MeerKAT System Overview

Thomas Kusel / Sias Malan

Overview

System
- Driving requirements

Site
- Geographical layout
- Array
- Site complex

Receptor
- Antenna Positioner
- Receiver
- Digitiser

Array processor
- KAPB layout
- Functional overview
- Correlator
- CAM subsystem
- Science Processor
- Time and Frequency Reference

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Driving Requirements

Use cases

- Imaging
- Pulsar timing
- Transients

Requirements

Survey speed

- Sensitivity (compact structures)
- Sensitivity (extended structures)
- Field of view
- Imaging dynamic range
- Bandwidth
- Slew speed
- Concurrent observation modes

Budget

Solution

- Small-ish dishes
- Sensitive receivers
- Array configuration
- Wideband back-end
- Concurrent modes

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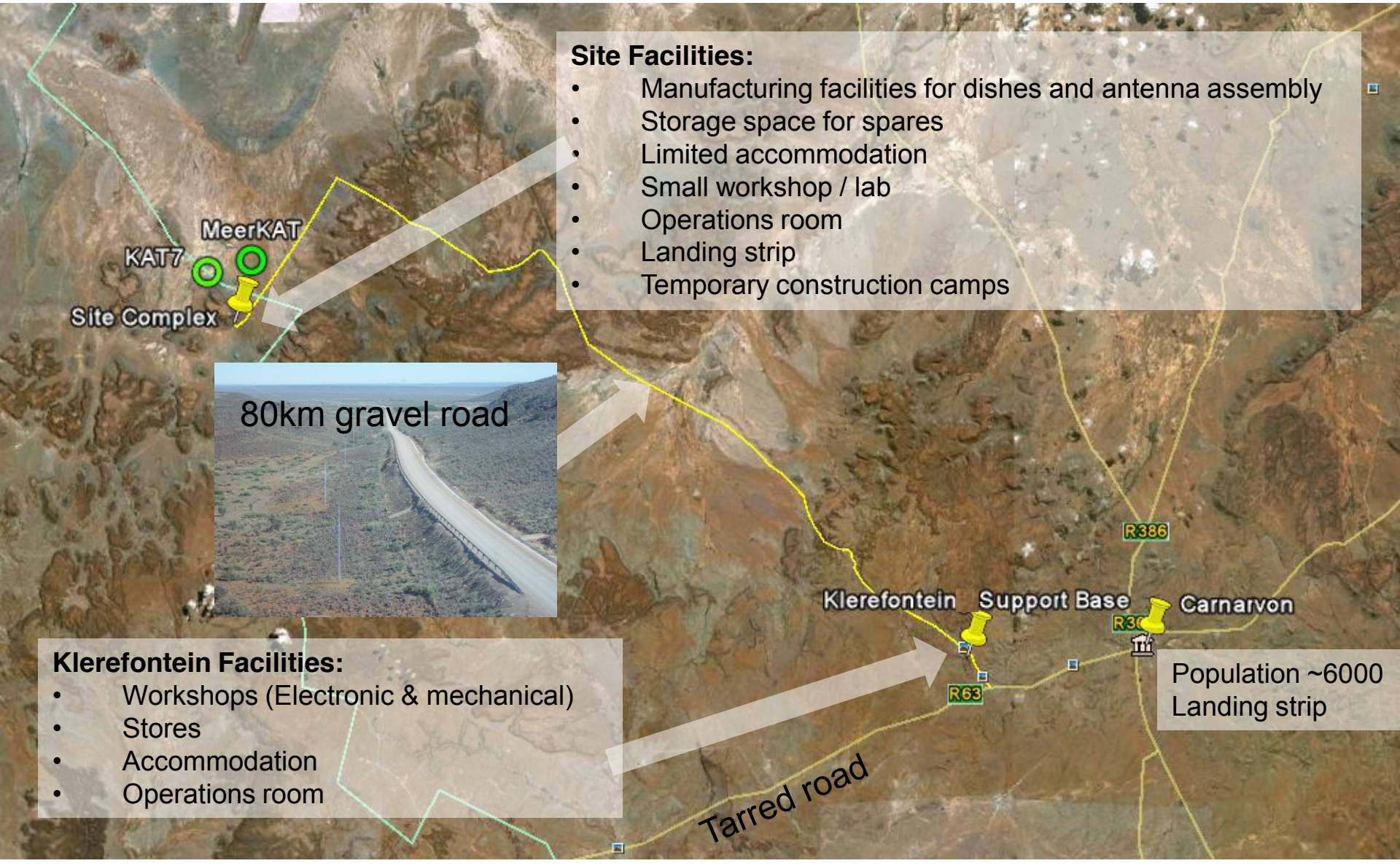
Geographical layout



Site Facilities:

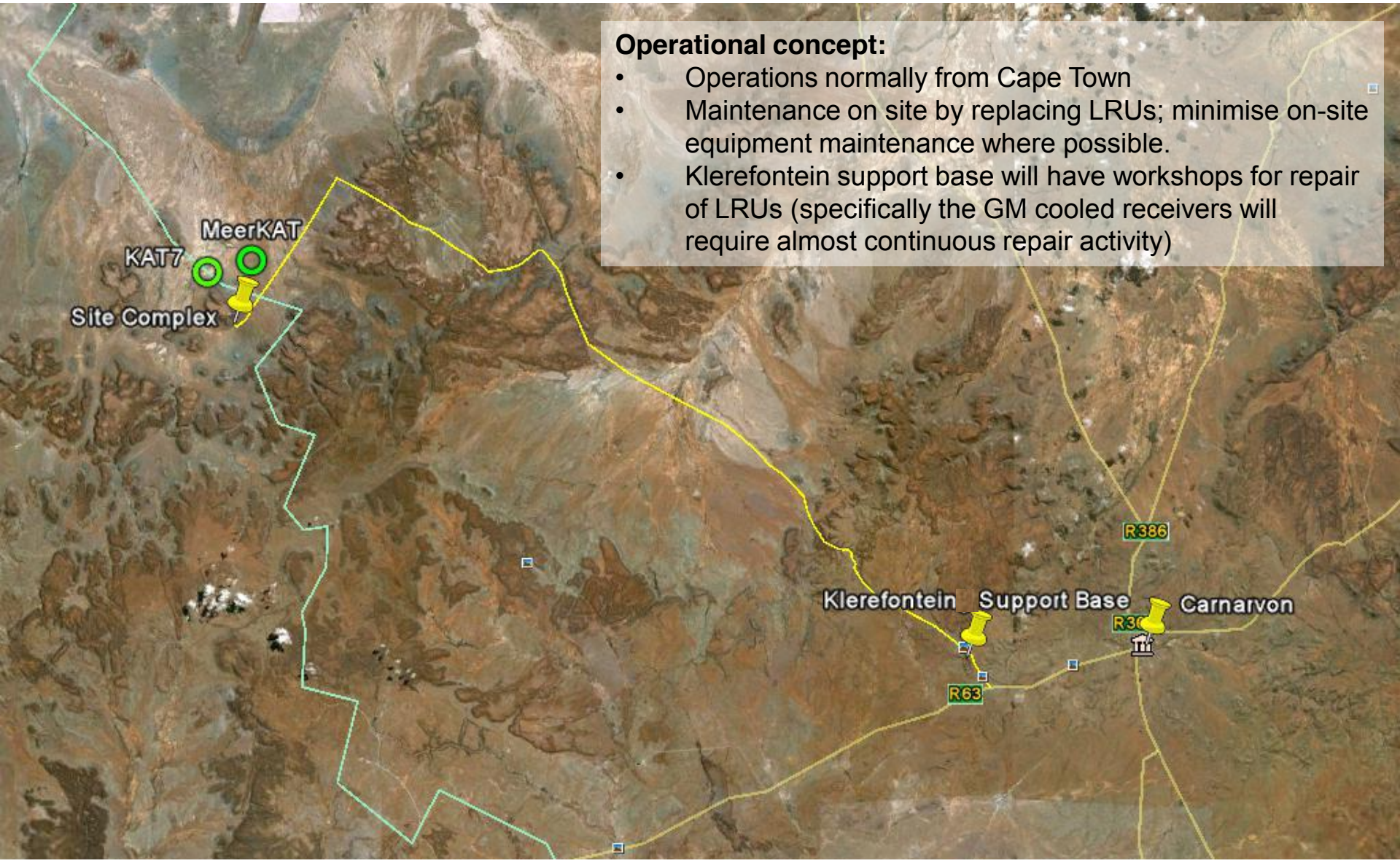
- Manufacturing facilities for dishes and antenna assembly
- Storage space for spares
- Limited accommodation
- Small workshop / lab
- Operations room
- Landing strip
- Temporary construction camps

Klerefontein Facilities:

- Workshops (Electronic & mechanical)
- Stores
- Accommodation
- Operations room

Population ~6000
Landing strip

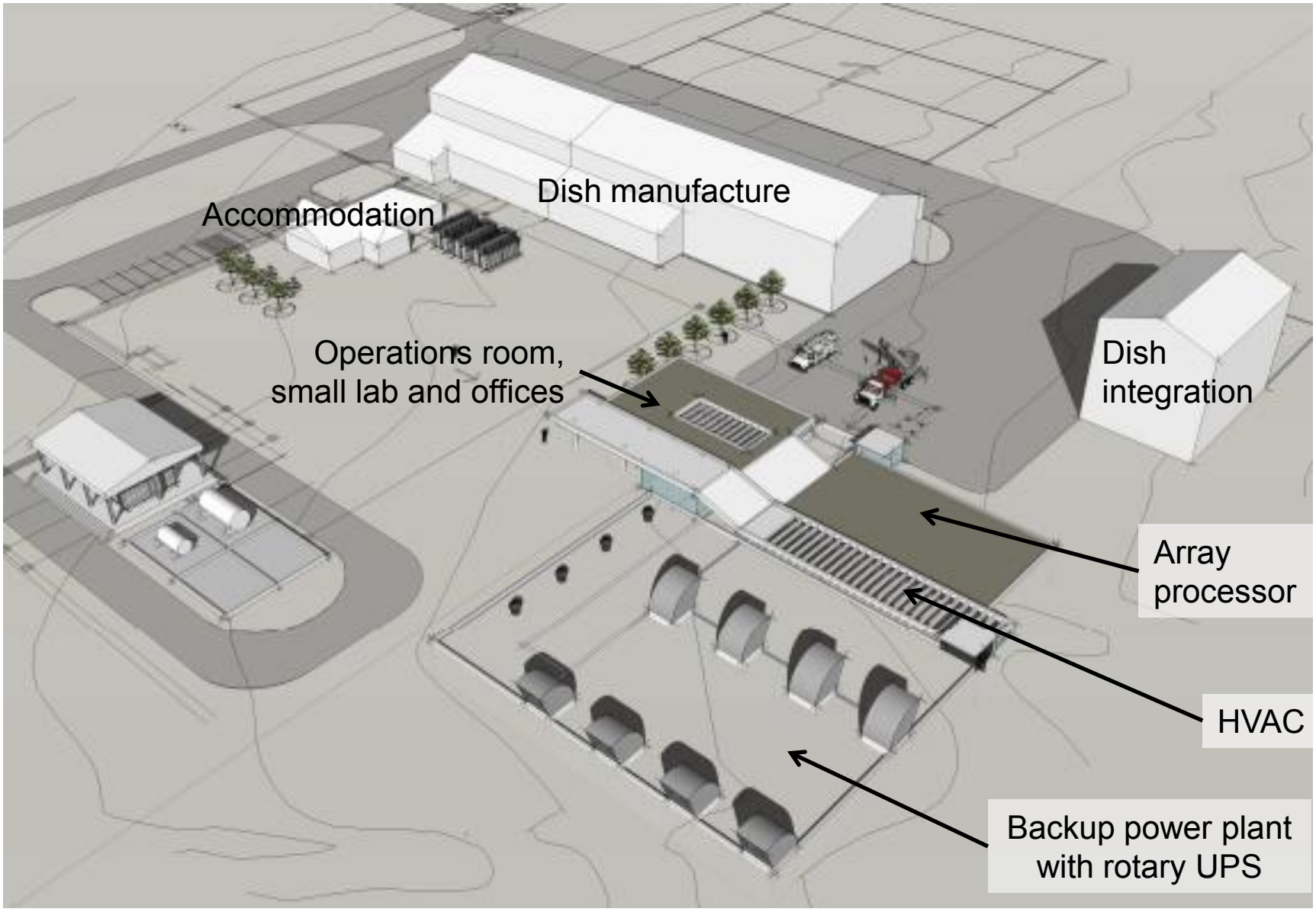
Geographical layout



Operational concept:

- Operations normally from Cape Town
- Maintenance on site by replacing LRUs; minimise on-site equipment maintenance where possible.
- Klerefontein support base will have workshops for repair of LRUs (specifically the GM cooled receivers will require almost continuous repair activity)

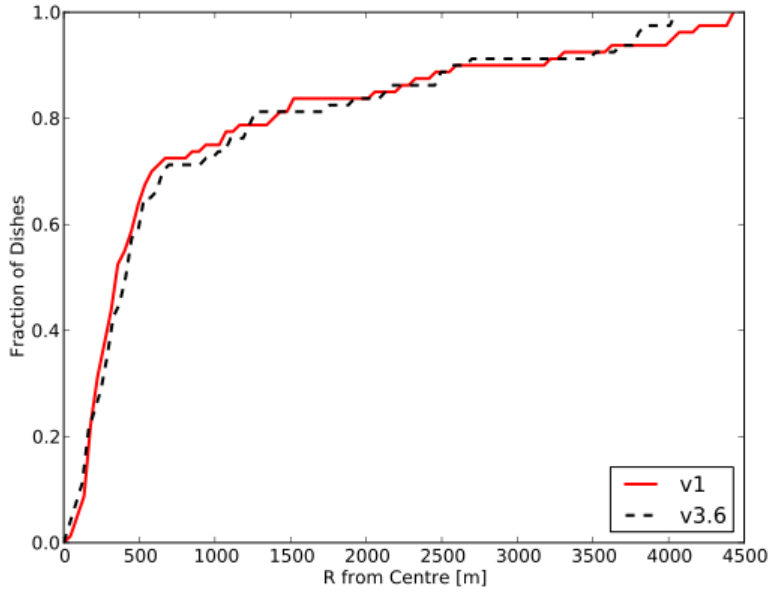
Site complex layout



Array layout

Array layout

1. Compact core for pulsar monitoring and transient search
   - 70% of antennas.
   - Gaussian uv-distr – dispersion of 300m; shortest baseline of 29m.
2. Imaging performance (sensitivity) for resolutions ~6” to ~100”
   - 30% of antennas outside core.
   - Baselines extended up to 8km.



