KSP DATA-ACQUISITION SYSTEM

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ABSTRACT

We have developed a new VLBI system based on the conventional K-4 system, whose data-acquisition mode includes VLBA and VSOP data modes. In developing the new VLBI data-acquisition system, multi-bit quantization sampling, high-speed (wide-bandwidth) data sampling, and the data acquisition mode were taken into consideration. The new acquisition system has one-bit and two-bit quantization sampling modes for VLBI, and four-bit and eight-bit sampling modes for general-purpose use. The total data rate is up to 256 Mbps, and up to 16 video channels can be selected. Anti-aliasing filtering is carried out in analog (32 MHz), and after sampling, the 16-MHz, 8-MHz, etc. filterings are carried out in the digital filter. The digital filter is used because it results in good phase characteristics. This system is specially designed for the Key Stone Project, and an input interface unit is incorporated in the VSOP.

1. Introduction

The conventional K-4 system, which is compatible with the Mark-III/K-3 system, has not only been the main VLBI data-acquisition system for domestic VLBI experiments in Japan, but has also been operated in other countries, including remote islands around Japan and Antarctica [1]. Since about 10 sets of the K-4 system are being operated, it is important for the new system to be compatible with the conventional one. The conventional K-4 system was designed for easy operation in remote stations, and was applied to the Antarctica project and the Marcus project [2]. The design concept was to achieve reliability, high-accuracy, and transportability. Each device of the K-4 system can be operated in stand-alone, which can be controlled via GP-IB. Reliability and transportability are achieved, and the K-4 is one-fourth the weight and one-fifth the size of the Mark-III or K-3 system.

We have developed a Key Stone Project (KSP) VLBI system based on the conventional K-4 system. The KSP VLBI system is being applied to the KSP which is a metropolitan-area crustal-deformation measurement project. The KSP system is already operated in daily observations in the Key Stone Project, for which an accuracy of 1 mm is achieved in every other day’s 24-hour experiments.

2. The KSP System

The high-end version of the K-4 system, the KSP system, has a maximum recording rate of 256 Mbps and its fully automatic operation is used in the Key Stone Project. To achieve high accuracy, it adopts digital filters instead of analog filters. The different features of these systems are given in table 1.

The KSP system has two families: one covers the Mark-III IF signal range (100 - 500 MHz), and the other covers the VLBA IF signal range (500 - 1000 MHz) for the KSP project. The KSP system and the conventional K-4 can be interfaced by video signal and tape data.

The KSP system consists of a reference distributor, an IF distributor, a local oscillator, a video converter, an input interface, a data recorder, and a digital mass-storage system (automatic tape changer).

The local oscillator synthesizes the local frequency signal for the video converter. The video converter converts windows in the IF signal input (100 - 500 MHz for the conventional system, or 500 - 1000 MHz for the KSP system) to video signals. The frequency is converted by the image-rejection mixer using single-sideband conversion. The input interface unit samples the video signal from the video converter. It then sends the digital data, together with the time data which is derived from an external time reference, to the data recorder. The digitized raw data output mode was provided for real-time VLBI. In the K-4 system, we adopted a rotary-head cassette recorder instead of a stationary head open reel recorder, which resulted in easy operation in the VLBI experiments. The bit-error rate after correction is better than 1×10^{-10}.

The KSP system (Fig. 1) was designed for astronomy and geodesy applications. It has a one- and two-bit quantization capability, a sampling rate of up to 64 Mbps/ch, multi-IF acceptability, a total data rate of up to 256 Mbps, and an automatic tape changer. A high-speed A/D converter with a threshold level control circuit, a digital filter, and a wide bandwidth image rejection mixer have been adopted in the new acquisition system. The system is optimized for frequency bandwidth synthesis. In the next section, we discuss the KSP system.

2.1. Reference Distributor

The system accepts 5-MHz or 10-MHz reference signals from hydrogen masers. Five 5-MHz and five 10-MHz output signals are obtained.

2.2. IF Distributor

The system accepts three IF signals from 500 MHz to 1000 MHz. Each signal is divided into eight signals, which are obtained for the video converter.

2.3. Local Oscillator

The local oscillator (Fig. 2) is specially designed for use with the KSP video converter. It supplies frequency and phase references to the converter in 10-kHz steps, which extracts video signals from the IF signal ranging from 500 MHz to 1000 MHz. The local oscillator outputs eight local signals, whose frequencies can be set locally or by remote control. Communications with a computer by the remote control are made through a conventional GP-IB interface. User-friendly messages are used for communication.

