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MEERKAT FUNCTIONAL INTERFACE CONTROL DOCUMENT

FOR

CORRELATOR BEAMFORMER VISIBILITIES AND TIED ARRAY DATA

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Author .... S Dennehy
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	Name	Designation	Affiliation	Signature /Date
Submitted by	S. Dennehy	CBF SE	SKA SA	
Accepted by	JR Manley	CBF TL	SKA SA	
Accepted by	S Ratcliffe	SP Subsystem Architect	SKA SA	
Accepted by	T Bennett	SP SE	SKA SA	
Approved by	T Abbott	MeerKAT SE	SKA SA	

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COMPANY DETAILS

Name	SKA SA, CPTN Office (Pinelands, Western Cape)
Physical/Postal Address	3rd Floor, The Park, Park Road Pinelands, Western Cape 7405
Tel.	+27 21 506 7300
Fax.	+27 21 506 7375
Website	www.ska.ac.za

Table of Contents

LIST OF FIGURES

LIST OF ABBREVIATIONS

AR	Antenna Release
CBF	Correlator Beam Former
CMC	Correlator Master Controller
DBE	Digital Back End
GbE	Gigabit Ethernet
ICD	Interface Control Document
ROACH	Reconfigurable Open Architecture Computing Hardware
OSI	Open Standard Interconnection Model
RS	Requirement Specification
RTS	Receptor Test System
SE	Systems Engineering
SEMP	Systems Engineering Management Plan
SKA	Square Kilometre Array

1. INTRODUCTION AND SCOPE

1.1. Identification

This document describes the radio astronomy data products issued across data interface I.TE.SD.2 by MeerKAT's Correlator-Beamformer (CBF) real-time signal processing system.

The requirements for this interface are captured in the CBF-SP Interface Requirements Definition (IRD) document [1]. The CBF uses the SPEAD protocol [2] for the transfer of data products to subscribers, which could include the Science Processor (SP) and/or User-Supplied Equipment (USE).

This ICD will be expanded and updated to keep track of the interface for each MeerKAT array release milestone.

In this document all references to the "system" apply to the Meerkat telescope system.

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1. Applicable Documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, the applicable documents shall take precedence.

[1] **INF-8438i** Specification for QSFP (Quad Small Formfactor Pluggable) Transceiver Rev 1.0 November 2006

[2] **IEEE Std 802.3ba** Media Access Control Parameters, Physical Layers, and Management Parameters for 40 Gb/s and 100 Gb/s Operation

[3] **IETF RFC 791** Internet Protocol

[4] **IETF RFC 2460** Internet Protocol, Version 6 (IPv6) Specification

[5] **IETF RFC 782** Transmission Control Protocol (TCP)

[6] **IETF RFC 2131** Dynamic Host Configuration Protocol (DHCP)

[7] S Dennehy, **M1200-0000-000**, Correlator-Beamformer Requirement Specification

2.2. Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, this document shall take precedence:

[8] Peens-Hough and C. Gumede. **M1000-0001-060**, Meerkat CBF-SP Interface Requirements Document.

[9] Jason Manley, Marc Welz, Aaron Parsons, Simon Ratcliffe, **SSA4700-0000-001**, SPEAD: Streaming protocol for exchanging astronomical data.

[10] Adriaan Peens-Hough, **M2100-0000-001**, Receptor Test System Requirement Specification.

[11] Mark Weltz, **M1000-0001-002**, Meerkat Correlator-Beamformer Control and Monitoring Interface Control Document.

[12] Simon Ratcliffe https://github.com/ska-sa/PySPEAD

[13] Jason Manley, SPEAD Identifier Listing - https://docs.google.com/a/ska.ac.za/spreadsheet/ccc?key=0AiI9RgeE5psidDJ5amFxQWQ4MTA0VjZZS19WRXFCQ1E&usp=drive_web#gid=0.

3. INTERFACE DEFINITION

3.1. Interface Identification

This document specifies the details of the functional interface I.TE.SD.2 between the Correlator Beamformer and data subscribers, as listed in [7].

3.2. Array Releases

3.2.1. Receptor Test System

The Receptor Test System (RTS) CBF uses an FX-correlator architecture that outputs correlated visibility data for all baselines, full cross-polarisation on 8 independent inputs (designed for 4 dual-polarisation antennas).

RTS is deployed on ROACH-2 hardware.

As per reference [10], the RTS delivers the following channelisation products:

- Wideband course L-band: 4096 channels over the full bandwidth (856MHz), giving a channel bandwidth of 208.98kHz
- Wideband fine L-band: 32768 channels over the full bandwidth (856MHz), giving a channel bandwidth of 26.12kHz
- RFI/Holography narrowband L-band: 32768 channels over 856/8=107MHz, giving a channel bandwidth of 3.27kHz

Note that an RFI data product is not available.

The resultant maximum data rate is 4 Gbps. The link between CBF and subscribers will be carried on one 40GbE link.

3.2.2. Array Release 1

Array Release 1 (AR-1) is also deployed on ROACH-2. Due to the size of this system, a larger data switch is required, and the system is distributed over multiple racks in the Karoo Array Processing Building (KAPB). AR-1 is an up scaled version of RTS, with the following added functionality:

- Support for UHF band channelisation products.
- Support for up to 32 inputs (16 dual-polarisation antennas).
- Support for a single TA beam (channelised voltage) with 32768 or 4096 channels over MeerKAT’s full L-band bandwidth.
- Support for a small voltage buffer consisting of 4096 ADC samples up scaled to 16 bits at native sampling rate (nominally 1712Msps). This can be used for debugging and gathering signal statistics.
- Support for simple sub-arraying , with possible combinations including:
  - five sub-arrays of 8 inputs, or
  - two sub-arrays of 16 inputs together with one sub-array of 8 inputs, or
  - a single array of 32 inputs together with one sub-array of 8 inputs.

The resultant maximum data rate is 121 Gbps. The link between CBF and subscribers will be carried on four 40GbE links.