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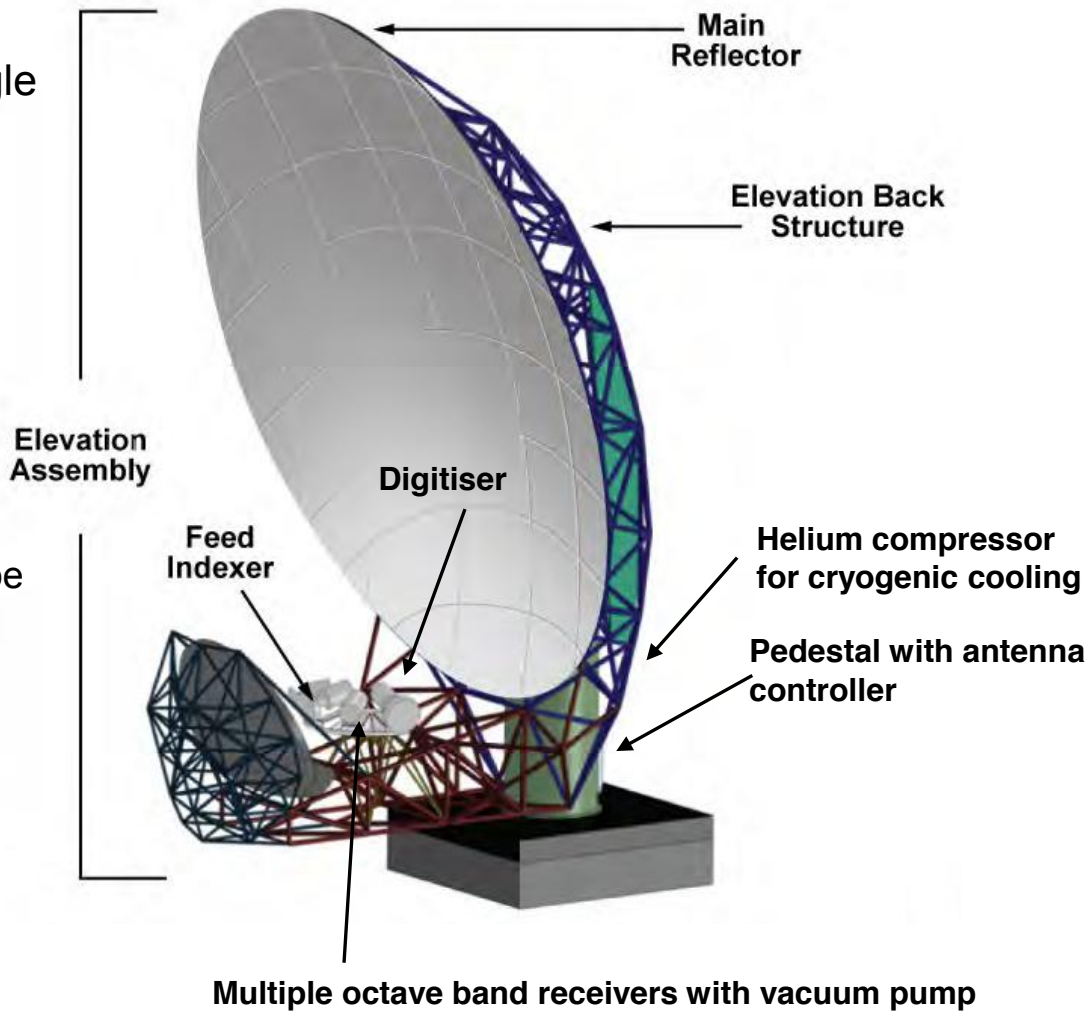
Receptor

- Gregorian offset antenna
- Multiple cryo-cooled, octave band single pixel receivers.
- Direct Digitisation at the receiver



Key performance (L-band):

- Sensitivity (Ae/Tsys)
- Rotationally symmetric beam and sidelobe pattern

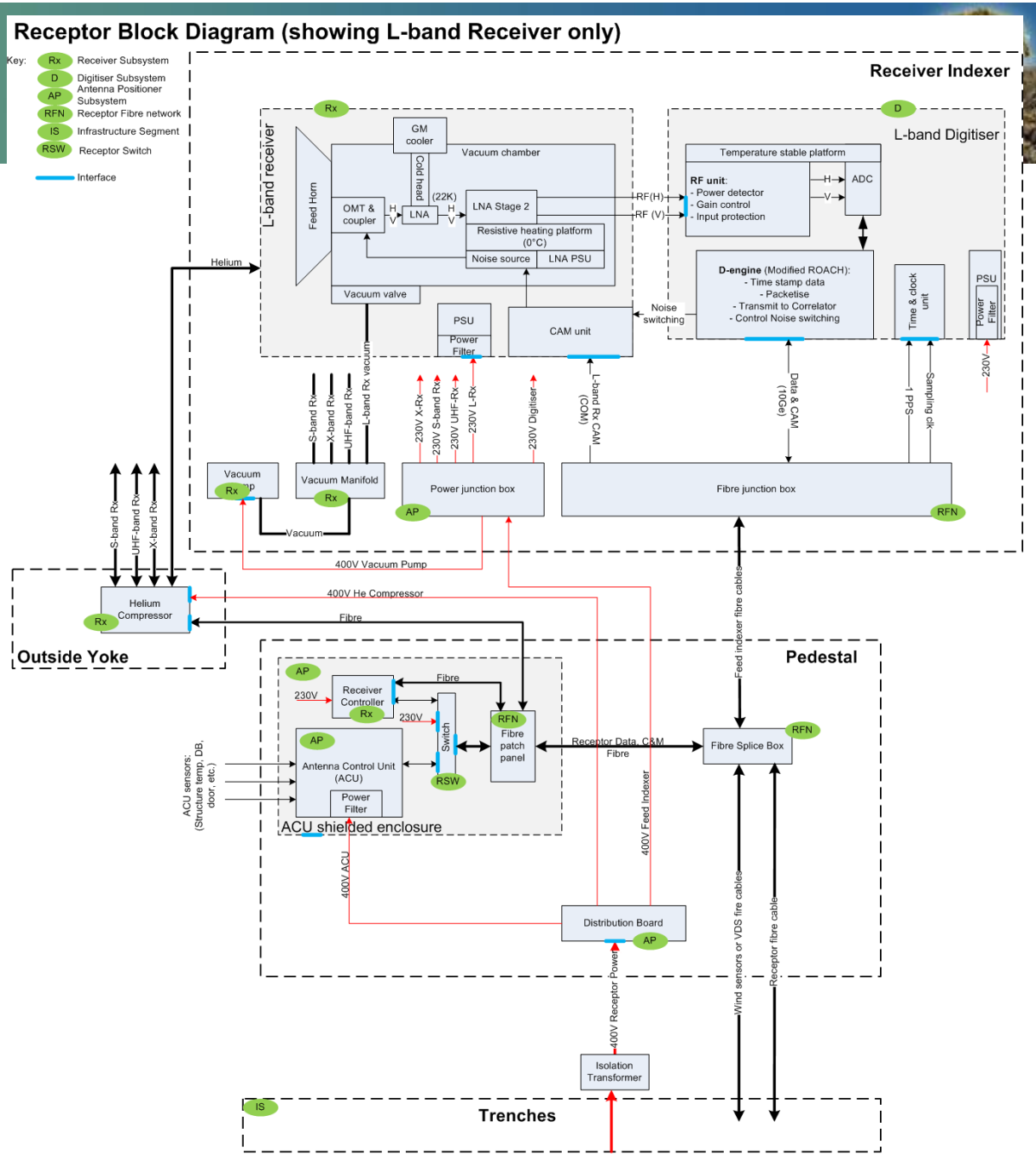
Ae/Tsys (sqm/K)	Spec	Achieved
1 Dish	3.4	6
64 Dishes	220	380

Frequency Bands

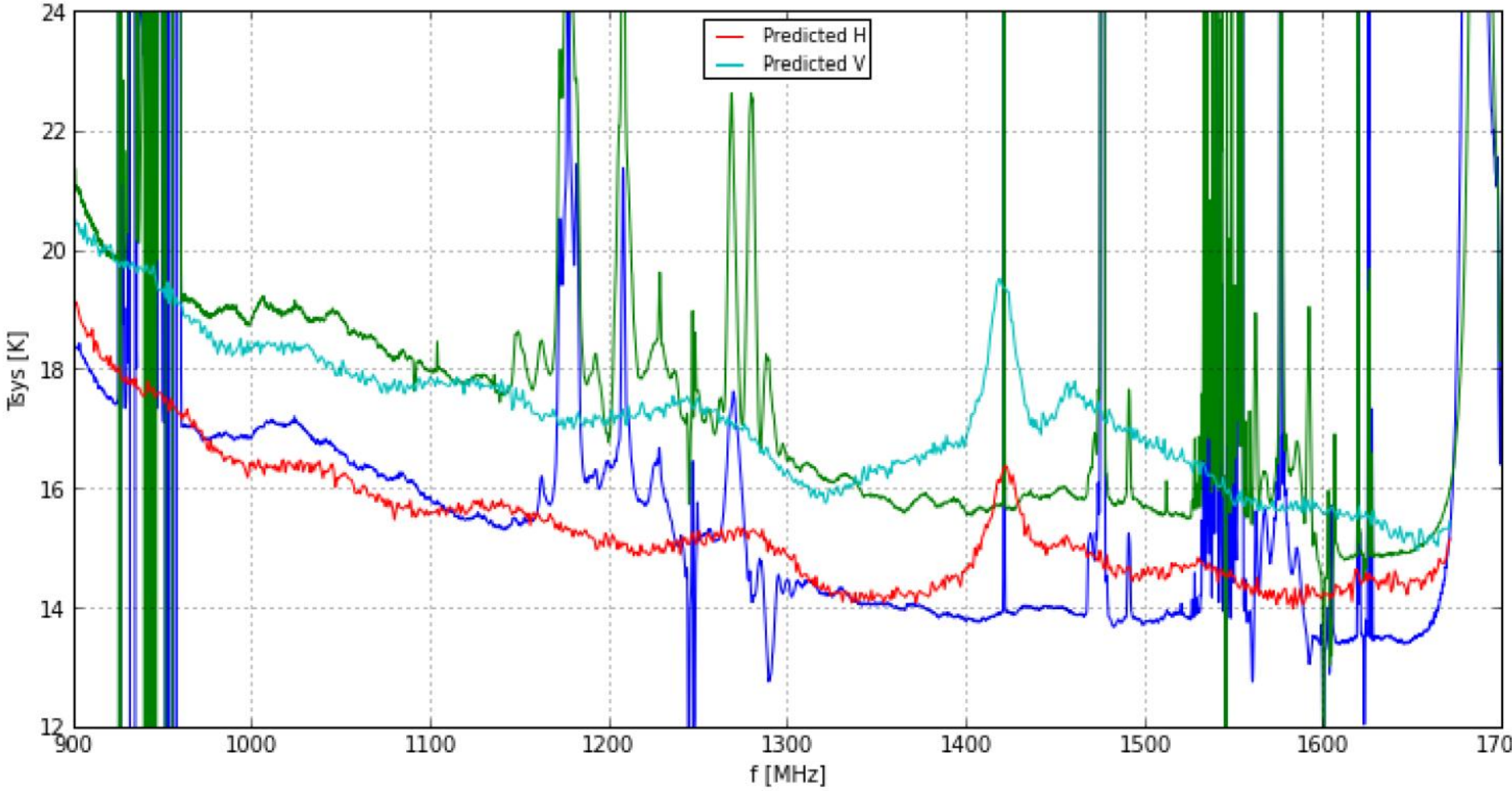
	Freq	Sampling rate (MSps)	Bits	Processed BW (MHz)	Project Stage
UHF-band	0.58 – 1.015	1088*	10	435	1
L-Band	0.9 – 1.67	1712	10	770	1
S-Band	*	*	*	*	2
X-band	8 – 14.5		3*	2000	3

