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Overview of the Single Pixel Feed Receiver System of Square Kilometer Array MID Telescope

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Abstract

The Square Kilometre Array (SKA) project is an ambitious international effort to build the world's largest radio telescope with an unprecedented sensitivity because of its huge collecting area. SKA will be a distributed observatory with radio telescopes at two different radio-quiet sites, SKA-MID in South Africa and SKA-LOW in Australia [1]. The first phase of SKA-MID telescope (SKA1-Mid) will consist of a 150-kilometre diameter array of 197 offset Gregorian antennas (dishes). This paper describes an overview of recent progress on design, test, and integration of the Single Pixel Feed Receiver (SPFRx) system of SKA1-Mid telescope.

Introduction:

The SKA1-Mid telescope will be able to achieve high sensitivity over a wide frequency range starting from 350 MHz to 15.4 GHz. This total observational bandwidth is segmented into 6 frequency bands (Band 1, 2, 3, 4, 5a, 5b). Each antenna (reflector dish) is equipped with feed packages, that are precision positioned in the sub-reflector focus by a feed indexer platform [2]. The Single Pixel Feed (SPF) is the first point in the SKA1-Mid signal chain, comprised of feed horn antenna package, converts electromagnetic (EM) signals focused by dish reflectors into dual linearly polarized radio frequency (RF) signals that can be processed in analog and digital domains. SPF also consists of a noise calibration unit and gain blocks. The RF signals from the SPF pass through a pair of 50-Ohm coaxial cables to the single pixel feed receiver (SPFRx) system. The main task of SPFRx is to condition the incoming RF signals, perform analog-to-digital conversion forward the digitized RF samples to SKA1-Mid Central Signal Processor (CSP).

SPFRx Overview:

The single pixel feed receiver is a key performance-determining sub-system, because of its impact on telescope sensitivity, through signal-to-noise ratio (efficiency) and linearity of analog and digital components. The architecture of the SPFRx aims to achieve the following specific objectives:

- maximize linear dynamic range without compromising noise performance.
- minimize the number of components directly in the analog path to increase the stability, this indicates the signal conversion from analog-to-digital should be close to RF frontends.
- minimize the electrical lengths of interconnects to reduce the ripple from impedance mismatch, loss, and temperature variation.
- maximize immunity to interference, both to radio frequency interference (RFI) as well as coupling between polarization channels. The region around the focal point of antennas will be extremely sensitive to electromagnetic interference (EMI), therefore the number of electronics devices, especially the digital circuits, should be minimized, and those that are essential must be sufficiently shielded.
- minimizing the contribution to mass on the focal platform, as the focal point (dish indexer) of reflector antenna is a cantilevered structure. This is a challenge because thermal stability requirements and EMI shielding yield to heavy structures.

The above-mentioned objectives have led to a three-sectional design of the SPFRx: Two EMI shielded enclosures at the dish indexer (named as Receiver Sampler or RXS) for Band123 and Band45, and one shielded unit in the pedestal of the antenna (named as Receiver Pedestal Unit or RXPU). The two enclosures located at the dish indexer include the analog components, ADCs with minimal digital support circuitry. Since the RXSs are placed on the indexer, SPF to SPFRx connecting coaxial cables are short and therefore minimize loss, gain-slope, and ripple from impedance mismatch, and maximize the stability of the RF signal chain. The digital signal processing hardware, which tends to emit high levels of EMI, is in the dish pedestal, enclosed in multiple layers of shielding.
Figure 1 depicts the SPFRx device locations. Although the RXS123 and RXS45 enclosures are open to the ambient

environment, they have been designed to maintain the required thermal stability without the need for active cooling. The enclosure-design thermally isolates the power supply, a major source of heat, from the temperature sensitive signal-chain components.

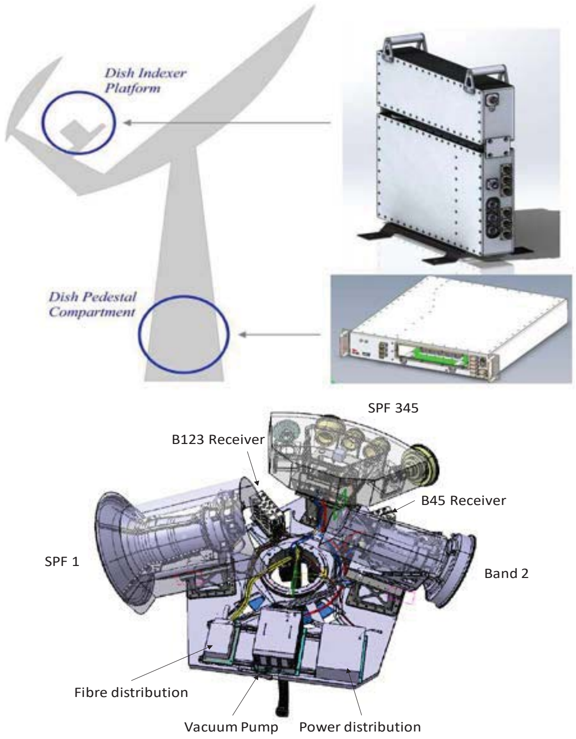

Figure 1: (Top) SPFRx Device Locations on Dish, (Bottom) Layout of the Dish Indexer showing the RXS123 and RXS45 enclosure positions.