3.2.3. Array Release 2

Array release 2 (AR-2) is deployed on ROACH-3 using 40GbE interconnect. AR-2 is an up scaled version of AR-1, with the following added functionality:

- Processing capacities permitting, any combinations of any supported instruments are possible.
- Support for up to 64 inputs (32 dual-pol antennas).
- Support for four TA beams (channelised voltage and correlation products) over MeerKAT’s full L-band bandwidth using wideband channelisation (32768 or 4096 channels).
- Support for incoherent summation of 4, 8, 16 or 32 inputs, 32768 or 4096 channels and integration periods of approximately 50μs.Fixed
- Support for antenna correlation products over MeerKAT’s full L-band bandwidth, using wideband channelisation (32768 or 4096 channels).
- Support for independently tuneable 13.375MHz (1712Msps/128) bands with 4096 channels each (Nf).
- Support for independently tuneable 6.6875MHz (1712Msps/256) bands with 4096 channels each (Nd).
- Support for simple sub-arraying, with possible combinations including:
  - nine simultaneous sub-arrays of 8 inputs, or,
  - four sub-arrays of 16 inputs, together with one sub-array of 8 inputs, or,
  - two sub-arrays of 32 inputs, together with one sub-array of 8 inputs, or,
  - a single sub-array of 64 inputs, together with one sub-array of 8 inputs.

The resultant maximum data rate is 253 Gbps. The link between CBF and subscribers will be carried on ten 40GbE links.

3.2.4. Array Release 3

Array Release 3 (AR-3) is also deployed on ROACH-3 using 40GbE interconnect. AR-3 is an upscaled version of AR-2, with the following added functionality:

- Processing capacities permitting, any combinations of any supported instruments are possible.
- Support for up to 128 inputs (64 dual-pol antennas).
- Support for simple sub-arraying, with possible combinations including:
    - 20 simultaneous sub-arrays of 8 inputs, or,
    - nine sub-arrays of 16 inputs, together with one sub-array of 8 inputs, or,
    - four sub-arrays of 32 inputs, together with one sub-array of 16 inputs and another with 8 inputs, or,
    - two sub-arrays of 64 inputs, together with one sub-array of 16 inputs and another with 8 inputs, or,
    - a single sub-array of 128 inputs, together with one sub-array of 16 inputs and another with 8 inputs.
- VLBI *(TBD)*.

The resultant maximum data rate is 602 Gbps. The link between CBF and subscribers will be carried on twenty four 40GbE links. Sixteen 40GbE links are allocated to Science Processing, and eight for User Supplied Equipment.

The number of ports available for data subscribers can be expanded to one hundred and twenty four (124) 40GbE ports with no change in switch architecture.

3.3. Interface Boundary of Responsibility

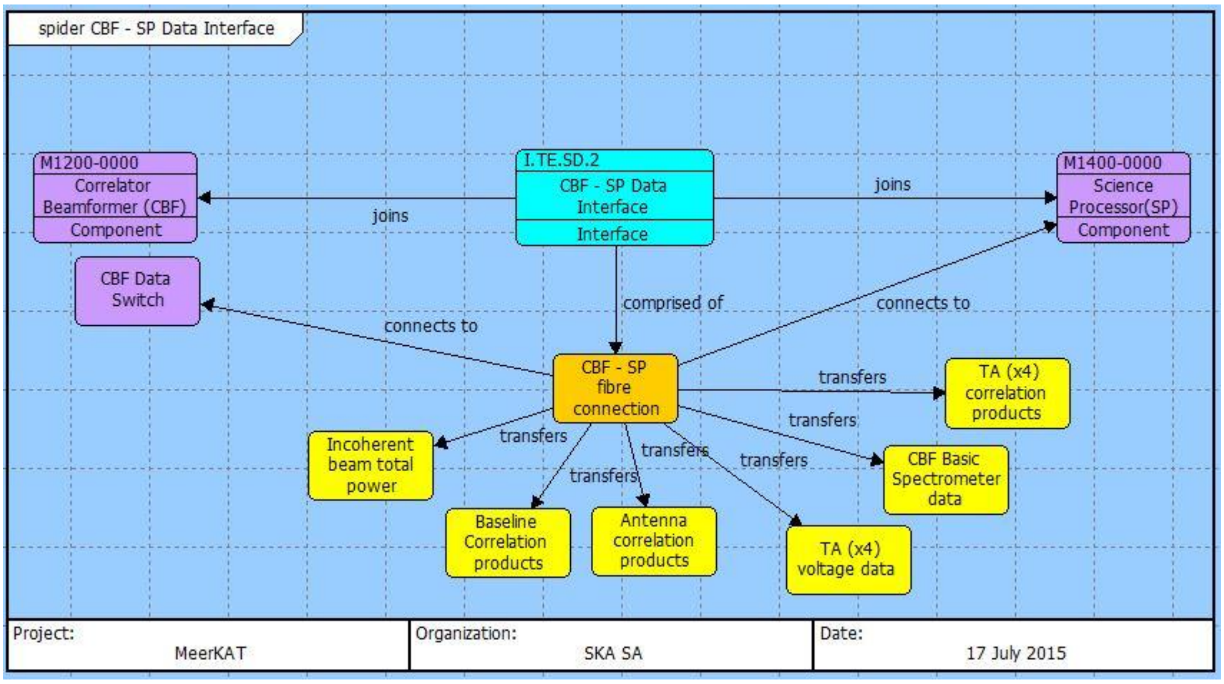

Figure 1: Boundary on responsibility on interface

3.4. Interface description

The functional interface is described in terms of Layers 1, 2, 3, 4 and 7 of the OSI model.

3.4.1. Physical Layer

The physical interconnect shall be on multiple QSFP [1] ports on a Mellanox SX1710 switch.

The number of physical interconnects is stated in [8]

3.4.2. Data Link Layer

The data link layer of this interface shall be compliant with IEEE 802.3ba [2] (40GbE over fibre).

3.4.3. Network Layer

The network layer shall be compliant with both Internet Protocol (IP) Version 4 (as described in IETF RFC 791 [3]) and IP Version 6 (as described in IETF RFC 2460 [4]).

