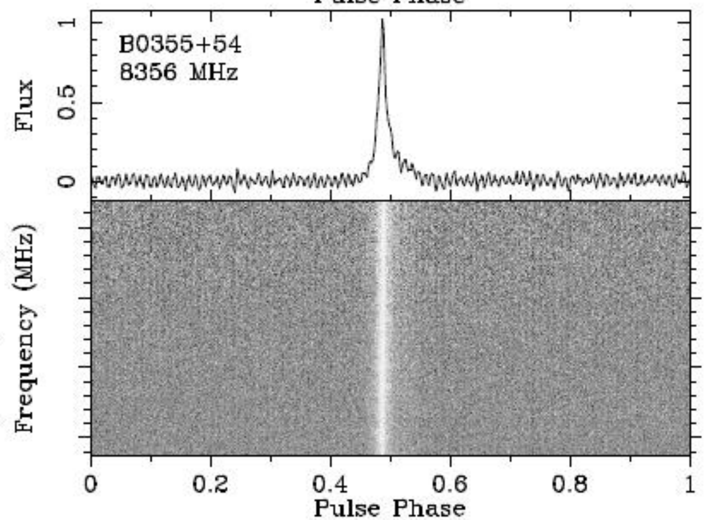


8.9mJy@1.4GHz, Ob: S-band, t_{int}~18min



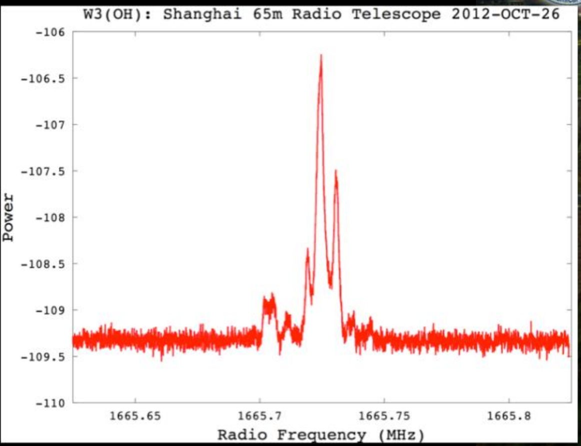


DM=370, Ob: S-band, t_{int}~15min

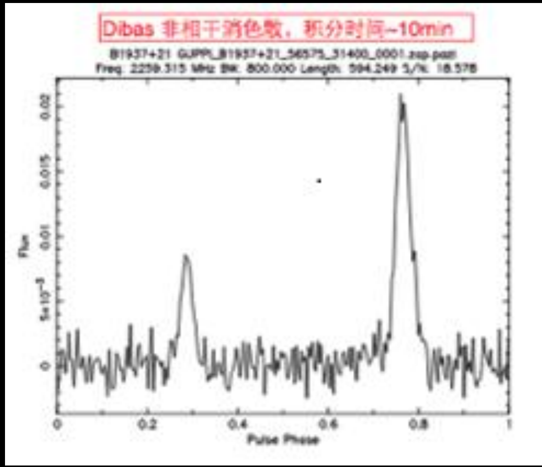


23mJy@1.4GHz, Ob: X-band, t_{int}~5min

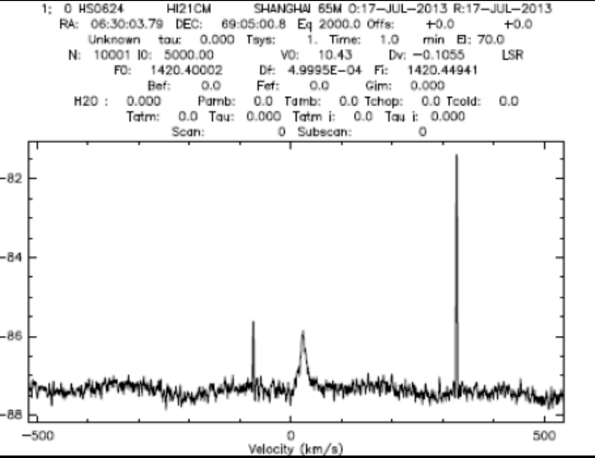
Testing observations



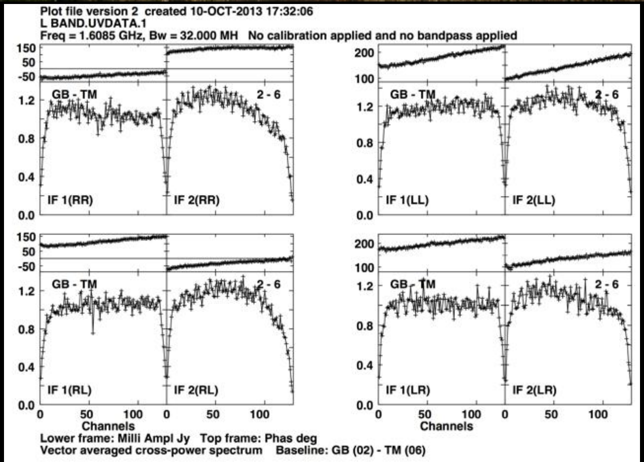
First light from W3(OH)



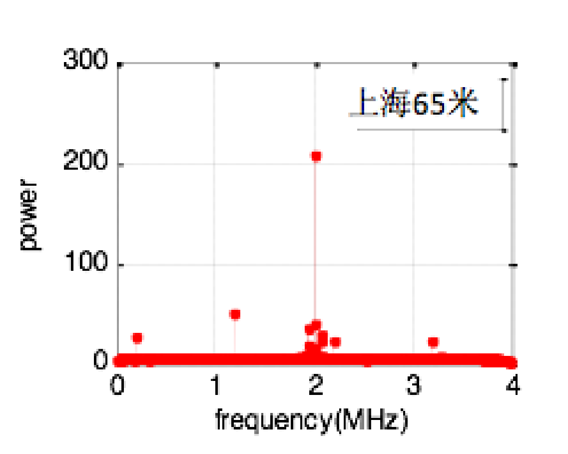
ms pulsar profile



HI 21 cm line



VLBI fringes with the GBT



Signals from the CE-2

The TianMa Telescope

Shanghai 65m RT

L band Rx

C band Rx

S band Rx

X band Rx

Ku band Rx

Ka band Rx

Q band Rx (2-beam)

K band Rx (2-beam)

VLBI terminal (CDAS) +correlator

General-purpose (DIBAS)

Continuum, line and pulsar + multi-beam

USERS

Multi beam system (2-beam at K- and Q-band)
(+ simultaneous observations of multiple lines)

Science with the TianMa 65m RT

- VLBI
- Single-dish
  - Line (maser)
  - pulsar
  - Continuum

Science with the 65m RT

- **Astrometry**
  - **Celestial reference frame**
  - **High-accuracy astrometry, space tracking & navigation**
- **Astrophysics**
  - **High-resolution polarization-sensitive VLBI Observations**
    - AGN and Jets
    - B-field in cluster of galaxies
    - Pol’n of galactic masers
  - **Galactic and Extra-galactic masers**
    - Physics of (high-mass) star formation
    - Structure, evolution of Galaxy and dark matter
    - Large scale structure (cosmological distance)
  - **Survey/Search of spectral line emission**
    - Molecular lines in Galaxy
    - Magamasers
  - **High-z CO observations**
  - **Radio stars and variables**
  - **…**