** TBD/TBC*

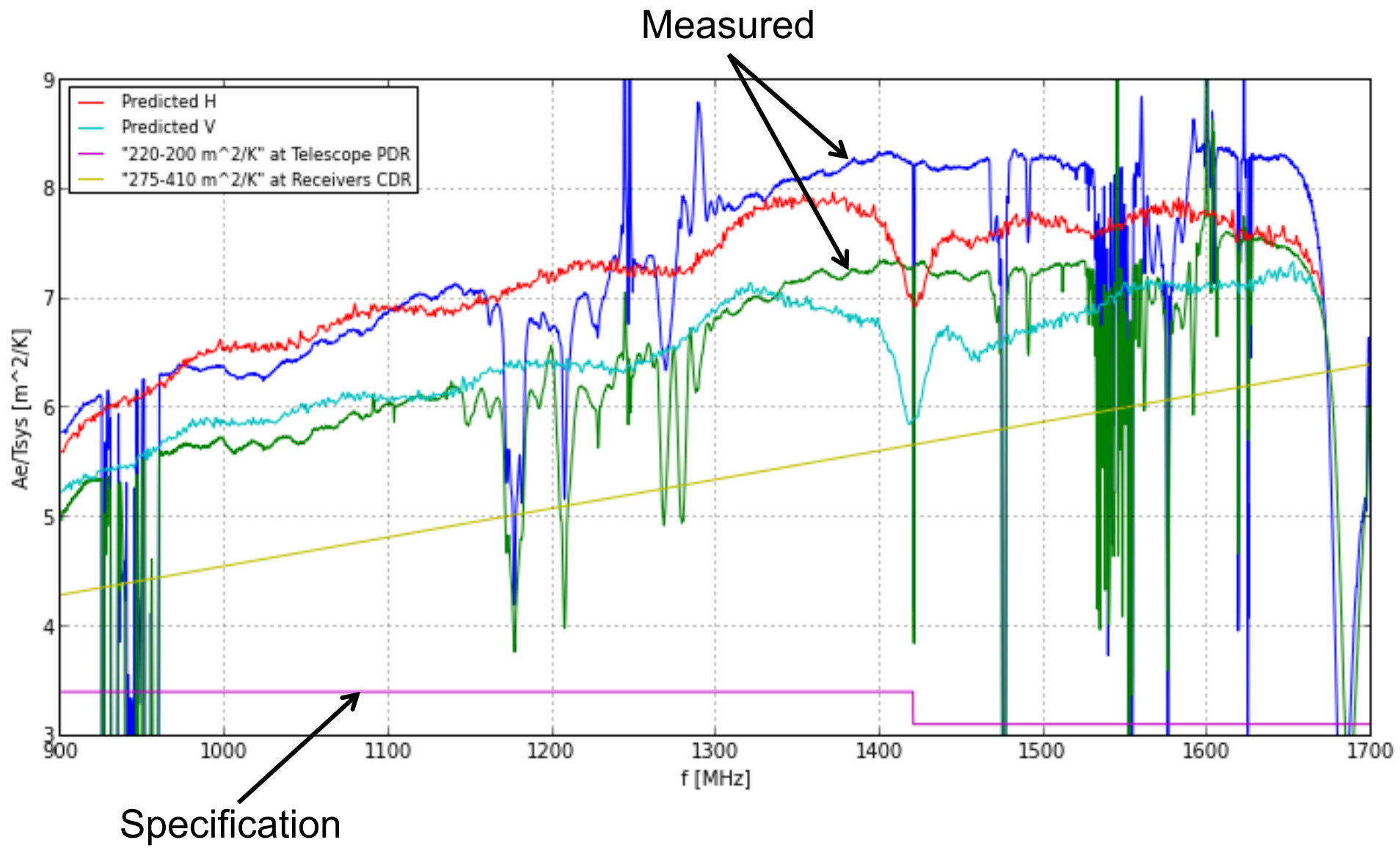
Receptor BD


Receptor Block Diagram (showing L-band Receiver only)
Key:
Rx Receiver Subsystem
D Digitiser Subsystem
AP Antenna Positioner Subsystem
RFN Receptor Fibre network
IS Infrastructure Segment
RSW Receptor Switch
Interface
Receiver Indexer
L-band receiver
Feed Horn
GM cooler
Cold head
Vacuum chamber
OMT & coupler
LNA
(22K)
LNA Stage 2
Resistive heating platform (0°C)
Noise source
LNA PSU
Vacuum valve
PSU
Power Filter
CAM unit
Helium
RF(H)
RF (V)
Noise switching
L-band Digitiser
Temperature stable platform
RF unit:
- Power detector
- Gain control
- Input protection
ADC
D-engine (Modified ROACH):
- Time stamp data
- Packetise
- Transmit to Correlator
- Control Noise switching
Time & clock unit
PSU
Power Filter
230V
S-band Rx
X-band Rx
UHF-band Rx
L-band Rx vacuum
230V X-Rx
230V S-band Rx
230V UHF-Rx
230V L-Rx
230V Digitiser
L-band Rx C&M (COM)
Data & C&M (10GbE)
1 PPS
Sampling clk
Vacuum Manifold
Power junction box
Fibre junction box
Vacuum
400V Vacuum Pump
400V He Compressor
Fibre
Helium Compressor
Outside Yoke
Pedestal
Feed indexer fibre cables
Receiver Controller
230V
Switch
RSW
Fibre patch panel
Receptor Data, C&M Fibre
Fibre Splice Box
Antenna Control Unit (ACU)
ACU sensors: (Structure temp, DB, door, etc.)
ACU shielded enclosure
400V ACU
400V Feed Indexer
Distribution Board
400V Receptor Power
Isolation Transformer
Wind sensors or VDS fire cables
Receptor fibre cables
Trenches

Receptor Performance – Tsys (L-band)



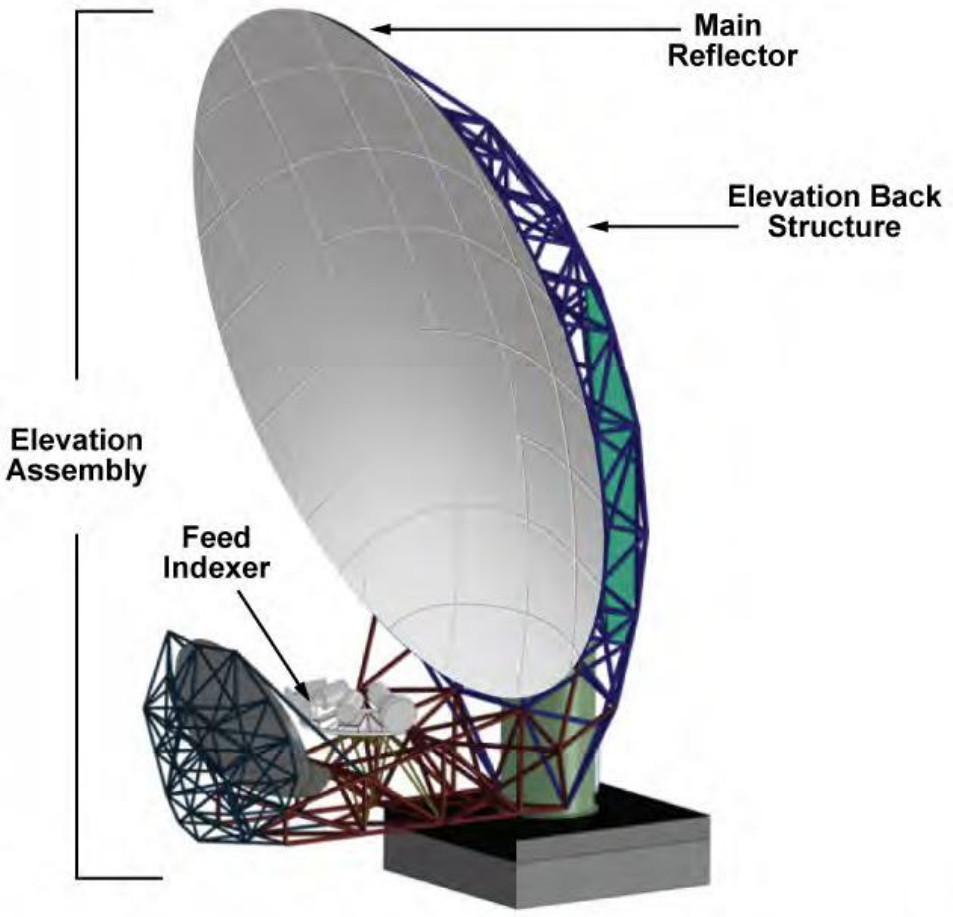
Receptor Performance – Ae/Tsys (L-band)



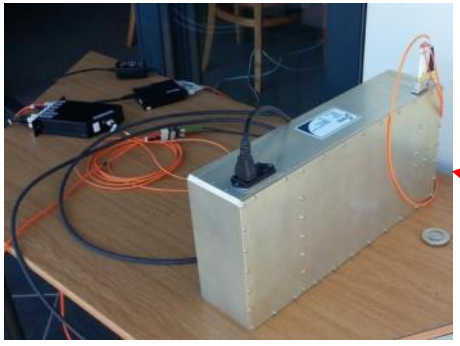
Antenna Positioner

Reflector and Positioner:

- Offset Gregorian optics gives rotationally symmetric beam for high imaging dynamic range
- High Aperture Phase Efficiency (91%) for sensitivity
- Low noise contribution (1.5K)
- High Pointing Accuracy (5” over 20min for good conditions, 25” over 4 hours for normal operational conditions)
- High slew speeds (2deg/sec Az, 1deg/sec El)



Receivers

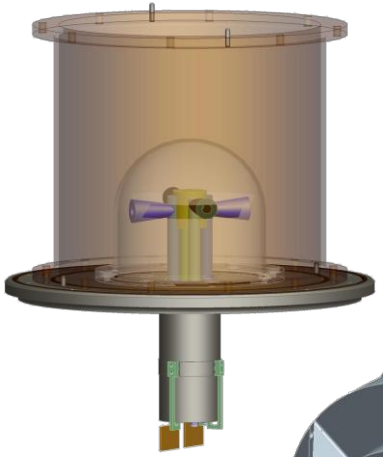


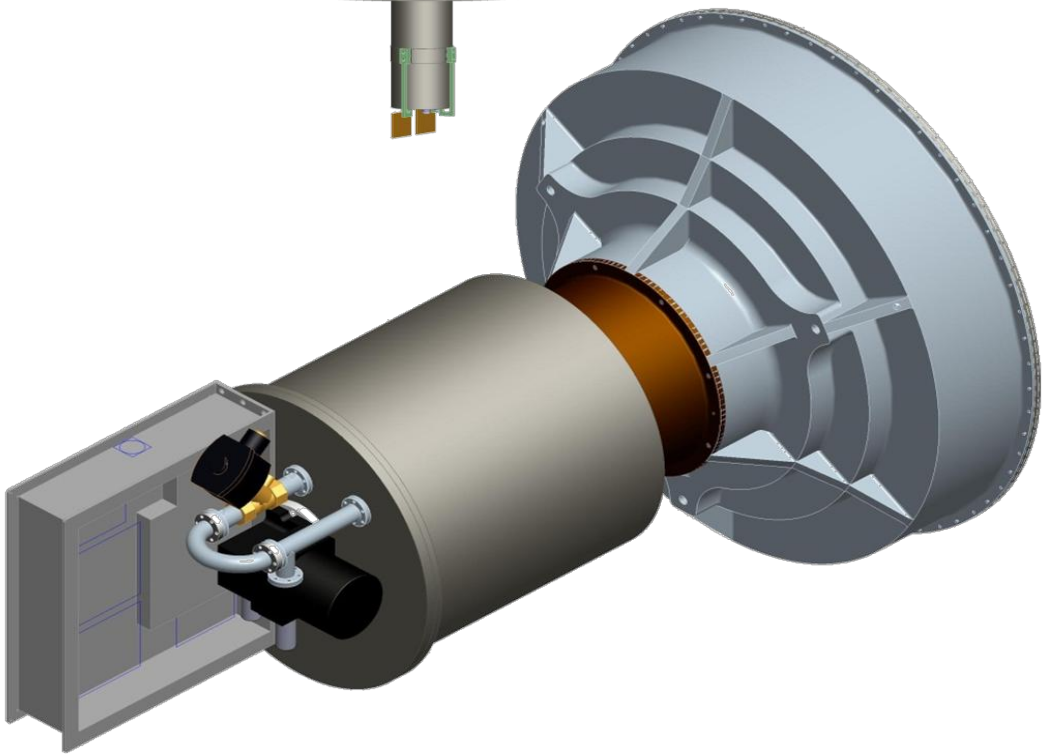
Receivers

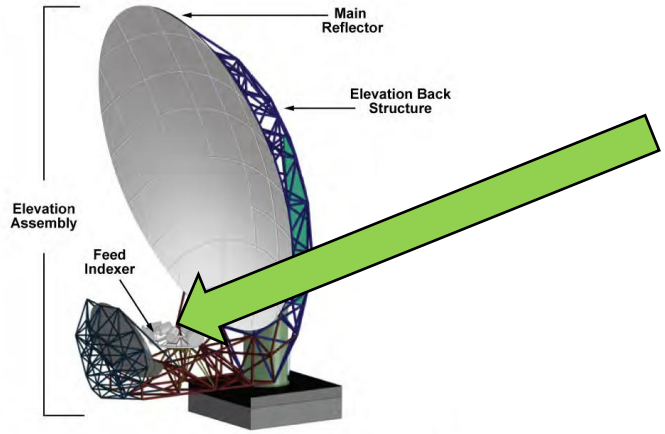
Receivers:

- UHF-band (580 – 1015MHz)
- L-band (900 – 1670MHz)
- X-band (8 – 14.5GHz)

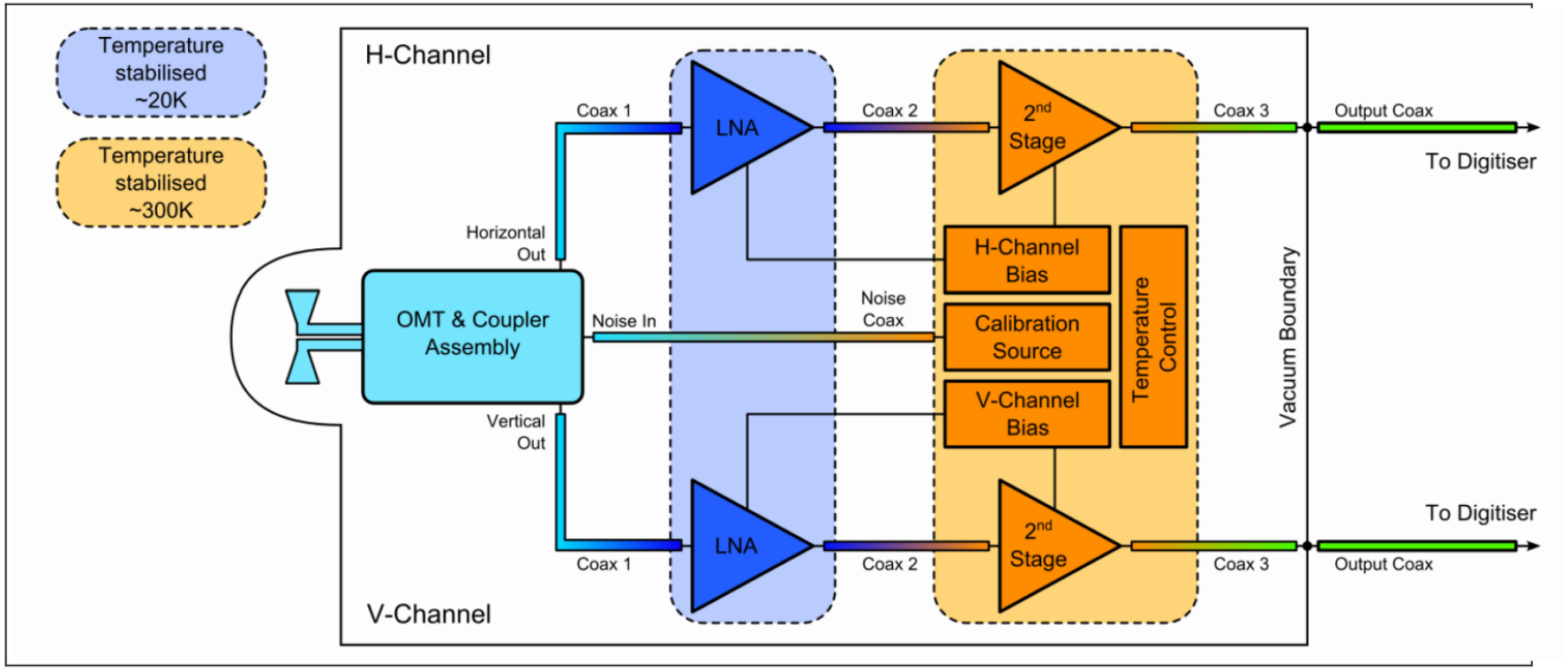
- Low receiver noise: GM cryogenic cooling with Novel OMT design
  - ($T_{Receiver}$ ~6K for L-band & UHF-band)
- High gain stability (0.7% over 20min)
- Polarisation Purity
- Stable calibration source
- Self-generated RFI was a big challenge







Receivers


Temperature stabilised ~20K
Temperature stabilised ~300K
H-Channel
Coax 1
LNA
Coax 2
2nd Stage
Coax 3
Output Coax
To Digitiser
Horizontal Out
H-Channel Bias
Noise Coax
OMT & Coupler Assembly
Noise In
Calibration Source
Temperature Control
Vacuum Boundary
Vertical Out
V-Channel Bias
To Digitiser
LNA
Coax 2
2nd Stage
Coax 3
Output Coax
Coax 1
V-Channel

L-band Receiver Noise Temperature

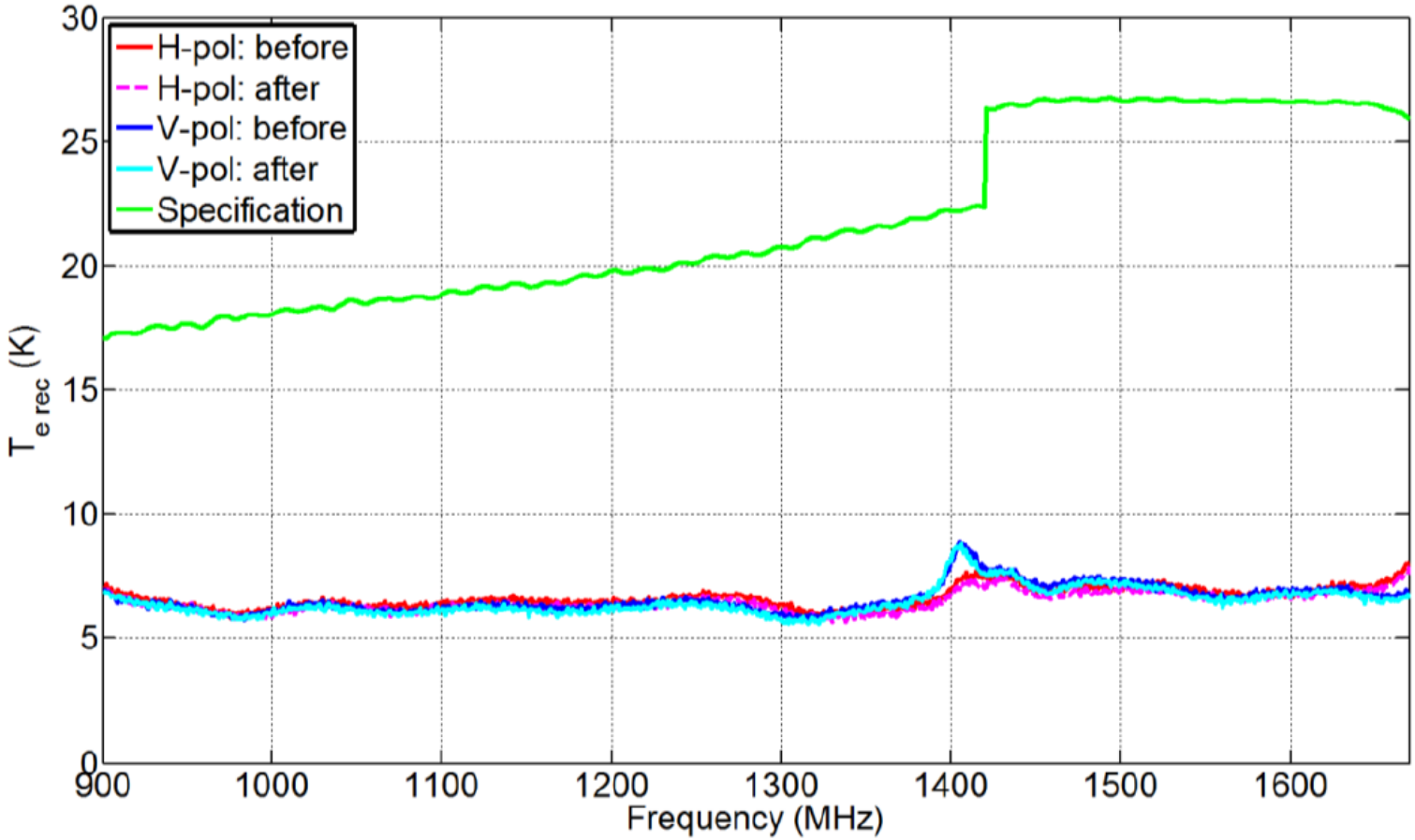
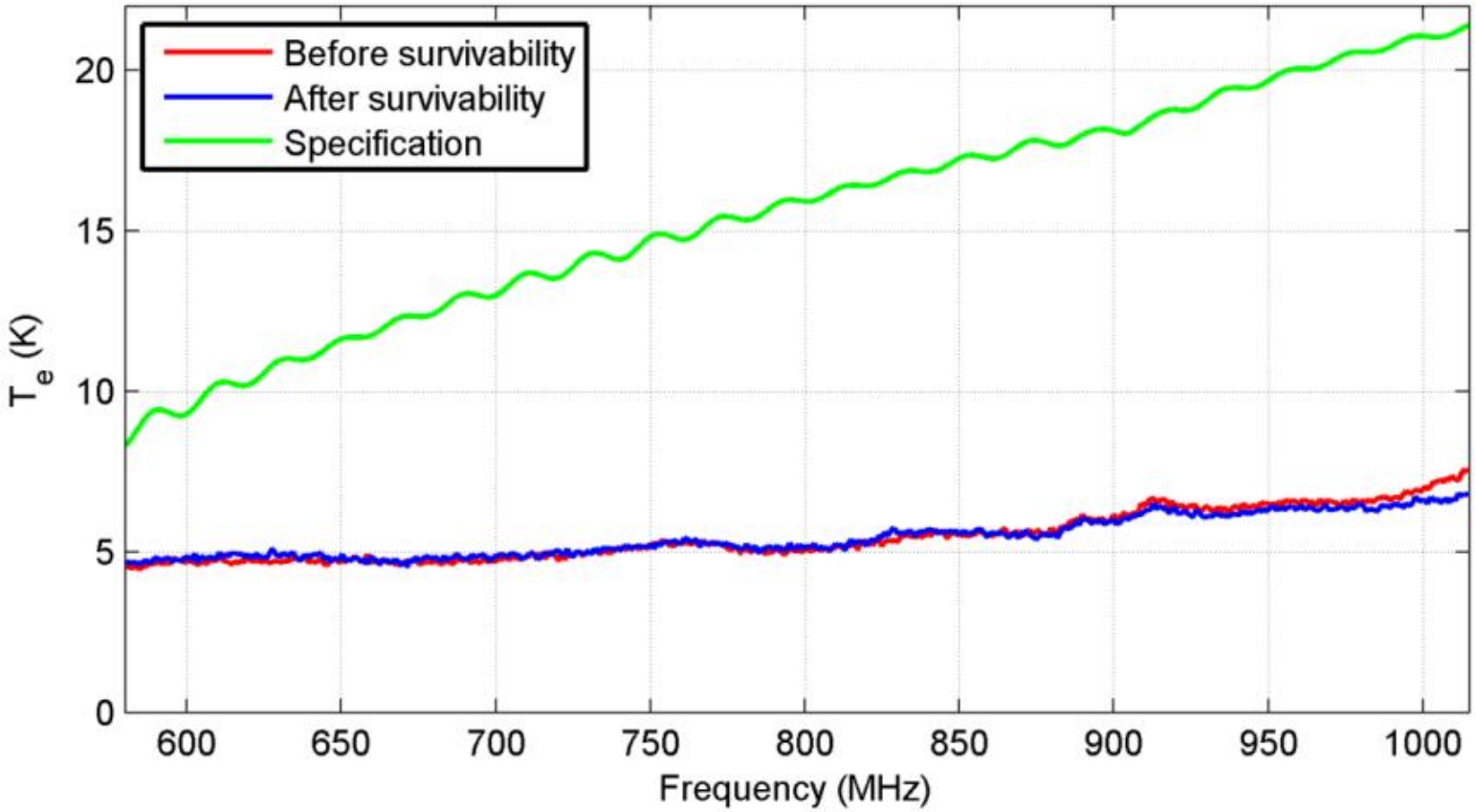


Figure 27: Receiver noise temperature measurement before and after destructive testing.