The CBF-SP network layer shall be compliant to Dynamic Host Configuration Protocol (DHCP) version 4 (as described in IETF RFC 2131 [6]), with the DHCP master being the CBF.

3.4.4. Transport Layer

The transport layer of this interface shall be compliant with TCP/IP protocol (as described in IETF RFC 782 [5]).

3.4.5. Application Layer

The application layer shall be compliant with SPEAD [9].

All data products are sent in multicast groups, assigned via the CAM interface.

3.4.5.1. Data Exchange Protocol

Sub-arrays are defined and instruments added using the CAM link [11]. As instruments are added to sub-arrays, and before the start of the data transmission, initial *ItemDescriptor* packets are sent as a number of metadata packets. These are issued during instrument initialisation, which can take up to 60 seconds.

In addition to instrument configuration parameters, these metadata *Heaps* contain the setup information of any *Item*s required to transport the CBF data product payloads. Once the descriptors have been transmitted, the receiver will be in a position to decode the option fields. These *ItemDescriptor* packets are typically issued by a control computer (the Correlator Master Controller, or CMC), and not by the FGPAs, even in cases where the FPGAs stream the actual SPEAD data. This leverages SPEAD's ability for multiple transmitters to contribute data to a single receiver in order to simplify the FPGA designs.

Once instrument initialisation is complete and all the the data product descriptions have been issued, data product transmission may be started by issuing a capture-start command over the out-of-band CAM link [11]. On receipt of the capture-start command, a SPEAD stream start packet will be issued.

A detailed description of the format of the *ItemDescriptor* packets can be found in Reference [12]. In general, an *ItemDescriptor* is a special SPEAD *Item* that may contain such metadata *Item*s such as NAME, DESCRIPTION, TYPE, SHAPE and ID. This metadata allows the receiver to automatically unpack and interpret the datastream. Section 3.4.5.1 describes the metadata and dataproducts associated with each instrument.

For example, any instrument implementing a per-channel gain control will require a number of parameters to describe the digital gain setting on each frequency channel for every ADC in the sub-array. The configured parameters for this gain control will differ for individual observations, and is dependent on the sky temperature. The settings for a given observation are propagated to the data receiver to be stored with the actual output datastream of the instrument.

A complete list of all SPEAD metadata *Items* can be found in Reference [13], which lists all known SPEAD *Identifiers*.

In the CBF implementation, retransmission of all the metadata may be requested at any time, through the out-of-band CAM KATCP control interface [11]. This is to allow any new receivers to lock on to an existing datastream.

3.4.5.1.1. Multiple Sub-Arrays

Each sub-array operates completely independently, and can redirect its data products to independant multicast groups.

3.4.5.1.2. Intermediate products shared by multiple instruments in the same sub-array

Each beamformer will share channelisers with a correlator. Anything affecting one instrument's channeliser also affects the other instrument. For example, changing the digital gain or phase centre of the correlator will also affect the beamformer. How these updates will be advertised and propogated is *TBD*.

3.4.5.2. Instruments

3.4.5.2.1. Baseline Correlation Products

For the FX correlator, all the SPEAD data descriptors and metadata relevant to a selected configuration are issued to the assigned receiver IP and port. The port and IP is assigned on command via the CAM interface. The following steps are performed, in order, upon instrument initialisation:

1. Send a single SPEAD heap containing the ItemDescriptors and system time synchronisation items.
2. Send the SPEAD heaps containing all the ItemDescriptors and initial values for the system's digital gain stages as each input is initialised.
3. Send the SPEAD heaps containing the ItemDescriptors and initial values of the labels, i.e. the names of all physical inputs, as well as baseline ordering as each input is initialised.
4. Send a single SPEAD heap containing the static ItemDescriptors and initial values for most static variables and system parameters.
5. Send a single SPEAD heap containing the ItemDescriptors only for the FPGA-based output products, to enable receivers to decode the emitted data.

Each stage is detailed below, along with its initial values. Note that, while indicative of typical received values, the initial values are subject to change. Unless otherwise noted, the initial values are for the c16n856M32k (32768 channel wideband) data product.

3.4.5.2.1.1. Baseline Correlation Products Static metadata

Data descriptors and initial values for all correlator-specific static metadata are emitted in a single heap. The static metadata is issued whenever:

