An Overview of the Japanese GALA-V Wideband VLBI System

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GALA-V Project Overview

Frequency comparison by using Transportable Broadband telescopes

- VLBI Sensitivity: \( \text{VLBI Sensitivity} = \propto D_1 D_2 \sqrt{BT} \)
  
  \( B: 16\text{MHz} \rightarrow 1024\text{MHz} \) (64 times)

- Radio Frequency: \( 3-14\text{GHz} \)

- Data Acquisition: 4 band (1024MHz width)
  - \( F_c = 4.0\text{GHz}, 5.6\text{GHz}, 10.4\text{GHz}, 13.6\text{GHz} \)
  - Effective Bandwidth: \( 3.8\text{GHz} \) (10 times of Conventional)

\[ \tau_{21} = \tau_{13} - \tau_{23} \]

Delay Resolution Function

\( 10 \text{ time higher resolution} \) will be gained by broader bandwidth
1. Broadband feed developed for Cassegrain Antenna (Kashima 34)
   - IGUANA-H: 6.5-15GHz
   - NINJA: 3-14.4GHz

2. Direct RF Sampling and Broadband Bandwidth Synthesis.
   A) Digitizing RF signal without frequency conversion.
   B) Broadband bandwidth synthesis without Phase-Cal system. ⇒ without Delay-Cal

3. Our Broadband VLBI Experiment shows, atmospheric delay changes order of 20 psec in hundreds seconds of timescale, thus quick switching short interval observation is required.
Broadband Antennas used in Gala-V Project

Kashima 34m

MARBLE1 1.6m @NMIJ(Tsukuba)

MARBLE12 1.5m @Konganei

Original broadband Feed
NINJA, IGUANA-H

Rindgren QRHA
Reason why NICT Developed Broadband Feeds

Requirement of Broadband Frequency and Narrow beam width
Broadband Feed for Cassegrain optics
Kashima 34m antenna

Planning change to Dual Polarization
Currently Single linear Polarization

IGUANA-H Feed (6.5-15GHz)

NINJA Feed (3.2-14.4GHz, nominal)
IGUANA-H Broadband Feed on 34m antenna
NINJA Broadband Feed on 34m antenna

SEFD of Kashima 34m with NINJA Feed

Modified System Temperature with NINJA Feed
Signal Chain From Feed to DAS

We have to be careful to compromise (1) avoiding saturation of system and (2) increase of noise figure, as discussed by Chris (2012).

**Broadband Antenna**
- Linear Polarization
- Gain = 20 dB
- 300 kHz = -174 dBm/Hz
- -74 dBm/10 GHz
- -54 dBm/10 GHz

**Observation Room**
- Down Conv.
- ADS3000+
  - 0.1-1.5 GHz
  - 16 ch x 64 Msps
- K6/GALAS
  - 0.1-16 GHz
  - 4 ch x 2048 Msps
- VTP/10GEthernet
- 10G-NIC+Raid PC
  - Or MK6

300 kHz = -174 dBm/Hz
-74 dBm/10 GHz
-54 dBm/10 GHz

Direct RF Sampling

We have to be careful to compromise (1) avoiding saturation of system and (2) increase of noise figure, as discussed by Chris (2012).
**Direct Sampling** of RF signal, Digital Filtering without Freq. Conv.

<table>
<thead>
<tr>
<th>IF Input Port</th>
<th>2</th>
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<tbody>
<tr>
<td>Input Freq. Range</td>
<td>0.1-16.4 GHz</td>
</tr>
<tr>
<td>Sampling mode</td>
<td>DBBC Mode Nch/unit=1,2,3, or 4 2048 Msps/ch Qbit=1, or 2 bit</td>
</tr>
</tbody>
</table>

| Output Port | 10GBASE-SR, 4port |
| Max Data rate | 16384 Mbps/port |

Basic Sampler system has been tested and developed by Prof. Kawaguchi, Dr. Kono, Dr. Oyama of NAOJ in collaboration with Elecs Co.Ltd.
Domestic Broadband Experiments
14-15 Aug. 2015

Ishioka 13m (GSI)

Kashima 34m (NICT)
As close as Zero Redundancy

Frequency allocation

Fine Delay Resolution
Without Ambiguity

Direct Sampling (K6/GALAS)

BW 1024MHz each

Lower Edge= 3.2, 4.8, 8.8, 11.6GHz
Delay Behavior Broadband Delay (3.2-12.6GHz)
Kashima34 – Ishioka 13m