SPFRx Elements' Functional Description

This section describes the functional building blocks of SPFRx. Figure 2 outlines the simplified block diagram.

SPFRx RF Analog Signal Chain (RXS123.RF)

The RF signals from the SPFs (two polarizations for each band) are transported for a short distance over coaxial cables and enter the RF conditioning units of the RXS. This section sits inside the RF cavity of the RXS enclosure. Here the RF signals are passed through the following major components:

- RF limiters to protect the analog chain from damage by excessive input power.
- Band-specific filters to reject the out-of-band interferences, hence avoiding the aliasing of sampled signals from adjacent Nyquist zones.
- Variable Gain Block (VGB), which connects to the specific band using band select switch and provides the necessary amplification using a combination of amplifiers, variable digital step attenuators, filters, equalizer. The variable gain serves to accommodate the different science targets and observing conditions.

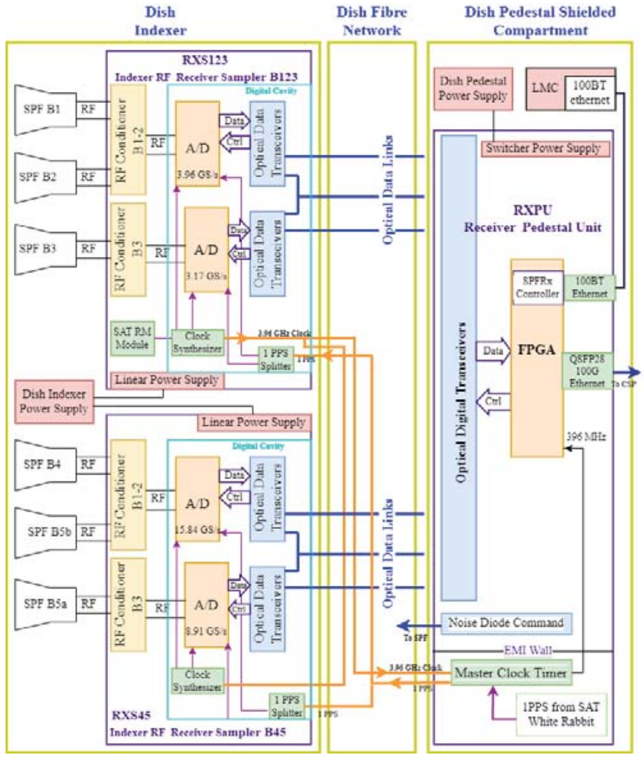

Figure 2: Simplified Block Diagram of SPFRx

SPFRx Digitizer (RXS123.ODL)

The Optical Digital Link (ODL) architecture used for the receiver offers the best compromise between RF performance and EMI suppression by distributing the system components between the feed indexer and the shielded compartment in the dish pedestal. The RXS.ODL is located inside the digital cavity of the RXS, and the major components of this module are:

- High performance ADCs.
- Optical transceiver for transmission of sampled data and control from ADC to RXPU digital signal processor.
- High-speed SERDES transceiver to perform serial-to-parallel and parallel-to-serial data conversion and optical transmission of the monitoring and control signals.
- Narrowband balun to convert the single-ended 50-Ohm clock signal to differential 100-Ohm signal without additive jitter.
- Broadband balun for single-ended to differential impedance conversion of the RF chain.
- ADC SYNC input to tag the RF samples with a 1 pulse per second marker (1pps).
- Local temperature sensors.

- Low-dropout (LDO) linear voltage regulators to supply power to the ADC and other support circuits.

Synchronization & Timing Receiver Module (SAT.RM)

The entire SKA1-Mid system is synchronized by distributing phase-locked reference signals to each antenna [4]. The reference frequency distribution system's endpoint SAT.RM delivers a nominal 3.96 GHz frequency to the RXS123 enclosure on each antenna. Location of SAT.RM inside RXS123 ensures minimum coherence loss due to path delay. SKA1-Mid implements the Sample Clock Frequency Offset (SCFO) scheme to suppress digitizer-generated self-interference and out-of-band interference by employing different sample clock frequencies at each dish. SAT.RM provides 3.96 GHz plus a unique offset frequency to the RXS123 of each antenna. This clock is then used to generate various sampling clocks for the respective bands.