- the system initiates a correlator or beamformer data product,
- the user explicitly requests a metadata reissue,
- if the center frequency selection changes in a narrowband data product, when the CBF is only processing a subset of the digitised bandwidth.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description	Initial value
				Static metadata	
0x1007	adc_sample_rate	('u',64)	1	Expected ADC sample rate (samples/second)	1712000000
0x1008	n_bls	('u',spead.ADDRSIZE)	1	The total number of baselines in the data product. Each pair of inputs (polarisation pairs) is considered a baseline.	40
0x1009	n_chans	('u',spead.ADDRSIZE)	1	The total number of frequency channels present in any integration.	wc=4096, wf=32768
0x100A	n_ants	('u',spead.ADDRSIZE)	1	The total number of dual-pol antennas in the system.	4
0x100B	n_xengs	('u',spead.ADDRSIZE)	1	The total number of X engines in a correlator system.	16
0x1011	center_freq	('f',64)	1	The center frequency of the DBE in Hz, 64-bit IEEE floating-point number.	1284000000
0x1013	bandwidth	('f',64)	1	The analogue bandwidth of the digitally processed signal in Hz.	856000000
0x1015	n_accs	('u',spead.ADDRSIZE)	1	The number of spectra that are accumulated per integration.	256
0x1016	int_time	('f',64)	1	Approximate (it's a float!) time per accumulation in seconds. This is intended for reference only. Each accumulation has an associated timestamp which should be used to determine the time of the integration rather than incrementing the start time by this value for sequential integrations (which would allow errors to grow).	
0x101E	fft_shift	('u',spead.ADDRSIZE)	1	The FFT bitshift pattern. F-engine correlator internals.	32767
0x101F	xeng_acc_len	('u',spead.ADDRSIZE)	1	Number of spectra accumulated inside X engine. Determines minimum integration time and user-configurable integration time step- size. X-engine correlator internals.	256
0x1020	requant_bits	('u',spead.ADDRSIZE)	1	Number of bits per sample after requantisation. For FX correlators, this represents the number of bits after requantisation in the F engines (post FFT and any phasing stages) and is the actual number of bits used in X-engine processing. For time-domain systems, this is requantisation in the time domain before any subsequent processing.	8
0x1022	rx_udp_port	('u',spead.ADDRSIZE)	1	Destination UDP port for data output.	7148
0x1023	feng_udp_port	('u',spead.ADDRSIZE)	1	Destination UDP port for F engine data exchange.	8888
0x1024	rx_udp_ip_str	string		Destination IP address for output UDP packets.	239.1.1.1
0x1026	eng_rate	('u',spead.ADDRSIZE)	1	Target clock rate of processing engines	225000000
0x1027	sync_time	('u',spead.ADDRSIZE)	1	Time at which the system was last synchronised (armed and triggered by a 1PPS) in seconds since the Unix Epoch.	
0x1041	x_per_fpga	('u',spead.ADDRSIZE)	1	Number of X engines per FPGA.	4
0x1043	ddc_mix_freq	('f',64)	1	Digital downconverter mixing frequency as a fraction of the ADC sampling frequency. eg: 0.25. Set to zero if no DDC is present.	0
0x1045	adc_bits	('u',spead.ADDRSIZE)	1	ADC resolution (number of bits).	10
0x1046	scale_factor_timestamp	('f',64)	1	Timestamp scaling factor. Divide the SPEAD data packet timestamp by this number to get back to seconds since last sync.	1712000000
0x1048	xeng_out_bits_per_sample	('u',spead.ADDRSIZE)	1	The number of bits per value of the xeng accumulator output. Note this is for a single component value, not the combined complex size.	32
0x1049	f_per_fpga	('u',spead.ADDRSIZE)	1	Number of F engines per FPGA.	2

3.4.5.2.1.2. Baseline Correlation Products Gain metadata

This SPEAD heap contains metadata for the gain settings.

Gain metadata is issued whenever:

- the system initiates a correlator or beamformer data product, or
- the user explicitly requests a metadata reissue.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
Gain				
0x1400+inputN	eq_coef_MyAntStr	(‘u’,32)	[n_coeffs,2]	The unitless, per-channel, digital scaling factors implemented prior to requantisation, post-FFT, for inputN. Complex number (real,imag) 32 bit integers.

The gain coefficients are complex scale factors, applied by the F-engines prior to 8 bit re-quantisation. Each input applies a separate complex scale factor for each frequency in the system. The length of each array is thus given by the *Item* n_chans.

3.4.5.2.1.3. Baseline Correlation Products Input and baseline labelling

The SPEAD labelling metadata items describe the labelling, location and connections of the system's inputs and their mappings to output baselines. The correlator input labelling metadata product is issued whenever:

- the system initiates a correlator or beamformer data product,
- the user explicitly requests a metadata reissue, or
- any input is renamed by the user.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
				Input and Baseline labelling
0x100C	bls_ordering	2-D array of strings	[n_bls,2]	The X-engine baseline output ordering. The form is a list of arrays of strings of user-defined antenna names ('input1','input2'). For example [('antC23x','antC23y'), ('antB12y','antA29y')]
0x100E	input_labelling	packed struct of (str,int,str,int)	[n_inputs]	The physical location of each antenna's connection. It is an array of structures, each with the following form in the case of KAT-7: (user-assigned_antenna_name, systemwide_unique_input_number, LRU, in- put_number_on_this_LRU). An example entry might be: ('antC23y',12,'roach030267',3)

For RTS, the input labelling item is a 2-D array with dimensions $N \times 4$ for N inputs. Each input N, indexed by a system-wide unique input number, is described by an array of the form:

[string] user-assigned_antenna_name,

[integer] instrument-wide_unique_input_number,

[string] LRU,

[integer] input_number_on_this_LRU

The user-assigned antenna name is as specified through the CBF CAM interface.

The instrument-wide unique input number is an integer describing the logical interface of this instrument. The afore-mentioned antenna is connected to this interface. In the case of RTS, this number ranges from 0 to 7.

The LRU is a hardware identifier for a line-replaceable-unit. An example description might be: *('antC23y' , 12 , 'roach030267' , 1)*.

The baseline ordering item lists the output order of the X-engines. The form is a matrix with dimensions of $N \times 2$, for N baselines. Each line contains two strings of user-defined antenna names ('input1','input2'). Two baseline example: [('antC23x','antC23y'), ('antB12y','antA29y')].

3.4.5.2.1.4. Baseline Correlation Products Hardware heaps

SPEAD data descriptors are issued from the control computer for the correlator's FPGA-based output in order to enable receivers to decode the data. This is the highspeed stream of heaps emitted from all X-engines.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
Hardware Heap				
0x1600	timestamp	(u,spead.ADDRSIZE	1	Timestamp of start of this integration. uint counting multiples of ADC samples since last sync (sync_time, id=0x1027). Divide this number by timestamp_scale (id=0x1046) to get back to seconds since last sync when this integration was actually started. Note that the receiver will need to figure out the centre timestamp of the accumulation (eg, by adding half of int_time, id 0x1016).
0x1601	flags_xeng_raw	('u',spead.ADDRSIZE)	TBD	Flags associated with xeng_raw data output bit 34 - corruption or data missing during integration bit 33 - overrange in data path bit 32 - noise diode on during integration bits 0 - 31 reserved for internal debugging
0x1800	xeng_raw	('i',32)	[n_freq,n_bls,2]	Raw data stream from all the X-engines in the system. For KAT-7, this item represents a full spectrum (all frequency channels) assembled from lowest frequency to highest frequency. Each frequency channel contains the data for all baselines (n_bls given by SPEAD Id=0x1008). Each value is a complex number – two (real and imaginary) signed integers.