Spectral line

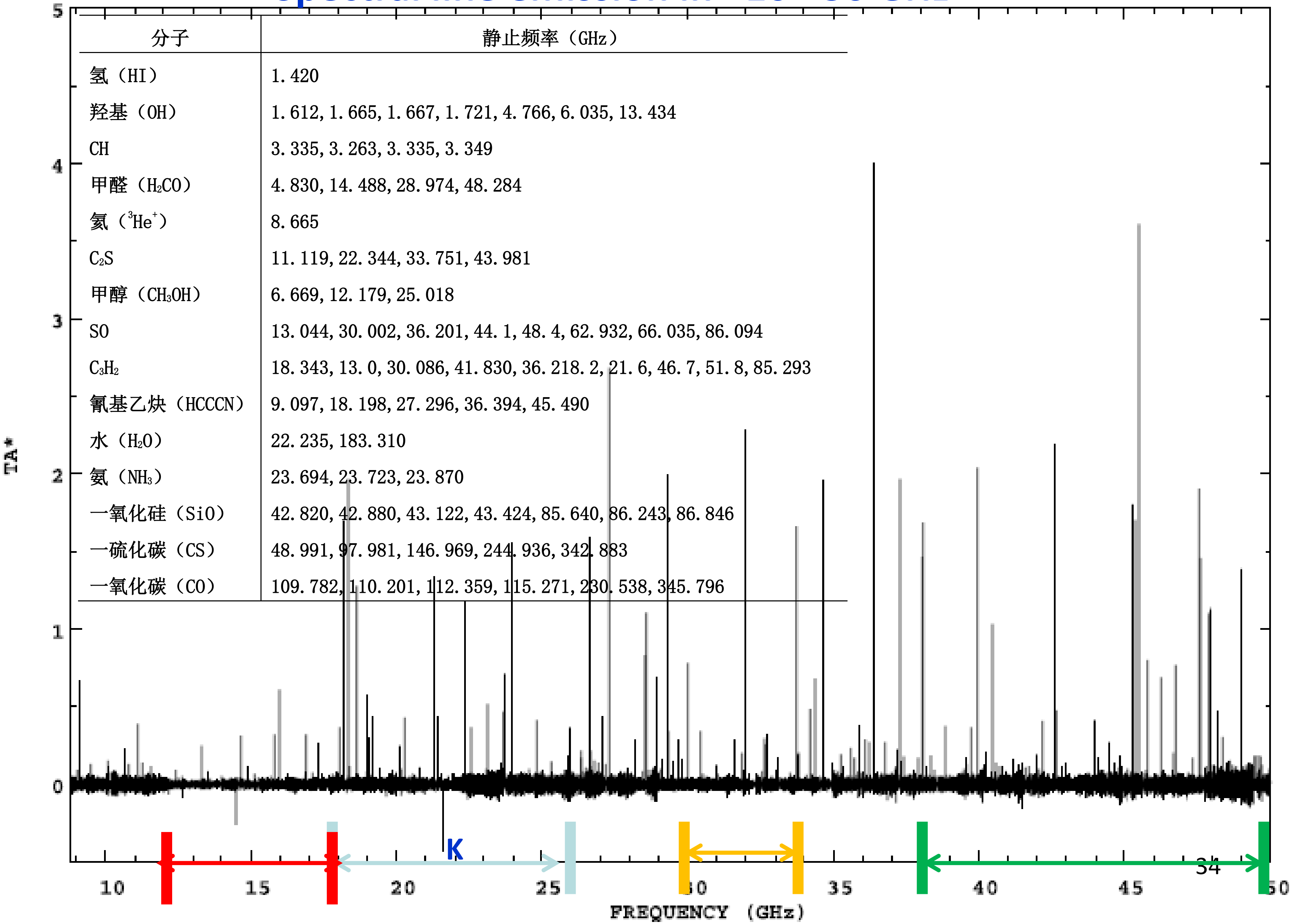
high sensitivity, wide frequency coverage

Suitable for spectral line observations.

- Discovery of new lines (masers)
- Search for some important line emissions, such as high-z CO (bw=4MHz, T=20hr, sigma=0.2 mJy@22GHz, or, 0.9mJy @ 43 GHz)
- Multiple-line observation towards SFRs
- Deep K-band Galactic Plane Survey

Spectral line emission in ~10 - 50 GHz

分子	静止频率（GHz）
氢（HI）	1. 420
羟基（OH）	1. 612, 1. 665, 1. 667, 1. 721, 4. 766, 6. 035, 13. 434
CH	3. 335, 3. 263, 3. 335, 3. 349
甲醛（H_2CO）	4. 830, 14. 488, 28. 974, 48. 284
氦（$^{3}He^{+}$）	8. 665
C_2S	11. 119, 22. 344, 33. 751, 43. 981
甲醇（CH_3OH）	6. 669, 12. 179, 25. 018
SO	13. 044, 30. 002, 36. 201, 44. 1, 48. 4, 62. 932, 66. 035, 86. 094
C_3H_2	18. 343, 13. 0, 30. 086, 41. 830, 36. 218. 2, 21. 6, 46. 7, 51. 8, 85. 293
氰基乙炔（HCCCN）	9. 097, 18. 198, 27. 296, 36. 394, 45. 490
水（H_2O）	22. 235, 183. 310
氨（NH_3）	23. 694, 23. 723, 23. 870
一氧化硅（SiO）	42. 820, 42. 880, 43. 122, 43. 424, 85. 640, 86. 243, 86. 846
一硫化碳（CS）	48. 991, 97. 981, 146. 969, 244. 936, 342. 883
一氧化碳（CO）	109. 782, 110. 201, 112. 359, 115. 271, 230. 538, 345. 796