RXS clock synthesizer (RXS123.CLK)

This module inside the digital cavity receives and conditions the 3.96 GHz clock signal to be used by the Band1-2 ODL and synthesizes the 3.168 GHz clock for Band3 ODL.

Once initialized, all the ADCs are clocked continuously to ensure that the coherence is maintained while switching between frequency bands.

The data sampling rates, bit depths, and sampling clock frequencies for bands 1-5 are detailed in Table 1.

Table1: Summary of SPFRx digitization parameters. Frequency offset index 'k' ranges from 1 - 2222.

Band	RF Freq. (GHz)	Digitized Band-width (MHz)	Sampling Rate (GSps)	Nyquist Zone	Transport Sampling Rate (GSps)	Transport bit depth
1	0.35 – 1.050	700	3.96 + kΔf	1	3.96 + kΔf	12
2	0.95 – 1.760	810	3.96 + kΔf	1	3.96 + kΔf	12
3	1.65 – 3.050	1403	3.168 + 0.8kΔf	2	3.168 + 0.8kΔf	12
4	2.80 – 5.180	2380	15.84 + 4kΔf	1	5.94 + 1.5kΔf	8
5a	4.60 – 8.500	2x2500	8.91 + 2.25kΔf	2	2(5.94 + 1.5kΔf)	4
5b	8.30 – 15.40	2x2500	15.84 + 4kΔf	2	2(5.94 + 1.5kΔf)	4

Receiver Pedestal Unit (RXPU):

The RXPU enclosure has two compartments inside, one houses the RXPU Digital Processor (RXPU.DGP), and another consists of the Master Clock Timer (MCT) board. The RXPU.DGP receives ADC sample data streams of all bands, processes all the data streams, converts data into the required format for transmission to the CSP via the 100G Ethernet link. The Intel Stratix-10 based TALON-DX FPGA board developed by NRC for the SKA1-Mid correlator [3], is selected for RXPU digital processing. The Stratix 10 FPGA also hosts an embedded Linux computer (SPFRx Controller) which performs the monitoring and control functions of the SPFRx and provides the interface to the dish local monitor and control (LMC).

The Master Clock timer (RXPU.MCT) unit sits inside RXPU, distributes the 1pps timing signal to the ADCs for time stamping. Timing distribution is carried out by a White Rabbit solution. The MCT derives a 396 MHz clock from the 3.96 GHz optically transported from the RXS123 and sends it to the FPGA board to keep the FPGA internal clocking in sync with the RXS sampling clocks.

SPFRx Measurements and Results

Extensive tests and validations are in the process of being carried out at present, a few of the results have been shown in this paper. The ENOB testing was done for Band123, also validated in different temperature ranges. The Figure 4 represents that all the three bands meet the SKA1-Mid minimum ENOB requirement – 8 bits for Band1 and Band2, 6 bits for Band3.

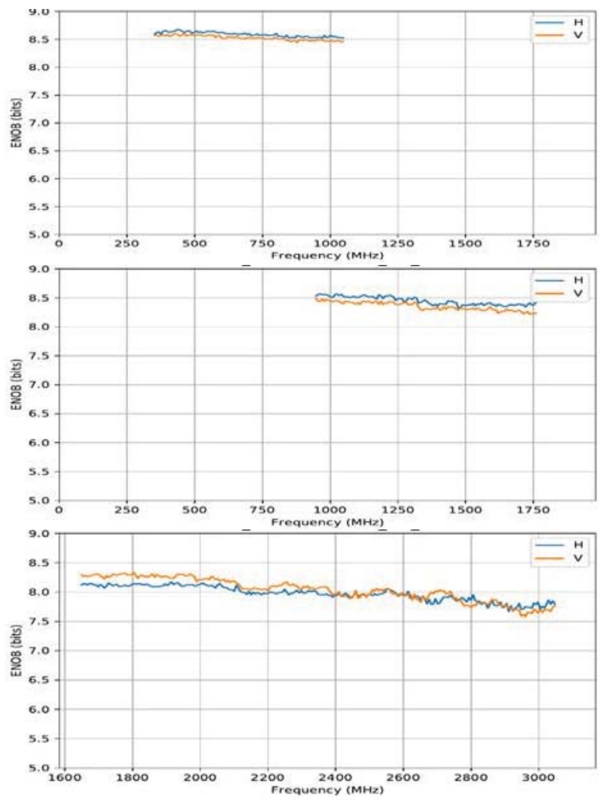

Figure 4: Effective Number of Bits (ENOB) plots for Band1 (top), Band2 (middle), Band3 (bottom)

In the figures, H and V signals correspond to the two polarizations: Horizontal and Vertical. Figure 5 depicts SPFRx Band2 gain stability plot, which meets SKA requirement to have a wide band gain stability over 5 seconds, when sampled with 20 milliseconds intervals, of

<=0.05% RMS (under standard and degraded operating conditions and in the absence of interfering signals).