The RTS correlator's datastream output (ID 0x1800) is collected into a single *Heap* by the receiver. This provides a convenient model for a single receiver, but this solution does not scale well for large systems with multiple, distributed receivers. In these cases we will need multiple xeng_raw outputs, each going to a separate receiver. The simplest way to achieve this is to split the output of each X-engine into a separate SPEAD stream, as is done for the beamformer. In this case, each receiver would receive all baselines for a subset of the band. This was implemented for early prototype systems with separate heaps from each X-engine in the system, with each heap containing the SPEAD item with ID 0x1800+*inputN* (instead of item ID 0x1800) representing a subset of the band. RTS no longer supports this data product as, in all cases, the correlator output data rates are considered low enough for a single receiver to cope with the entire structure of all dataproducts.

3.4.5.2.2. Antenna Channelised Voltages

Input time domain data is first channelised and then correlated. The output of the channeliser, prior to correlation, is available as a data product.

The channelised voltage data metadata is issued in the following order upon initialisation:

1. A single SPEAD Heap containing the ItemDescriptors and system time synchronisation items is issued.
2. SPEAD Heaps containing all the ItemDescriptors and initial values for gain are issued as each input is initialised.
3. A single SPEAD Heap containing the static ItemDescriptors and initial values for most static variables and system parameters is issued.
4. SPEAD Heaps containing the ItemDescriptors and labels of all physical inputs are issued as each input is initialised.
5. A single SPEAD Heap is issued, containing the ItemDescriptors only for the FPGA-based output products, to enable receivers to decode the emitted data.

3.4.5.2.2.1. Channelised Voltage Data Static Metadata

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
				Static
0x1007	adc_sample_rate	('u',64)	1	Expected ADC sample rate (samples/second)
0x3100	n_inputs	('u',spead.ADDRSIZE)	1	The total number of analogue inputs in the stream.
0x1011	center_freq	('f',64)	1	The center frequency of the DBE in Hz, 64-bit IEEE floating-point number.
0x1013	bandwidth	('f',64)	1	The analogue bandwidth of the digitally processed signal in Hz.
0x1021	feng_pkt_len	('u',spead.ADDRSIZE)	1	Payload size of packet exchange between F and X engines in 64 bit words. Usually equal to the number of spectra accumulated inside X engine. F-engine correlator internals.
0x1022	rx_udp_port	('u',spead.ADDRSIZE)	1	Destination UDP port for data output.
0x1024	rx_udp_ip_str	string		Destination IP address for output UDP packets.
0x1045	adc_bits	('u',spead.ADDRSIZE)	1	ADC resolution (number of bits).
0x1020	requant_bits	('u',spead.ADDRSIZE)	1	Number of bits per sample after requantisation. For FX correlators, this represents the number of bits after requantisation in the F engines (post FFT and any phasing stages) and is the actual number of bits used in X-engine processing. For time-domain systems, this is requantisation in the time domain before any subsequent processing.
TBD	eng_rate			

3.4.5.2.2.2. Channelised Voltage Data Gain

Gain metadata is issued whenever:

- the system initiates a correlator or beamformer data product, or
- the user explicitly requests a metadata reissue.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
				Gain
0x1400+inputN	eq_coef_MyAntStr	('u',32)	[n_coeffs,2]	The unitless, per-channel, digital scaling factors implemented prior to requantisation, post-FFT, for inputN. Complex number (real,imag) 32 bit integers.

3.4.5.2.2.3. Channelised Voltage Data Timing

Timing metadata is issued whenever:

- the system initiates a correlator or beamformer data product, or
- CBF receives notification that the digitisers have been re-synchronised, or
- the user explicitly requests a metadata reissue.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Timing		
0x1027	sync_time	('u',spead.ADDRSIZE)	1	Time at which the system was last synchronised (armed and triggered by a 1PPS) in seconds since the Unix Epoch.
0x1046	scale_factor_timestamp	('f',64)	1	Timestamp scaling factor. Divide the SPEAD data packet timestamp by this number to get back to seconds since last sync.

3.4.5.2.2.4. Channelised Voltage Data Input Labelling

The input labelling metadata product is issued whenever:

- the system initiates a correlator or beamformer data product,
- the user explicitly requests a metadata reissue, or
- any input is renamed by the user.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Input Labelling		
0x100E	input_labelling	packed struct of (str,int,str,int)	[n_inputs]	The physical location of each antenna's connection. It is an array of structures, each with the following form in the case of KAT-7: (user-assigned_antenna_name, systemwide_unique_input_number, LRU, in- put_number_on_this_LRU). An example entry might be: ('antC23y',12,'roach030267',3)

3.4.5.2.2.5. Channelised Voltage Data Hardware heap

The channelised voltage data output is issued into a single *Heap*.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
Hardware Heap				
0x1600	timestamp	(u,spead.ADDRSIZE	1	Timestamp of start of this integration. uint counting multiples of ADC samples since last sync (sync_time, id=0x1027). Divide this number by timestamp_scale (id=0x1046) to get back to seconds since last sync when this integration was actually started. Note that the receiver will need to figure out the centre timestamp of the accumulation (eg, by adding half of int_time, id 0x1016).
0x4103	frequency	(`u',spead.ADDRSIZE)	1	The frequency channel of the data in this HEAP.
TBD	flags_feng_raw			
0x4300	feng_raw	nominally ('i', 8)	[xeng_acc_len,2]	Raw, complex, streaming frequency-domain data (usually out of F-engines). This is channelised voltage data (no squaring or accumulation). In the case of complex data, real comes before imaginary part. These are packed as two back-to-back numbers. Note that each packet normally forms a separate HEAP, and represents a different frequency channel (see 0x4103).

3.4.5.2.3. Tied Array Beamformer Voltage Data

The beamformer is added-on to the correlator discussed in 3.4.5.2.1. Much of the underlying infrastructure is shared between these two instruments. If the selected correlator data product also supports frequency-domain beamforming, additional beamformer metadata will be issued during initialisation, after the normal correlator metadata. This metadata is detailed here.