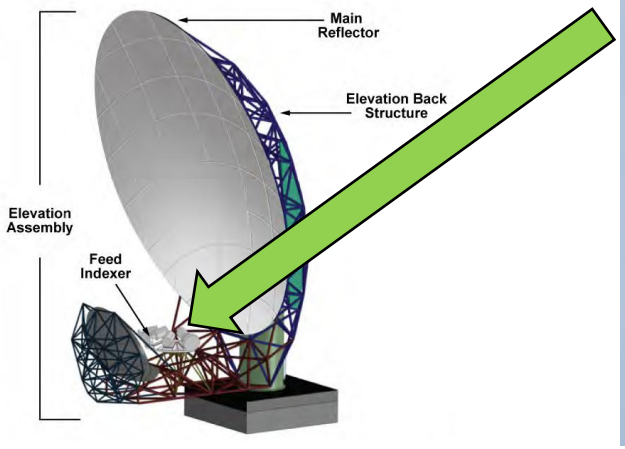
UHF-band Receiver Noise Temperature



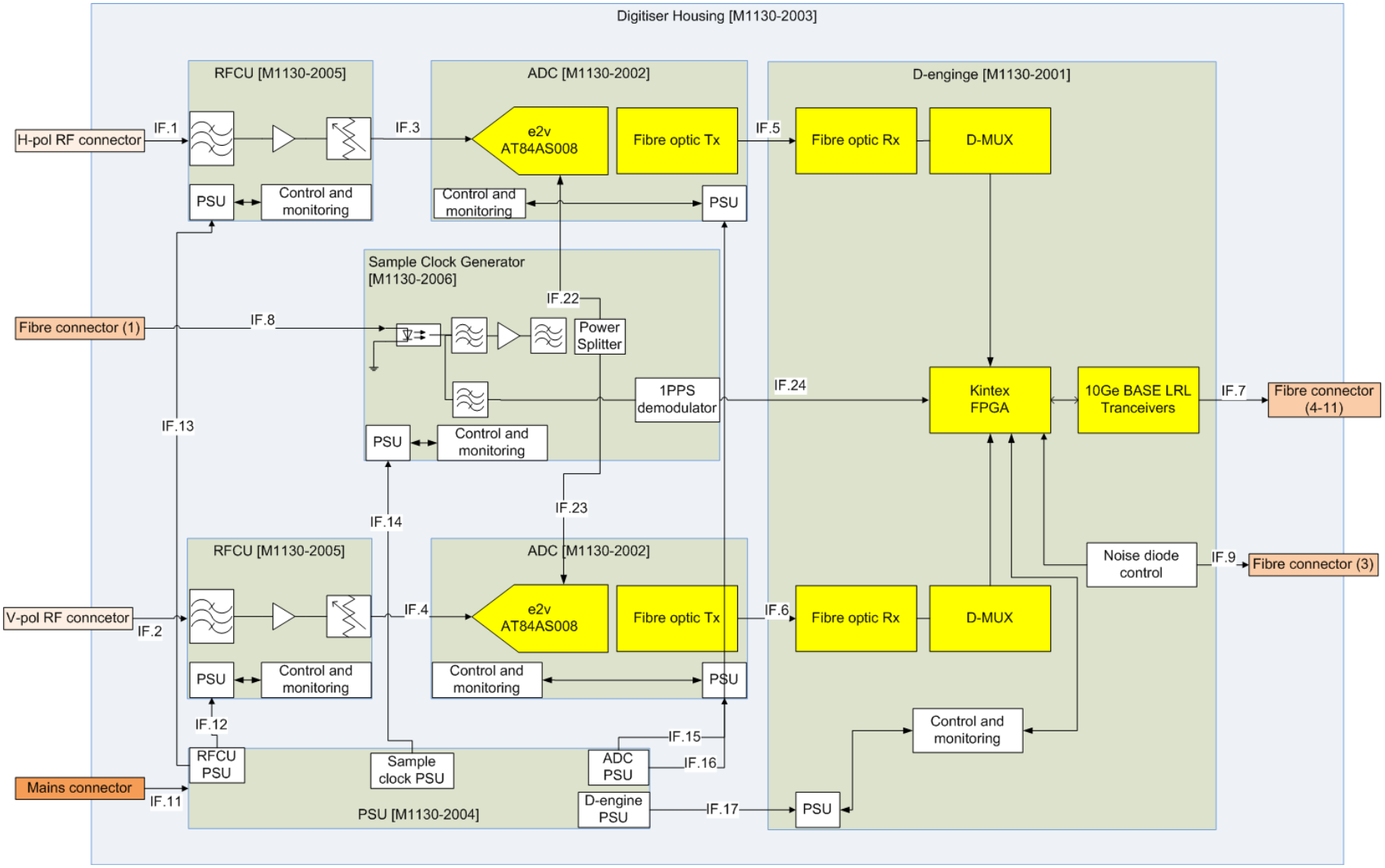
Digitiser

Digitiser:

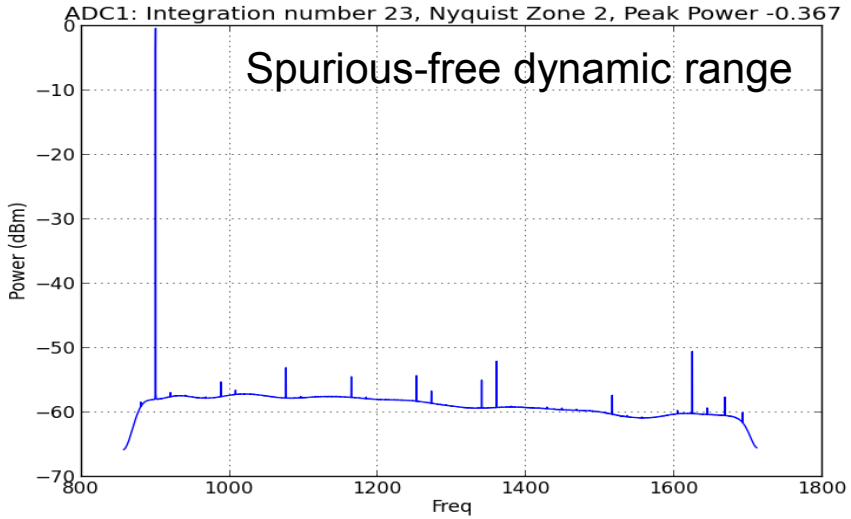
- Bandwidth (1.7GS/s for L-band sampling)
- Dynamic range /headroom for RFI → 10- bit sampling in L-band
- Gain & phase stability
- RFI is a big challenge