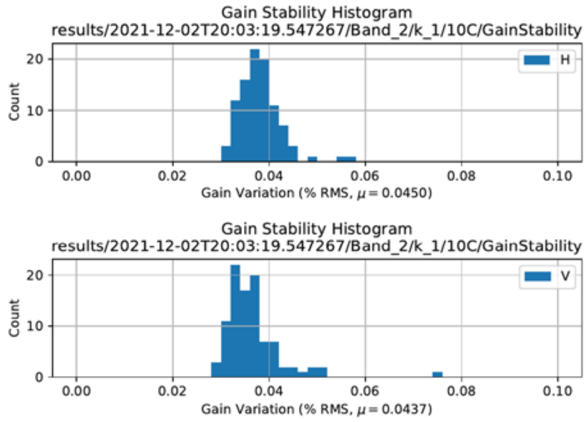

Figure 5: Gain stability plot for Band2.

Figure 6 shows the measurement of Band1 phase stability tested on two corner frequencies 350 MHz and 1050 MHz. The results meet requirement of phase stability <= 8° peak to peak and <= 0.5° RMS, over 5 minutes when sampled with 5 seconds of intervals.

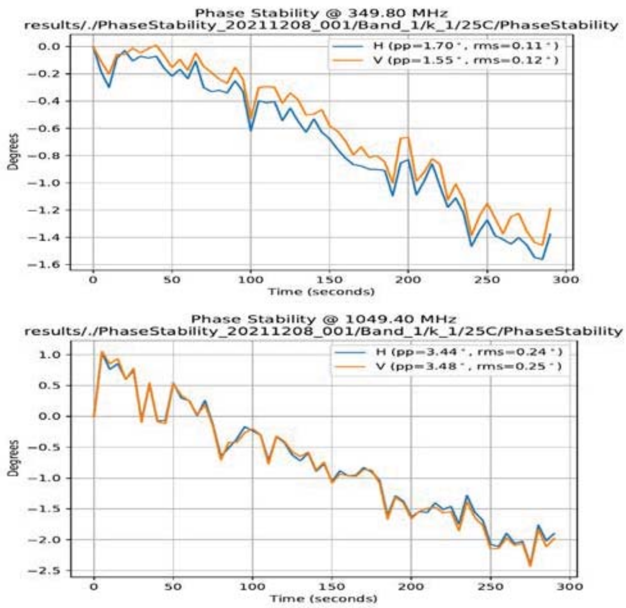

Figure 6: Phase stability plot for measurement on two corner frequencies of Band1.

One of the crucial parameters of the SKA1-Mid signal chain is the suppression of RF occurring outside the selected frequency bands. Figure 7 shows the out-of-band suppression plot for Band2 which meets the requirement of a minimum of 40 dB out-of-band suppression, although the V polarization line shows 5 dB in-band deviation, improvement work is in progress.
Figure 8 depicts the zoomed plot of the passband spectra of Band1, tested with a wideband noise signal as input, representing passband flatness that meets SKA SPFRx requirement of <2 dB peak-to-peak variation in gain.

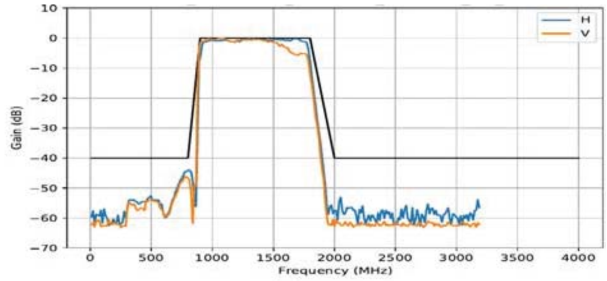

Figure 7: Anti-aliasing filter Out-of-band Suppression measurement for Band2.

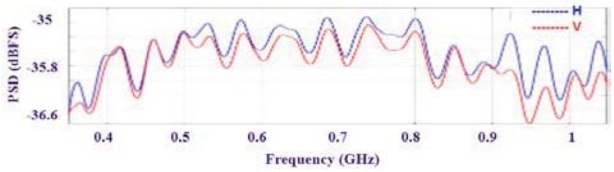

Figure 8: Passband flatness measurement for Band1.

Conclusion

An overview of the design and prototyping of the Single Pixel Feed Receiver System for the SKA1-Mid telescope has been discussed in this paper. The Band123 receiver system design details and some measurement results have been provided, while the Band45 receiver design and testing is still in progress. Detailed qualification tests for the SPFRx system are being carried out at the time this paper is written and will be subject to future publications.

Acknowledgements

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