Molecular lines at cm-band

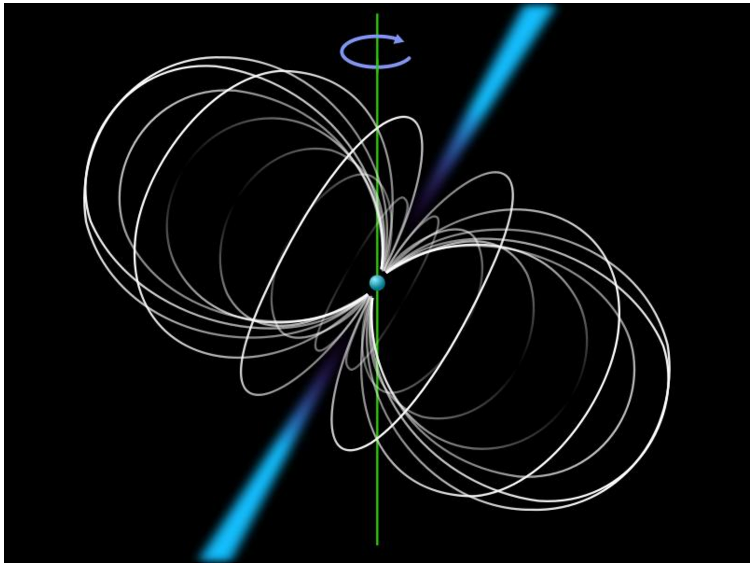
Table 1. The First Interstellar "Radio" Molecules

Name	Species	Transition	Frequency (MHz)	Reference
Hydroxyl	OH	$^2\Pi_{\frac{3}{2}}, J=\frac{3}{2}$	1665.4018(2)[a]	Weinreb et al. 1963
Ammonia	NH_3	$(1,1)$	23694.4955(1)[b]	Cheung et al. 1968
Formaldehyde	H_2CO	$1_{11}-1_{10}$	4829.660(1)[b]	Snyder et al. 1969
Water	H_2O	$6_{16}-5_{23}$	22235.08(2)[b]	Cheung et al. 1969
Methyl alcohol	CH_3OH	1^+-1^-	834.267(2)	Ball et al. 1970
Formic acid	$HCOOH$	$1_{11}-1_{10}$	1638.804(1)	Zuckerman et al. 1971
		$2_{11}-2_{12}$	4916.319(3)	*GWi & Churchwell 1975*
Formamide	NH_2CHO	$1_{11}-1_{11}$	1539.58(2)[c]	Palmer et al. 1971
		$2_{11}-2_{12}$	4618.55(2)[c]	Rubin et al. 1971
Cyanoacetylene	HC_3N	$1-0$	9098.6537(3)[c]	Turner 1971
	$H^{13}C_3N$	$1-0$	~ 9060[d]	*Gardner & GWi 1975a*
	$H^{12+13}C_3N$	$1-0$	~ 9000[d]	*Churchwell et al. 1977*
Acetaldehyde	CH_3CHO	$1_{10}-1_{11}$	1065.075(5)	Ball et al. 1971
Methylidine	CH	$^2\Pi_{\frac{1}{2}}, J=\frac{1}{2}$	3263.788(10)[e]	Rydbeck et al. 1973
Thioformaldehyde	H_2CS	$2_{11}-2_{12}$	3139.38(3)	Sinclair et al. 1973
Methanimine	CH_2NH	$1_{10}-1_{11}$	5290.31(4)	Godfrey et al. 1973
Methylamine	CH_2NH_2	$2_{02}-1_{10}$	8776.2(1)[f]	Fourikis et al. 1974
Vinyl cyanide	H_2CCHCN	$2_{11}-2_{12}$	1371.8262(1)	*Gardner & GWi 1975b*
Methyl formate	$HCOOCH_3$-A	$1_{10}-1_{11}$	1610.2445(7)	Brown et al. 1975
	$HCOOCH_3$-E	$1_{10}-1_{11}$	1610.91(10)	Churchwell & GWi 1975
Dimethyl ether	$(CH_3)_2O$	$2_{02}-1_{11}$	9119.668(15)[c]	*GWi & Gardner 1976*
Cyanodiacetylene	HC_5N	$4-3$	10650.650(4)	Avery et al. 1976
		$2-1$	5325.328(2)	*Gardner & GWi 1978*