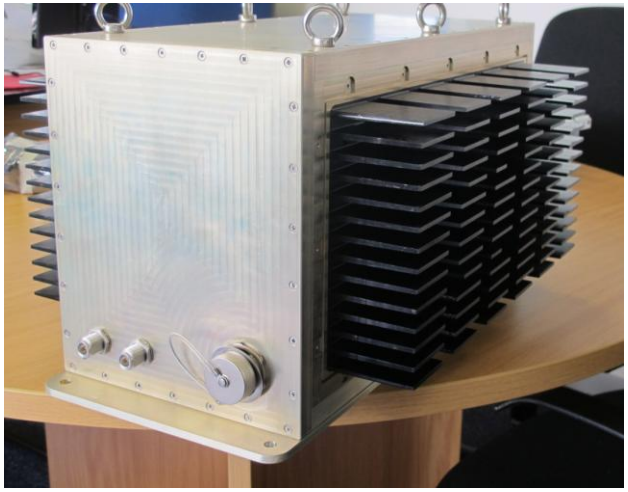


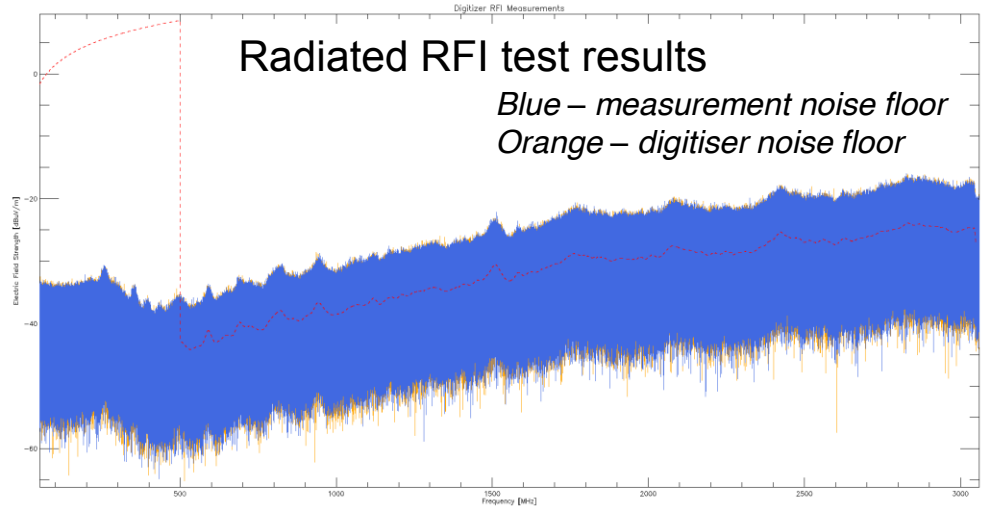
L-band Digitiser

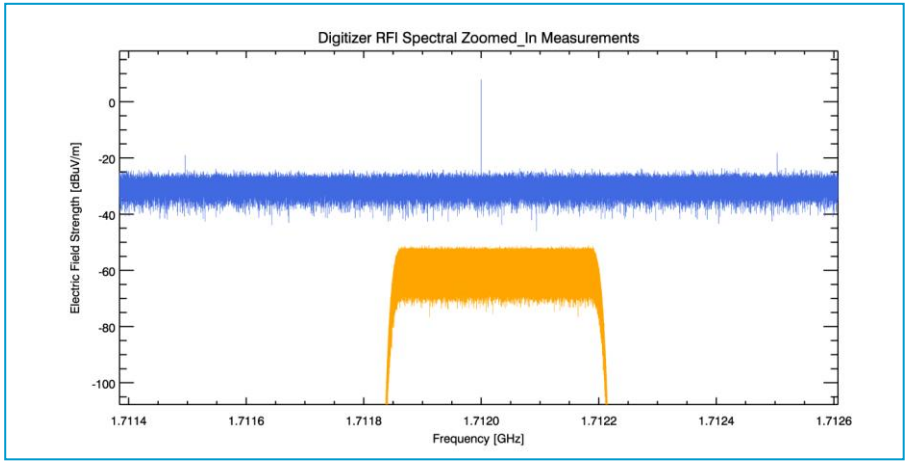


Digitiser

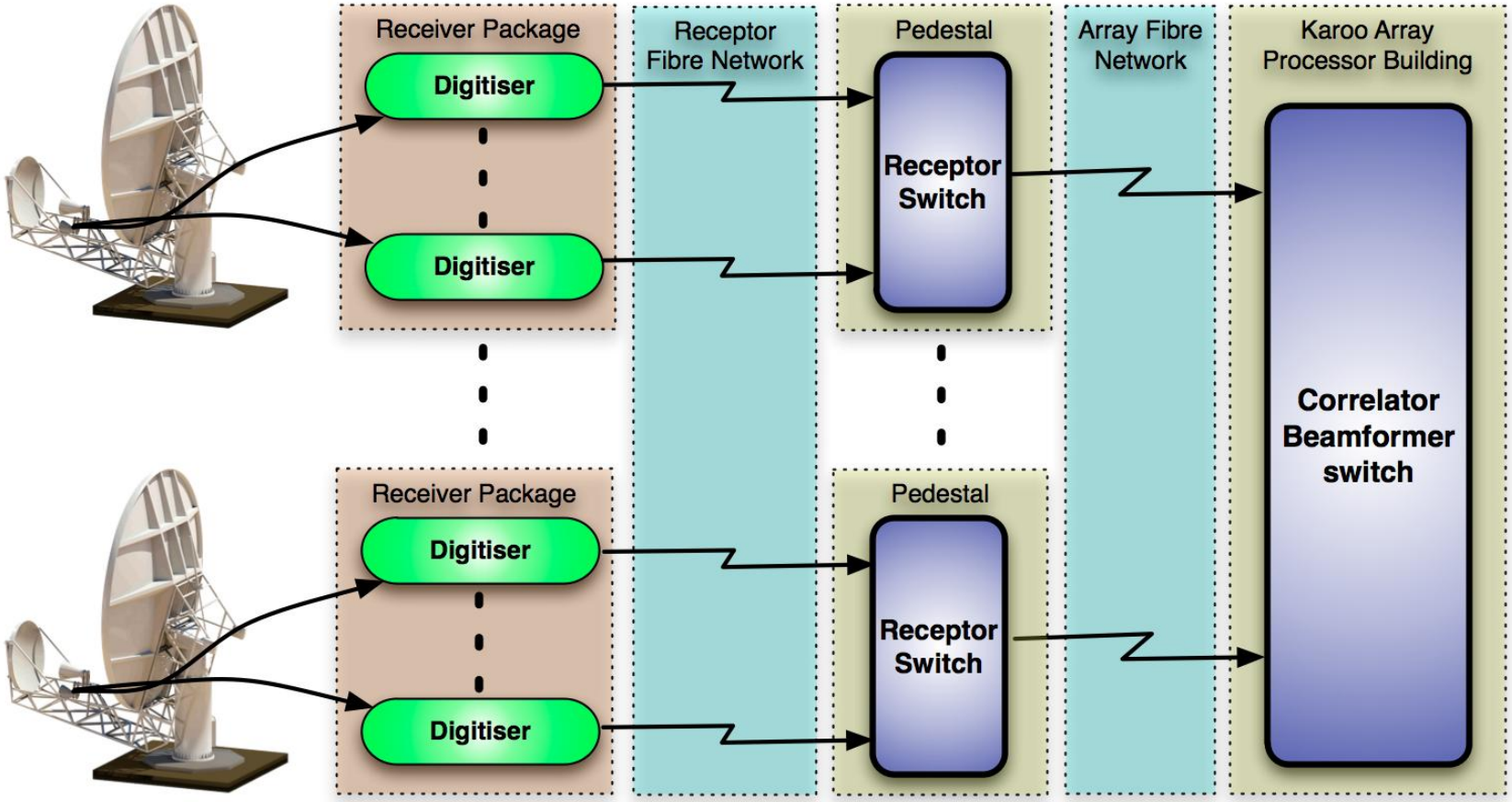

ADC1: Integration number 23, Nyquist Zone 2, Peak Power -0.367
Spurious-free dynamic range
Power (dBm)
0
−10
−20
−30
−40
−50
−60
−70
800
1000
1200
1400
1600
1800
Freq




Digitizer RFI Measurements
Radiated RFI test results
Blue – measurement noise floor
Orange – digitiser noise floor
Electric Field Strength [dBuV/m]
0
−20
−40
−60
500
1000
1500
2000
2500
3000
Frequency [MHz]


Digitizer RFI Spectral Zoomed_In Measurements
Electric Field Strength [dBuV/m]
0
-20
-40
-60
-80
-100
1.7114
1.7116
1.7118
1.7120
1.7122
1.7124
1.7126
Frequency [GHz]

From Receptors to Array Processor



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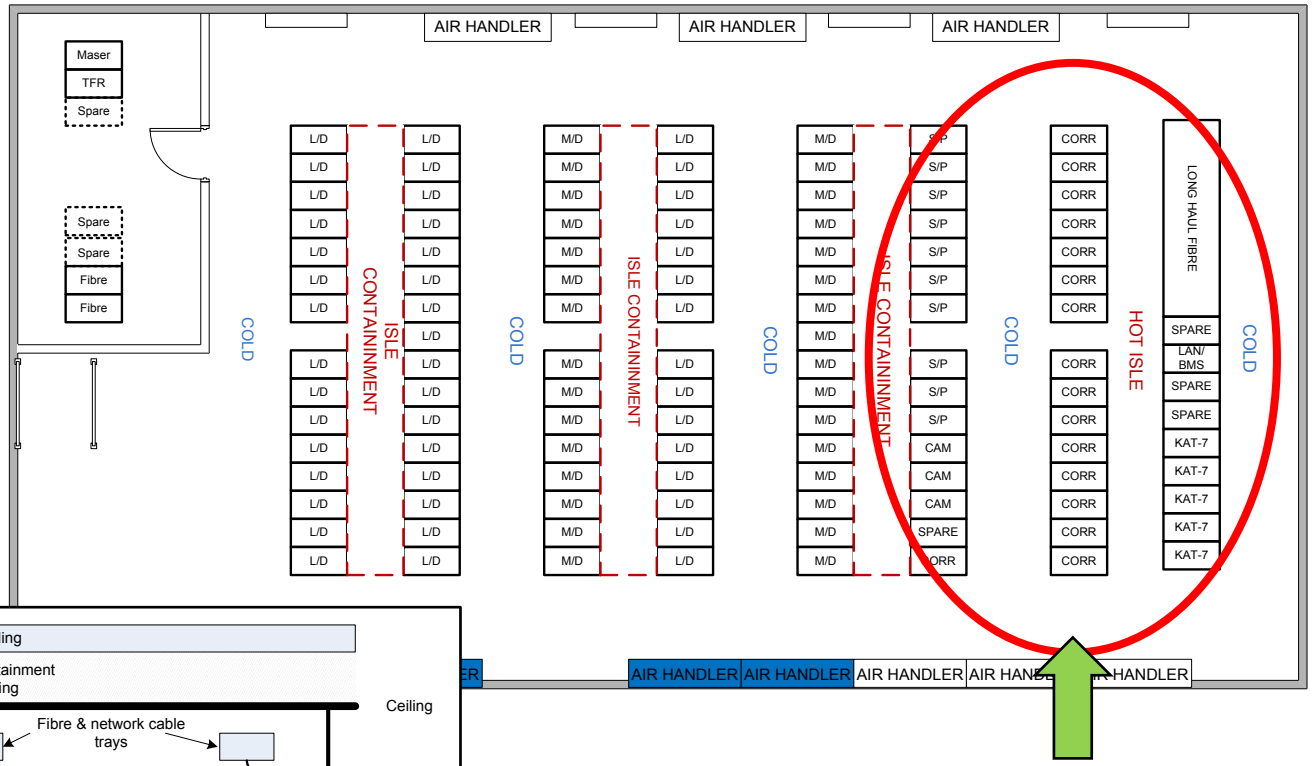
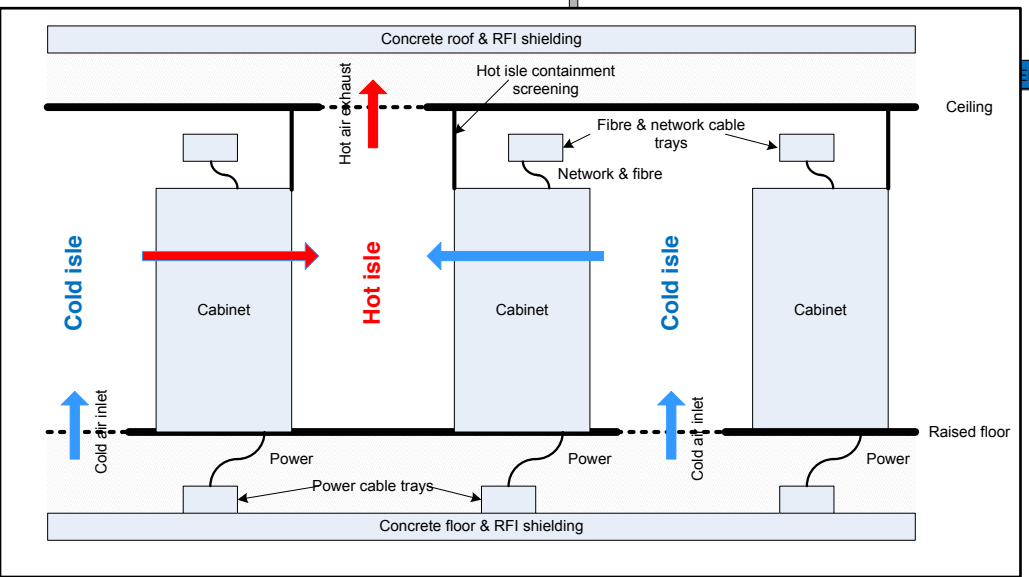
Site complex layout

