Development of Broadband VLBI System

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Gala-V Project Overview

Distant Frequency Comparison with Transportable Broadband telescopes

- VLBI Sensitivity: $\text{VLBI Sensitivity} \propto D_1 D_2 \sqrt{BT}$
- $B$: 16MHz → 1024MHz (64 times)
- Radio Frequency: 3–14GHz
- Data Acquisition: 4 band (1024MHz width)
  - $F_c$: 4.0GHz, 5.6GHz, 10.4GHz, 13.6GHz
  - Effective Bandwidth: 3.8GHz (10 times of Conventional)

Delay Resolution Function
10 time higher resolution will be gained by broader bandwidth

$$\tau_{21} = \tau_{13} - \tau_{23}$$
**VGOS (Next Generation Geodetic VLBI System)**

Promoted by IVS

- **What is VGOS?**
  - System: Broadband (2-14GHz), Fast Slew antenna
  - Targeting precision: 1 mm
  - Progress of Stations: USA, Germany, Spain, Japan, Russia, Australia, Sweden, Norway, China, ...

- Japanese VGOS station at Ishioka GSI.
  - Completed First fringe in 2014

- Original Broadband VLBI Development by NICT
1. VGOS Compatible broadband VLBI System Development
   1. Original Broadband Feed for Cassegrain Antenna (IGUANA-H: 6.5-15GHz, NINJA: 3.2-14.4GHz)
   2. Direct Sampling technique with high speed sampler K6/GALAS

2. Broadband Experiments in 2015
   1. Westford, GGAO -- Kashima34
      * International exp. with broadband feed on 20 Jan. 2015
   2. Kashima34 -- Ishioka 13
      * 6-14GHz Broadband observation 8GHz bandwidth, 16 Jan. 2015

3. Advantage of Direct Sampling
Developments
NICT Development of Broadband Feed

Requirement of Broadband Frequency and Narrow beam width

~120deg.

~34deg.
Broadband Feed for Cassegrain optics
Kashima 34m antenna

IGUANA-H Feed (6.5-15GHz)

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

Broadband Antenna

Linear Polarization

E/O

O/E

Observation Room

0.1-1.5GHz ADS3000+ 16ch x 64Msps

0.1-16GHz K6/GALAS 4ch x 2048Msps

Down Conv.

VSI-H

VTP/10GEthernet

10G-NIC+Raid PC Or MK6

Direct Sampling
K6/GALAS Sampler

Direct Sampling of RF signal, Digital Filter and Freq. Conv.

<table>
<thead>
<tr>
<th>IF Input Port</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Freq. Range</td>
<td>0.1-16.4 GHz</td>
</tr>
<tr>
<td>DBBC Mode Nch/unit=1,2,3, or 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2048 Msps/ch</td>
</tr>
<tr>
<td></td>
<td>Qbit=1, or 2 bit</td>
</tr>
<tr>
<td>Output Port</td>
<td>10GBASE-SR, 4port</td>
</tr>
<tr>
<td>Max Data rate</td>
<td>16384 Mbps/port</td>
</tr>
</tbody>
</table>
Experiments
The first Intercontinental VLBI with Broadband Feed 20 Jan. 2015

Collaboration with MIT Haystack and NASA/GAFC
### Target of the Experiment

* Fringe detection with Broadband feed on intercontinental Baseline.
  * Linear Polarization, Hour angle difference
* Compatibility test with each DAS systems.
  * DAS of USA (RDBE+MK6) and Japanese DAS (ADS3000+, PC−VSI)
* Radio Frequency: 10.2 – 10.7GHz

<table>
<thead>
<tr>
<th>Westford, GGAO</th>
<th>Kashima34</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling Recording</strong></td>
<td>RDBE and Mark6 → VDIF</td>
</tr>
<tr>
<td><strong>Correlation</strong></td>
<td>DiFX Sfoftware Correlator Fourfit: Bandwidth Synthesis</td>
</tr>
</tbody>
</table>
### NICT side: Software Correlator GICO3

**Single channel processing**

<table>
<thead>
<tr>
<th></th>
<th>Polarization V−V</th>
<th>Polarization V−H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kashima34m — NASA/GGAO</strong></td>
<td><img src="image1.png" alt="Polarimeter" /></td>
<td><img src="image2.png" alt="Polarimeter" /></td>
</tr>
<tr>
<td><strong>Kashima34m — MIT/Westford</strong></td>
<td><img src="image3.png" alt="Polarimeter" /></td>
<td><img src="image4.png" alt="Polarimeter" /></td>
</tr>
</tbody>
</table>
Domestic Broadband Experiments
30 Jan. 2015

Ishioka 13m (GSI)

Kashima 34m (NICT)
Frequency allocation

BW 1024MHz each

Direct Sampling (K6/GALAS)

Down/Conv. + ADS3000+
Full Bandwidth Synthesis #1-#6 (6-14GHz) after Intra, Interband Phase correction

Cross Spectrum

Delay Resolution Function

Theoretical delay precision is 27 femto sec.

The first 8GHz BWS in the world!!
Delay variations in 15min tracking

A few ps variation can be seen even in 15 min
Delay Measurement Precision

Difference of delay observable at 1 sec. interval is plotted for each of bandwidth synthesized data set.

\[ \tau = s + n_t \]
\[ \sigma_y^2 = \left( (\tau_{(t+1)} - \tau_{(t)})^2 \right) \]
\[ \approx \left( (n_{(t+1)} - n_{(t)})^2 \right) \approx 2\sigma_n^2 \]
RMS of the noise in 1sec

<table>
<thead>
<tr>
<th>Band width</th>
<th>RMS/sec [ps]</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1GHz</td>
<td>3.08</td>
<td>Band #2</td>
</tr>
<tr>
<td>2GHz</td>
<td>2.01</td>
<td>Band #1 and #2</td>
</tr>
<tr>
<td>4GHz</td>
<td>1.29</td>
<td>Band #1 to #4</td>
</tr>
<tr>
<td>4GHz</td>
<td>0.96</td>
<td>After intra-band correction</td>
</tr>
<tr>
<td>8GHz</td>
<td>0.60</td>
<td>All 6 Bands</td>
</tr>
</tbody>
</table>

If we operate 7.5sec integration like VGOS, RMS will be 200 femto second!
Behavior of white noise component is observed until about 15 sec. One source has a duration of 7.5 sec integration in VGOS specification.
Great Advantages of Direct Sampling Technique

Advantages of Direct sampling

1. Simple and Smart
2. Small Delay variation between band
   Easy data processing and BWS
   Possibility to avoid P-cal device
   
   => Delay-Cal device is not necessary
Summary

1. Original developed Broadband feed for Cassegrain focus telescope is in progress.
   * Please contact us if you upgrade your antenna to Broadband!

2. The Super Broadband BWS (8GHz width) was achieved.
   * Delay precision reaches to sub-pico second.

3. We are proving the direct sampling technique is quite effective for broadband observation.
   * Interband delay/phase variations are small and stable because A/D conversion is made at once.
   * Pcal and D-cal device might be avoidable. To be investigated.
Acknowledgements

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