2.4. Video Converter

Image-rejection mixers (IRM) are integrated networks comprising an in-phase power divider, two double-balanced mixers and quadrature hybrids (networks). The primary function of the circuit is to separate the desired signal from its image. In the IRM the image (undesired) signal is separated from the desired signal by vector subtraction. Since we use a 16-ch, 16-Mbps (total 256 Mbps) data rate, we have adopted an 8-MHz IRM for the video converter (Fig. 2).

2.5. Input Interface Unit

A block diagram of the input interface unit is shown in Fig. 3. This unit quantizes the 16-channel (max.) video signal and produces a data train of up to 256 Mbps (max.). The acquisition system is provided with one-bit and two-bit quantization sampling modes for VLBI, as well as four-bit and eight-bit sampling modes for general-purpose data acquisition. This interface produces all of the clock signals. The phase of this internal 1-PPS signal is always compared with the leading edge of the external 1-PPS signal, and the error is within 3 clock lengths in terms of the 10-MHz clock.

The input interface measures the amplitude and phase of the 10-kHz phase calibration signals, which are included in the video signals, by product-detection with a set of phase-quadrature 10-kHz signals derived from the external 10-MHz reference signal.

The KSP input interface was designed so that it makes best use of the recording ability of the 256-Mbps recorder. Anti-aliasing filtering is done in analog (32 MHz), and after sampling, the 16-MHz, 8-MHz, etc. filtering are done by a digital filter. The digital filter is advantageous for obtaining good phase characteristics, and for reducing any coherence loss for the wide bandwidth. Suitable coefficients of the digital filter can be selected for each observation. For example, the digital filter can be used as a band-pass filter for line observations. The coefficients of the basic low-pass filter for Nyquist sampling are provided in the ROM.

The input part can convert data through A/D conversion at 64 Mbps by an 8-bit/sample to achieve a suitable data rate, sampling bit, and channels. The suitable quantization threshold level of the A/D converter is adjustable. In VLBI, the threshold level must be selected at 0.95σ ($\sigma = 0.224$ V for a 0-dBm input signal) [3], where σ is the conventional deviation of the input signal. Eight-bit A/D and bit reduction through digital filters result in good linearity for the two-bit mode.

This input interface can be interfaced in analog to the Mark-III system with no modifications, using some BNC cables. This input interface is adopted as a VSOP data-acquisition terminal, and is used in the KSP real-time VLBI system.

2.5.1. Data configuration

The configuration for one- and two-bit sampling is shown in table 2. It supports various terminals. The single asterisk indicates the Mark-III mode, the double asterisk indicates the VLBA data-acquisition mode, and VS indicates the VSOP data-acquisition mode. Although not necessary for ordinary VLBI, four-bit and eight-bit quantization sampling modes are provided, which are useful for general-purpose data acquisition. We are planning to apply this system for pulsar timing measurements and surveying, which require multi-bit sampling. The recorder-based system and real-time system using a high-speed ATM (asynchronous transfer mode) network can use the same data format.

2.6. Data Recorder

We adopted a rotary-head type recorder that uses a cassette tape (American National Standard Institute X3.175-1990 19-mm Type ID-1 Instrumentation Digital Cassette Format). The data recorder's error rates during recording and replaying can be read through a host computer. Helical-scan recording is used to record high-rate digital signals. With a large cassette, the K-4 recorder provides up to 770 Gbits of data-storage capacity. The recording time is 200 min. (large cassette, 16-μm thick tape), with a 64-Mbps recording rate. Recording and playback are possible at different data rates: 256, 128, 64, 32, and 16 Mbps, making the data recorder suitable for many different applications. The playback heads are placed so that the recorded data are immediately played back during recording. This read-after-write facility makes it possible to monitor the error conditions of recording in real time. The bit error rate after correction was better than 1×10^{-10}. The data recorder employs a built-in diagnostic system, which is designed to detect operation errors or hardware faults. Error messages or warning information is fed to the host computer via the remote control interface, and to the front panel display.