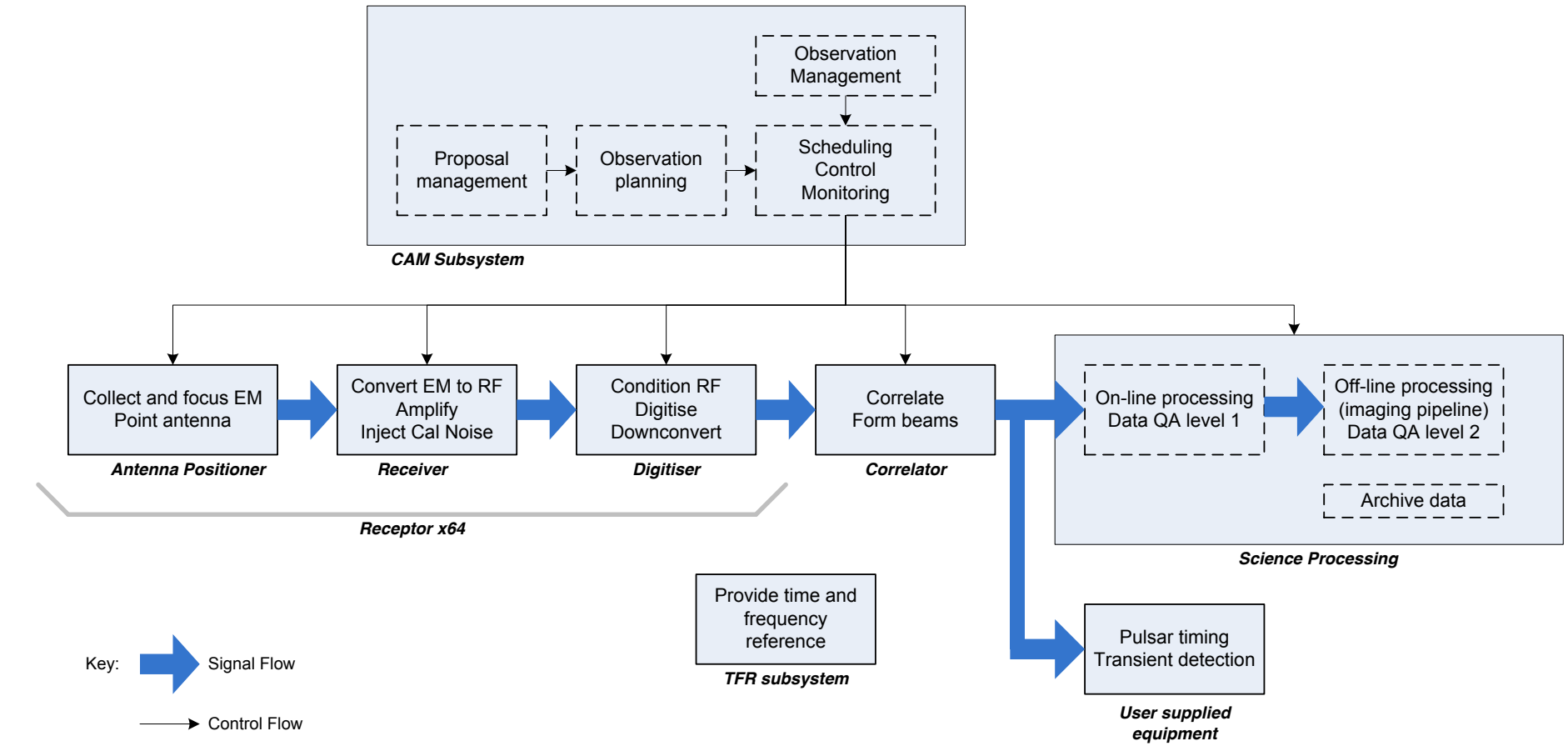
Karoo Array Processor Building



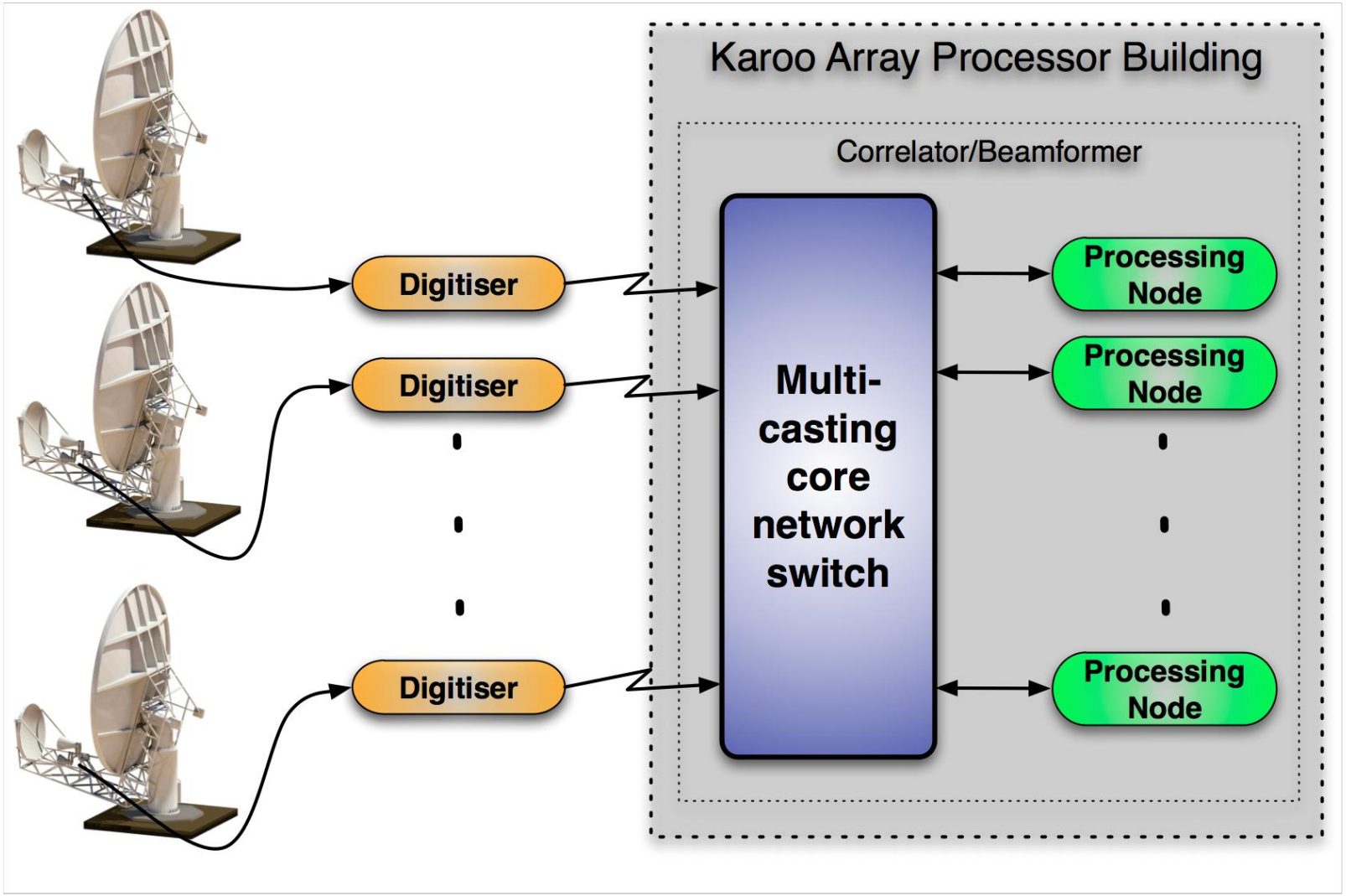
Used for MeerKAT & KAT-7



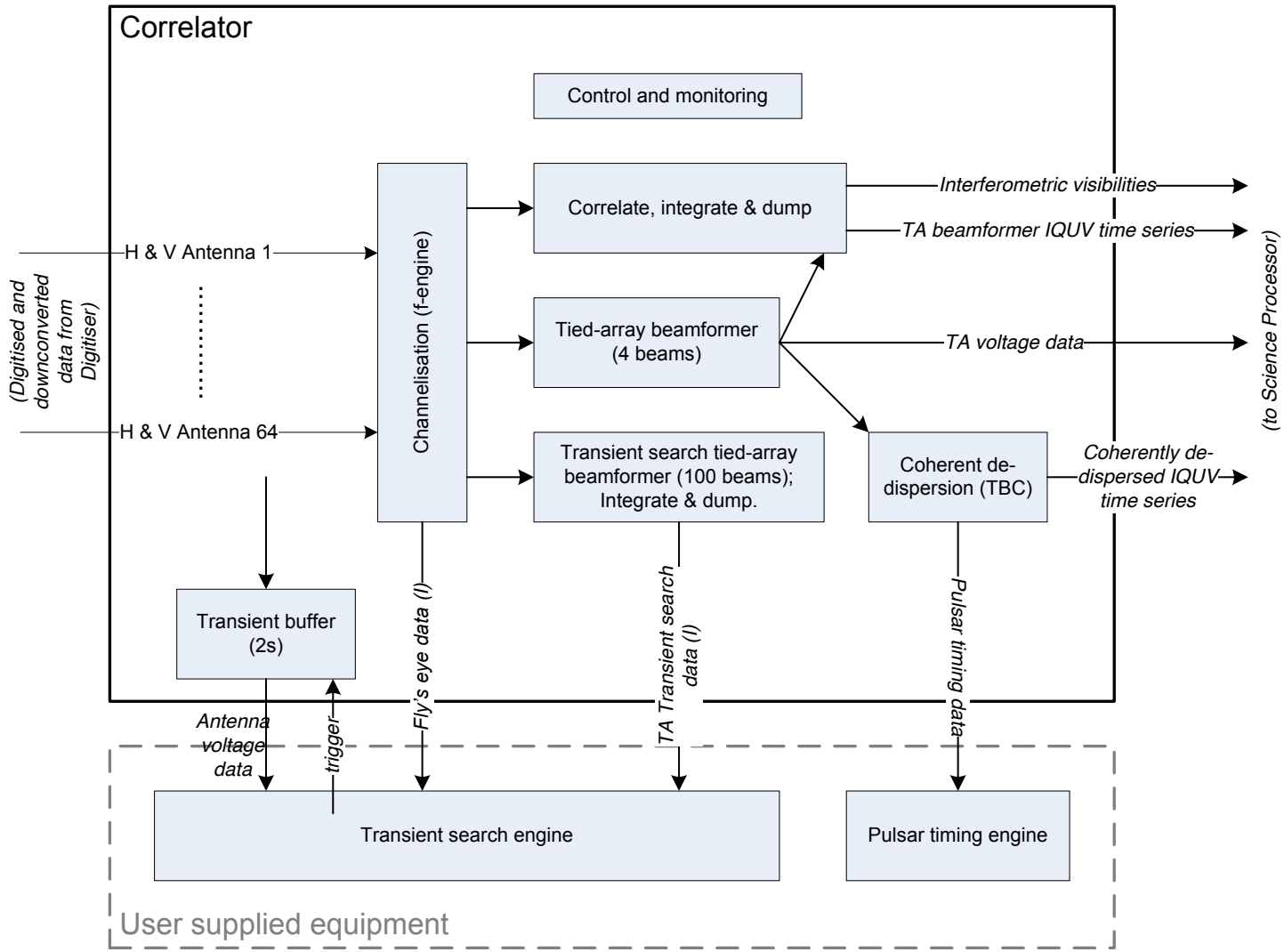
Back-end: functional overview



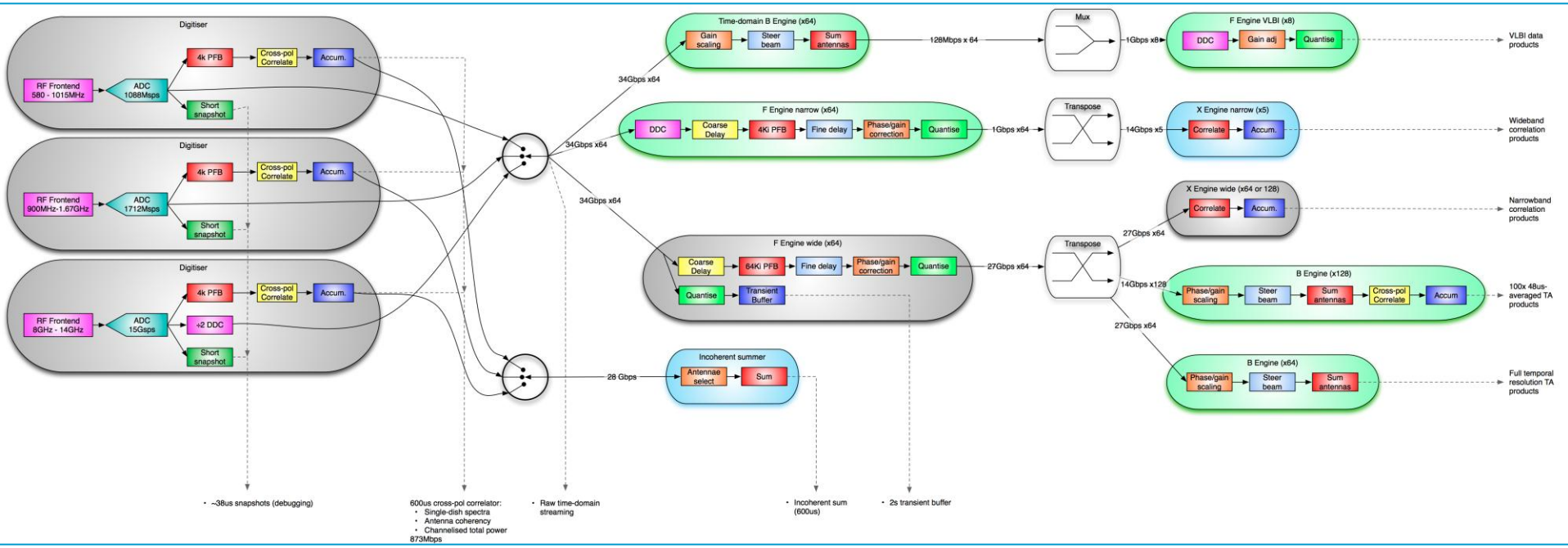
Correlator


Karoo Array Processor Building
Correlator/Beamformer
Digitiser
Digitiser
Digitiser
Multi-casting core network switch
Processing Node
Processing Node
Processing Node

Correlator functionality



Correlator functionality



Correlator functionality

Modes:	Channelisation configuration							Data products								
	Continuum	Spectral line full bandwidth	Spectral line fine resolution	Spectral line double resolution	Transient search	Pulsar timing	VLBI	Interferometric visibilities	TA cluster (x100) total power	Sum of antennas total power	Antennas voltage buffer	Antennas coherency products	TA (x4) voltage	TA (x4) Coherently de-dispersed coherency products	TA (x4) coherency products	
Imaging *sa & (sb or sc)*	Not im-plemen-ted	sa	sb	sc				sa & (sb or sc)		sa		sa				
Pulsar Timing	c					p		p		c		c		p		
Transient search					t			t	t	t		t				
Fly's Eye					t					t		t				
VLBI	c						v	v		c		c	v			
Generic TA	c							c		c		c	c		c	
Nr of sub bands	1	1	5 (6 for X)	5	1	TBD	1	0.1 - 1	50us	1ms	NA	600us	NA	1us	0.1 - 1	Time resolution
Channel BW (kHz): UHF (spec)	200	19.35	1.93	0.97	300	TBD	2^N x 500	32	32	64	8	32	8/16	64	64	Bit width
Channel BW (kHz): UHF (impl)	67.14	16.78	1.05	0.52	134.28	TBD	2^N x 500	SP	USE	USE	USE	USE	SP	SP&USE	SP	Transfer to (spec)
Channel BW (kHz): L (spec)	200	33.36	3.34	1.67	300	TBD	2^N x 500	106	66.7	0.04	28.2	28.8	65.5	0.65	0.03	Max data rate (spec) [Gbps]
Channel BW (kHz): L (impl)	110.35	27.59	1.72	0.86	220.7	TBD	2^N x 500	227	262	2.1	28.2	83.9	282	1.54	0.13	Max data rate (impl) [Gbps]
Channel BW (kHz): X (spec)	800	133.43	4	N/A	300	TBD	2^N x 500	y	y	y	n	y	y	n	y	Channelised
Channel BW (kHz): X (impl)	268.55	67.14	2.1	N/A	268.55	TBD	2^N x 500				2.5s					Buffer depth
Nr of channels: UHF (spec)	2175	22481	3495x5	3495x5	1450	TBD	32									
Nr of channels: L (spec)	3750	22483	3498x5	3498x5	1667	TBD	32	**Key:**		Required						
Nr of channels: X (spec)	2500	14990	3628x6	N/A	1667	TBD	32			Available data that may be subscribed to by the SP/USE						
Nr of channels: all (impl)	8192	32768	8192x5(6)	8192x5	4096	TBD	32			Used for TA phase up, not a system data product						
Tunable centre frequency	No	No	Yes	Yes	No	TBD	Yes			Probable implementation						
									SP	Science Processing Subsystem						
									USE	User Supplied Equipment						