Multiple, simultaneous beams are supported (initially one for each of the two polarisations). It is intended that each beamformer's output will be routed to separate SPEAD receiver(s) and so no attempt was made to keep variable names globally unique. All beamformer-applicable metadata is reissued to each receiver's network port using the same SPEAD Item IDs and variable names.

The beamformer metadata is issued in the following order upon initialisation or metadata reissue request:

1. A single SPEAD Heap containing the ItemDescriptors and system time synchronisation items is issued.
2. SPEAD Heaps containing all the ItemDescriptors and initial values for gain are issued as each input is initialised.
3. A single SPEAD Heap containing the static ItemDescriptors and initial values for most static variables and system parameters is issued.
4. SPEAD Heaps containing the ItemDescriptors and labels of all physical inputs are issued as each input is initialised.
5. A single SPEAD Heap is issued, containing the ItemDescriptors only for the FPGA-based output products, to enable receivers to decode the emitted data.

3.4.5.2.3.1. Beamformer Static metadata

The beamformer static metadata takes the form of a SPEAD heap containing static variables.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description	Initial value
				Static	
0x1007	adc_sample_rate	('u',64)	1	Expected ADC sample rate (samples/second)	1712000000
0x1009	n_chans	('u',spead.ADDRSIZE)	1	The total number of frequency channels present in any integration.	wc=4096, wf=32768
0x100A	n_ants	('u',spead.ADDRSIZE)	1	The total number of dual-pol antennas in the system.	4
0x100F	n_bengs	('u',spead.ADDRSIZE)	1	The total number of B engines in a beamformer system.	
~~0x1011~~	~~center_freq~~	~~('f',64)~~	~~1~~	~~The center frequency of the DBE in Hz, 64-bit IEEE floating-point number.~~	~~1284000000~~
~~0x1013~~	~~bandwidth~~	~~('f',64)~~	~~1~~	~~The analogue bandwidth of the digitally processed signal in Hz.~~	~~856000000~~
0x1020	requant_bits	('u',spead.ADDRSIZE)	1	Number of bits per sample after requantisation. For FX correlators, this represents the number of bits after requantisation in the F engines (post FFT and any phasing stages) and is the actual number of bits used in X-engine processing. For time-domain systems, this is requantisation in the time domain before any subsequent processing.	
~~0x1043~~	~~ddc_mix_freq~~	~~('f',64)~~	~~1~~	~~Digital downconverter mixing frequency as a fraction of the ADC sampling frequency. eg: 0.25. Set to zero if no DDC is present.~~	
0x1045	adc_bits	('u',spead.ADDRSIZE)	1	ADC resolution (number of bits).	10
0x1022	rx_udp_port	('u',spead.ADDRSIZE)	1	Destination UDP port for data output.	
0x1024	rx_udp_ip_str	string		Destination IP address for output UDP packets.	
0x1050	beng_out_bits_per_sample	('u',spead.ADDRSIZE)	1	The number of bits per value of the beng accumulator output. Note this is for a single component value, not the combined complex size.	

n_chans gets reissued, to contain the actual number of channels in the stream. Significant if a subset of the stream is emitted (using ?beam-passband KATCP command).

3.4.5.2.3.2. Beamformer Input scaling and weightings

This is a per-input, per-frequency complex value allowing for correction of phase and amplitude mismatches between inputs, and to configure the relative contributions of each input to the summed beam.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Input Scaling and Weightings		
~~0x1400+inputN~~	~~eq_coef_MyAntStr~~	~~('u',32)~~	~~[n_coeffs,2]~~	~~The unitless, per-channel, digital scaling factors implemented prior to requantisation, post-FFT, for inputN. Complex number (real,imag) 32 bit integers.~~
0x2000	beamweight	('i',32)	[n_inputs]	The unitless digital scaling factors implemented prior to combining signals for this beam. See 0x100E (input_labelling) to get mapping from inputN to user defined input string.

The beam weightings are complex scale factors, applied by the B engines to the incoming requantised numbers before summing. Each input applies a separate complex scale factor for each frequency in the system (as with eq_coef, the length of each array is thus given by the Item n_chans).

3.4.5.2.3.3. Beamformer Input labelling

Beamformer input labelling metadata items describing the labelling, location and connections of the system's inputs are issued whenever:

- the system initiates a correlator data product that supports beamformer functions
- the user explicitly requests a metadata reissue
- any input is renamed by the user.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Input Labelling		
0x100E	input_labelling	packed struct of (str,int,str,int)	[n_inputs]	The physical location of each antenna's connection. It is an array of structures, each with the following form in the case of KAT-7: (user-assigned_antenna_name, systemwide_unique_input_number, LRU, in- put_number_on_this_LRU). An example entry might be: ('antC23y',12,'roach030267',3)

MeerKAT's beamformer follows the same labelling scheme as the correlator, but with only the subset of items.

3.4.5.2.3.4. Beamformer timing

Timing metadata is issued whenever:

- the system initiates a correlator or beamformer data product, or
- CBF receives notification that the digitisers have been re-synchronised, or
- the user explicitly requests a metadata reissue.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Timing		
0x1046	scale_factor_timestamp	('f',64)	1	Timestamp scaling factor. Divide the SPEAD data packet timestamp by this number to get back to seconds since last sync.
0x1027	sync_time	('u',spead.ADDRSIZE)	1	Time at which the system was last synchronised (armed and triggered by a 1PPS) in seconds since the Unix Epoch.

3.4.5.2.3.5. Beamformer Hardware heap

The beamformer hardware outputs a number of frequency channels, given by the *Item* n_chans. These channels are processed by a number of engines (*n_bengs*) and the beamformer output can be chosen from each of these engines). With *n* B-engines and a 856MHz band, the output centre frequency and bandwidth can be chosen in increments of $\frac{856MHz}{n}$ MHz. Data for unused portions of the band will not be emitted, so this feature can be used to save data bandwidth in the event that the full analogue band is not needed.