2.6.1. Data format

In the Mark-III format, there is 0.8% data loss due to the inserted time code. This data loss is undesirable for general-purpose use. The periodicity of the time code is undesired for spectrum analysis. Only the sampled raw data are desired. The K-4 recorder has helical data tracks, two longitudinal annotation tracks and a control track (Fig. 4). The VLBI data are recorded on the helical data tracks. A set of four helical data tracks has one track set ID number, which is a sequential number as a tape counter. The track set ID numbers are recorded on the control track, and can be read at any tape speed, even when fast forwarding or rewinding. There is an obvious relationship between the track set ID and the time code, and it is possible to manage the time code under the track set ID and time code block. The time data are written over the data train as the time code block in pre-observation. After the time-code block, the data timing is checked by track set ID, which means that the output data are only raw data digitized during observation. A data format fully compatible with the conventional K-4 system is also provided.

2.7. Digital Mass Storage System (Automatic Tape Changer)

In KSP, we adopted an automatic tape changer as a digital mass-storage system. The system accommodates one tape drive and 24 tapes, or two tape drives and 16 tapes. The mass-storage capability is up to 2.3 TB. A barcode reader is built into the cassette-handling system to identify individual cassettes within the mass-storage system. Information from the barcode reader is available to the host controller via the remote control interface, and is written on the log which is utilized for correlation processing.

3. New IRM

To achieve a high SNR (signal-to-noise ratio) and to utilize the ability of the input interface (64-Msample/sec), an image-rejection ratio of better than 20 dB over 32 MHz is required.

Figure 5 shows the measured image-rejection ratio of the prototype of the IRM currently being developed. The horizontal axis shows the frequency from DC to 100 MHz on a linear scale, and the vertical axis shows the detected power and image rejection ratio on a log scale, with 10 dB per division. The upper line shows the detected power of the desired sideband signal, and the middle line shows that of the undesired (image) sideband signal. The lower line shows the image rejection ratio calculated by the differential of the two upper lines. This result satisfies the requirements of the full specification of the K-4 system.

This IRM has not been in produced commercially.

4. Coherence estimation

We now discuss the coherence loss of the K-4 VLBI systems. The detailed coherence estimation is described in reference [4].

4.1. Video Conversion

4.1.1. Image leakage (this is shown in the image rejection ratio)

The coherence loss of imperfect image rejection is a loss of cross-talk from the opposite sideband. In conventional VLBI, the observed data are affected by the Doppler shift caused by the earth's rotation.

This is called "fringe rotation". We must consider the coherence loss in two cases, with and without fringe rotation. This is because of the fringe rotation is different between the upper side band and the lower side band. The image signals have a weak correlation in the case of no fringe rotation, however. If the image-rejection ratios for two stations are 19.5 dB and 22 dB, the coherence loss is 0.87% with fringe rotation and 0.04% without fringe rotation.

4.1.2. Phase noise of local signal

The phase noise of the 10-kHz step synthesizer decreases the signal coherence. The phase noise is measured in Allan variance. The coherence loss (Lc) caused by any instability of the frequency standard can be calculated [5, 6, 7] from the Allan variance.

The actual values of the K-4 system are given in table 3. The measured phase noise was found to be white phase noise. The measured phase noise of the KSP system is better than that of the K-4 system; we obtained an $\alpha_p= [\sigma_y(t=1s)]^2$, which is less than $(3x10^{-11})^2$ at 500 MHz as the worst case. The estimated coherence loss (worst case) caused by phase noise is less than 0.15%.

4.1.3. Imperfect band pass

The anti-aliasing filters are composed of 7th order butterworth low-pass filters (9th order butterworth low-pass filters for the KSP system). The loss L_C caused by an imperfect band pass can be estimated using the method described in reference 5 and 6.

The worst case of coherence loss of the K-4 system is as follows:

imperfect band pass = 1.28 %

4.1.4. Aliasing noise

If under sampling occurs, there is a component whose frequency is more than half of the sampling frequency. The digitized data has some deformation caused by aliasing noise. The coherence loss is defined by L_C, and it is calculated using the method described in 5 and 6.

The worst case of coherence loss of the K-4 system is as follows:

aliasing noise = 1.99 %.

4.2. Sampling

4.2.1. Fuzzy digitizing

Analog input video signals are digitized (1-bit sampling) by comparators. There is a region of fuzzy digitizing because of the offset and hysteresis of the comparator. The results for a measurement of the sampling characteristics are shown in Fig. 6. If the input signal power is 0 dBm then V_e = 0.224 V, and V_O is smaller than 2 mV (<1mV: KSP). The coherence loss is less than 0.36 %.

The calculated coherence loss, in the worst case of a 2-mV DC comparator offset, is less than 0.052 %.