Correlator functionality

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Modes:	Continuum	Spectral line full bandwidth	Spectral line fine resolution	Spectral line double resolution	Transient search	Pulsar timing	VLBI	Interferometric visibilities	TA cluster (x100) total power	Sum of antennas total power	Antennas voltage buffer	Antennas coherency products	TA (x4) voltage	TA (x4) Coherently de-dispersed coherency products	TA (x4) coherency products	
Imaging *sa & (sb or sc)*	Not im-plemen-ted	sa	sb	sc				sa & (sb or sc)		sa		sa				
Pulsar Timing	c					p		p		c		c		p		
Transient search					t			t	t	t		t				
Fly's Eye					t					t		t				
VLBI	c						v	v		c		c	v			
Generic TA	c							c		c		c	c		c	
Nr of sub bands	1	1	5 (6 for X)	5	1	TBD	1	0.1 - 1	50us	1ms	NA	600us	NA	1us	0.1 - 1	Time resolution
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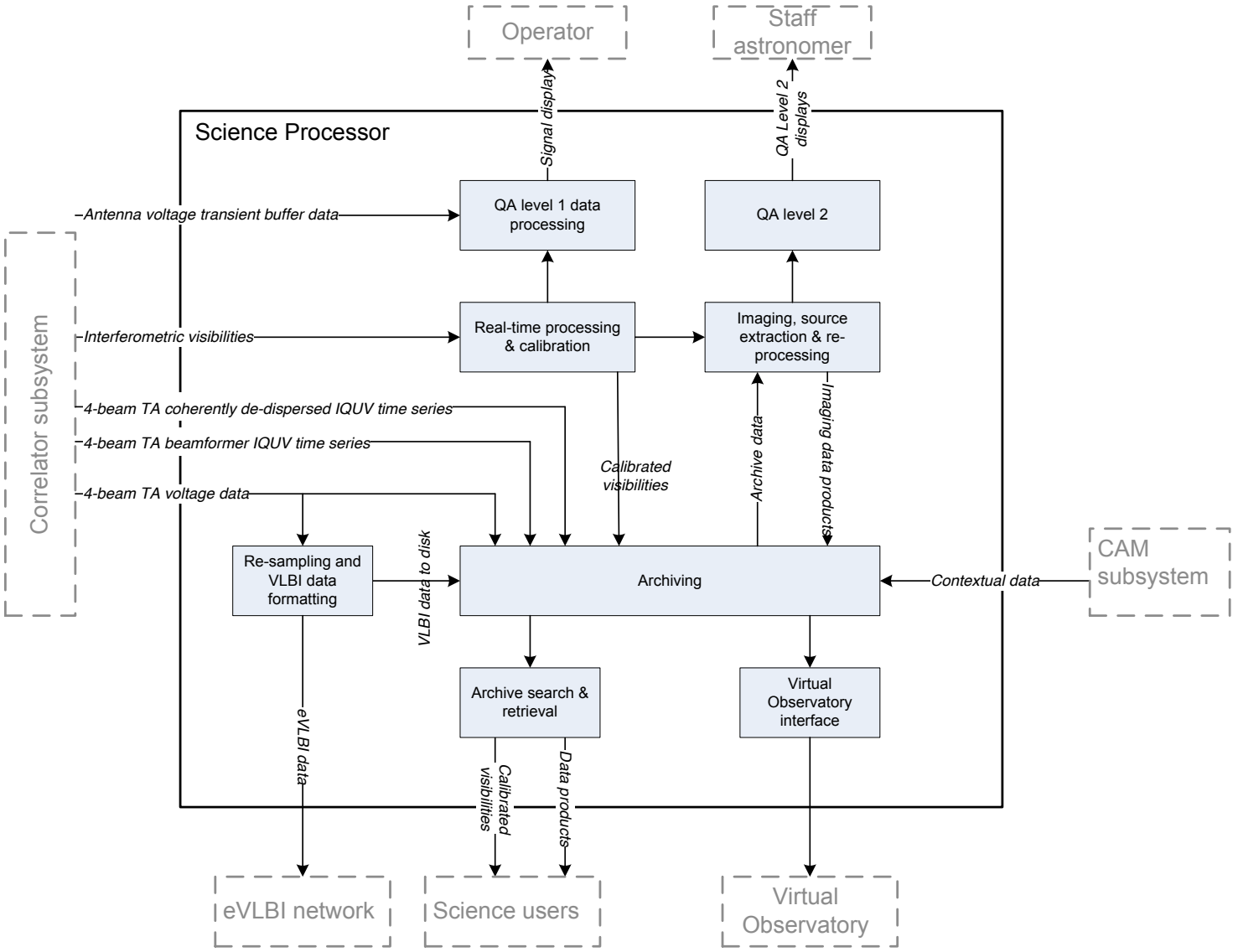
Nr of channels: L (spec)	3750	22483	3498x5	3498x5	1667	TBD	32									
Nr of channels: X (spec)	2500	14990	3628x6	N/A	1667	TBD	32									
Nr of channels: all (impl)	8192	32768	8192x5(6)	8192x5	4096	TBD	32									
Tunable centre frequency	No	No	Yes	Yes	No	TBD	Yes									

Key:

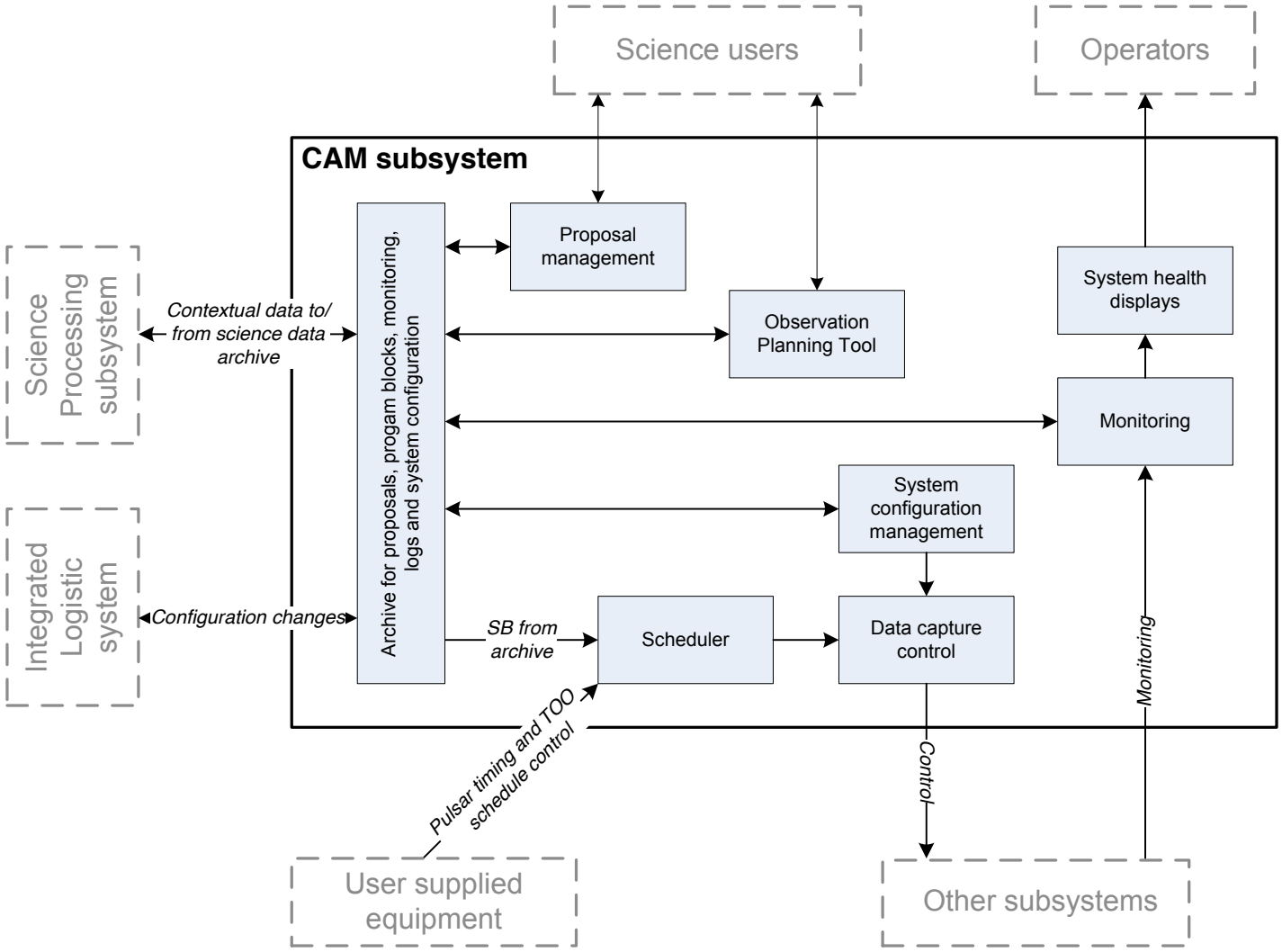
	Require
	Availab
	Used fo
	Probabl
SP	Science Processing Subsystem
USE	User Supplied Equipment

Update required for S-band

Science Processing



Control and Monitoring Subsystem (CAM)



Time and Frequency Reference

Generate stable reference tone:
(Active Hydrogen MASERs)

Generate absolute time reference:
- Calculate offset to UTC 5ns
- Produce stable 1PPS

Distribute stable reference tone (fibre)
Measure Round-trip phase (X-band only)

Distribute 1PPS (fibre)
Synch data time stamp to 1PPS (Digitiser)
Round trip time measurement

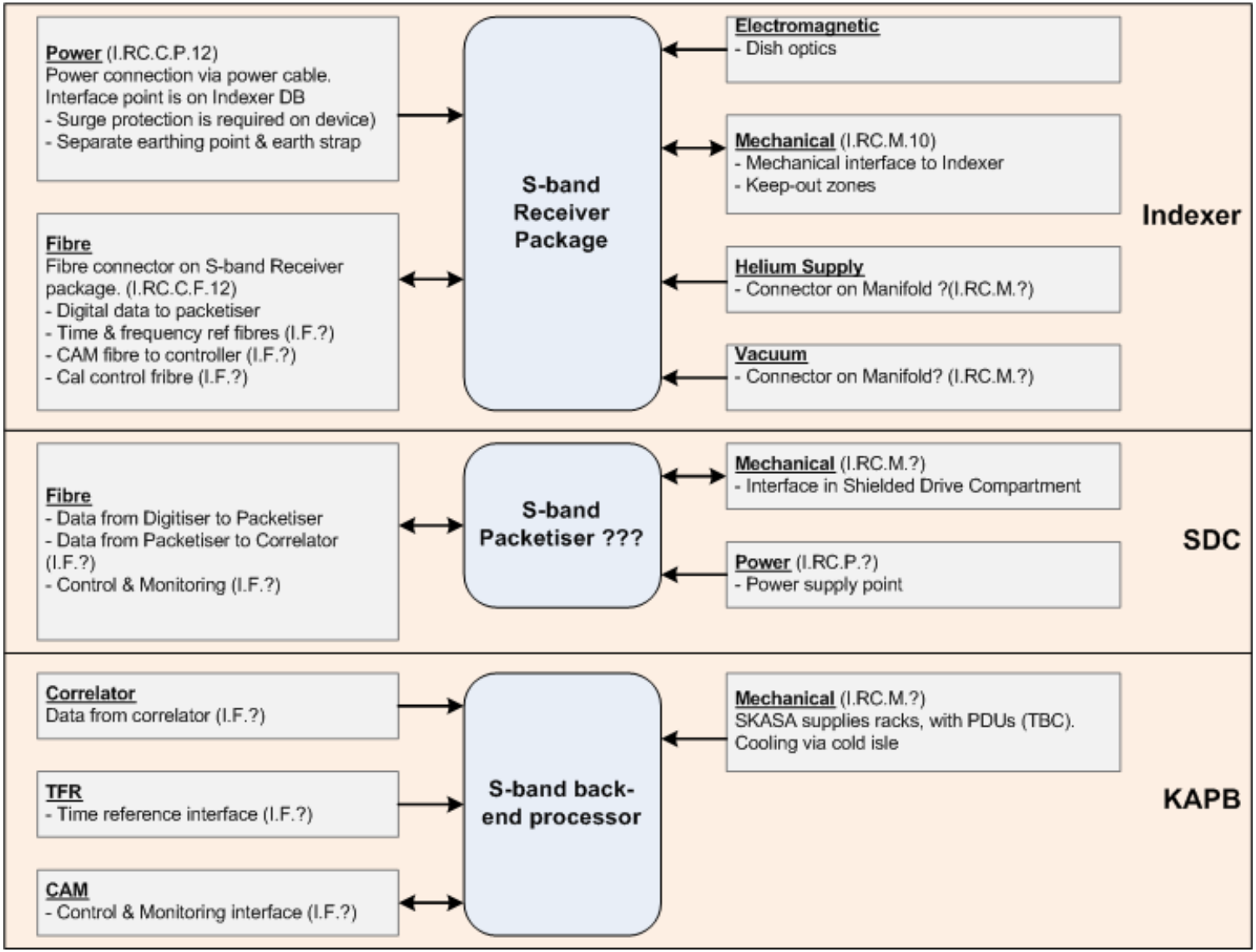
Distribute accurate time
(over the network using PTP or equivalent)

Coherent reference tone with stability of
$\leq 5 \times 10^{-15}$ for t > 1000 sec.
(for data sampling → Digitiser)

Absolute time ~1.6ns
(for data time stamping)

Absolute time ~100us
(for pointing control → antenna and correlator)

S-band Receiver interfaces



System Overview

End