Beams can be arbitrarily renamed and the output SPEAD variable name will reflect this string precisely. No provision is made to prevent overlapping namespaces nor are there any safety or sanity checks done on the chosen name.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Hardware Output		
0x1600	timestamp	(u,spead.ADDRSIZE	1	Timestamp of start of this integration. uint counting multiples of ADC samples since last sync (sync_time, id=0x1027). Divide this number by timestamp_scale (id=0x1046) to get back to seconds since last sync when this integration was actually started. Note that the receiver will need to figure out the centre timestamp of the accumulation (eg, by adding half of int_time, id 0x1016).
0x4103	frequency	(`u',spead.ADDRSIZE)	1	The frequency channel of the data in this packet.
TBD	flags_feng_raw			
0xb000+beamN	bf_MyBeamName	('i', 8, 16 or 32)	[n_chans, xeng_acc_len,2]	Beamformer output for frequency-domain beam. User-defined name (out of band control). Record length depending on number of frequency channels and F-X packet size (xeng_acc_len).

The beam name, centre frequency, bandwidth, output IP address and port etc. are configured through a separate CAM interface which falls outside of the scope of this document.

Beamformer data is emitted as a time series of spectra. It is presented in frames of n_chans by feng_pkt_len complex integer numbers.

Each heap represents a number of sequential complete spectra. A single packet contains a series of complex time samples from a single spectral channel. The number of time samples thus determines the size of the packet payload. For RTS, this is fixed at 256 samples. Also, dual-polarisation data is packed into a single packet. At 8 bits per value, this results in packet payloads of 1024 Bytes. When the heap is reassembled, you thus get 256 * n_chans, complex, 8 bit values.

3.4.5.2.4. Antenna Voltage Buffer

This data product allows for raw streaming of ADC voltages for one or both polarisations.

Upon initiating the raw voltage capture data product, the following SPEAD metadata is issued:

1. A single SPEAD Heap containing the ItemDescriptors and system time synchronisation Items is issued.
2. A SPEAD Heap containing all the ItemDescriptors and initial values for each ADCs' analogue gain as well as the system's digital gain stages is issued as each input is initialised.
3. A SPEAD Heap containing the ItemDescriptors and initial values of the labels (names) of all physical inputs is issued as each input is initialised.
4. A single SPEAD Heap containing the static ItemDescriptors and initial values for most static variables and system parameters is issued.
5. A single SPEAD Heap containing the ItemDescriptors only for the FPGA-based output products is issued to enable receivers to decode the emitted data.

3.4.5.2.4.1. Antenna Voltage Buffer Static metadata

Antenna Voltage Buffer static metadata takes the form of a SPEAD heap containing static variables.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description	Initial value
				Static	
0x1007	adc_sample_rate	('u',64)	1	Expected ADC sample rate (samples/second)	1712000000
0x3100	n_inputs	('u',spead.ADDRSIZE)	1	The total number of analogue inputs in the stream.	4
0x1011	center_freq	('f',64)	1	The center frequency of the DBE in Hz, 64-bit IEEE floating-point number.	1284000000
0x1013	bandwidth	('f',64)	1	The analogue bandwidth of the digitally processed signal in Hz.	856000000
0x1022	rx_udp_port	('u',spead.ADDRSIZE)	1	Destination UDP port for data output.	7148
0x1024	rx_udp_ip_str	string		Destination IP address for output UDP packets.	239.1.1.1
0x1045	adc_bits	('u',spead.ADDRSIZE)	1	ADC resolution (number of bits).	10
0x1020	requant_bits	('u',spead.ADDRSIZE)	1	Number of bits per sample after requantisation. For FX correlators, this represents the number of bits after requantisation in the F engines (post FFT and any phasing stages) and is the actual number of bits used in X-engine processing. For time-domain systems, this is requantisation in the time domain before any subsequent processing.	

3.4.5.2.4.2. Antenna Voltage Buffer Gain metadata

Gain metadata is issued whenever:

- the system initiates a correlator or beamformer data product, or
- the user explicitly requests a metadata reissue.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
	Gain			
	gain			

3.4.5.2.4.3. Antenna Voltage Buffer Input labelling metadata

Input labelling metadata items describing the labelling, location and connections of the system's inputs are issued whenever:

- the system initiates a correlator data product that supports Antenna Voalteg Buffer functions
- the user explicitly requests a metadata reissue
- any input is renamed by the user.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Input Labelling		
0x100E	input_labelling	packed struct of (str,int,str,int)	[n_inputs]	The physical location of each antenna's connection. It is an array of structures, each with the following form in the case of KAT-7: (user-assigned_antenna_name, systemwide_unique_input_number, LRU, in- put_number_on_this_LRU). An example entry might be: ('antC23y',12,'roach030267',3)

3.4.5.2.4.4. Antenna Voltage Buffer Timing

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Timing		
0x1027	sync_time	('u',spead.ADDRSIZE)	1	Time at which the system was last synchronised (armed and triggered by a 1PPS) in seconds since the Unix Epoch.
0x1046	scale_factor_timestamp	('f',64)	1	Timestamp scaling factor. Divide the SPEAD data packet timestamp by this number to get back to seconds since last sync.

3.4.5.2.4.5. Antenna Voltage Buffer Hardware heap

The Antenna Voltage Buffer data output is issued into a single *Heap*.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
		Hardware Heap		
0x1600	timestamp	(u,spead.ADDRSIZE	1	Timestamp of start of this integration. uint counting multiples of ADC samples since last sync (sync_time, id=0x1027). Divide this number by timestamp_scale (id=0x1046) to get back to seconds since last sync when this integration was actually started. Note that the receiver will need to figure out the centre timestamp of the accumulation (eg, by adding half of int_time, id 0x1016).
0x3300+inputN	raw_data_MyAntStr	('i',n_adc_bits)	[pkt_len]	Raw time-domain data stream from an ADC. Each packet normally represents a complete heap.

3.4.5.2.5. CBF Basic Spectrometer Data

Basic Spectrometer Data is generated in the Digitiser, and merely routed through the CBF. The hardware heap structure is repeated here for convenience.