Menten 2004

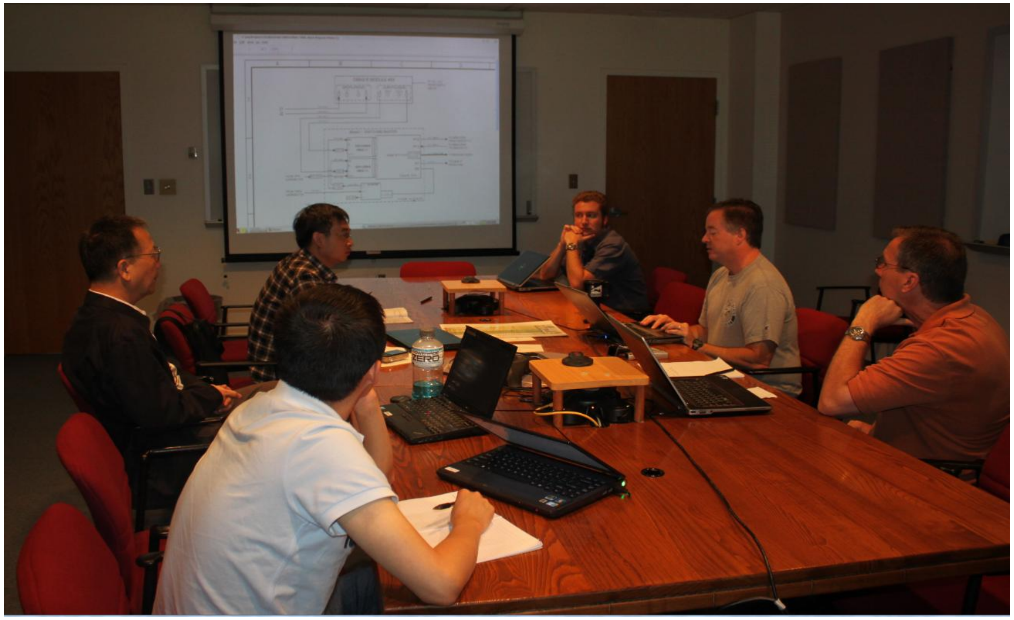
pulsar — an important target

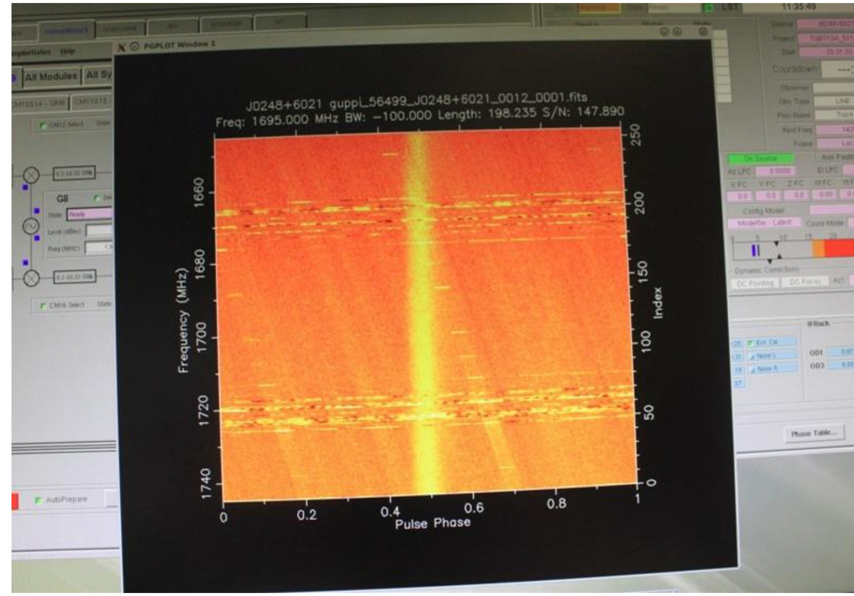
- Survey at C-band
- Join the Pulsar timing observations
  - There are 3 major GW detectors: space-based (LISA), ground-based (LIGO) and, pulsar timing arrays
- Pulsar Astrometry
- ……



More testing work ongoing

- pointing
- OTF
- Active surface control system (hologrammetry, photogrammetry)
- …





NRAO/GBT visit: (July 17- August 1, 2013);

Hardware arrived: September 9, 2013

NRAO engineers visit: Mid-October 2013

Thanks for your attention !