Effective BW: 6.7 GHz

Delay [psec]

Time [sec]

Effective BW: 6.6 GHz

Alan Standard Deviation

Subopico second delay resolution at 1 sec.
Full Bandwidth Synthesis 

by Phase Calibration with Radio Source

Cross Spectrum

SOURCE: 3C273B
PRT 2015/226 05:57:15 Integ(sec)= 30.00

Delay Resolution Function

SEARCH FUNCTION (64x128)

KAS14 – ISHIK
Source : 3C84
PRT: 2015/1 18:12:30
BW(MHz): 7880.00

Ref Freq(MHz) = 6144.00
Integration (sec) = 80.0
Peak Position (deg, s) = (32, 62)
Amplitude = 2.344e-003
$\Delta f$ (Hz) = -0.0127
$\Delta f$ (s) = -2.063e-012
Procedure of Broadband Phase Calibration with radio source

\[ \tau_{ref} = \tau_{r-scan} + \tau_{atm1} + \tau_{inst} \]

\[ \Delta \phi_{ref}(f) = \phi_{inst2}(f) - \phi_{inst1}(f) \]

\[ C_{ref(f)} = \exp\left(2\pi f \tau_{ref} + \Delta \phi_{ref(f)}\right) \]
Procedure of Broadband Phase Calibration with radio source

\[ C_{\text{scan}}(f) = A_{\text{scan}}(f) \exp \left( i2\pi f \tau_{\text{scan}} + \Delta \phi_{\text{ref}}(f) \right) \]

\[ \frac{C_{\text{scan}}(f)}{C_{\text{ref}}(f)} = A_{\text{scan}}(f) \exp(2\pi f i \Delta \tau_{\text{scan}}) \]

\[ \Delta \tau_{\text{scan}} \equiv (\tau_{\text{scan}} - \tau_{\text{ref.scan}}) \]

\[ \tau_{\text{ref}} \equiv \tau_{\text{ref.scan}} + \tau_{\text{ref.atm}} + \tau_{\text{inst}} \]

\[ \Delta \phi_{\text{ref}}(f) \equiv \phi_{\text{inst2}}(f) - \phi_{\text{inst1}}(f) \]

\[ C_{\text{ref}}(f) \equiv \exp i \left( 2\pi f \tau_{\text{ref}} + \Delta \phi_{\text{ref}}(f) \right) \]
Advantages of Direct RF Sampling Technique proposal of Pcal-free system

Advantages of Direct sampling
1. Simple and less system components.
2. Stable phase/Delay relation between band gives possibility of BWS without P-cal device.

If verified Delay-Cal device is not necessary, too.
Full Bandwidth Synthesis #1-#4 (3.2-11.6GHz) by Phase Calibration with Radio Source

Cross Spectrum after calibration

Phase/delay characteristics for calibration

Calibration Cross Spectrum Phase

SEARCH FUNCTION (64x128)

INNER-BAND PHASE CALIBRATION DATA
KASHIM34 - ISHIOKA
SOURCE: 3C273B PRT 2015/226 05:57:15 Integ(sec)= 30.00

SOURCE: 3C273B PRT 2015/226 05:57:15 Integ(sec)= 30.00
Least Square Estimation of $\delta TEC$ and $\delta \tau$

$$\phi [\text{deg.}] = \alpha \frac{\delta TEC}{f} + 360 \times \delta \tau \times f + c$$
How much this calibration strategy will be stable?
⇒ One evaluation with existing data...

After removing known phase curve by fitting

\[ \delta \phi = a \frac{\delta \text{TEC}}{f} + 360 \times \delta \tau \times f + c \]

Standard deviation of phase were computed over whole bandwidth or each scans of 24 hours experiment.

20 deg. / 10GHz ~ 6psec~2mm
1. We developed Broadband feed for Cassegrain focus telescope to enable VGOS compatible observation with existing 34m telescope.

2. The Broadband BWS software started to work.
   * We need long baseline VLBI data for testing/improvement.

3. Direct RF sampling technique is quite useful especially in case of broadband Pcal device is difficult.
   * Un modeled phase variation rms was evaluated to be less than 20 deg. For 24 hours on Kashima34 - Ishioka 13m.
Development of Broadband Feed is was supported by a grant (2013-2014) of Joint Development Research from National Astronomical Observatory of Japan (NAOJ).

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Thank you for attention.