3.4.5.2.5.1. Basic Spectrometer Hardware heap

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
0x1600	timestamp	(u,spead.ADDRSIZE	1	Local Digitiser time stamp of the first (oldest) ADC sample in this payload. Upon the reception of a DMC time stamp synchronization command, the local Digitiser time stamp is set to the value supplied by the DMC time stamp synchronization command. This value is an offset from the UTC time stamp. The local time stamp is then incremented by 8, every 1/(fs/8) ns, where fs is the applicable sample frequency in Hz.
0x3101	digitiser_id	('u',spead.ADDRSIZE)	TBD	[47:24] Digitiser Serial Number [23:16] Digitiser Type (0 = L-Band Digitiser [1712MHz], 1 = UHF-Band Digitiser [TBD MHz], 2 = X-Band Digitiser [TBD MHz], 3 = S-Band Digitiser [TBD MHz], 4 - 255 Reserved) [15:2] Receptor ID [1:0] Polarization ID (0 = Vertical, 1 = Horizontal)
0x3102	digitiser_status	('i',32)	[n_freq,n_bls,2]	[47:32] ADC Saturation Count (Number of ADC Samples that saturated in this payload) [31:2] Reserved (set to 0) [1] ADC Sample(s) Saturation Flag (0 = There are no saturated ADC samples in this payload, 1 = There are saturated ADC samples in this payload, see ADC Saturation Count field) [0] Noise Diode Status (0 = Noise diode was Off for this entire payload, 1 = Noise diode was On in this payload)
0x3300+inputN	raw_data_MyAntStr	('u',32)	[n_chans]	[47:32] ADC Saturation Count (Number of ADC Samples that saturated in this payload) [31:2] Reserved (set to 0) [1] ADC Sample(s) Saturation Flag (0 = There are no saturated ADC samples in this payload, 1 = There are saturated ADC samples in this payload, see ADC Saturation Count field) [0] Noise Diode Status (0 = Noise diode was Off for this entire payload, 1 = Noise diode was On in this payload)
0x3301	VV*_auto_correlation	('u',32)	128	Payload Word 1: [63:32] - Channel 0, [31:0] - Channel 1 Payload Word 2: [63:32] - Channel 4, [31:0] - Channel 5 etc
0x3302	HH*_auto_correlation	('u',32)	128	Payload Word 1: [63:32] - Channel 0, [31:0] - Channel 1 Payload Word 2: [63:32] - Channel 4, [31:0] - Channel 5 etc
0x3303	(VH)*_cross_correlation_real	('u',32)	128	Payload Word 1: [63:32] - Channel 0, [31:0] - Channel 1 Payload Word 2: [63:32] - Channel 4, [31:0] - Channel 5 etc

0x3304	(VH)*_cross_correlation_imaginary	('u',32)	128	Payload Word 1: [63:32] - Channel 0, [31:0] - Channel 1 Payload Word 2: [63:32] - Channel 4, [31:0] - Channel 5 etc

3.4.5.2.6. Digitisers Raw Data

Raw time domain data from a Digitiser may be subscribed to by a user. That data will then be routed through the CBF provided sufficient bandwidth is available on that link.

Note that the link capacity budgets did not cater for raw data.

SPEAD Item ID	SPEAD Item Name	Format	Shape	Description
0x1600	timestamp	(u,spead.ADDRSIZE	1	Local Digitiser time stamp of the first (oldest) ADC sample in this payload. Upon the reception of a DMC time stamp synchronization command, the local Digitiser time stamp is set to the value supplied by the DMC time stamp synchronization command. This value is an offset from the UTC time stamp. The local time stamp is then incremented by 8, every 1/(fs/8) ns, where fs is the applicable sample frequency in Hz.
0x3101	digitiser_id	('u',spead.ADDRSIZE)	TBD	[47:24] Digitiser Serial Number [23:16] Digitiser Type (0 = L-Band Digitiser [1712MHz], 1 = UHF-Band Digitiser [TBD MHz], 2 = X-Band Digitiser [TBD MHz], 3 = S-Band Digitiser [TBD MHz], 4 - 255 Reserved) [15:2] Receptor ID [1:0] Polarization ID (0 = Vertical, 1 = Horizontal)
0x3102	digitiser_status	('i',32)	[n_freq,n_bls,2]	[47:32] ADC Saturation Count (Number of ADC Samples that saturated in this payload) [31:2] Reserved (set to 0) [1] ADC Sample(s) Saturation Flag (0 = There are no saturated ADC samples in this payload, 1 = There are saturated ADC samples in this payload, see ADC Saturation Count field) [0] Noise Diode Status (0 = Noise diode was Off for this entire payload, 1 = Noise diode was On in this payload)
0x3300+inputN	raw_data_MyAntStr	('i',n_adc_bits)	[pkt_len]	10 Bit (Signed) ADC Samples, packed contiguously, over 64 bit word boundaries. Payload Word 1: [63:54] - ADC Sample 1 [9:0] (oldest sample), [53:44] - ADC Sample 2 [9:0], [43:34] - ADC Sample 3 [9:0], [33:24] - ADC Sample 4 [9:0], [23:14] - ADC Sample 5 [9:0], [13:4] - ADC Sample 6 [9:0], [3:0] - ADC Sample 7 [9:6], Payload Word 2: [63:58] - ADC Sample 7 [5:0], [57:48] - ADC Sample 8 [9:0], etc

3.4.5.2.7. Antenna Correlation Products

TBD, to be defined in a later release of this ICD.

3.4.5.2.8. Incoherent Beam Total Power

TBD, to be defined in a later release of this ICD.

3.4.5.2.9. Tied Array Beamformer Correlation Products

TBD, to be defined in a later release of this ICD.

4. TBD LIST

Page Number	Section	Description
10	3.2.4	VLBI (*TBD*)
13	3.4.5.1.2	How these updates will be advertised and propogated is *TBD*
32	3.4.5.2.7	Antenna Correlation Products
32	3.4.5.2.8	Incoherent Beam Total Power
32	3.4.5.2.9	Tied Array Beamformer Correlation Products