4.3. Formatting

In the Mark-III format, there is 0.8 % data loss due to the insertion of the time code (160-bit time-code in each 20000-bit data). The inserted time-code in Mark-III format has the role of canceling the effect of dynamic skew caused by the difference of channel-timing of a stationary head, and frequently inserted time-codes are indispensable for a high error rate recorder (bit error rate from 10^{-4} to 10^{-6}). The Mark-III format is redundant for the K-4 system, and it is not suitable for general-purpose use. We adopted a new format (sub-section 2.6.1. and Fig. 4).

5. Overall coherence check of the K-4 VLBI system [4]

We made an overall coherence check.

5.1. Measurement method

The block diagram of the measurement system is shown in Fig. 7. Two independent interrelated systems were used: system A and system B. It is possible to change the S/N in order to obtain the relationship between the correlated amplitude and the S/N ratio. The signal source is a noise diode instead of a signal from a star, and the signal is stable in amplitude so it is suitable for coherence measurement. This signal from the noise diode is divided and injected into system A and system B through a 40-dB directional coupler at the low-noise amplifier (LNA) input port. X-band sky noise is used as a noise source for system A and S-band sky noise is used for system B. The coefficient of cross-correlation function ρ_o estimated from the system temperature is as follows:

$$\rho_o = \sqrt{\frac{\{S_1 * S_2\}}{\{(N_1 + S_1)*(N_2 + S_2)\}}} \quad ,$$

where S_1 = signal temperature in system A,

S_2 = signal temperature in system B,

N_1 = system noise temperature in system A, and

N_2 = system noise temperature in system B.

The coherence can be estimated by the next equation. ρ_1 is the coefficient of the cross-correlation function from the correlation processor.

$$Coherence\ loss = 1 - \frac{\rho_1}{\rho_o}$$

The relationship between ρ_1 and ρ_o is shown in Fig. 8. ρ_1/ρ_o shows coherence. If ρ_1/ρ_o is 1, then coherence is 1. Here, coherence (= 0.975) was obtained as an inclination of ρ_1/ρ_o from Fig. 8. The overall coherence loss was 2.5% at 250 MHz, but that does not include the loss due to aliasing noise in the case where there was no fringe rotation. Table 4 shows a summary of the estimated coherence loss as discussed above.

The estimated total coherence loss is less than 5% in K-4 VLBI data acquisition systems, but this value does not include the correlation processing loss or the atmosphere loss, fringe stopping, phase scintillation etc. The measured coherence loss of the K-4 system was less than 5%.

6. View of the acquisition system

A photograph of the data acquisition system is shown Fig. 9. From the left side, we have an ATM transmitter, a weather monitoring rack, an antenna control rack, a receiver control and monitoring rack, and a backend rack, a digital mass-storage system. Three IF signals are received by IF receivers in the receiver control and monitoring rack. The IF signals are sent to an IF distributor in the backend rack. The two units of video converters (500 - 1000 MHz: 8 ch/unit) convert the IF signal to video signals.

The other video converter (100 - 500 MHz: 16 ch/unit) is a conventional K-4. The video signals are sent to the input interface (black panel), and the digital data is sent to the digital mass-storage system. The data is recorded on the magnetic tapes, or by-passed to the ATM transmitter.

7. Conclusion

We have developed a new VLBI system based on the conventional K-4 system. The KSP data acquisition mode includes VLBA and VSOP data modes. The digital filter has good phase characteristics. Daily observations are carried out automatically at a remote station, in the KSP. An input interface unit is incorporated in the VSOP. We estimated and measured the coherence loss in the worst case, and the measured coherence loss of the K-4 system was less than 5%. This shows that the K-4 systems perform well enough for the VLBI experiments.

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Fig. 1. Block diagrams of the KSP system.

(observing station configuration)

Fig. 2. Block diagram of the KSP video converter and local oscillator.

Fig. 3. Block diagram of the KSP input interface.

Fig. 4. Tape format and data format.

Fig. 5. Measured image rejection ratio of the prototype image rejection mixer.

Upper line : detected power of the desired sideband signal,

Middle line : detected power of the undesired (image) sideband signal,

Lower line : image rejection ratio calculated by differential of two upper lines.

Fig. 6. Measured sampling characteristics.

Fig. 7. Block diagram of the measurement system.

Fig. 8. Results of overall coherence check.

Fig. 9. A photograph of the data acquisition system

Table 1. The different features of K-4 systems and other VLBI systems.

Table 2. KSP data configuration.

* = Mark-III mode, ** = VLBA mode, vs = VSOP mode

Table 3. Measured phase noise.

Table 4. Summary of coherence loss.